EINDHOVEN UNIVERSITY OF TECHNOLOGY

The biaxial rig, exploring the possibilities and boundaries

Eindhoven University of Technology
Department of Mechanical Engineering
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Marjolein van der Glas

WFW-report nr. 98.038

Under supervision of:

Prof. P.J. Hunter
Dr.Ir. C.W.J. Oomens

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Preface

My stay in Auckland, New Zealand, has taught me a lot. Not only did I get the opportunity to do a part of my studies in a environment totally different from the one at the Eindhoven University of Technology. I was also able to experience the lifestyle of the far south. Furthermore, I improved my English, even though I got a really strange accent.

The study described in this report has been carried out at the University of Auckland as a part of my course in Biomechanical Engineering. I really enjoyed this part of my studies, thanks to many people who helped me. Special thanks goes to:

- Dr. Ir. Cees Oomens, who got me in touch with the University of Auckland and coached me during my stay.
- Prof. Peter Hunter, who invited me to his department and helped me doing my study.
- Dr. David Bullivant, who was able to connect and explain the setup.
- Phd-student Chris Bradley and Phd-student Warren Hedley, who explained me how to work with all those different software programs.
- Erik Folgering, for supporting me during my project, our holidays and the completion of this project
- The lads from the lab, as David Budgett once put it, for showing me around and having budgies with me.
- My friends in the Netherlands, for their huge amounts of e-mails which kept me in touch with home.

Furthermore I want to thank the Dutch Heart Foundation for the financial support they gave me and the Eindhoven University of Technology for their contribution in the travel expenses.

Finally, for most important people during my stay; Rob and Leanne thank you for giving me a place to stay, showing me around, introducing me to all your friends and family and good luck finding a new Dutch slave!

Samenvatting

Het bepalen van materiaal eigenschappen van natuurlijk weefsel is erg complex. Door het beschrijven van het mechanisch gedrag van het weefsel in een mathematisch model, kunnen er uitspraken gedaan kunnen worden over het gedrag van dat weefsel onder een mechanische belasting. Tevens kan de relatie tussen spanning en rek beschreven worden, zodat met een voldoende nauwkeurig constitutieve wet, de materiaal parameters van het weefsel te bepalen zijn.

Met behulp van een multi axiale trekbank kan het gedrag van een weefsel onder mechanische belasting bekeken worden. Het weefsel wordt in de trekbank met een grote nauwkeurigheid opgerekt door zestien actuatoren die zich in een cirkel om het weefsel heen bevinden. De krachten die nodig zijn om het weefsel op te rekken zoals is voorgeschreven, worden gemeten met behulp van zestien krachtopnemers. Het verplaatsingsveld van het weefsel wordt bepaald met behulp van markers die op het weefsel zijn aan gebracht. Met behulp van de verkregen verplaatsings- en krachtendata kunnen de materiaal eigenschappen van het geteste weefsel bepaald worden.

De vorm van het geteste stukje weefsel wordt gemodelleerd als een eindige elementen mesh. Met behulp van de verplaatsingsdata kan de vervormde mesh voor iedere oprekking bepaald worden. Deze vervormde mesh is ontstaan door oplegging van de gemeten krachten. Invoeren van deze krachten en de constitutieve wet van het Mooney Rivlin model zorgt ervoor dat de materiaal parameters bepaald kunnen worden.

De experimentele opstelling en de numerieke berekeningen geven een indruk van het materiaal gedrag van de geteste weefsels. De mogelijkheden en beperkingen van de totale opstelling worden in dit onderzoek bekeken.

De experimenten zijn uitgevoerd met twee verschillende materialen, rubber en pericardium. Er is gebruik gemaakt van drie verschillende rubber membranen, een homogeen isotroop, een inhomogeen isotroop en een homogeen anisotroop membraan. Het gedrag van deze membranen is door de bekende vorm te voorspellen. Over het gedrag van het pericardium daarentegen is nog weinig bekend.

Na de uitvoer van de experimenten en de numerieke berekeningen blijkt dat het mogelijk is om inhomogeniteit aan te tonen. De nauwkeurigheid van de experimentele opstelling wordt echter beperkt door de krachtopnemers, die slechts in een richting krachten kunnen meten. Verder zal een

complexer constitutief model waarschijnlijk leiden tot meer inzicht in andere materiaal eigenschappen, zodat het ook mogelijk wordt om bijvoorbeeld de vezel richting van anisotroop materialen te bepalen.

Summary

Determination of the material properties of natural tissue is rather complex. Describing the mechanical behaviour of the tissue in a mathematical model makes it possible to predict the behaviour of this tissue under a mechanical load. The relationship between stress and strain can be determined at the same time. With this information and an accurate constitutive model, the material parameters of the tested tissue can be estimated.

The biaxial rig makes it possible to examine the behaviour of a tissue under stress. The tissue in the rig is stretched with high accuracy by means of sixteen actuators arranged concentrically around the tissue. The forces, necessary to stretch the tissue as prescribed, are measured by sixteen force transducers. The displacement field in the tissue can be determined by using markers on the tissue. With the known forces and displacements fields, the material properties of the tested tissue can be calculated.

The shape of the tested membrane is converted into a finite element mesh. The deformed mesh can be calculated by fitting the different displacement fields. This deformation is caused by the measured forces. Introducing these forces into the model and adding the constitutive law of Mooney-Rivlin makes it possible to estimate the material parameters.

The experimental setup and the numerical calculation gives an opportunity to get an impression of the material behaviour of the tested tissue. The possibilities and boundaries of the total setup are being explored in this study.

The experiments are run with two different materials, rubber and pericardium. Three different rubber membranes are used; a homogeneous isotropic, an inhomogeneous isotropic and a homogeneous anisotropic membrane. Because of the known form, the behaviour of these rubber membranes is predictable. Of the behaviour of the pericardium membrane however is known little.

Results of the experiments and numerical calculations show the possibility of determining the inhomogeneity of a material. The accuracy of the experimental setup depends on the accuracy of the force transducers, that only measure forces in radial direction.

Applying a more complex constitutive law probably will give more understanding in the material properties. This will give the opportunity to determine, for example, the fibre direction of an anisotropic material.

Contents

Chapter 1

Introduction

Biological tissue normally has a complex structure. Knowledge of the mechanical behaviour of biological tissues is important for many reasons. Knowledge of the mechanics of cardiac tissue can, for example, contribute to a better understanding of the hearts electrical activation, coronary blood supply and chemical energetics. It is important to identify the structure and mechanical behaviour of the cardiac tissue in order to determine the causes of the rhythm disturbances that lead to failure.

It is preferable to catch the mechanical behaviour into a mathematical model, from which statements can be posed about he behaviour of a certain material under the influence of a mechanical load. These models are able to describe the geometry of the material as well as the relation between strains and stresses in the material, i.e. the constitutive laws. Under the assumption that, for all material types, a sufficiently accurate constitutive law exists, this law can be quantified by means of a set of material parameters. The challenge is to determine the values of these material parameters as accurate as possible.

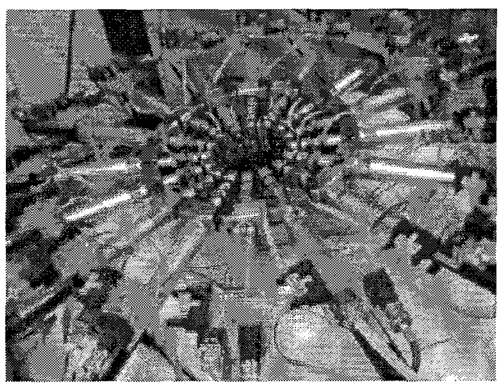


FIGURE 1.1: The biaxial rig

The material properties of natural tissue are too complex to be determined by simply stretching the material in two points. That is why the biaxial rig is developed. With this rig, the material is stretched in sixteen different directions. The data gain from experiments with the biaxial rig will give more information about more material parameters of the tested material.

The possibilities of this rig are not unlimited. In this report, the possibilities and boundaries of the biaxial rig are discussed. Furthermore, interpretation of the results of tests done on the rig is made possible by numerics.

Before examining the rig, the material out of which the membranes tested on the rig are made, are presented in the chapter 2. In this chapter the kinematics of highly deformable materials are explained.

The experimental setup, consisting of the biaxial rig and a data control system is described in chapter 3. The accuracy and reproducibility of the setup are also discussed in this chapter.

The experiments run with the biaxial rig are done with four membranes, three different orientated rubber made membranes and one pericardium membrane. The way this experiments are done, the results and the numerical calculations are explained in chapter 4.

Finally, in chapter 5 the steps made in this report are discussed. The conclusions are drawn and recommendations for next studies are done.

Chapter 2

Theory

The material behaviour of biological tissue is not easy to determine. Not only is the behaviour inhomogeneous and anisotropic, it varies in time as well. The material properties depend on the condition the biological material is in. In order to predict the behaviour of biological tissue, it is important to understand why materials react in the way they do.

2.1 Material properties of rubber

Rubber is known for its elasticity, which shows high elastic deformability under comparatively small loads. As long as the loads are small enough, plastic deformation will not occur, which means that after removing the load, the rubber will change back to his original size. The maximum extensibility for rubber normally varies from 500 to 1000 percent.

The Young's modulus of rubber is, for small extensions, in the range of 0.05 [GPa] for synthetic rubbers to 3.5 [GPa] for volcanic rubbers. This values are very low in comparison to the values for hard materials, which range from 70 [GPa] up to 205 [GPa]. The maximum extensibility is in the order of one percent.

The values of this material properties for rubber are similar to the values for various biological tissues, which makes rubber a tissue that represents the simplest form of biological tissue.

Normally rubber is produced in a way that it is homogeneous and isotropic, but by changing the form and height, it can be made inhomogeneous and even anisotropic. By understanding the behaviour of different shaped rubber, the behaviour of biological tissue can be predicted more closely.

2.2 Pericardium

In this study, bovine pericardium is used for the experiments, as an example of a biological tissue. Pericardium is the membraneous sack, which encloses the heart of most mammals. Pericardium is thought to be the tissue that holds the heart in a fixed position, protects it from other organs and prevents over-distension of the heart. Because of its expected role in the mechanics of the heart, it is important to get a detailed knowledge of the mechanical behaviour of the pericardium.

The pericardium consists of two membranes, made of two different tissues; fibrous and serous pericardium. Fibrous pericardium is composed of interlaced collagen and elastin fibres, while the serous pericardium is made of a smooth layer of epithelial cells. The inner membrane, the visceral pericardium or epicardium, covers the outside of heart wall and consists of one layer of serous pericardium. The outer membrane, the parietal pericardium or pericardial sack is made of an inner layer of serous pericardium and an outer layer of fibrous pericardium. The structure of the pericardial sack causes the non-linear behaviour of the pericardium. The outer membrane has been studied mostly, because of its mayor role in cardiac mechanics. In this study, the parietal pericardium will simply be referred to as 'pericardium'. The pericardium is thought to have several functions:

- It holds the heart in fixed position
- It prevents over-destension of the heart
- It protects the heart from neighbouring organs
- It enhances the interaction between the ventricles
- It affects the ventricular pressure-volume curve
- It restricts free myocardial expansion, which can effect myocardial wall stresses

It is known that the role of the pericardium in cardial mechanics can not be neglected.

2.3 Kinematics

Mathematical tools, used to describe the deformation quantities of highly deformable materials, such as rubber, are necessary to predict the mechanical behaviour of the particular materials. The kinematics of a deforming body can be described with the deformation tensor $\boldsymbol{F}$. This tensor transforms an infinitesimal material vector in a reference situation into a vector in a deformed situation.

$$dx = \boldsymbol{F} \cdot dx_0 \tag{2.1}$$

This tensor contains information about the rotation and the stretching of the material vectors. The right Cauchy-Green tensor $\boldsymbol{C}$ is independent of rigid body motion and contains information on the squared material vector lengthes and can easily be computed by:

$$\boldsymbol{C} = \boldsymbol{F}^T\boldsymbol{F} \tag{2.2}$$

The tensor $\boldsymbol{C}$ is a second order symmetric tensor and has three invariants I_1, I_2 and I_3 which are given by:

$$I_1 = tr(\boldsymbol{C}); I_2 = 0.5(tr(\boldsymbol{C})^T - tr(\boldsymbol{C}^2); I_3 = det(\boldsymbol{C}) \tag{2.3}$$

The invariants are independent of the coordinate system at a given deformation state. For incompressible material, $det(\boldsymbol{C}) = 1$. A special truncated form of the strain energy function, that is often used for rubber is the Mooney-Rivlin function, which is valid for strains up to about 100 % (Crisfield 1997):

$$\phi = C_1(I_1 - 3) + C_2(I_2 - 3) \tag{2.4}$$

In which C_1 and C_2 are material parameters that determine the properties of the considered material.

Chapter 3

Experimental setup

The experimental setup is described shortly in this chapter. This setup has been made by Peter Apperley (Apperley 1996) and improved by Henri Brouwers (Brouwers 1997). The experimental setup consists of two parts, the biaxial rig and a data and control system. The actual testing of membranes takes place in the biaxial rig. The control system controls the movement of the actuators and collects the output information. The flow diagram for this experimental setup is shown in figure 3.2. Instructions, on how to use this setup and run a test are given in appendix A. The accuracy of this setup is tested and discussed in the last section of this chapter.

3.1 Biaxial rig

The biaxial rig consists of a frame with sixteen computer controlled actuators, arrayed circularly, being capable of moving independently in the radial direction. The frame has the shape of a cylinder with an inner radius of 82 [mm] and a height of 78 [mm]. The frame has sixteen equally spaced holes along the edge. These holes are used to house the ends of the actuators.

The actuators consist of a massive cylindrical inner part and a hollow outer part. The inner part can be moved in relation to the outer part of the actuator in a direction along its axis, with a travel range of 50 [mm]. The position of the inner part can be read directly, with an accuracy of 0.1 [mm]. The end of the inner part of the actuator is attached to a force transducer.

One of the force transducers is schematically shown in figure 3.1. It consists of a cantilever beam, which is fixed at one end and has a hook at the other end. This hook has one degree of freedom in radial direction. On the side of the beam, pointing towards the actuators, a Hall effect sensor (Honeywell, type SS495A) is attached. When a force is applied on the hook of the beam, the beam will undergo a small deformation, which changes the position of the sensor. Two roughly identical magnets are glued to the frame of the transducer on each side of the beam, with their N-poles facing each other. The magnets cause a static position dependent magnetic field. The Hall

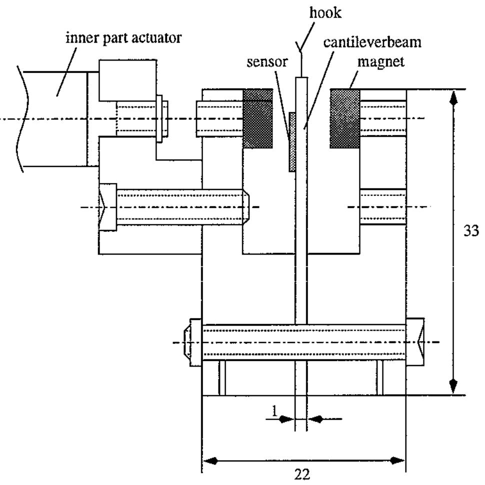


FIGURE 3.1: The force transducer

effect sensor measures the magnetic field strength and produces an output voltage which is related to this strength. Because of the position dependent field, the output voltage is an indication for the displacement of the beam and therefore the force applied on the hook.

The relation between the applied force on the hook and the output voltage can be determined after calibration of the sixteen force transducers, as explained in appendix B.

3.2 Data and control system

The entire experimental setup, as shown in figure 3.2 is controlled in real time by a IBM RISC System/6000 workstation and a UNiversal Interface Modules and Adapters box (UNIMA). The IBM workstation provides a graphic user interface (Biaxial) to adjust the system parameters easily. This interface sends commands to the UNIMA. UNIMA sends digital signals via a 24 bit custom bus to four "Quad Controller" printed circuit boards (PCBs), which contains four HCTL-1100 chips each. Each chip controls the movement of one actuator via a small actuator control card.

The analog output voltages from the force transducers are sent to voltage dividers, which transform the original output voltage span from [-10:10] [V] to a span of [-350:350] [mV]. These analog output voltages are acquired by an Electro physiological MAPping system (EMAP) and converted to digital signals. These signals are sent and recorded to the disk of a Silicon Graphics O2 workstation via UNIMA and the IBM workstation.

A black and white camera (640x480 pixels, Pulnix TM-9701 Progressive Scanning) is mounted over the test rig and connected to the O2 workstation and a TV monitor (Sony). The O2 workstation contains a frame-grabber which communicates with the IBM workstation via Internet and saves the incoming video image to disk. In this setup, the camera has a pixel spacing of 0.1985 [mm/pixel] along the x-axis and 0.2201 [mm/pixel] along the y-axis.

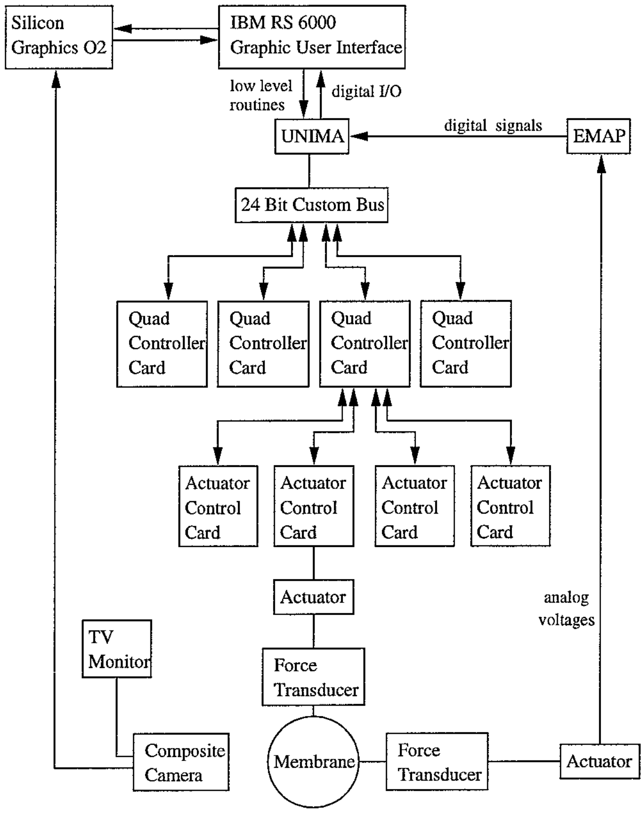


FIGURE 3.2: Flow diagram for the experimental setup

3.3 Accuracy and reproducibility

Results of tests are useless, unless the accuracy and reproducibility of the experimental setup are known. Knowledge of the reproducibility can help to improve the way test results are interpreted. When the same experiment is run twice the same output is expected. This means that the displacements of each of the actuators should be equal to the forced translation and the output voltages of the force transducers should be the same for every equal position of the actuators.

In this section the accuracy and reproducibility of an experiment are discussed. First the accuracy of the actuators and the reproducibility of the force transducer are discussed. Secondly, the magnetic interference of the force transducers will be explained. Lastly the accuracy of the computational processing of the measured images and voltages will be discussed.

3.3.1 Actuators

The accuracy of the displacement of the actuator can be determined by moving the actuators back and forward over the same distance. This movements are controlled by the graphic user interface. During this experiment, each actuator is marked with a dot on the moving part. All actuators are moved at the same time over a distance of 10.0 [mm], followed by a displacement of -10.0 [mm].

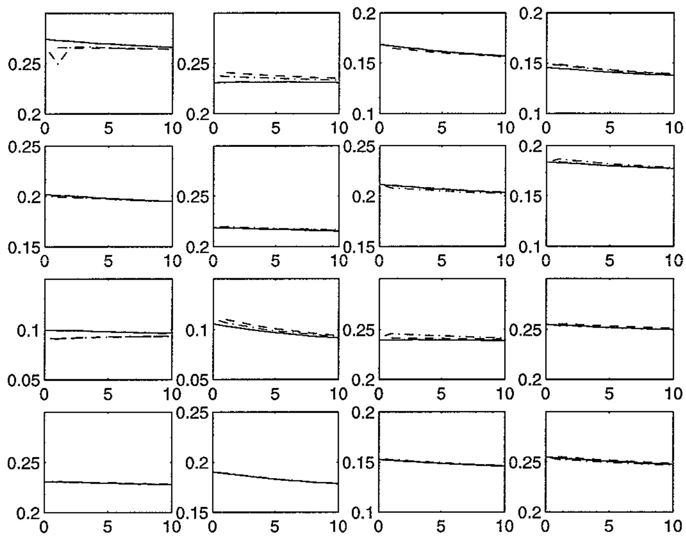


FIGURE 3.3: Output voltages of three experiments run under same conditions

Each time the actuators stop, an image is grabbed. This test is repeated ten times. The position of the dots in each images is determined and compared to the expected position.

After ten tests, the ultimate position should be equal to the first position. Reading the position of each actuator on the inner part of the actuator shows an unexpected displacement of 0.3 [mm]. Calculating the difference between the positions of the dots by java, shows a displacement of 0.2 [mm]. The difference between these two outcomes is probably caused by inaccuracy when reading the inner part of the actuator. The outcome itself can be explained by the fact that the actual movement of the actuators is not exactly equal the movement ordered by the user interface. A difference of 0.2 [mm] after moving ten times over 10 [mm] is acceptable. The difference in displacement between the actuators is in the order of 0.05 [mm] which won't affect the experiments.

3.3.2 Force transducers

When all actuators stay in the same position, the force transducers should give the same output, even after the actuators are moved and put back in the previous position. Without moving the actuators, the output of the force transducers varies in the order of 0.15 [mV], which is 0.1 % of the total output. When moving the actuators and putting then back in exactly the same position variations of about 2 [mV] occur, which still is accurate enough.

During an experiment, the actuators will move to their final position in ten steps of 1 [mm]. The output voltages measured during this experiment should be the same as a second experiment run under the same conditions, i.e., same starting position, same step size and same membrane. The output voltages of three equal experiments run over a large period of time are shown in figure 3.3. During this experiments, no membrane was mounted on the rig.

Figure same for every force transducer, the output voltages of a certain transducer at a certain position stays the same, within an accuracy of about 5 % of the measured voltage.

3.3.3 Magnetic interference

The magnets of all force transducers are relatively closely spaced together and the interference between the magnetic fields of the transducers has to be taken into account. The output voltages as shown in figure 3.3 are measured without membrane and represent the offset voltage and the magnetic interference. With the assumption that the magnetic fields are not being influenced by the membrane, placed in the rig, the magnetic interference can be eliminated by only looking at the difference between the output voltages of the experiments with and without membrane. The inaccuracy, as determined in 3.3.2, means that every experiment has to be run twice, first without a membrane and afterwards the actual experiment with membrane.

3.3.4 Computational processing

The output of the biaxial rig contains of two parts; grabbed images, used to determine the displacement of the actuators and the dots on the membrane and matlab files with the measured forces in [V].

The position of the dots and the actuators in an image are determined by using java SpeedSpots, which calculates the centre of each dot after finding the edges of the dot by looking at changes in intensity. Java Speedspots will always find an edge, even if it does not exist. Fortunately, the results of java SpeedSpots are easily checked and corrected, which makes sure the centre found by the programme is closer to the actual centre than a centre found manually. The centres found by java SpeedSpots are first expressed in pixels and afterwards changed into millimeters. The relation between pixels and millimeters depends on the position of the camera and can not be measured directly, which leads to extra inaccuracies.

The applied forces, reported by the matlab files, are expressed in [V]. Calibration, as explained in appendix B, is necessary to determine a relation between [V] and [N]. Unavoidable inaccuracies have influenced this calibration, which will effect the output of the experiments as well.

The determined forces and the position of the dots are used in cmiss, to fit the displacements and to determine the parameters of the tested membranes.

Chapter 4

Experiments

The results of the experiments run with different membranes on the biaxial rig are shown and evaluated in this chapter. The way the membrane is shaped, in order to put it on the rig is explained first. This is followed by a description of the tests done with different rubber membranes, which are respectively homogeneous, inhomogeneous and anisotropic. Finally the experiments done with pericardium is evaluated.

All experiments are performed identically, containing a undeformed reference state and ten deformed states. The extension of the membrane is completely symmetric, i.e., the movements of the sixteen actuators are equal for all deformation steps. During an experiment, the actuators will move outward in ten steps of 1 [mm], after every step output voltages are measured and an image is grabbed.

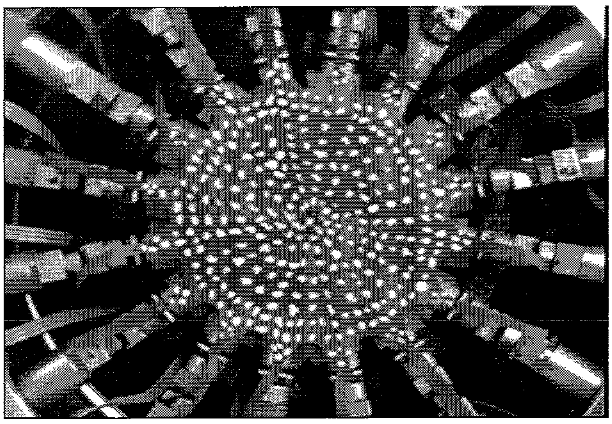


FIGURE 4.1: A rubber membrane mounted on the rig

4.1 Mounting a membrane on the rig

A membrane can be mounted onto the hooks of the force transducers. Because the force transducers can only measure a force in radial direction, the rubber membrane is shaped as shown in figure 4.1. The membranes are made from a thin sheet of rubber, with an averaged thickness of 0.14 [mm]. The middle of the membrane, which is circular shaped, with a radius of 30 [mm] is the actual place of interest, the strings shaped in a way that the force will be applied on the entire edge of the circle are used to connect the centre to the hooks of the force transducers. There are a few reasons to choose this rather complex shape:

- The curved shape of the strings makes sure the displacement is forced over the entire edge of the circle, not only on sixteen points.
- The membrane is made out of one piece of rubber, which avoids attachment criteria.
- The size of the pericardium membrane will be too small, the minimum radius described by the hooks of the force transducer is about 40 [mm], when they are moved further inward, the will hit each other.
- The strings avoid tangential stress around the force transducers, which limits the tangential force component, which can not be measured directly
- The direction of the string points in the direction of the total force. With the known radial force, the smaller tangential force can be determined.

A disadvantage of this shape is the reduced stiffness of the strings. This results in a much bigger displacement in the strings, than in the centre. To avoid this, an extra layer of rubber is glued on the string, this thicker sheet of rubber has a averaged thickness of 0.26 [mm] and must be taken into account when modelling the membrane. The membrane is provided with a random dot pattern on the membrane are made with correction fluid. This pattern is used to determine the displacement field.

4.2 Numerics

Numerical simulations of the multi-axial tensile experiments on a membrane are performed with the finite element package CMISS. Numerical simulations of the tests performed on the biaxial rig are used to determine the material parameters. The information from the experiments, such as size and shape of the membrane and the positions of boundary conditions is used to create a numerical model that satisfies this restrictions. The results of a numerical parameter estimation are created by straight forward numerical analysis. The undeformed membrane is taken as the reference state, three deformed states of the stretched membrane are used to determine the material parameters.

4.2.1 Finite element mesh

The finite element method is an appropriate method for the analysis of the large volume of data generated by the experiments. The finite element method will be used for the creation of the geometry of the deformed membrane and for the characterisation and quantification of the constitutive laws of the material under consideration, i.e. parameter estimation.

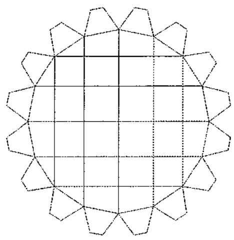


FIGURE 4.2: Finite Element mesh

The geometry of the undeformed membrane is used to make a finite element mesh, as shown in figure 4.2. This mesh consist of 69 nodes and 48 elements.

4.2.2 Boundary conditions

The boundary conditions are obtained from the deformed states of the membrane. The positions of the dots on the membrane during the experiment are determined and used to predict the displacement of the nodes by fitting and to determine the deformed mesh (fig. 4.3).

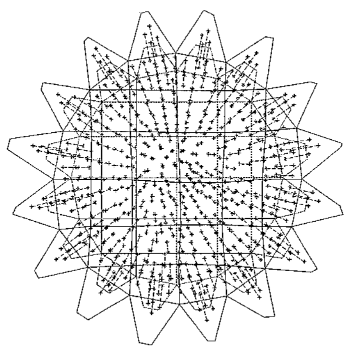


FIGURE 4.3: Data fitting

The measured forces are applied on the nodes on the outer edge of the deformed mesh. All these boundary conditions can be described independently and each individual boundary condition is prescribed in the right node of the finite element mesh. As a result of the applied boundary conditions, the difference between the reference state and the deformed states is determined. The strain in the membrane necessary to achieved the calculated deformation can now be determined, as can the material parameter C_1 and C_2 from equation 2.4.

4.3 Homogeneous rubber

A homogeneous membrane is made as described above. The experiment is run and the forces necessary to achieve the displacement of the membrane is determined. In figure 4.4 this force is projected as a function of the movement of the actuators, and thus the displacement of the membrane.

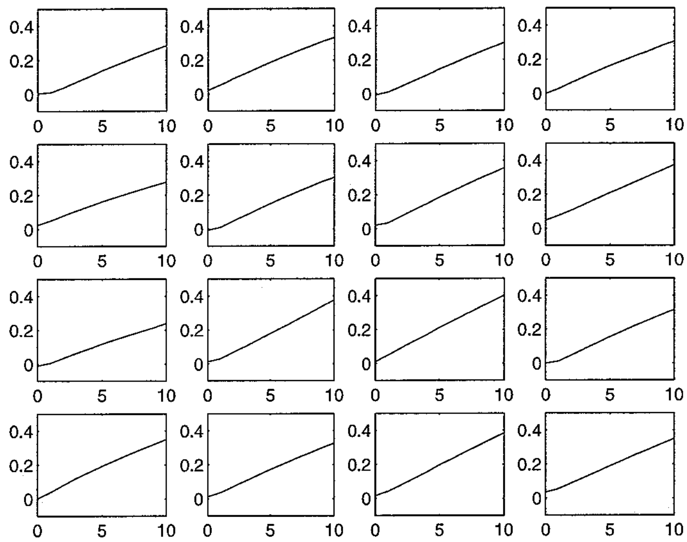
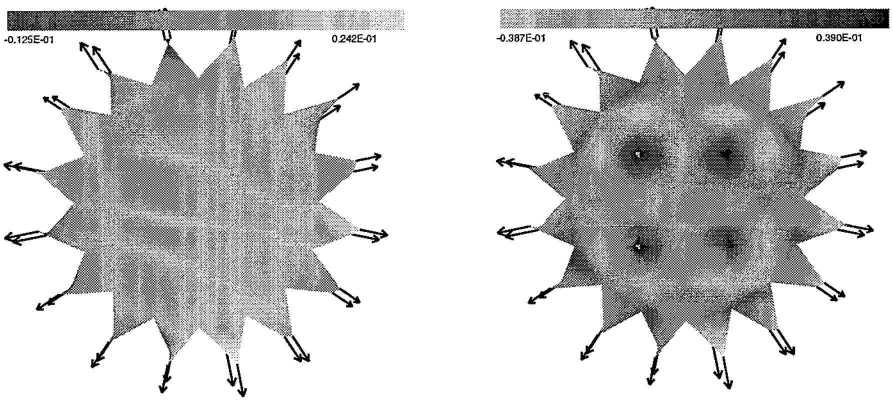


FIGURE 4.4: Force-displacement curves for homogeneous rubber

The figure shows that the relation between force and displacement is linear, but not equal for every force transducer. This difference is probably caused by inaccuracies in the size of the strings. The parameter fit with cmiss leads to the images as shown in figure 4.5. In the centre of the membrane is the value of the material parameter C_1 almost constant, which indicates homogeneous isotropic material. The value of material parameter C_2 changes quite a lot, but shows a remarkable pattern, which is caused by the mesh, not by the boundary conditions.

4.4 Inhomogeneous rubber

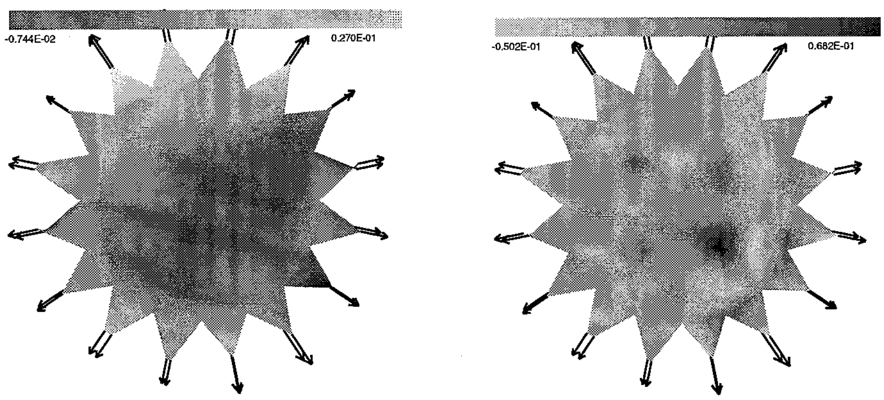
Out of a linear rubber membrane, a inhomogeneous one can be made by gluing a smaller circular membrane, with a radius of 11 [mm] and a thickness of 0.26 [mm] on top of the first one. The



(a) C_1 (b) C_2

FIGURE 4.5: Material parameters for homogeneous membrane

material parameter of the material in each point will be equal in all directions. Figure 4.7 shows the relation between force and displacement in this membrane.



(a) C_1 (b) C_2

FIGURE 4.6: Material parameters for inhomogeneous membrane

Comparing the slopes in this figure, with the slopes in figure 4.4, shows a increase of the slope of force transducer 1, 8, 9 and 16. This shows the place where the extra layer is situated.

The results of the parameter fit done by cmiss, are shown in figure 4.6. The values of material parameter C_1 show a decrease in a certain area of the centre of the membrane. During the experiment was the extra circle located in the centre of the darker spot. Even the values of C_2 show an increase in this same area, which is only partly caused by the mesh definition.

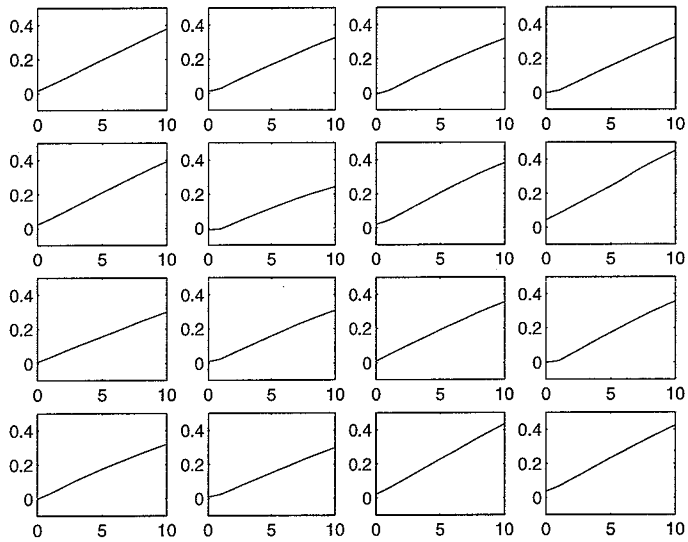


FIGURE 4.7: Force-displacement curves for inhomogeneous rubber

4.5 Anisotropic rubber

An anisotropic membrane is made by gluing thin strips of rubber on top of the membrane. These strips are placed in parallel, which makes it harder to stretch the membrane in the direction of this strip in comparison to other directions. The relation between force and displacement is shown in figure 4.8.

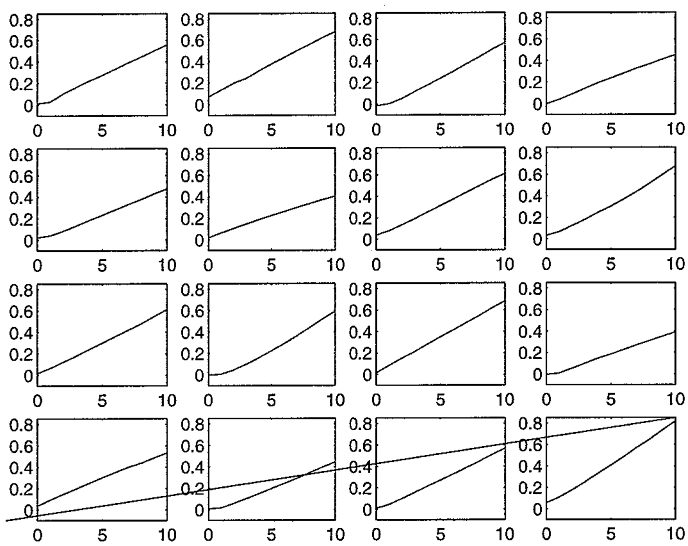


FIGURE 4.8: Force-displacement curves for anisotropic rubber

This figure shows, in comparison to figure 4.4, a increase of the slope of transducer 1, 2, 3, 8, 9, 10, 11 and 16 can be noticed. The strings are orientated from transducer 1 to 9, which explains the increase of the slopes of that transducers and the transducers around it. The numerical parameter estimation can not be applied on the anisotropic material, because of the assumption of an isotropic material. Adjustment of this assumption can be done, but is not included in this study.

4.6 Pericardial membrane

The membrane used in this test is made from a preserved piece of bovine pericardium (Mitroflow non-sterile peripatch, Richmond, Canada, size 60 x 80 [mm]). Because of the maximum size of a pericardium specimen, the tested membrane is sized a bit smaller than the one used for the experiments with rubber membranes, but shaped the same way. The dot pattern is made by using Indian ink. The pericardium is kept wet during the experiment by sprinkling some preservation fluid on the membrane. During a experiment, he actuators are moved outward in five steps of 1 [mm], the measured forces are shown in figure 4.9.

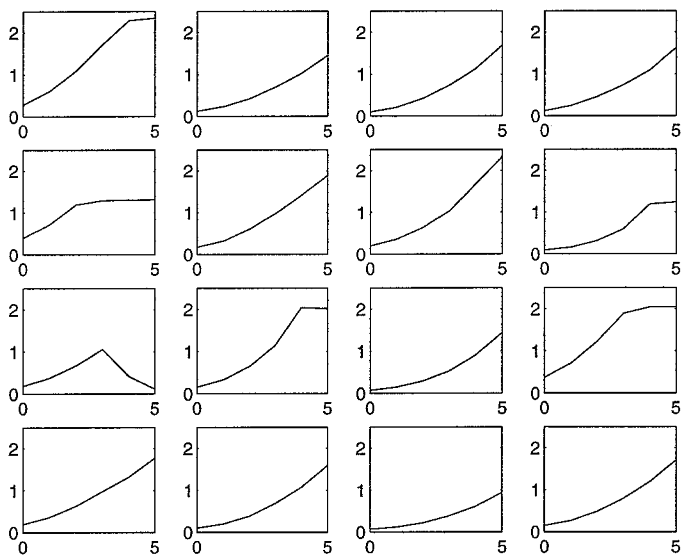
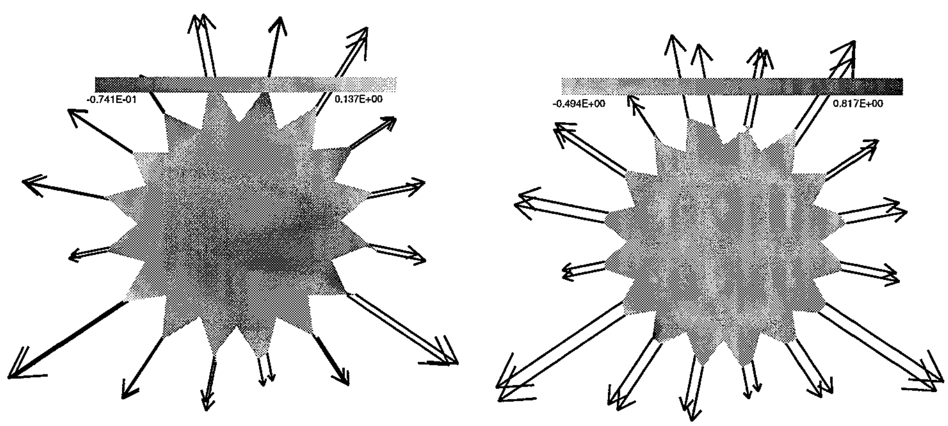


FIGURE 4.9: Force-displacement curves for pericardium

The string attached to transducer 9 is broken after a stretch of 3 [mm], this affects the forces applied on the opposite transducer and the ones around it. The data of this test is fitted with cmiss to a reference mesh, that is 90% of the size of the original mesh. The parameter estimation, with the assumption of isotropic material led to the pattern showed in figure 4.10. This patterns are quite similar to the patterns of the homogeneous membrane. Apparently, the pericardium membrane is homogeneous under small loads, but non-linear as well.



(a) C_1 (b) C_2

FIGURE 4.10: Material parameters for pericardium

Chapter 5

Discussion, conclusions and recommendations

Experiments are performed on four membranes of two different material types. The experimental membrane is modelled as a finite element model and the values of the material parameters of an assumed constitutive model are estimated.

5.1 Discussion

Some of the differences between the estimated and the true material parameters can be explained:

- It is very hard to cut the membrane in the right shape. Not every string has the same width.
- The current setup does not have the possibility to use a physiological bath for the pericardium. When the pericardium dries up, the material behaviour will change. During the experiments, the pericardium was fully damped to minimise this change.
- The forces during the experiments with the homogeneous membrane are expected to be equal for each force-transducer. Differences between the expected and the measured forces is probably caused by inaccuracies of the force-transducers and their calibration.
- The initial forces that are present in the reference state are not modelled. All initial stresses and strain are set to zero in the reference state of the numerical model. This causes a increase in stiffness.
- The constitutive model assumes the membranes to be inhomogeneous and isotropic. This assumption causes problems in the parameter estimation of the anisotropic membrane. In this membrane the fibres do have a preference for a direction of the fibre.

- The finite element model of the membrane affects the parameter estimation, which causes an unnatural distribution of the material parameters. Smoothing solves this problem partly.

5.2 Conclusion

After exploring the possibilities and boundaries of the biaxial rig and its numerics the following conclusions can be drawn:
With respect to the experiments:

- The accuracy of the actuators is high enough to run all kinds of experiments.
- The one dimensional force-transducers determine the accuracy of the tests. The offset voltage and the moderate reproducibility must be taken into account.
- Using hooks to mount the membrane on the rig requires deformations of the sample.

With respect to the numerics:

- The displacement field of the dots on the membrane is important to determine the material parameters.
- It is difficult to characterize the undeformed state under experimental conditions.
- Parameter estimation of a less complex material than modelled is possible.
- A reasonably good fit of the numerical model is obtained

5.3 Recommendations

The biaxial rig and its numerics are useful to estimate the material parameters of a membrane. The experimental procedure could become more useful after a few changes and improvements:
With respect to the experiments:

- The magnitude and the direction of the reaction forces of the membrane have to be measured directly. The force-transducer should be able to measure forces in two directions, without offset voltages.
- The hooks, used to mount the membrane on the rig, should be replaced by an attachment, that does not require deformation of the sample.

- Due to the maximum size of the pericardium, the minimum distance between the attachment points should be decreased from 80 [mm] to 60 [mm].
- To obtain a more natural chemical environment for the biological tissue, the possibility to use a bath filled with a physiological saline solution have to be created.

With respect to numerics:

- Refining the mesh improves the accuracy of the parameter estimation
- The assumption of isotropic inhomogeneous material, should be changed into anisotropic inhomogeneous material. This improvement gives the opportunity to estimate the parameters of anisotropic materials.
- Finite element modelling with other element types should be done to improve the constitutive laws

General

At this moment Duane Malcolm is trying to develop improved force transducers, that can measure force in two directions. If he succeeds, the biaxial rig will become more useful in research on biomaterials. Improvement of the parameter estimation will hopefully lead to a larger suitability of the biaxial rig. The biaxial rig seems to be a project with a future.

Appendix A

How to run a test

The experimental setup, as discussed in chapter 3, can be run by following the next steps. **Commands** are commands that must be typed, *commands* are displayed in the used programme.

Turn on the esu22, login as **paulc** and go to **/usr/people/paulc/xvg/cmgui** and run xvg. Turn on the RS6000, login and type **startx**. Connect the Pulnix camera to esu22 and the Sony monitor. Make sure that the video panel on the esu22 is set on *Composite video*. If you get the images from the right camera, switch on the actual setup, starting with the six HP power supplies, followed by Emap and Unima. Check if the values of the power supplies are, from top to bottom; 15V; 15V; 9V; 12V; 12V; 12V. Turn on the 5V actuator control, go to the aixterm window on the RS6000 and run **Biaxial**. Click *Set Hardware*, notice that Unima starts flashing yellow lights. If the status for all channels is 0xc0, it is safe to turn on the 12V actuator control. The actuators can be moved by using global or individual control. Check the voltages on the power supplies and correct if necessary.

Before running a experiment, check the values in the experimental control. The control type should be *linear position*. Enter the number of steps/cycle, the step delay and the step size. Make sure that the Socket Port is *2000*, the Internet address is *esu22.auckland.ac.nz* and the output file is **rubber**, when using a membrane and **rubber-offset** without membrane. Run **xvg** on the esu22. Go to *IP operations* and use the right hand button in the upper window. Choose *LoadNewIpOp*, followed by *Grabbing ops* and *NetworkGrab*. Write down the argument **/usr/tmp/biaxial/** and use the right hand button in the lower panel. Choose *AddNewIpOp After* and select the operation, click *Exec Ops*. Esu22 is now waiting for response of RS6000. Start the experiment by clicking *start experiment* in Biaxial. The actuators will start moving. At the end of the experiment, esu22 will have ten *rubber*.tif* and ten *rubber*-forces.mat* files in the chosen argument. Be aware of the fact that there are no measurements of the original position. The forces in this position can be read by using *Read forces* and a picture should be grabbed.

The created images contain information about the local displacement of the dots on the membrane. This information can not be used directly. The position of centre of each dot has to be found and put into a file. To change the *rubber*.tif* files into *rubber*.gif* files, run **xv** for every image. Use the right hand button and save the file as a *rubber*.gif* file. The *rubber*.gif* files can be used to create *rubber*.ipdata* files by using **java SpeedSpots (lein: /java/spots)** for each file. Select the centre of every dot in the right order and check if the actual centre has been found, then save the points. SpeedsSpots produces two files *spotsFile.txt* and *spotsFile2.txt. spotsFile2.txt* gives the position in [mm] with a steady point as zero point. *spotsFile.txt* relates all points to the first point of the file. Renaming the files to *rubber*.ipdata* gives the required file with the positions of the centres of the dots in [mm]. These files are necessary to run **datafit** of cmiss, which can be found in the argument **lein:/cmiss/membrane/fitting**. *spotsFile.txt*, with the centre of the membrane as point 1 is best to be used. Datafit produces *rubber*.ipnode* files, containing 69 nodes. The files can also be used to determine the displacement of each dot, between two images. Stay in the directory spots and type **ipdataCompare 'name of first ipdata file' 'name of second ipdata file' 'number of dots in each file'**. SpeedSpots uses the relation between [pixels] and [mm] as mentioned in section 3.2, when the camera is moved, these relations have to be changed in SpeedSpots.

The *rubber*-forces.mat* files can be read with matlab by opening a workspace. With the command **forces**, you can see the measured values of the forces in [V]. This forces can be calculated in [N] by using the relations found by doing a calibration, as explained in appendix B. The calculated forces and the *rubber*.ipnode* files are needed to estimate the material properties. Cmiss *force*.ipnode* files have to be made, containing 69 nodes and the values of the forces in x and y direction on each node on the edge of the mesh, shown in figure 4.2. To use the *rubber*.ipnode* files, as made with **datafit. example7171 (lein:/cmiss/membrane/parameter)** is used to estimate the material properties. To get a better fit, smoothing is used, the smoothing is defined in *mesh.ipfit*. All cmiss programmes only use the files made from the original position, *rubber2.tif*, *rubber5.tif* and *rubber9.tif*. Because of the smaller membrane and the smaller deformation, tests done with pericardium are modelled in a slightly different way. To estimate the material parameters of pericardium, use **example7172** instead of **example7171** and **paraperi** instead of **parafit**. The used files are made from the original position, *peri2.tif* and *peri3.tif*. If necessary, the mesh used for parameter estimation can be refined by using **newmesh*** which refines the mesh to one with 161 nodes.

Appendix B

Calibration

Calibration of the sixteen transducers needs to be done, in order to determine the relationship between the output voltage signal of the transducers and the applied forces. During this calibration the applied force is calculated by looking at the displacement and measuring the stiffness of the tested rubber.

The stiffness of a rubber strip can be determined by attaching weights at the end of the strip and measuring the displacement. The force applied on the rubber is equal to the applied weight multiplied by the gravitation constant g = 9.81 $[m/s^2]$.

The rubber strip, used in this calibration is composed of three layers of the rubber that is used for membranes. The layers are glued with vulcanising rubber solution. Taking three layers was necessary to cover the voltage range of an experiment run with a circular rubber membrane. The force elongation curve of this strip is shown in Figure B.1. The line fitted through the measured points determines the relation between displacement and force:

$$F = 0.0276 \,.\, dl \tag{B.1}$$

The same strip, marked with dots, is now attached to two transducers which are mounted opposite to each other on the biaxial rig. During the experiment, both transducers are moved in eight steps of two millimeter. After each step an image is made and the output voltages are measured. This experiment is repeated for each set of opposite transducers. During this experiment the entire range of the actuators is used.

The images of the dots on the rubber and the actuators give the precise displacements of the actuators. Because the length of the strip is known, the pre-stress can be calculated, this is equal to the difference between the distance between the actuator and the length of the rubber. The expected force for each transducer depends on this pre-stress and its displacement an can be calculated by multiplying the difference between the distance between the hooks and the original length of the

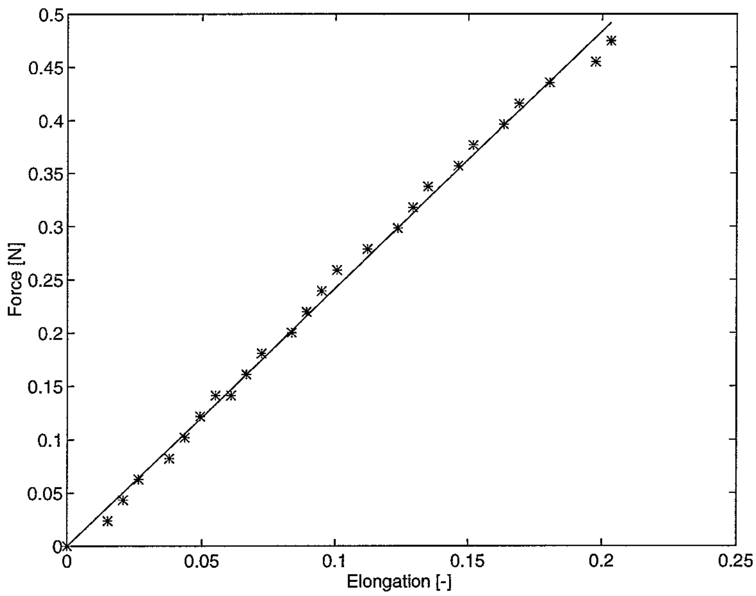


FIGURE B.1: Force-elongation curve of the rubber string

rubber with the stiffness of the string (eq. B.1). The output voltages minus the offset voltages, as explained in section 3.3, can be compared to the expected forces applied to the transducer for each step.

The relation between the voltage output minus offset voltage and the applied force on a transducer depends on many things and is not equal for each transducer. This calibration resulted in sixteen different two order regression curves and can is valid for a difference in voltage output in the range of $-199--23$ [mV].

$$F_1 = 5.9249V_1^2 - 1.1859V_1 + 0.0035 \quad \text{(B.2)}$$
$$F_2 = 4.3682V_2^2 - 1.5694V_2 + 0.0114 \quad \text{(B.3)}$$
$$F_3 = 7.4384V_3^2 - 1.6782V_3 - 0.0066 \quad \text{(B.4)}$$
$$F_4 = 7.7165V_4^2 - 2.0323V_4 - 0.0027 \quad \text{(B.5)}$$
$$F_5 = 5.9362V_5^2 - 1.3704V_5 + 0.0240 \quad \text{(B.6)}$$
$$F_6 = 4.7992V_6^2 - 1.4369V_6 - 0.0067 \quad \text{(B.7)}$$
$$F_7 = 6.3376V_7^2 - 1.6724V_7 + 0.0198 \quad \text{(B.8)}$$
$$F_8 = 6.8980V_8^2 - 1.6240V_8 + 0.0384 \quad \text{(B.9)}$$
$$F_9 = 6.6108V_9^2 - 1.5018V_9 - 0.0051 \quad \text{(B.10)}$$

$$F_{10} = 9.5648V_{10}^2 - 1.7121V_{10} + 0.0093 \quad (B.11)$$

$$F_{11} = 7.7213V_{11}^2 - 1.6729V_{11} + 0.0012 \quad (B.12)$$

$$F_{12} = 6.4774V_{12}^2 - 1.7117V_{12} - 0.0003 \quad (B.13)$$

$$F_{13} = 4.4877V_{13}^2 - 1.9476V_{13} - 0.0035 \quad (B.14)$$

$$F_{14} = 7.8856V_{14}^2 - 1.6168V_{14} + 0.0117 \quad (B.15)$$

$$F_{15} = 7.3348V_{15}^2 - 1.4807V_{15} + 0.0122 \quad (B.16)$$

$$F_{16} = 6.4498V_{16}^2 - 1.3229V_{16} + 0.0325 \quad (B.17)$$

In this equations V_x is the difference between the output voltage and offset output voltage in [V] of the x^{th} force transducer, F_x is the calculated force on this transducer in [N]. The accuracy of this fitted lines is shown in Figure B.2, in which the 'o' are the measured values.

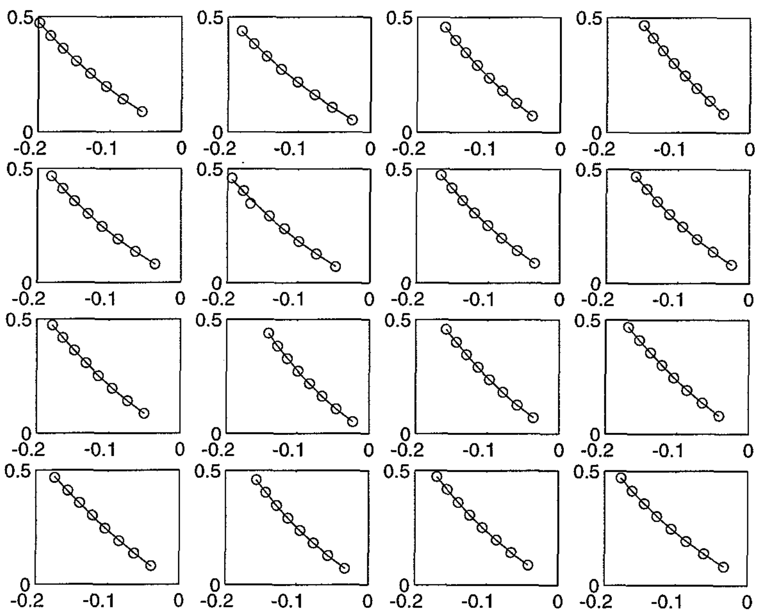


FIGURE B.2: Measured ('o') and calculated (solid line) reaction forces as function of measured voltages

Appendix C

Used programmes

The way from the start of an experiment till the presentation of the result, takes many steps, using different programmes. Biaxial and XVG are used to collect data, cmiss, java and matlab are used to process this data into results. The programmes written for the rig are shown.

C.1 Biaxial

Biaxial contains the graphic user interface of the biaxial rig. This interface, as shown in figure C.1, provides an easy way of adjusting the system parameters. The actuators can be moved individually and global. The conditions of the experiment can be defined as well.

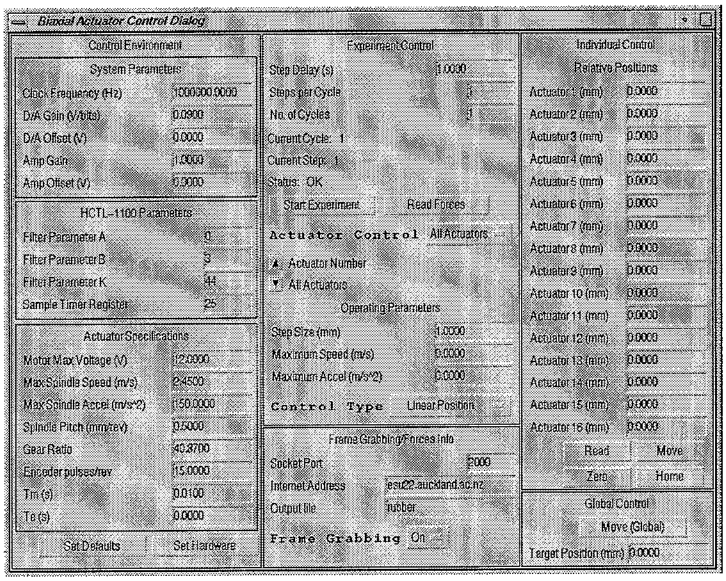


FIGURE C.1: Graphic interface 'Biaxial'

C.2 CMISS

Cmiss is a programme developed at the University of Auckland. It has many applications. In this study it has been used as a Finite Element Method (FEM). A mesh has been made to represent the membrane. This mesh contains 69 nodes and 48 elements, as shown in figure C.2.

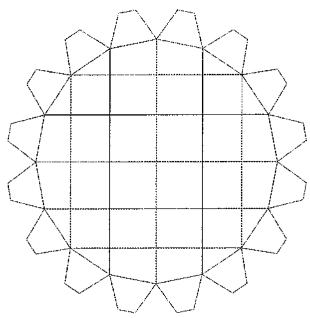


FIGURE C.2: Finite Element Mesh

Files, containing the positions of the dots on the membranes in four different positions are used to fit the movement of the dots and predict the deformed mesh (example 21c). This information together with the files containing the forces applied on the transducers are used to determine the material properties of the tested membranes (example 7171).

C.3 XVG

XVG is the graphic interface of the Silcon Graphics O2 workstation. It connects with the IBM workstation and saves the data of the experiments in the right argument.

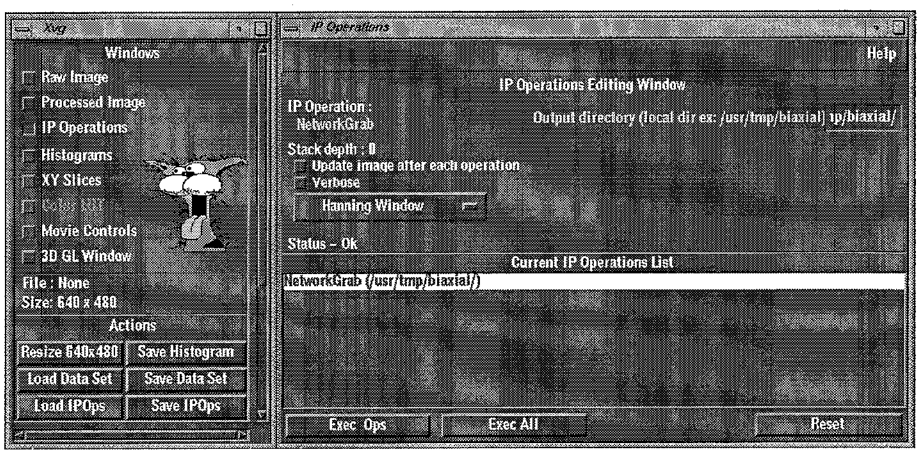


FIGURE C.3: Interface'XVG'

Appendix D

A kiwi experience

New Zealand cannot be described in one word. The Maori, the original inhabitants of this beautiful country, used to call it 'Aotearoa', 'land of the long white cloud'. I would prefer to call it the country of extremes. My 'kiwi experience' can be divided in two parts; my time in Auckland, the largest city of New Zealand and my holidays in the rest of the country. In New Zealand, the word kiwi is often used. It has three different meanings; the well known kiwi-fruit must not be confused with the national symbol, the flightless bird. The confusion is made even greater by the pet name of the New Zealanders, kiwis.

D.1 Auckland

In Auckland, I got the opportunity to experience the daily life of the kiwis. The descendants of the European settlers have formed one nation with the Maori. Therefore the New Zealander can be seen as a European with a laid back 'subtropic island' lifestyle. This combination leads to the acceptance that you only do a certain amount of work during one day and that the less important part of that job must wait till the next.

The university culture is therefore also more relaxed than the ones in other countries. No superfluous dressing codes, shorts and sport-shoes, or even no shoes are common practice for both students and lecturers. Sports during the lunch-break is no exception. A day at work, however, can easily last twelve hours in which a lot of work is done.

'Flatting', as kiwis call sharing a flat, is often done to reduce costs and increase fun. After their studies, kiwis often choose to go overseas for a few years. Because of the isolated location of New Zealand, many young people want to work and live abroad to experience new cultures Europe and the USA are in demand.

D.2 New Zealand

The country is divided in a North and a South Island. The South Island was the first settling place of the Europeans. Its nature is incredible, but unpredictable and therefore not suitable for many industries. The North Island has a subtropic climate, beautiful bays in the north and thermal activity in the middle.

Traveling by camper van is probably the best way to explore this rough land. With only three and and half million people in a country as large as the United Kingdom, you can drive for hours without seeing any signs of civilization. The 'highways' however are very well maintained. The same can be said for the paths to the most scenic views and tourist attractions, which can be right in the middle of nowhere.

During a tour of four weeks, we got the opportunity to see the most beautiful parts of the country. On the South Island, the very English city of Christchurch, the turquoise Lake Tekapo, the misty sounds and mountain ranges in Fiordland with the most southern rainforest of the world, Edinburgh of the south; Dunedin, which is a great student town and Queenstown, the city of adrenaline with its skiing and bungy jumping. Further North are some special glaciers, close to the sea and surrounded by rain forest and the Abel Tasman National park, named after the Dutch sailor that discovered New Zealand.

And on the North Island there is the windy capital of Wellington, which was very much alive because of a great rugby game, the unbelievably large Lake Taupo, the geysers and bubbling mud pools in Te Whaka, 'bounty' beaches in the Coromandel and the hot water beach with a natural thermal spa.

The subtropical climate in the North is entirely different from the cold South with its penguins. The mountains in the Southern Alps and the vulcanoes on the North Island are not to be compared with the flat land between Auckland, Hamilton and Tauranga. The blue sea and the white beaches with palm trees are beautiful and not exactly like the spooky misty sounds.

Extremes all over the country, sometimes even within one kilometer of each other, that is why it is worth traveling all the way to New Zealand. If you ever get the opportunity to work and live in this country, do not hesitate, go!

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