NTNU – Trondheim
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Modeling and testing of small diameter composite tubes under hydrostatic pressure

Emir Dzubur

Mechanical Engineering
Submission date: June 2014
Supervisor: Andreas Echtermeyer, IPM

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THE NORWEGIAN UNIVERSITY

OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS SPRING 2014

FOR

STUD.TECHN. EMIR DZUBUR

Modeling and testing of small diameter composite tubes under hydrostatic pressure

Modellering og testing av liten diameter kompositt rør under hydrostatiske trykket

Composite tubes are widely used as pressure pipes. This study shall investigate how filament wound small diameter tubes can withstand external hydrostatic pressure. The mechanical response shall be modeled with finite element analysis. Special emphasis shall be put on obtaining relevant material input parameters for the model. Experimental and modeling work shall be combined in an optimal way to provide the required input parameters and to validate the accuracy of the approach.

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The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

The thesis shall be submitted electronically via DAIM, NTNU's system for Digital Archiving and Submission of Master's thesis.

Torgeir Welo — Andreas Echtermeyer

Head of Division — Professor/Supervisor

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Preface

This master thesis is written by Emir Dzubur to achieve a Master of Science degree within Mechanical Engineering at the Department of Engineering Design and Materials at the Norwegian University of Science and Technology (NTNU).

The motivation for this thesis is the potential for using composite materials to meet the needs of the oil industry. The industry is moving into deeper and colder subsea environments, challenging the equipment and materials used today, and the need for new materials is increasing.

I would like to thank my supervisor Andreas Echtermeyer, Professor in composites and polymers at the Department of Engineering Design and Materials at NTNU, for constructive discussions and guidance throughout this thesis. I would also like to thank Carl Magnus Midtbø, Mechanical Engineer at NTNU, for assisting with the use of optical fibers and all experimental testing of the tubes. Additionally, I would like to thank Farvin Moses for assistance with filament winding of the tubes. Finally, I would like to thank Nils Petter Vedvik, associate professor, for guidance related to Abaqus.

Abstract

This thesis investigates the behavior of small diameter composite tubes that are exposed to external pressure. Composite tubes have a superior strength to weight ratio compared to steel tubes. The oil industry is facing new challenges and the demand for more robust materials is increasing. Prior to substituting steel material with composites in tubes, it is important to gain knowledge about the behavior of composite tubes and develop reliable analytical methods.

An experimental and analytical study of small diameter carbon fiber tubes was carried out in this thesis. The tubes were made using filament winding with a layup of [±75] and a wall thickness of 1.5 mm. The tubes were tested under external pressure with optical fibers attached to measure the strain during the tests. A linear buckling analysis and Riks analysis was done using the Abaqus solver to predict buckling and compare strain results to the experimental tests. The transverse and longitudinal Young's modulus were experimentally found and implemented into the finite element analysis.

The predicted buckling value deviated significantly from the experimental tests. In the experimental tests, the tubes buckled at 52.5% lower pressure than what was expected from the finite element analysis. The strain readings from the optical fibers gave higher values than the strains from the finite element analysis at equal pressures. However, strain at equal pressure might not be comparable because the tube from the analysis could withstand higher pressure before it started showing tendencies of buckling.

In conclusion, the analytical model in this thesis has its weaknesses and can be further improved to capture the imperfections of the tube more accurately.

Sammendrag

Denne masteroppgaven tar for seg oppførselen til komposittrør med liten diameter når de utsettes for utvendig trykk. Fordelen med kompositter sammenlignet med stål er at de har langt bedre styrke til vekt forhold. Oljeindustrien står ovenfor nye utfordringer og behovet for mer robuste materialer øker. Før stålrør kan erstattes med komposittrør er det viktig å samle kunnskap om oppførselen til slike rør og utvikle pålitelige analytiske beregningsmetoder.

En eksperimentell og analytisk studie ble utført på karbonfiber rør med liten diameter. Rørene ble laget med filamentviklingsmetoden med en fiberstruktur på [±75°] og en veggtykkelse på 1.5 mm. Rørene ble testet mot utvendig trykk med optiske fibre påsatt for å måle tøyningen under testingen. En lineær knekkingsanalyse og en Riks analyse ble utført i Abaqus for å forutse tøyning og sammenlikne resultatene med de eksperimentelle testene. Den transverse og den langsgående E-modulen ble funnet eksperimentelt og implementert i finite element analysen.

Den forventede knekkingsverdien avvek betydelig fra de eksperimentelle testene. I de eksperimentelle testene knakk rørene på 52% lavere trykk enn hva som var forventet fra finite element analysen. Tøyningsverdiene fra de optiske fiberne ga høyere resultater enn tøyningsverdiene fra finite element analysen ved tilsvarende trykk. Resultatene er riktignok ikke nødvendigvis sammenlignbare ved tilsvarende trykk, fordi røret i analysen tålte et høyere trykk før det viste tendenser til knekking.

Det kan konkluderes med at den analytiske modellen i denne masteroppgaven har noen svakheter og kan med fordel gjøres mer realistisk ved å finne bedre metoder for modellering av imperfeksjoner.

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Symbol	Description
V_f	Fiber volume fraction
W_f	Fiber weight
W_m	Matrix weight
ρ_f	Fiber density
ρ_m	Matrix density
E_{1T}	Tensile Young's moduli in longitudinal direction
E_{2T}	Tensile Young's moduli in transverse direction
E_{3T}	Tensile Young's moduli in out-of-plane direction
ν_{12}	Poisson's ratio in longitudinal direction
ν_{13}	Poisson's ratio through thickness
ν_{23}	Poisson's ratio out-of-plane
G_{12}	In-plane shear moduli
G_{13}	Through thickness sear moduli
G_{23}	Out-of-plane shear moduli
X_T	Ultimate tensile strength in longitudinal direction
X_C	Ultimate compressive strength in longitudinal direction
Y_T	Ultimate tensile strength in transverse direction
Y_C	Ultimate compressive strength in transverse direction
S_{12}	In-plane shear strength
σ_1	Circumferential stress
σ_2	Longitudinal stress
τ_{12}	In-plane shear stress
Ψ	Eventual transition zone
ϕ	Minimum winding angle

1 Introduction

In the oil industry, the need for better equipment is increasing as the industry is developing. Because of new environments where the pressure is high or the temperatures are extreme, the interest in composites has increased. Composites are very versatile and can be tailor-made. Therefore, they can be a solution to the needs in the future. Pipes used in the oil and gas industry today are mainly made of steel. These are well known materials which satisfy many of the traditional requirements. However, when these pipes are used in very deep waters the weight becomes an issue. Composites have a good strength to weight ratio and can be a possible substitution for the standard metal pipes in this situation. This master thesis is based on a pre project the author has done in the autumn 2013. Some background information and testing methods are taken from this project.

1.1 Task definition

This thesis will investigate how well short, small diameter tubes with thin wall thickness can withstand external pressure. The purpose of this work is to gain knowledge about the creation of carbon fiber tubes using filament winding, their behavior when exposed to external pressure and analysis methods used to predict buckling. To perform the analysis, realistic input data has to be found.

1.2 Literature study

A considerable amount of literature has been written on the behavior of carbon fiber composites exposed to pressure covering different aspects of the topic.

Tanguy Messager, Mariusz Pyrz, Bernard Gineste and Pierre Cauchot [23] study buckling failure caused by high external hydrostatic pressure. Optimal stacking sequence of the layers was investigated in this report. To achieve the best lamination, an optimization code was developed which always lead to typical [$90/\Psi_1/\phi_{N2}/\ \Psi_2/\phi_{N3}$] laminations. The purpose of this study was to increase the resistance against buckling in thin walled tubes. The test results were compared to the Finite Element Analysis (FEA) buckling analysis results. The optimization codes were made for carbon fiber and glass fiber tubes.

C.W Waver and J.G Williams [8] describe the deformation of carbon-epoxy composites under hydrostatic pressure. They tested carbon fiber rods with a pressure of 100MPa studying the failure modes.

Another relevant study was done by Paul.T Smith, Carl T.F Ross and Andrew P.F. Little [18]. They studied the collapse of composite tubes under external pressure. The tubes used in the experiment were 22 carbon and glass fiber mixed tubes with the layup of [0/90/0/90/0]. The tubes were tested in a high pressure tank. The observation was that the longest models failed due to elastic buckling, but they returned to the original shape after pressure release. The medium sized tubes had large deformations and buckled without returning to the original shape.

Lauren Kougias [13] studied the effect of imperfections in buckling analysis. Special emphasis was put on the ovality of tubes and how to implement this in the FE analysis. In addition, the importance of mesh density and shell elements was studied. However, this study focused on isotropic materials, but the fact that ovalization affects the buckling capabilities of a cylindrical structure is still valid for composite materials.

2 Theory and methodology

2.1 Composites

Composites are materials made up of layers bonded together to make a new material. Typical examples are fiber composites made of glass, carbon or aramid fibers, mixed with a matrix. The matrix is typically epoxy, polyester or polypropylene [17]. By changing the orientation and arrangement of the fibers, the properties of the material can be accustomed to meet the desired requirements. There are almost infinite numbers of combinations on how to make a composite, which opens up a new world of opportunities to solve issues related to the standard materials used today. The advantages composites have compared to isotropic materials like steel or aluminum is high strength to weight ratio, good fatigue- and corrosion resistance.

A homogenous material is a material with the same properties at every point, while a heterogeneous material has properties that vary from point to point [17]. When looking at a microscopic level on a composite with continuous or discontinuous fibers embedded in a matrix, the properties vary from point to point and the composite is heterogeneous. If considering the same material on a large scale with respect to the fiber diameter, the properties of the fibers and matrix can be averaged. Because of this the material can be treated as homogenous on a macroscopic level [17].

There are different types of composites based on the fiber orientation and shape. Some composite material systems are short fiber composites, particulate composites, long fiber composites, unidirectional lamina and woven fabrics. The composites with short fibers or particles give poor strengthening and are therefore known as low-performance composites [12]. In this case the load is mainly carried by the matrix. In high-performance composites like the long fiber composites, the desired stiffness and strength comes from the fibers, while the matrix acts as a protective material around the fibers. The matrix also functions as a load-bridge because it helps to transfer load from broken fibers to adjacent intact fibers [12].

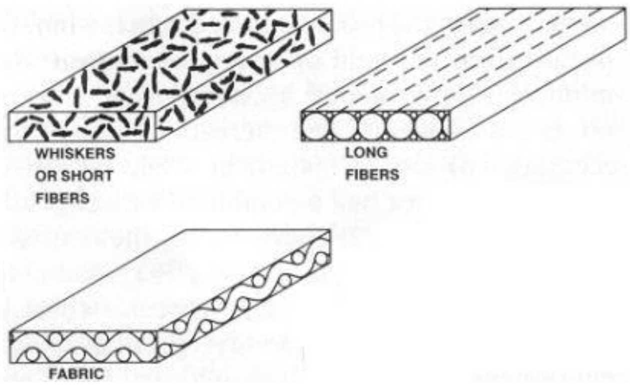

Figure 1 Composite material systems [10]

The volume fraction is also essential to the capacity or performance of a composite. A high fiber volume fraction yields high performance composites, where the volume fraction is defined in Equation 1.

$$V_f = \frac{\rho_m W_f}{\rho_m W_f + \rho_f W_m} \tag{1}$$

2.2 Laminate

The purpose of the laminate method is to improve the material properties by stacking material layers (plies) together (Figure 2).

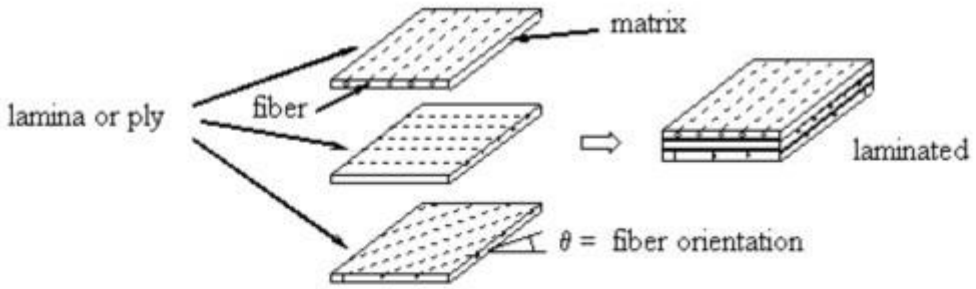

Figure 2 Stacking of plies to make a laminate [20]

Stacking of layers is frequently called lay-up, and describes the orientation angle, thickness and material of the laminate. The orientation angle is relative to the x axis of the laminate coordinate system [17].

2.3 Stresses in a thin-walled cylinder

Thin-walled tubes exposed to pressure generally develop two types of relevant stresses in the walls:

- Circumferential or hoop stresses (σ_1) work in the tangential direction perpendicular to the length of the tube. (Figure 3)
- Longitudinal or axial stresses (σ_2) work longitudinal or parallel to the axis of the tube. (Figure 3)

The ratio between the radius and wall thickness of the tube needs to be higher than 10 for the tube to be considered as thin-walled ($\frac{r}{t} > 10$).

The formulas defining hoop and axial stresses in a cylinder are in Equation (2) and (3).

$$\sigma_1 = \frac{Pr}{t} \tag{2}$$

$$\sigma_2 = \frac{Pr}{2t} \tag{3}$$

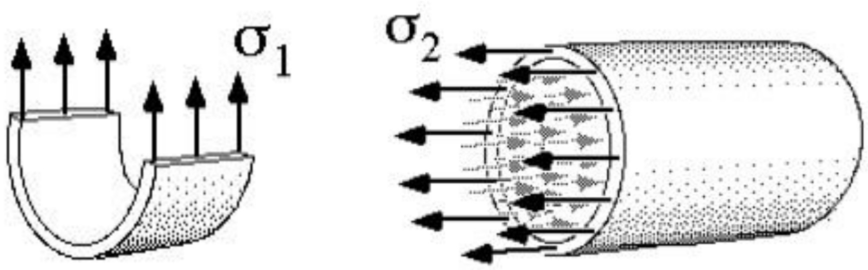

Figure 3 Hoop and axial stresses working on thin-walled tubes [7]

2.4 Failure criteria

Typical failure modes for fiber-reinforced composites can be seen in Figure 4 and are:

- Fiber buckling
- Fiber breakage
- Matrix cracking
- Delamination

Fiber buckling is characterized by a reduction of compressive stiffness and strength of the laminate. The onset and magnitude of the fiber buckling and the compressive property loss is dictated by the properties of the fibers and matrix. [12]

Fiber Breakage occurs when fibers break, making them unable to carry tensile loads. When fibers are surrounded by a matrix, the matrix works as a bridge across the broken fiber transmitting the load. This is called fiber bridging. [12]

Matrix cracking in itself is not normally a reason for ultimate laminate failure. However, matrix cracks may cause other harmful effects. Among those effects are normally moisture absorption, stiffness reduction dominated by the matrix, and it may provoke delamination. [12]

Delamination is a failure mode where the layers of the material separate from each other. Transverse impact loads on the laminate is a normal cause of delamination.

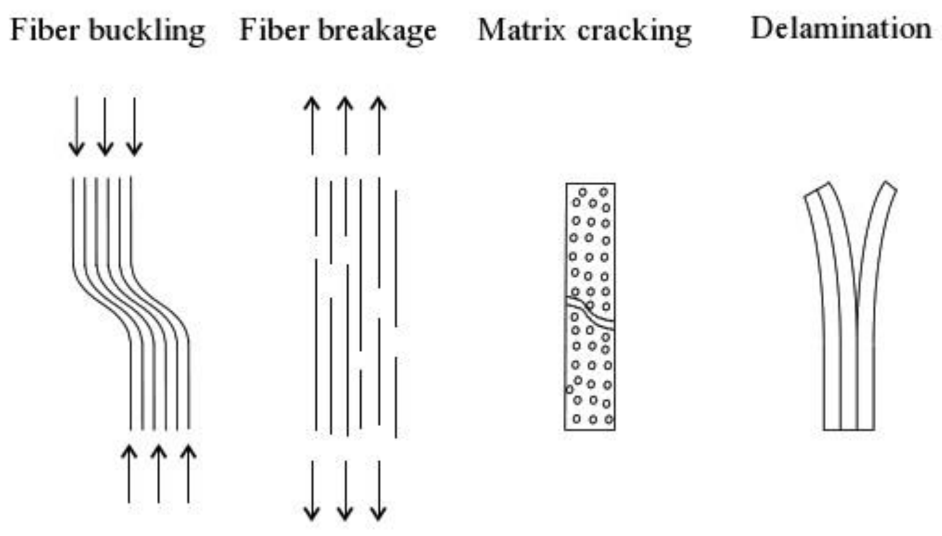

Figure 4 Typical failure modes in fiber-reinforced composites [12]

2.5 Maximum stress criterion

The maximum stress criterion states that failure occurs when one stress component exceed the corresponding strength component as given in Equation 4.

$$f = Max\left(\frac{\sigma_1}{X_T}, \frac{\sigma_1}{X_C}, \frac{\sigma_2}{Y_T}, \frac{\sigma_2}{Y_C}, \frac{\tau_{12}}{S_{12}}\right)\begin{cases} < 1\ no\ failure \\ = 1\ failure\ limit \\ > 1\ failure \end{cases} \quad (4)$$

In formula x, σ_1 is the stress in hoop direction while σ_2 is the stress in the axial direction. τ_{12} is the in-plane shear stress. This criterion is able to detect failure modes, and the modes that can be identified are:

- Fiber fracture
- Matrix cracking
- Shear matrix cracking

2.6 Linear buckling analysis

The linear buckling analysis, also known as the eigenvalue buckling analysis, is a linear perturbation procedure used to determine the critical buckling load of stiff structures. Stiff structures usually have very little deformation before reaching the critical load and collapse [1]. The eigenvalue buckling analysis can provide useful results even when a structure has a non-linear behavior prior to the buckling. To calculate the buckling load of a structure based on this analysis, the lowest eigenvalue is multiplied with the load applied. The effect of the geometry change is usually not relevant because stiff structures imply that small deformations occur. The eigenvalue buckling theory is based on this, and relies on little geometrical change. However, if large deformations are present, it is more suitable to perform a Riks analysis to determine the buckling loads [1].

2.7 Riks analysis

In the Abaqus Analysis User's Manual [2] the Riks method is defined as:

- A method used to predict unstable, geometrically nonlinear collapse of structures.
- A method that can include nonlinear materials and boundary conditions.
- A method that is often used after a linear buckling analysis to provide complete information about the structure collapse.
- A method used to speed convergence of snap-through problems.

In this report, a Riks analysis will be used after a linear buckling analysis to analyze post buckling behavior and achieve full information about the collapse. The Riks analysis is a non-linear static analysis that is used in cases with proportional load. According to the Abaqus Analysis User's Manual [2], the Riks method solves simultaneously for loads and displacements and uses arc length to measure the progress of the solution regardless of a stable or unstable response.

To calculate the critical buckling load using Riks analysis, the load proportionality factor is multiplied with the load applied.

To analyze post buckling behavior using the Riks method, an imperfection has to be implemented to the perfect geometry. This is done to create response in the buckling mode before the critical load is reached [2]. Loads that can be used in a Riks analysis are concentrated loads, distributed pressure forces or body forces.

2.8 Filament Winding Method

The filament winding method was used for making the tubes in this thesis.

Filament winding is the most cost efficient and effective method for fabrication of composite structures with complicated shapes [22].The method is based on winding fiber embedded in epoxy on a mandrel. Today, most of the winding machines are computer aided and consist of minimum three axes. For making even more complex shapes, machines with six axes are commonly used. This advanced technology gives winders the ability to wind non-cylindrical and non-symmetrical shapes.

The fibers are pulled through a resin bath and then through an eye that controls the angle of the fiber on to the mandrel. The carriage travels along the rotating mandrel applying the fibers embedded in epoxy on to the mandrel with desired tension. Applying the right amount of tension when winding is important because the tension dictates the frictional force between the fibers and the mandrel, as well as the resin control [5].

The winding machine used to make the tubes in this project is MAW 20 LS 4/1 [15]. This winding machine consists of four axes of control (X,Y,Z,W). The X-axis controls the rotation of the mandrel, while the Y-axis is the horizontal movement of the carriage. The Z-axis controls the cross carriage motion, and finally, the W-axis controls the wind eye rotation as seen in Figure 5.

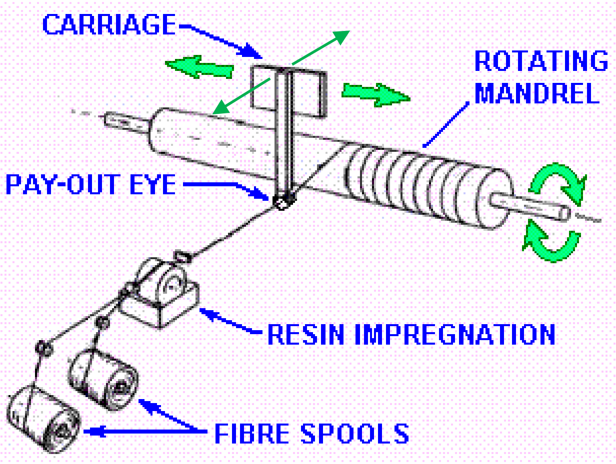

Figure 5 Filament Winding Concept [11]

METS-8 electronic tensioning control system is used to control the fiber tension. The system consists of eight servo motors and eight electronic sensors. The servo motors are equipped with gear boxes to drive the spool, while the main task of the electronic sensor is to detect real online tension for each fiber [15]. To control the tension and get good readings, the main CPU and electronic components are interconnected with CAN bus [15].

2.9 Split disc method

An approach to the split disc method is suggested in the ASTM standard D2290, "Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe". The basic principal behind this method is to pull apart two half-discs that are fitted into a ring shaped test specimen. The specimen has fibers oriented in a hoop.

Strain gauges are placed on each side of the test specimen on the same line as the split of the split disc. To determine the longitudinal Young's modulus in the fiber direction, E_1, the strain gauges are attached along the fiber direction of the test specimen.

Using this method, an apparent tensile strength is found rather than a true tensile strength. The reason for this is the bending moment present during the test at the split between the split disc and the test fixture [4]. In Figure 6 a test fixture that minimize this bending moment is recommended by the ASTM standard D2290.

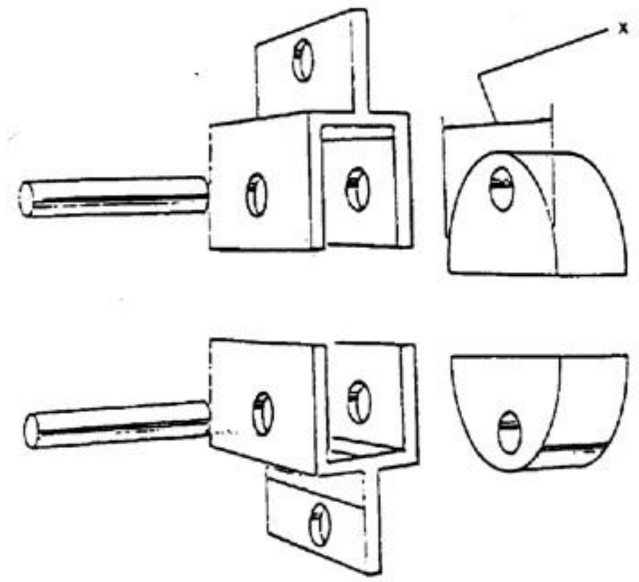

Figure 6 An example of fixture that minimize bending moments [4]

3 Material selection

3.1 Carbon fiber

The carbon fiber used in this thesis is T700S, a product from Toray Carbon Fiber America. T700S is well suited for filament winding and intended for high tensile applications like pressure vessels, both recreational and industrial. [24]

Tensile strength (MPa)	4.900
Tensile modulus (GPa)	230
Strain (%)	2.1
Densilty (g/cm^3)	1.80

Table 1 Carbon fiber T700S properties

3.2 Resin and curing agent

The resin agent used in this thesis is Epikote Resin MGS RIMR 135 and the curing agent is Epikure Curing Agent MGS RIMH 137. The properties can be found in Table 2 and Table 3. Because this system has good mechanical properties it is suitable for production of components featuring high static and dynamic loadability. It has a low mixing viscosity, which is good for infusion and injection processes [16]. The elastic modulus of the epoxy was 2950 MPa [16]. This was used to calculate the transverse and longitudinal Young's modulus in section 6.7 and 6.8.

Density (g/cm^3)	1.13 – 1.17
Viscosity (mPas)	700 – 1100
Epoxy equivalent (g/equivalent)	166 – 185
Epoxy value (equivalent/100g)	0,54 - 0,60
Refractory index	1.548 – 1.552

Table 2 Properties for Epikote Resin MGS RIMR 135

Density (g/cm^3)	1.13 – 1.17
Viscosity (mPas)	700 – 1100
Amine value	166 – 185
Refractory index	0.54 – 0.60

Table 3 Properties for Epikure Curing Agen MGS RIMH 137

3.3 Carbon/epoxy material

Because of the lack of material data for the carbon/epoxy used in this thesis, data for Hexel T300/914 [prepreg] [21] was used in this thesis. However, the longitudinal Young's modulus, E_1, and the transverse Young's modulus, E_2, were found experimentally in this thesis and substituted with the values given from Hexel T300/914.

Property	Value	Experimentally found value
V_f (%)	60.0	64.5 (burn off test)
E_1 (GPa)	129.0	146.2 (Split disc test, ASTM D2290)
E_2 (GPa)	9.5	6.3 (compression test, kapxx)
v_{12}	0.34	
G_{12} (GPa)	4.7	
G_{13} (GPa)	4.7	
G_{23} (GPa)	3.2	
X_T (MPa)	1439.0	
X_C (MPa)	1318.0	
Y_T (MPa)	98.0	
Y_C (MPa)	215.0	
S_{12} (MPa)	79.0	

Table 4 Material properties of Hexel T300/914 and the elastic properties found in this thesis

4 Finite Element Analysis,FEA

To compare the results from the experimental work with analytical methods, a Finite Element Analysis (FEA) was carried out on a small diameter tube. The result of interest in this analysis was how much external pressure a tube with [±75] layup can withstand before buckling. Two types of analyses were performed in Abaqus, linear buckling analysis and Riks analysis as described in section □ and 2.7.

4.1 Model and material assignment

A tube with an inner diameter of 32 mm and a thickness of 1.5 mm was made using a 3D shell model and extruded to a depth of 300 mm. Elastic properties were added as shown in Table 4, and the material type was set to lamina. In Abaqus there are two different ways of creating a composite layup. A composite section can be created and added to the model, or the function "Create Composite Layup" can be used. The latter was chosen here because the model is very simple, making it easier to assign a material orientation. If the model had consisted of different parts, creating a composite section would have been a better choice because a section can be applied to any part, while the composite layup can only be assigned to one part [9]. A composite layup was made for 32 plies using conventional shell as the element type. A region, material, thickness and a rotation angle was added to each ply. Each layer in the wound tube consisted of fibers stacked with [±75] orientation. It was made in four sequences giving the tube four layers. In Abaqus however, each ply consists of fibers in either +75° or -75° orientation. To make the model as similar as possible to the real tube, a large amount of plies were made (32 plies) as seen in Figure 7. The thickness of each ply was set to 0.046875 mm. The layup orientation was chosen by creating a discrete material orientation with the normal axis defined as the surface of the tube, and the primary axis was a datum axis.

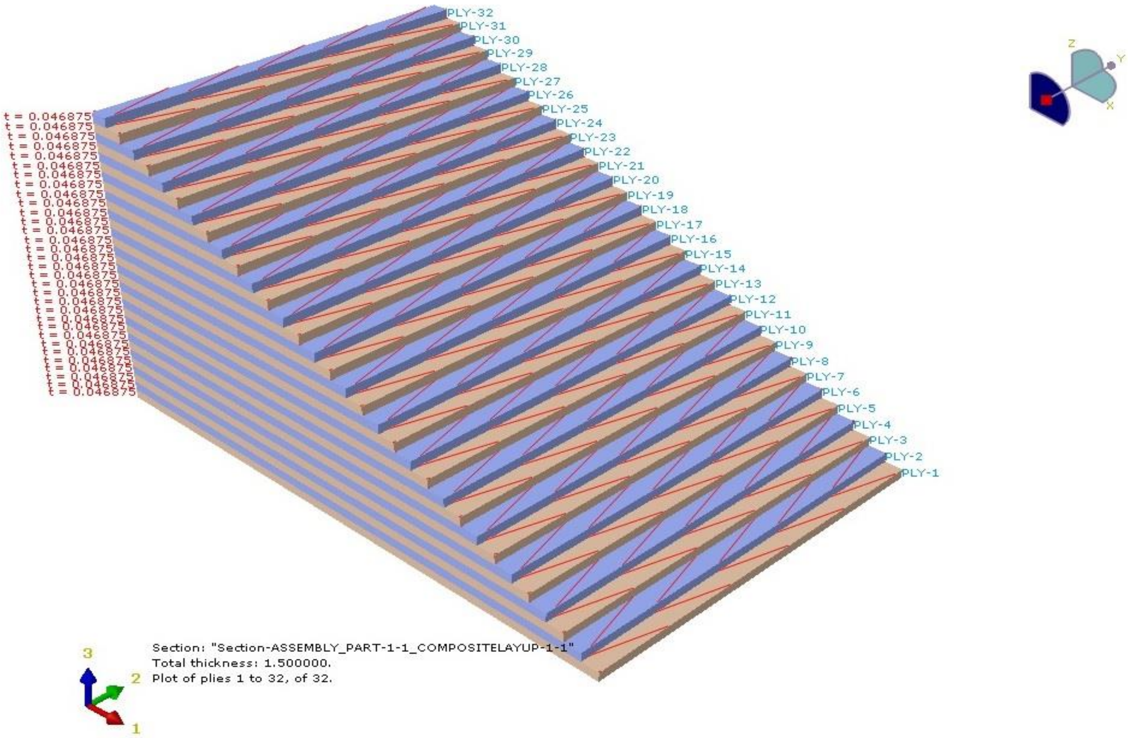

Figure 7 Ply stacking is illustrated showing the thickness and orientation of every layer

4.2 Loads, boundary conditions and mesh

Linear quadrilateral S4R elements were used when meshing the tube [3]. The element size was chosen to be 2 mm as shown in Figure 8 and is further discussed in 7.3.

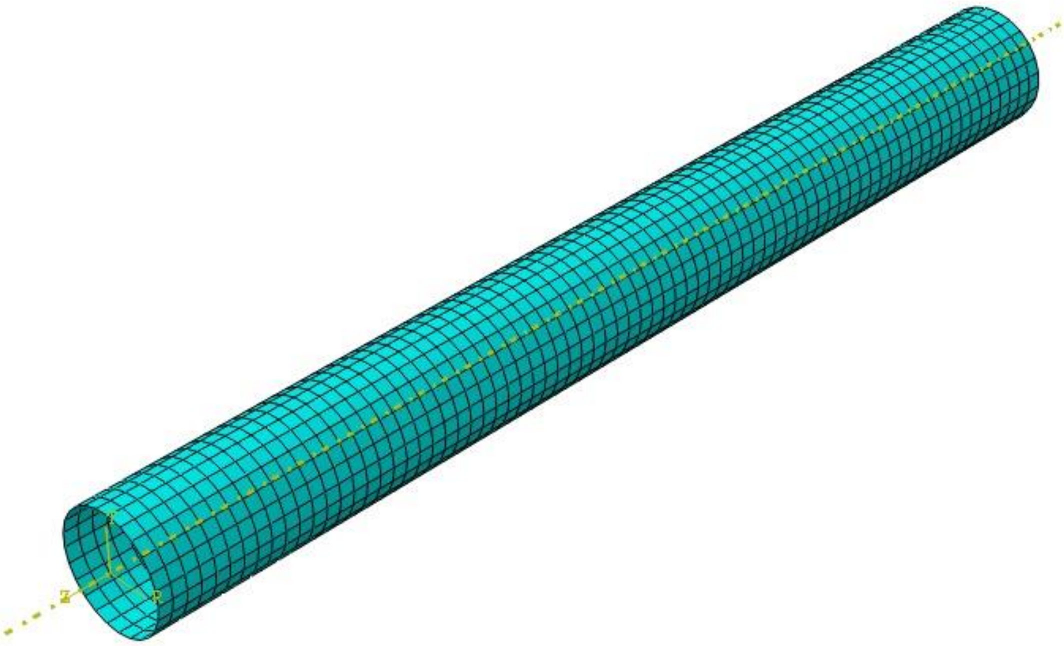

Figure 8 Tube meshed with 2 mm linear quadrilateral S4R elements

Element type	Total number of nodes	Total number of elements	Element size (mm)
S4R	1900	1875	2

Table 5 Mesh information

Before assigning loads and constraints, two node sets were made selecting the nodes by feature edge function. The two node sets were placed on the circumferences on both sides of the tube as shown in Figure 9 . Two constraints were created using rigid body motion, constraining the nodes selected in the sets to a reference point made on each side of the tube. This made the nodes from each set act as slave nodes to the respective reference points.

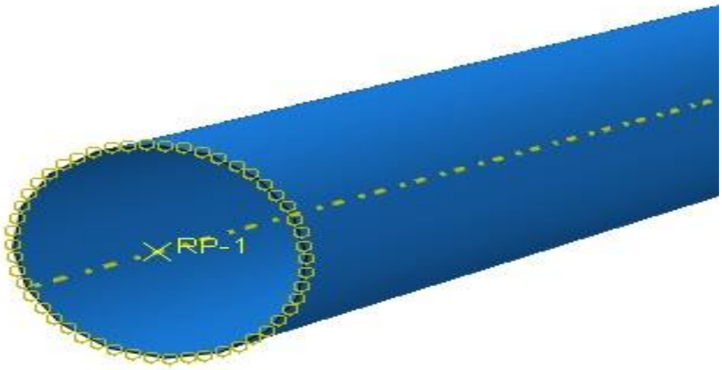

Figure 9 A set created at the circumference of one side of the tube constrained to the correlated reference point

As part of the scope of this thesis, the tube was to be tested against external pressure. A pressure of 10 MPa was applied at the top surface of the tube, compressing it. This pressure was used for the linear buckling analysis. High loads caused problems for the Riks analysis to run properly, and a smaller initial load had to be applied. The exact value of the initial load is not very relevant as long as the analysis converge, because when running the Riks analysis, the load is increased until buckling occurs. To simulate the same scenario as in the experimental tests, a concentrated force was applied to the reference point on one side of the tube. This concentrated force was calculated using Equation 5 where P is the applied pressure, r is the radius of the tube and t is the wall thickness.

$$F = P \cdot (\pi(r + t)^2) \qquad (5)$$

This load simulates the pressure on top of the end fittings, pressing the tube in the negative Z direction. The loads and constraints applied are shown in figure 10.

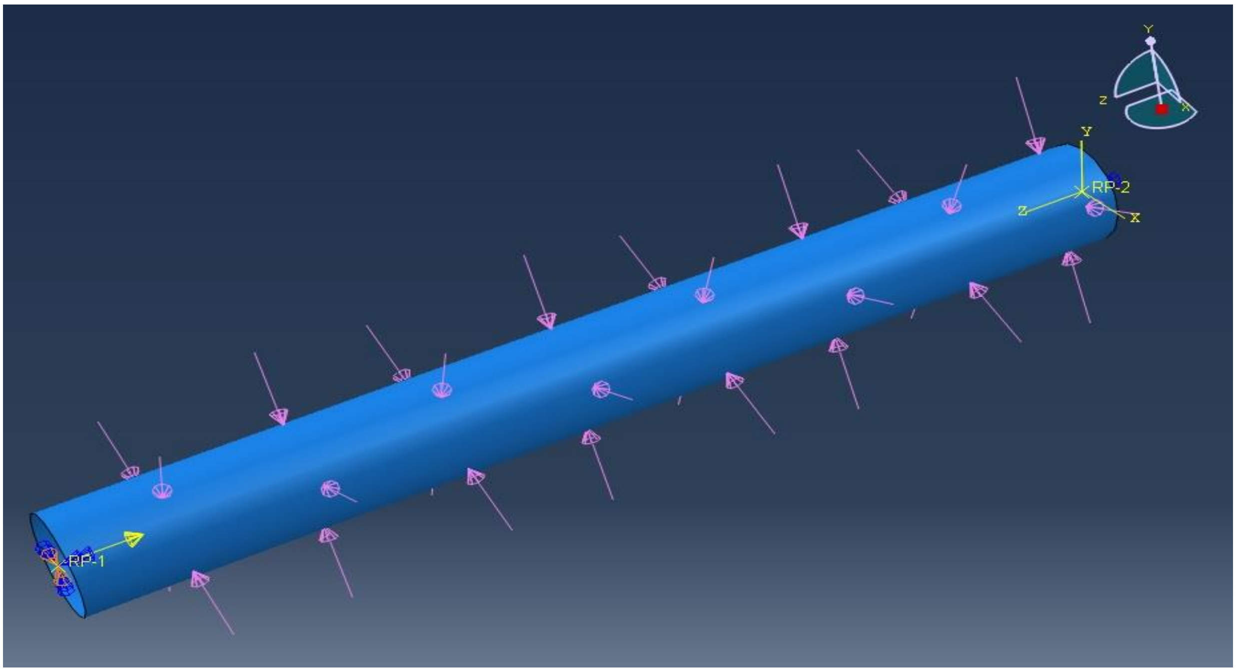

Figure 10 The constraints are shown at the reference point coloured orange, the purple arrows show the external pressure while the yellow arrow illustrates the load applied on the circumference of the tube in negative Z direction

Two boundary conditions were applied, one at each reference point. The displacement and rotation on one side was completely constrained. On the side where the concentrated load was applied, movement in Z direction was allowed.

4.3 Applying imperfections for the Riks analysis

Two different methods were used for applying imperfections to the model. The first method was to add ovality manually at sketch level by drawing an oval circle. The analysis was tested with different ovalities to determine when the buckling behavior occurs.

Ovality (%)	Successful analyses
0.01	No
0.1	No
0.2	No
0.3	No
0.46	Yes

Table 6 Ovality analysis

A coarser mesh size was used during the ovality analyses to decrease the solving time. A finer mesh was used on the final Riks analysis. When a too small ovality was used, the analysis aborted.

These analyses did not converge and the load proportionality factor(LPF)-graph showed a linear curve. With an ovality of 0.46% the analysis completed successfully giving an LPF-graph showing instability where buckling behavior first occurs.

The second method was to add imperfection directly through the edit keyword function for the relevant model in Abaqus. This method is done in two parts. First, a linear buckling analysis is created before the edit keyword function is chosen for this model. The code used is given in Figure 11.

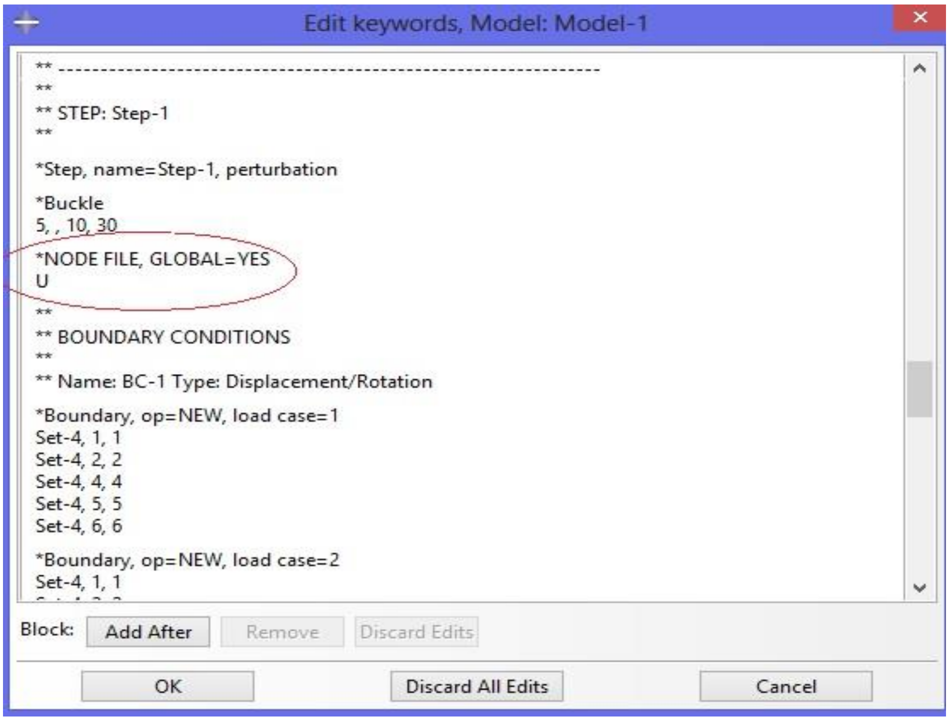

Figure 11 Code used in the edit keywords function for the linear buckling analysis

A new model was created by importing the linear buckling analysis Model-1, and the step was changed to Riks analysis. The additional line of code used in "edit keyword" in the new model is highlighted in Figure 12, and is as follows.

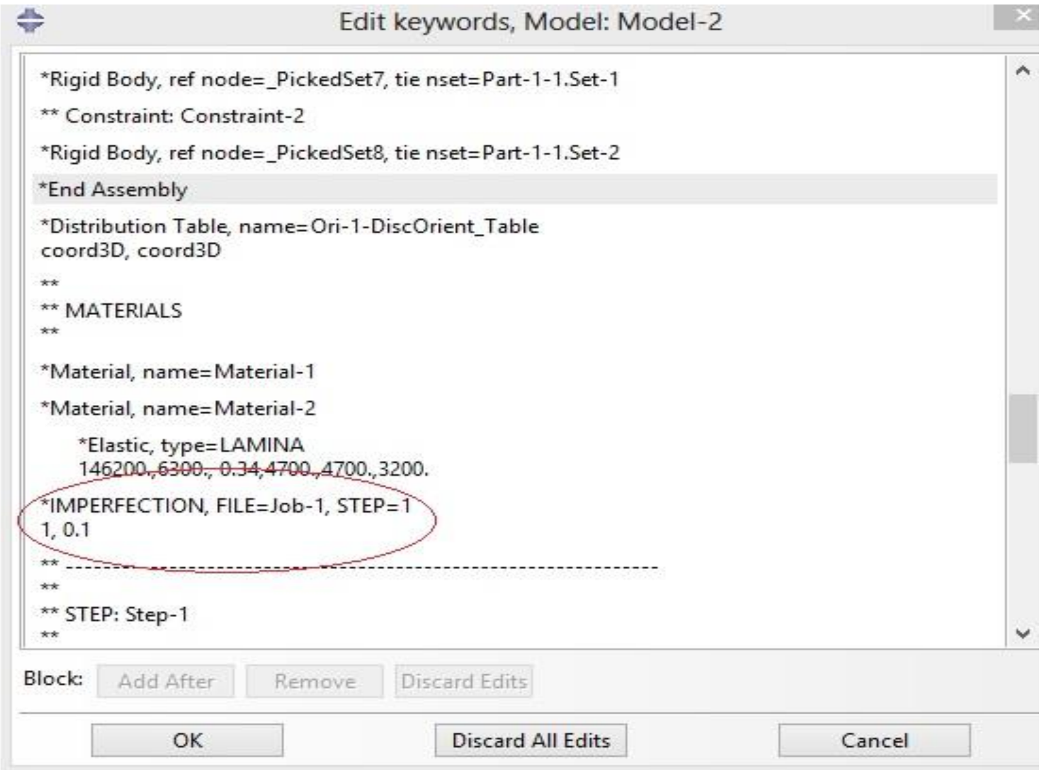

Figure 12 Code used to add an imperfection in the new model

In this method, the buckling mode shapes found in the linear buckling analysis are imported and further used as imperfections in the Riks analysis. The first mode, 1, was used from the linear buckling analysis with a scaling factor of 0.1. This was done because the first mode was of special interest in this analysis because it gave the lowest eigenvalue.

5 Filament winding

5.1 Preparing of the mandrel

A cylindrical rod with a diameter of 32 mm was used as a mandrel, and fixed on the filament winding machine with a chuck jaw and a live tailstock center. The main goal of the mandrel preparations is to make the surface as smooth as possible to simplify the extraction process of the tube. First, the mandrel is polished and oil is applied to reduce the friction between the wound tube and the mandrel. Then, two layers of plastic film are wrapped around the mandrel. This is to avoid the tube sticking to the mandrel directly, making it easier to pull off.

The carbon fibers came spooled on bobbins and were placed in the tensioning cabinet. The purpose of the tensioning system is to make sure that the fibers have constant tension during winding, and squeezing accessible epoxy from the fiber. The fiber passes through a resin bath, and then through the eye, before it is connected to the mandrel as shown in Figure 13.

Resin RIM 135 was mixed with the hardener RIMH 137. The mixing ratio used to make the epoxy was 100:30 [16].

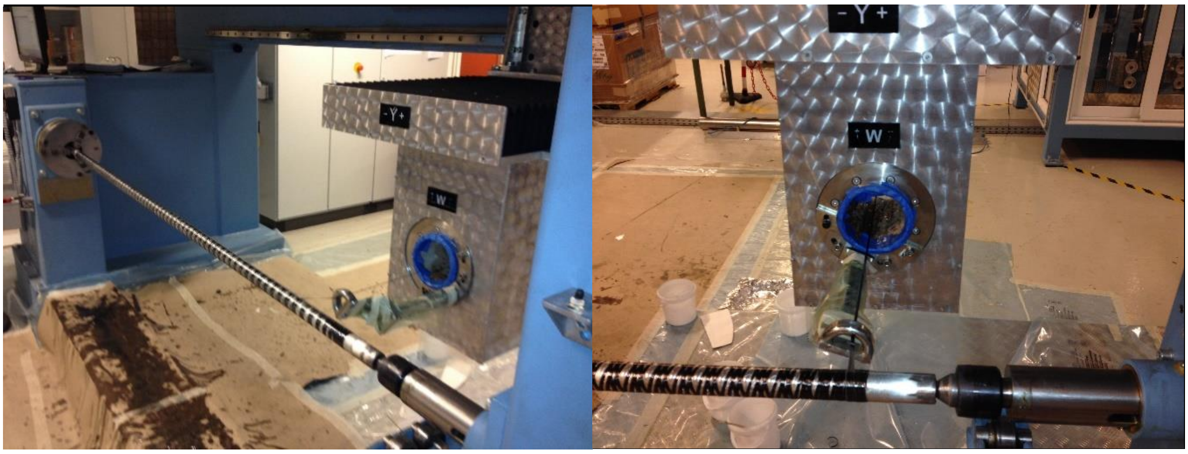

Figure 13 Filament winding process with the rotating mandrel and the eye controlling the angle of the fibers

5.2 Programming the filament winding machine

Winding Expert 1.185 [15] was used to program the winding process. A mandrel with 32 mm diameter was pre-made and imported into Winding Expert. The program suggested a "3 over 1" pattern to be effective when winding with angles of [±75°](Figure 14).This pattern was used with a fiber thickness of 4 mm. The pattern was set to run eight times back and forth before covering the mandrel completely. The program was then transported into the Winding Commander 8.0 [15] which was used to run the filament winding machine. To get the desired wall thickness of 1.5 mm, the chosen program was restarted four times before the tube was finished.

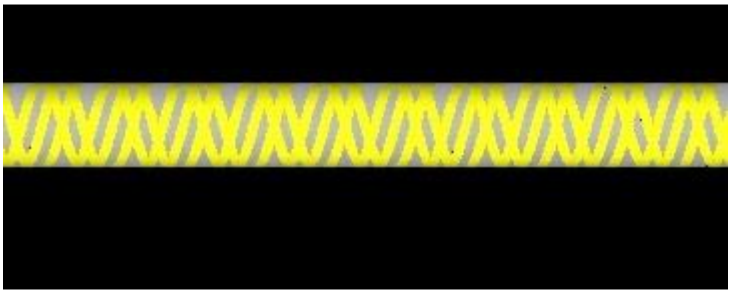

Figure 14 3 over 1 pattern used to wind the tubes

5.3 Curing, extracting and cutting

When the filament winding process was finished, the tube was left to cure for 24 hours at room temperature before it was put in the oven for 15 hours at 80°C. While curing, the tube was continuously rotating at a low speed to avoid epoxy dripping off. Then the tube was heated up to 100°C for one hour. The reason for this was to melt the plastic film layers creating a small clearance between the mandrel and the tube. This makes the extraction of the tube easier by making it possible to pull of the entire tube at once. The tube was pulled off the mandrel manually using a winch, and cut into 30 cm long test tubes (Figure 15).

Figure 15 The extraction process of the tube

6 Experimental work

6.1 Determining the fiber volume fraction

Test pieces from the carbon fiber tube were cut out and put into ceramic cups. The weight of the cups with and without the test pieces was measured, and the cups with the test pieces were put in an oven and heated to 500°C for 240 minutes. The epoxy then evaporated leaving only the carbon fibers in the ceramic cups, as seen in Figure 16. The cups were then weighed again without the epoxy. By knowing the weight of the test pieces with and without epoxy, the density of the matrix and the carbon fibers, the volume fraction was calculated using Equation 1.

	Test 1	Test 2
Weight carbon fiber (g)	0.0058	0.006
Weight matrix (g)	0.0022	0.0022
Density fiber (g/cm^3)	1.75	1.75
Density matrix (g/cm^3)	1.20	1.20
Fiber volume fraction	0.64	0.65

Table 7 Determining the fiber volume fraction

The average fiber volume fraction value was 0.645.

Figure 16 Fibers left after the epoxy evaporated

6.2 Microscopy test

A microscopy test was done on the tubes to determine the thickness of each layer of the tube and detect defects or voids. To perform a microscopy test, small test pieces were cut from the tubes as seen in Figure 17. The test pieces were grinded to get a fine surface that gives good results when using the microscope. Because the [±75] layers were wound into each other, it was not possible to detect any trends showing the separation in layers. The tests also showed that the tube has voids shown as black dots in Figure 18.

Figure 17 Test piece used in the microscopy test

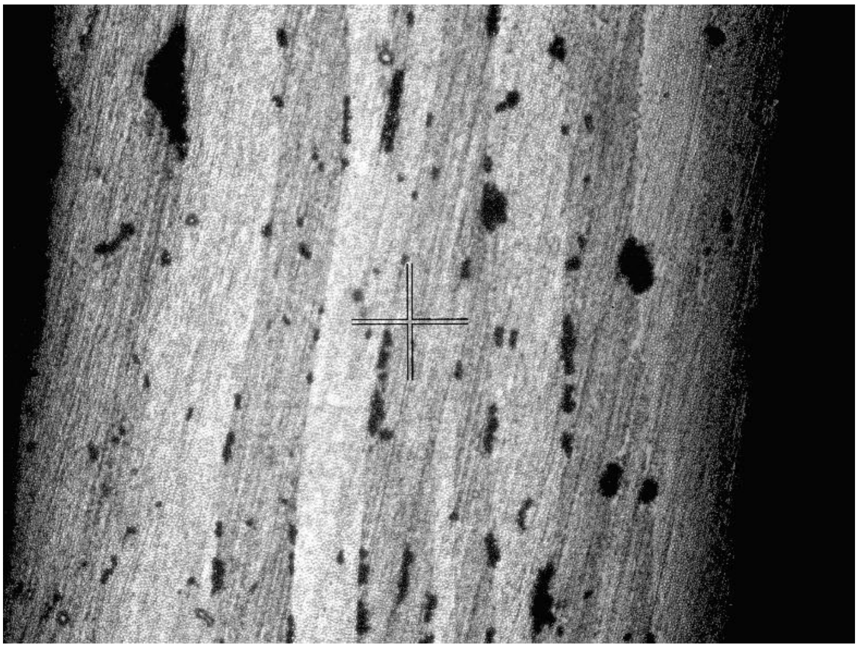

Figure 18 Microscopy of the tube showing voids as black dots

6.3 Optical fibers

The tube was grinded to get a smooth surface required for the attachment of optical fibers (Figure 19). The optical fiber was glued on by using cyanide optic fiber glue. The placement of the optical fiber on the tube was decided by studying the deformation of the tube using FEA. The approximate areas of interest were at 75 mm, 150 mm and 225 mm on the tube where the optical fibers were laid in hoops, as seen in Figure 20. These areas will be referred to as hoop 1, hoop 2 and hoop 3, respectively, in the rest of the thesis.

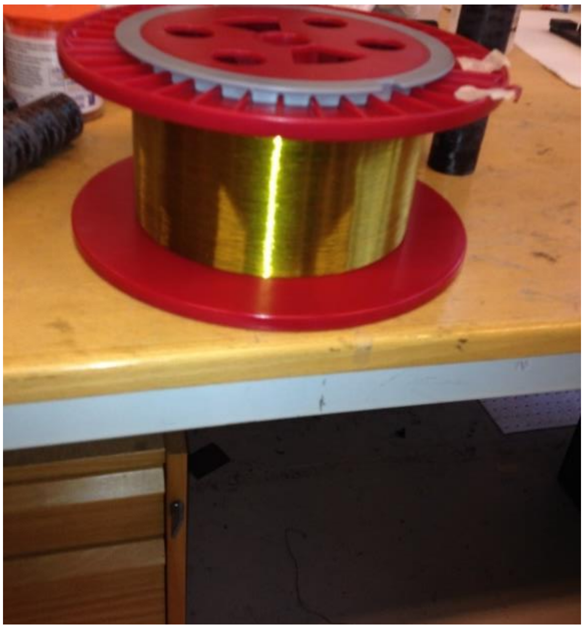

Figure 19 The optical fiber used

Figure 20 Optical fibers attached to the tube in hoops

6.3.1 External pressure testing

To perform the external pressure test, an autoclave was used as Figure 21 shows. The machine was filled with water using a water supply, and the test tube was put inside. A compressor was used to increase or decrease the pressure in the autoclave, and a manometer was used to measure the pressure. The manometer was connected to a computer and a Control Center Series 30 program [6] was used to read and record the pressure at any time.

Figure 21 Autoclave with the test tube before testing

To be able to connect the optical fibers attached to the tube to a computer, an end cap with a hole was used with a T-fitting (Figure 22). This enabled the wire connected to the optical fiber on the tube to come out of the autoclave, and into the computer reading the strain measurements. Aradite glue was used to keep the end cap glued to the T-fitting, keeping it tight and sealed. A pressure hose from the compressor was also attached to the T-fitting.

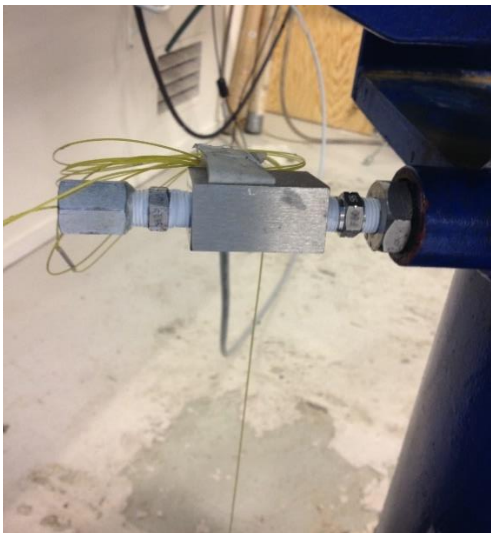

Figure 22 T-fitting installed on the autoclave with the wire connecting the optical fibers to the computer

6.4 Strain measurement technologies

Optical Backscatter Reflectometer 4200 from Luna, OBR, was used to read the strains from the external pressure tests. This is a portable reflectometer that excels at detecting any minor detail that can cause poor results even before the testing begins. It detects for example bad splices, bends and optical fiber damage [14], as seen in Figure 23.

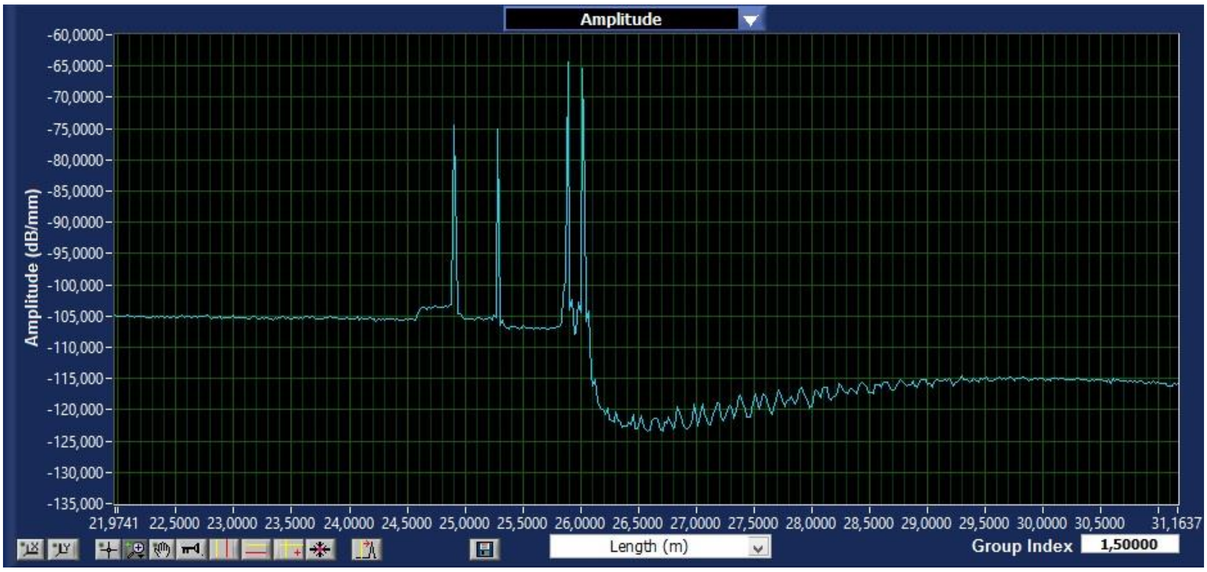

Figure 23 The software program used to measure strain showing high peaks indicating the location of the damage in the optical fiber

Strain gauges of the FLA-5-11-1L type were used in the compression tests and split disc tests to measure the strains needed to calculate the elastic properties.

Strain gauge properties:

- Length : 5 mm
- Gauge factor: 2.13 ±1
- Gauge resustance: 120.3 ± 0.5Ω

6.5 End caps

End caps were used on each side of the tube to keep water from entering the tube while tested (Figure 24). The end caps were sealed by using "stickytape"[25] on the circumference of the end cap and pressing it on the tube.

Figure 24 A shows the end caps before they are mounted on the tube, while B shows an end cap fitted into the tube and sealed with "stickytape"

6.6 Checking the optical fibers

To check if the optical fibers are broken or damaged before starting a test, a laser was used. If the laser goes through the entire fiber and glows at the end tip, the fiber is intact. If the fibers are slightly damaged the laser will glow at the points of damage, but still go through to the end tip of the fiber as seen in Figure 25. If the fiber is broken, the laser will stop at the location where it is broken. Damaged optical fibers have an effect on the strain graphs, resulting in noise which makes the graphs difficult to interpret.

Figure 25 Damaged optical fibers are detected with a laser glowing red at the damaged area

6.7 Determining the transverse Young's modulus

To determine the transverse Young's modulus, E_2, hoop wounded tubes were tested in axial compression.

A tube with an inner diameter of 32 mm, fibers oriented only in 90 degrees (hoop) and a wall thickness of 2 mm was made using the filament winding technique. Strain gauges were glued to the test tubes perpendicular to the fiber direction (Figure 26).

Figure 26 Strain gauge attached to the tube perpendicual to the fiber direction

Figure 27 shows the test tubes fixed using two flat steel pieces in the Intron test machine. The test was set to compress at a speed of 0.60 mm/min.

Figure 27 A test tube is ready to be compressed

The transverse Young's modulus was calculated using Equation 6.

$$\frac{1}{E_2} = \frac{(1 - V_f)}{E_m} + \frac{V_f}{E_f} \qquad (6)$$

6.8 Split disc testing

ASTM D2290 standard [4] for split disc testing was used as a basis for the split disc test.

Inner diameter of test specimen (mm)	32.0
Wall thickness of test specimen (mm)	2.0
Width of split disc (mm)	12.0
Speed of testing (mm/min)	2.5

Table 8 Information about the split disc test

The fixture was made with a minimum clearance between the split disc and the fixture as Figure 28 and Figure 29 shows. This was done to reduce the bending moment that occurs in this area when the test is running. Otherwise, there is a risk of finding the modulus of the bolts instead of the test piece.

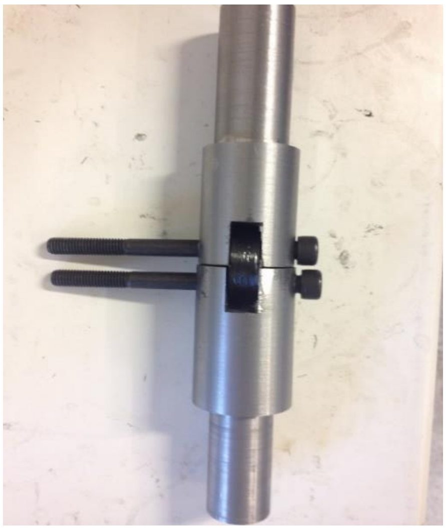

Figure 28 Split disc fixture with the split disc and test piece installed

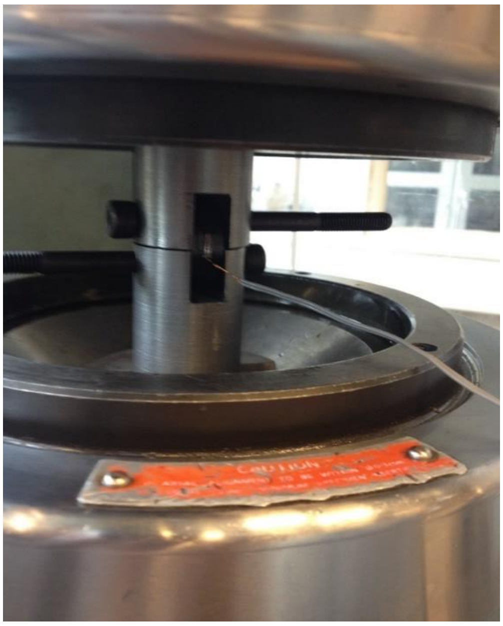

Figure 29 Test piece ready to be tested using the Instron tension machine

Estimations of the longitudinal Young's modulus was done by using Equation 7 with the volume fraction found experimentally for the tubes used in this thesis. The fiber modulus and matrix modulus were taken from table x.

$$E_1 = E_f \cdot V_f + E_m\,(1 - V_f) \qquad (7)$$

7 Results

7.1 Split disc test results

Five test pieces were tested using the split disc method, and the longitudinal Young's modulus, E_1, is found for the tubes with 0.64 fiber fraction. The results are shown in Table 9 . The calculated E_1 was 149.4 GPa. Table 29 shows the stress-strain graph for sample 5. Graphs for the remaining samples can be found in Appendix C.

Sample	Wall thickness (mm)	Width (mm)	Orientation (degrees)	Longitudinal Young's modulus, E1 (GPa)
1	2	11	90	145.8
2	2	10	90	146.6
3	2	10	90	173.8
4	2	10	90	129.9
5	2	10	90	134.9
Average value				146.2

Table 9 Split disc test results

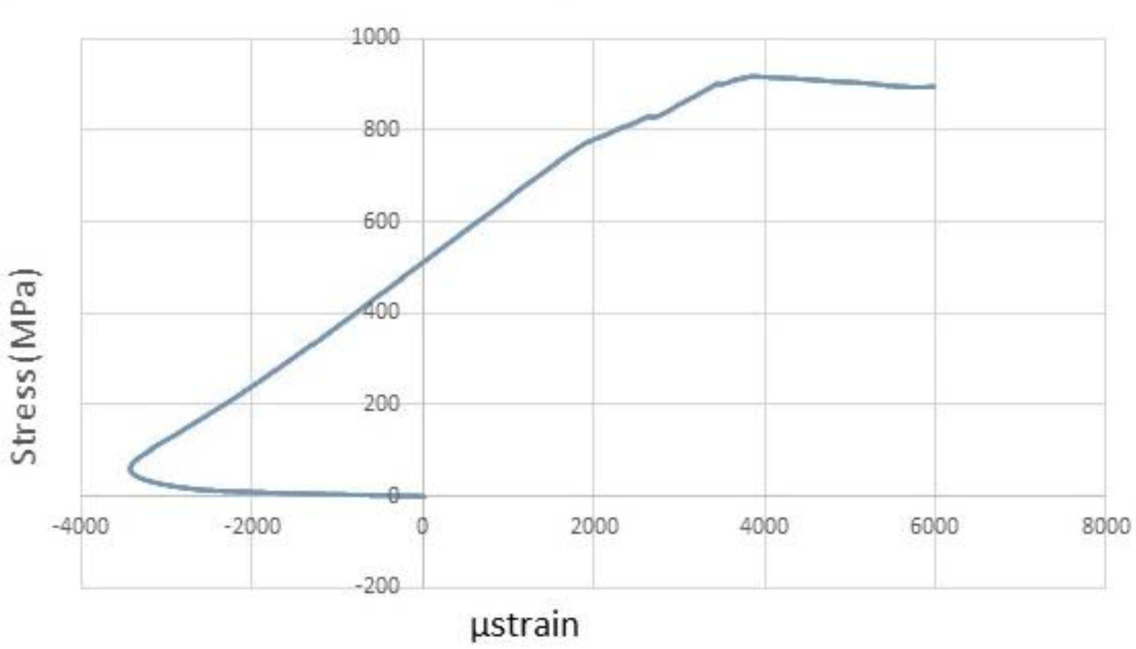

Figure 30 Stress-strain curve for sample 5

Figure 31 and Figure 32 show the visual failure of the rings tested with the split disc method.

Figure 31 Failure of the ring tested with the split disc method

Figure 32 The ring tested using the split disc method failed at the location of the strain gauge

7.2 Transverse Young's modulus results

Six test pieces were tested with different lengths to see if a shorter tube with potentially less defects would have an effect on the results. It can be seen in Table 10 that the length difference did not have a significant influence on the results in the tests as E_2 varies from 5.4-7.2 GPa despite the length of the tube. The calculated E_2 using equation 6 was 8.2 GPa.

Sample	Length (cm)	Wall thickness (mm)	Orientation (degrees)	Transverse Young's modulus E_2 (GPa)
S1	30	2	90	7.1
S2	30	2	90	6.3
S3	16	2	90	5.4
S4	10	2	90	7.2
S5	10	2	90	5.4
S6	10	2	90	6.4
Average value				6.3

Table 10 Compression test results

The following graph in Figure 33 shows the stress-strain curve of test sample S2. For the remaining stress-strain graphs, see Appendix B.

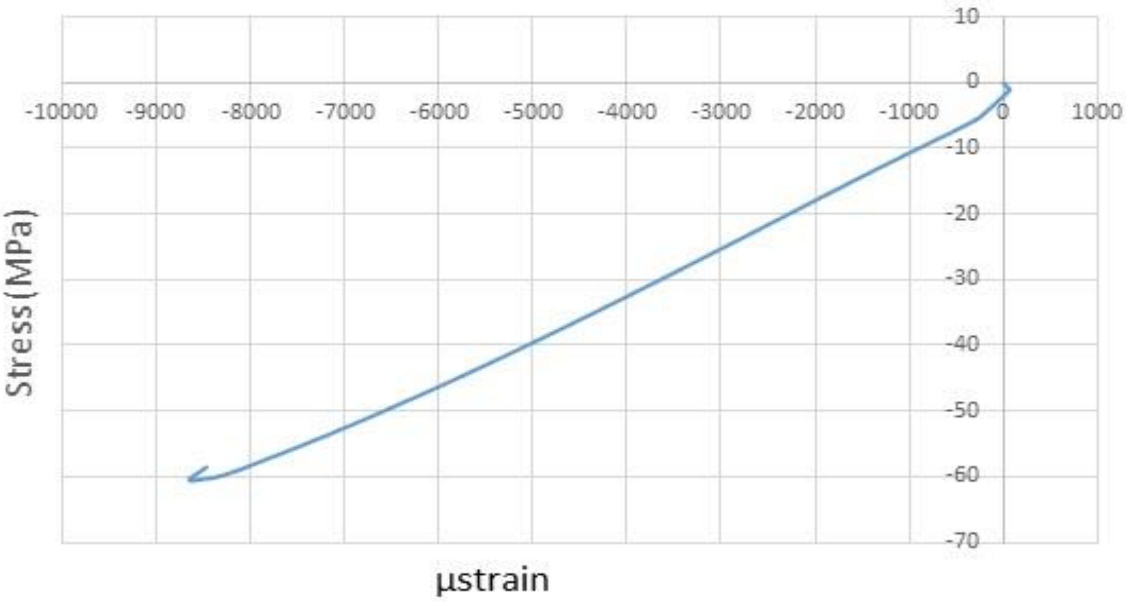

Figure 33 Stress-strain curve for sample S2

7.3 Mesh sensitivity analysis

Choosing the right mesh size is essential when performing a FEA analysis. A coarse mesh may be used when the geometry is not very complex. However, if the mesh is too large, important details may not be captured in the analysis resulting in poor end results. A mesh study is performed to see how the buckling load varies with different mesh size. As seen in Figure 34, the curve shows a relatively stable buckling load for small mesh sizes. However, at mesh sizes larger than 3 the curve starts to grow, resulting in much larger buckling loads. The very fine mesh sizes 0.5 and 1 were time consuming and required large computer capacity. Because of this, a mesh size of 2 was chosen, as this was fine enough to capture essential details and give satisfying results.

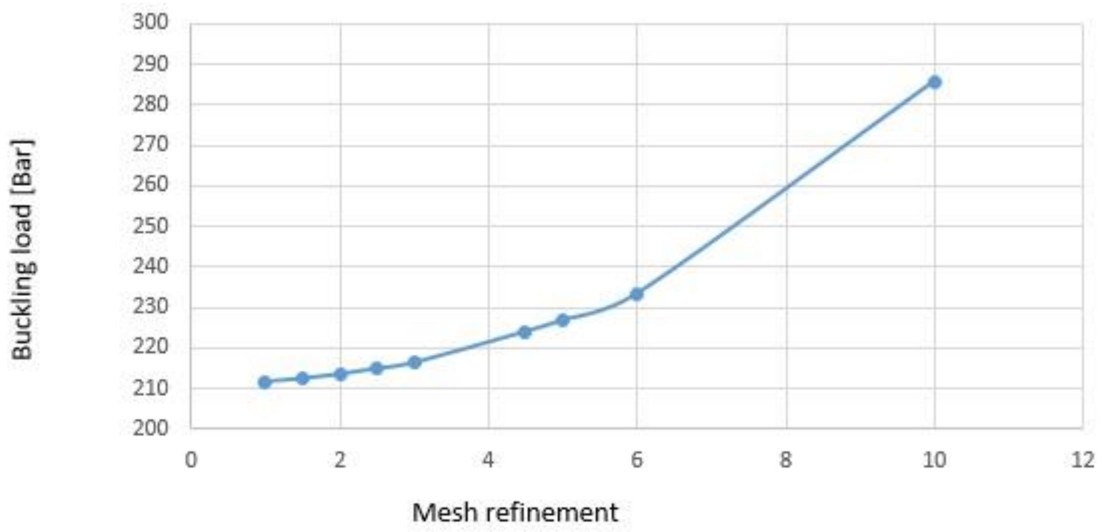

Figure 34 Mesh sensitivity graph

7.4 Linear buckling analysis

A buckling load of 24.4 MPa (244 bar) was calculated from the linear buckling analysis, and the deformed shape of the tube for the lowest eigenvalue mode is shown in Figure 35. The first deformation mode is further used as imperfection in the Riks analysis.

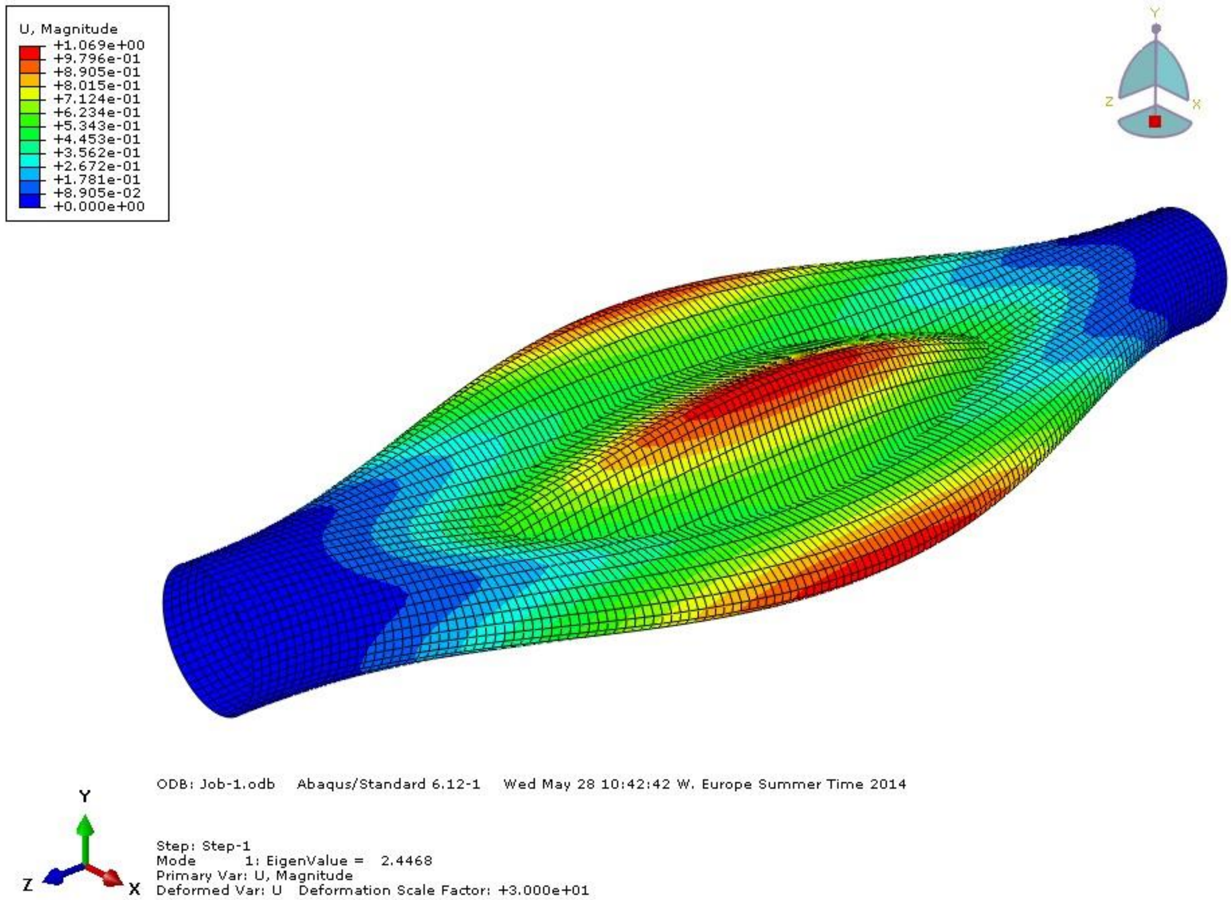

Figure 35 Linear buckling analysis

7.5 Riks analysis

The load proportionality factor for the whole model is plotted against the arc length in Figure 36. The Riks analysis shows that the initial buckling occurs at approximately 240 bar (24 MPa). The curve continues to increase with no further instabilities after initial buckling. The results from the Riks analysis correspond well with the linear buckling analysis showing similar initial buckling value of 240 bar.

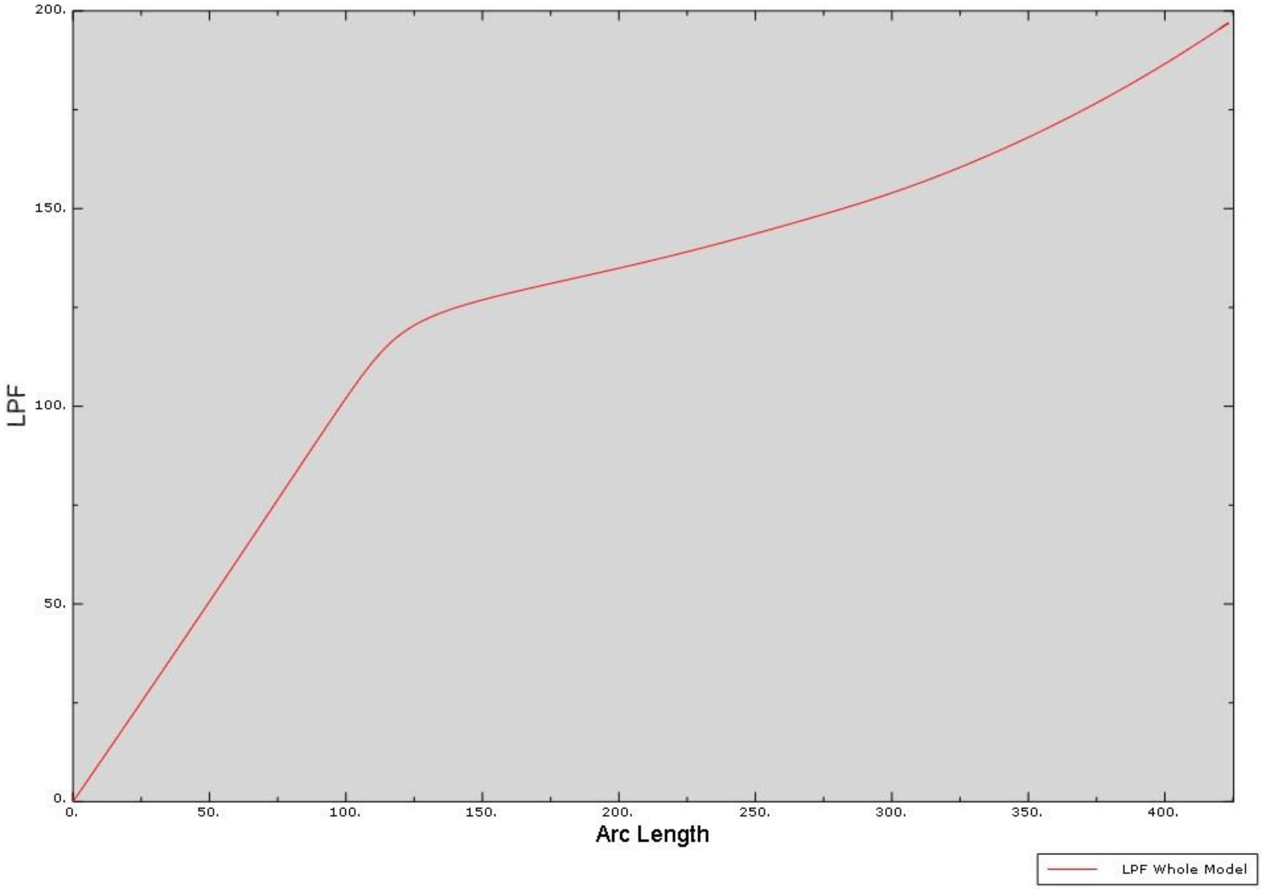

Figure 36 Load proportionality factor plotted against arc length

The strain readings on the tube were found by using the path function in Abaqus. Creating a path enables the user to define specific areas on the tube to be studied. Three hoop shaped paths were made to simulate the optical fibers from the experimental tests. The logarithmic strain at integration points, LE, was used as field output from the analysis. The strain results for the top ply (ply 32) were of interest because the optical fibers were attached to top of the tubes. Strain readings were found for the same pressure as the strains in the experimental tests, and are shown for hoop 2 in Figure 37.

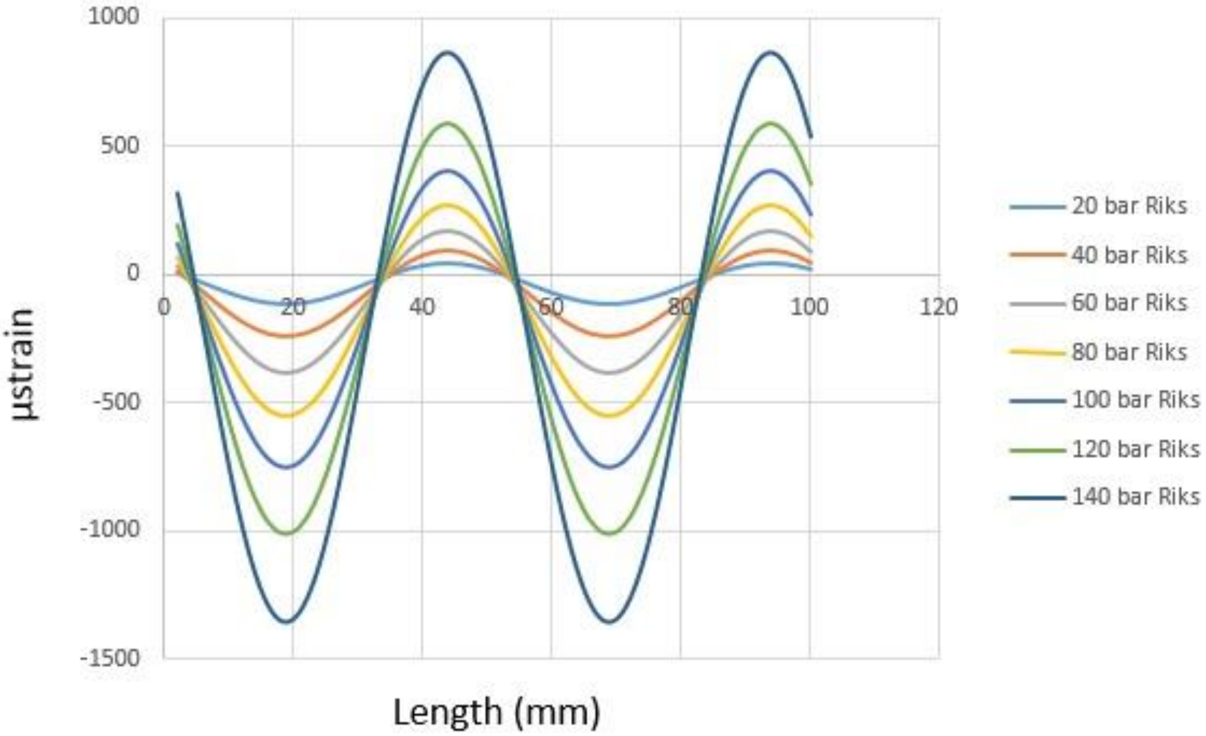

Figure 37 Strain readings at the location of hoop 2 for the equal instances of pressure as in the experimental tests

7.6 Pressure test

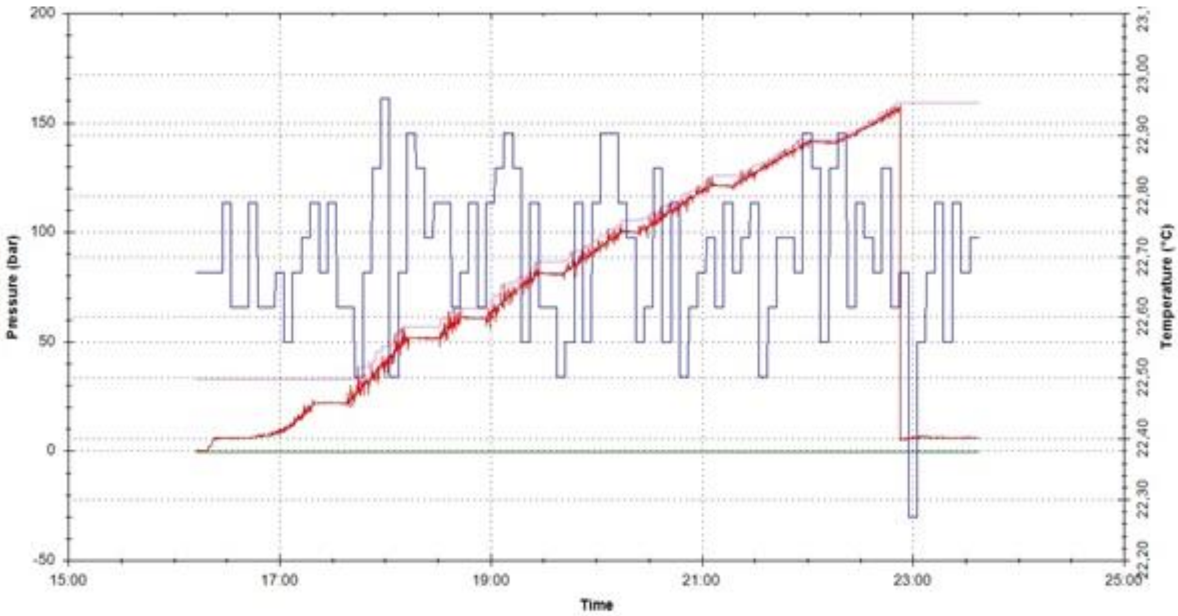

Figure 38 Pressure against time curve

Several tubes with [±75] layup were tested against external pressure at the fatigue laboratory at NTNU. The maximum average pressure obtained was 160 bar. Figure 38 shows the pressure against time for tube 1. When the pressure reaches approximately 160 bar the tubes fail, causing a sudden drop in pressure where it stabilizes at 4-5 bar, which corresponds to the water pressure. The tubes were taken out and inspected after failure. More similar graphs can be found in Appendix D.

Two tubes were tested with optical fibers attached. Buckling values can be seen in Table 11.

Sample	Orientation	Resin / cuing agent	Carbon Fiber	Thickness (mm)	Length(mm)	Buckling value (Bar)
1	$[\pm 75]_4$	MGS RIMR 135 / Epikure RIMH 137	T700S	1,5	30	157,1
2	$[\pm 75]_4$	MGS RIMR 135 / Epikure RIMH 137	T700S	1,5	30	163,8

Table 11 Buckling values shown for the tubes tested with optical fibers

The second sample had damaged optical fibers at three places, resulting in non-readable strain graphs. The damages are detected by a laser test as seen in Figure 39 and Figure 25. Because of this, the strain graphs used in this thesis are taken from sample 1.

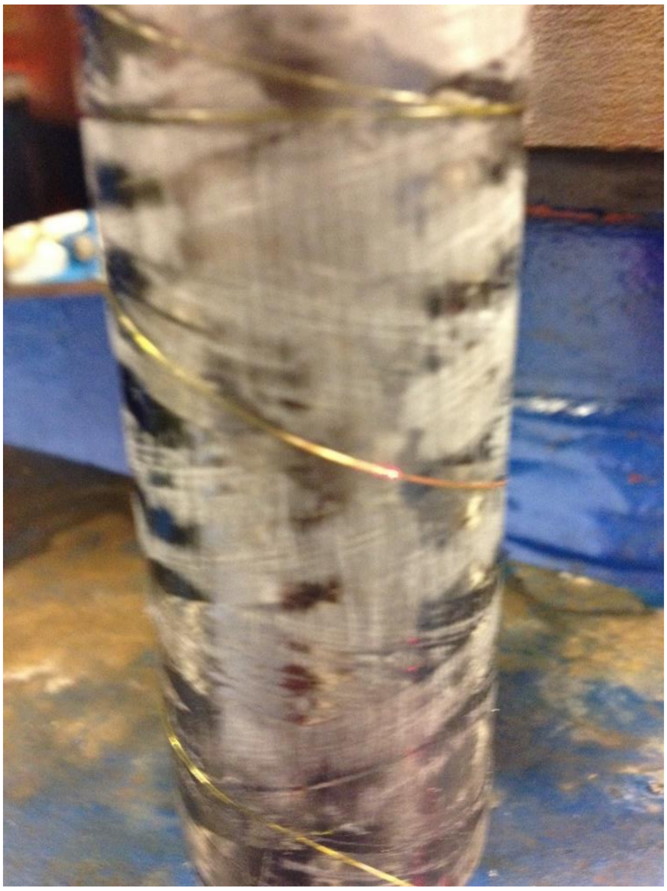

Figure 39 A laser test detecting damage on the optical fiber for test sample 2

Visual inspections were done on the tubes after reaching failuar when exposed to external hydrostatic pressure. As seen in Figure 40 the tube had excessive damage, and it may seem like it failed due to high hoop stresses, giving failure along the axial direction of the tube.

Figure 40 Failed tube after external pressure test

The strain curves for hoop 2 can be seen in Figure 41. The strains increase slowly with increasing pressure, until the pressure reaches 140 bar which is close to buckling. At 140 bar the strain curve increases drastically with maximum negative µstrain of approximately -3000 and positive µstrain of approximately 4000.

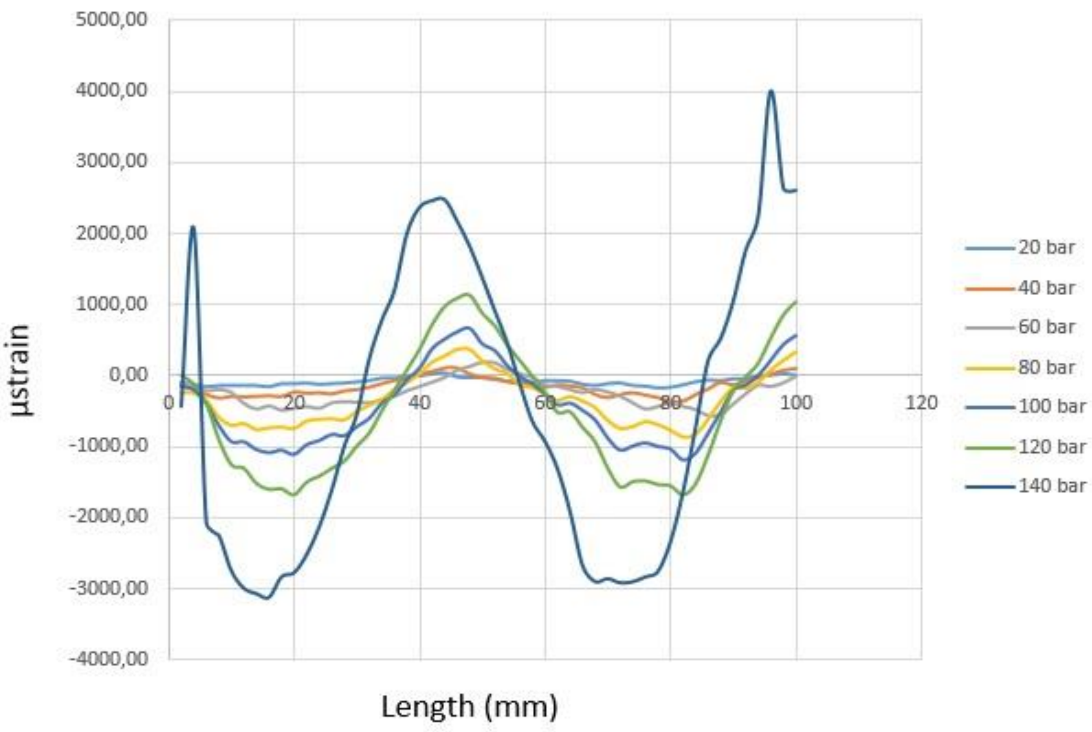

Figure 41 Strains plotted for hoop 2 at each instance measured during the test

7.7 Maximum stress criterion

The maximum stress criterion was found using the envelope function in Abaqus. The method calculated the maximum exposure factor f from Equation 4 to be 0.877 in longitudinal direction of the fiber (hoop). However, the envelope method did not give the ply in which the maximum exposure factor was found. This was done by checking the maximum compressive stresses for each ply in hoop direction. The maximum stress was found to be -1156 MPa at the bottom ply. The stress was approximatly the same for the top ply, as expected because of the [±75] layup. The maximum hoop stress, σ_1, was compared to the maximum strength, X_T, from Equation 4, giving an value of 0.877. This confirmed that the maximum stress occurred in the top and bottom ply.

7.8 Comparing experimental pressure tests with finite element analysis

From the pressure tests, an average buckling value of 160 bar was found. The FEA computed buckling to occur at 244 bar.

$$Percentage\ difference(\%) = \frac{P_{FEA} - P_{experimental}}{P_{experimental}} 100 \qquad (8)$$

By using Equation 8, it can be seen that the FEA predicts that the tube can withstand 52,5 % higher pressure before failing than the tubes from the experimental tests.

In Figure 42 the strain results from hoop 2 of the experimental pressure tests plotted against the equivalent strain results from the FEA model. The complete strain graphs comparing the individual strains can be found in Appendix A. Figure 43 shows the strain comparison at only 40 bar, while Figure 44 compares the last measurement taken before the tube buckled. The graphs show similar tendencies in strain behavior, however the match is not perfect. At lower pressure, the curves have a decent match and are almost overlapping. With increasing pressure, the match accuracy between the strains decreases. At 140 bar the experimental curve shows a drastic increase in strain compared to the FEA.

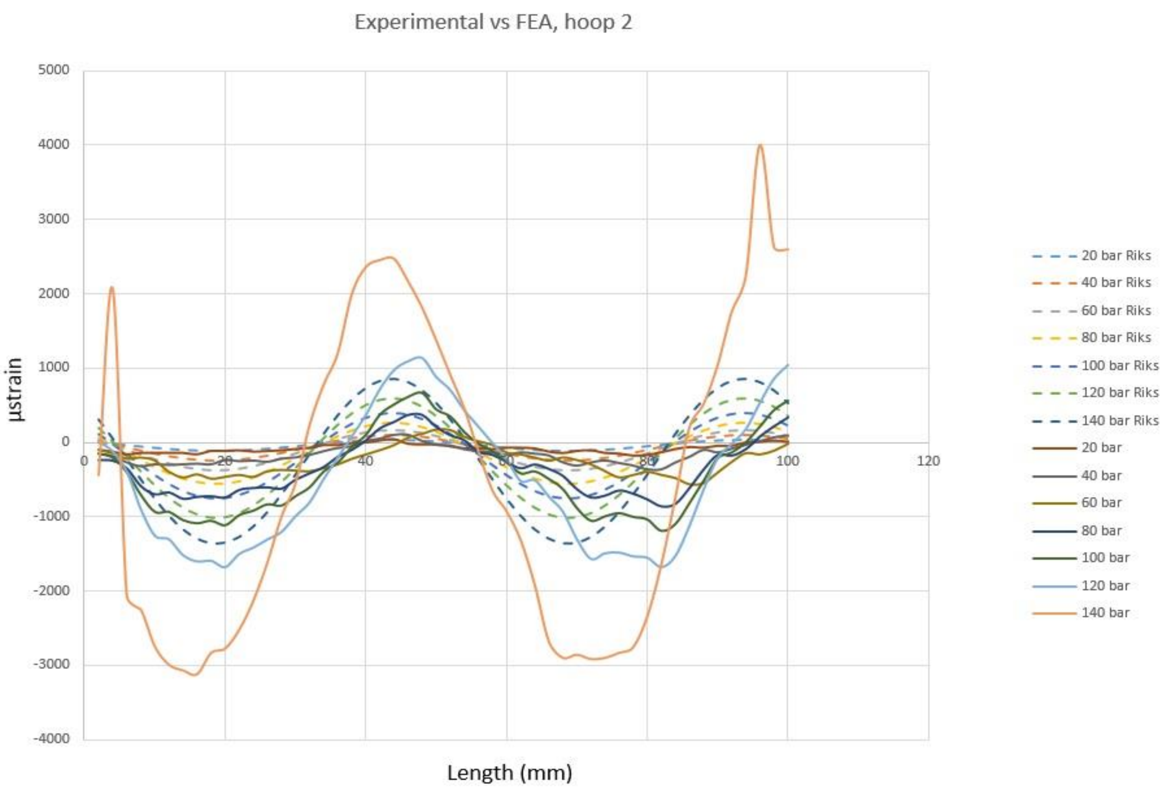

Figure 42 Graph showing the Riks strains compared to the strains found experimentally

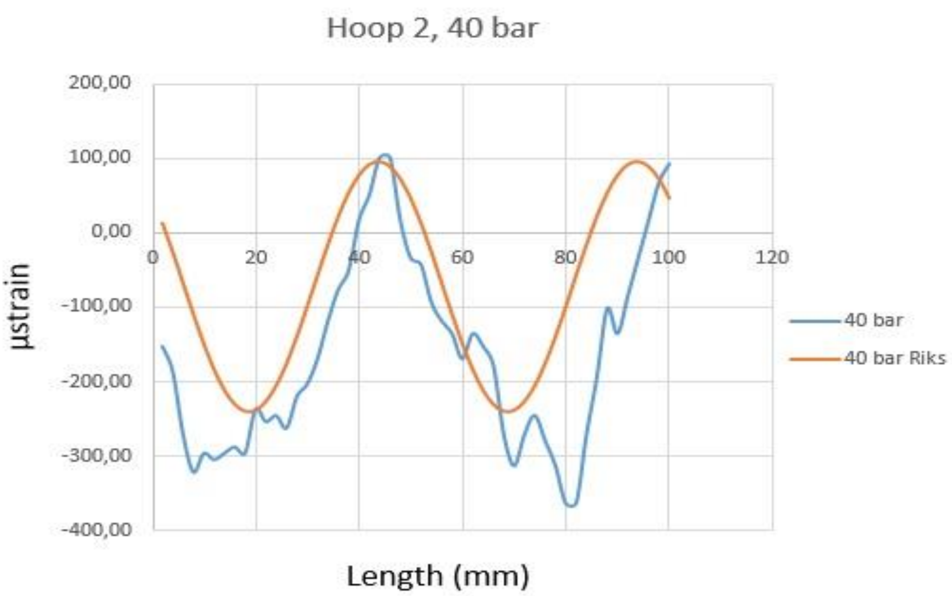

Figure 43 Comparing strains at 40 bar

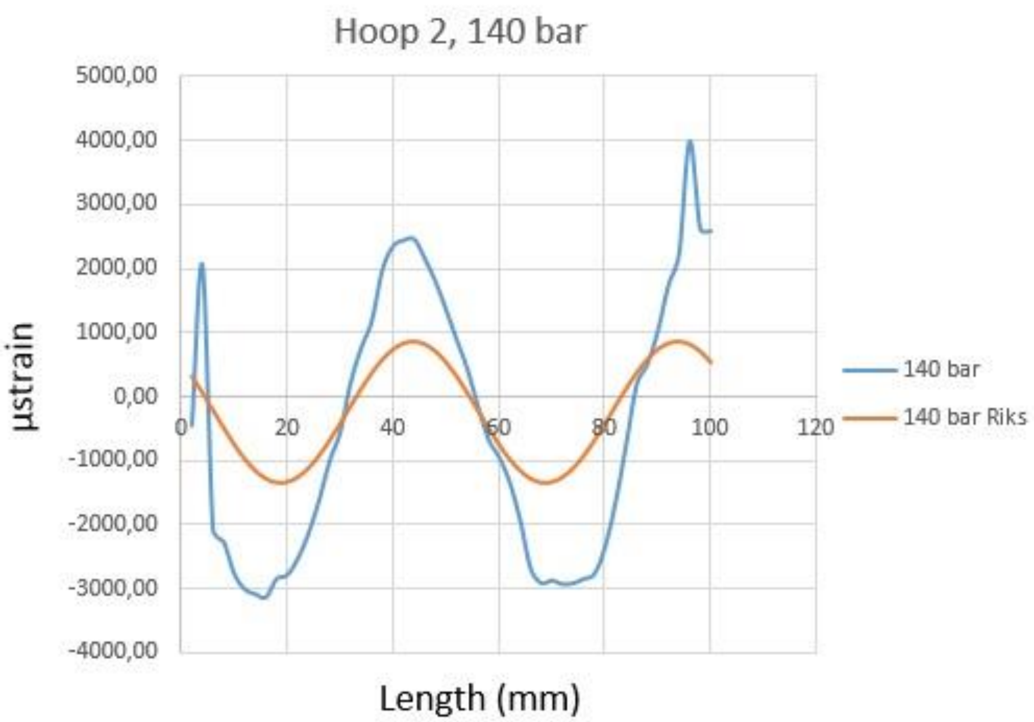

Figure 44 Comparing strains at 140 bar

Figure 45 compares the experimental strain reading at 140 bar with a strain closer to the buckling load generated from the FEA. This comparison gives a much better match.

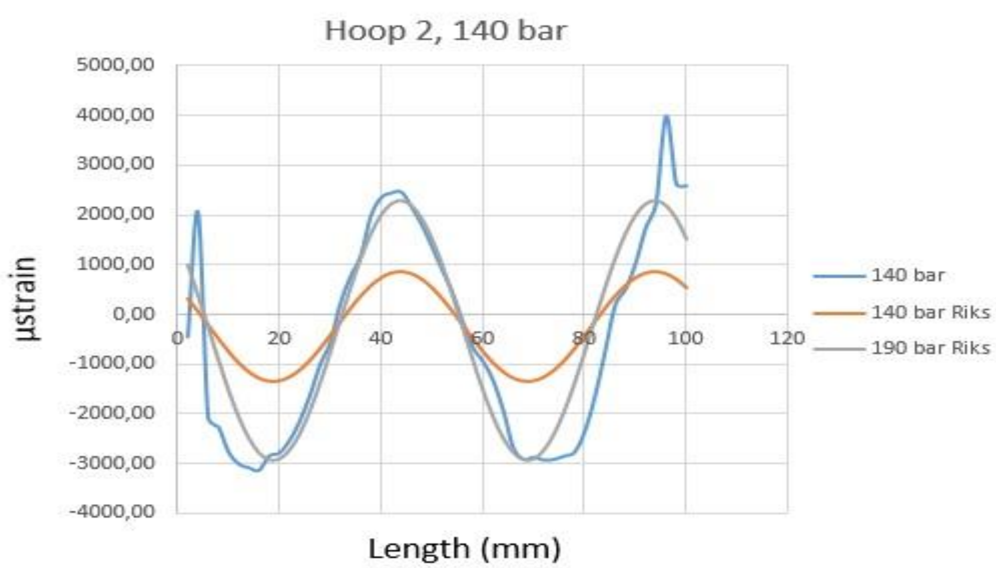

Figure 45 Comparing strains at pressure close to buckling for the experimental test and FEA

8 Discussion

8.1 Production and preparation of the tubes

The filament winding method produced good tubes with a high fiber volume fraction of 0.645. However, some voids were detected with the microscopy tests, reducing the properties of the tubes.

The preparation of the mandrel before winding proved to be successful, making the extraction process easy. Even the tubes with fibers in only 90° were extracted fairly easily, despite the poor properties in the transverse direction of the fibers.

Preparing the tubes with optical fibers was challenging due to the small diameter of the tubes. Optical fibers are very sensitive and break easily, which lead to damaged optical fibers on one of the tubes being tested. However, the optical fibers proved to give good strain measurements during the external pressure testing.

8.2 Comparing experimental tests with finite element analysis

Comparing the buckling value of 244 bar generated by FEA, with the buckling value of 160 bar found in the experimental tests, there is a large deviation in the results. This corresponds to a difference of 52.2%, which may be caused by several factors. It is difficult to model the imperfections in Abaqus realistically, and this may cause some error in the analysis. A varying wall thickness throughout the wound tube is normal, as it is difficult to control the thickness completely when using the filament winding method. This was not considered in the Abaqus model, where a constant wall thickness of 1.5 was added to the shell model. Further, the input data did not belong to the exact fiber and matrix mixture used to make the tubes in this thesis, with the exception of E_1 and E_2. One other aspect to consider is that the FEA is based on a perfect scenario where the carbon fiber is perfectly attached to the epoxy. However, as we can see from the microscopy tests in Figure 18, there was a considerable amount of air bubbles present, causing voids in the composite. The voids contribute to lower performance of the tube. Poor wetting of fibers can cause air bubbles to form during winding of the tube. Measures to be taken to improve the wetting action can be lowering the viscosity of the resin or reducing fiber speed [5].

The strain comparison analysis had a poor match, especially at higher pressure. The strain graph from the experiments showed much larger strain at 140 bar (close to buckling), than the strain found for the corresponding pressure using FEA. In other words, the strains found for the Abaqus model were lower at 140 bar because the modeled tube could withstand higher pressure than the tubes tested experimentally. A strain reading was therefore taken at a pressure of 190 bar, closer to the buckling load for Abaqus model. This strain graph matched very well with the graph at 140 bar for the experimental tests, proving that the FEA can in some cases estimate strain quite well.

8.3 Failure mode

High exposure factor caused by σ_1 from the maximum stress criterion indicated that the tubes would most likely fail due to compressive stresses in the hoop direction. Because of this, fiber fraction was the expected failure mode. The maximum stress criterion results matched well with the visual inspection of the tubes in section 7.6.

8.4 Determining longitudinal Young’s modulus

The longitudinal Young’s modulus was determined by using the split disc method. This method gave overall good results. However, as shown if Figure 30, the curve starts with negative strains while tension is being applied. The reason for this is that the radius of the test piece is small compared to the length of the strain gauge (5 mm). When the strain gauge is attached to the test piece, it gets a small bend due to the radius. This results in tension on the top side of the gauge at starting position before testing. As force is applied, the radius of the ring decreases at the area where the strain gauges are attached, applying compression on the gauges. At one point, the strain gauges are straightened and stop compressing. They begin to be pulled apart and tension is applied to them. This is where the values of the curve turn from negative to positive strain. An illustration of this case can be seen in Figure 46.

The average value of the longitudinal Young’s modulus found from the tests was 146.2 GPa. This is very close to the calculated longitudinal Young’s modulus of 149.4 GPa.

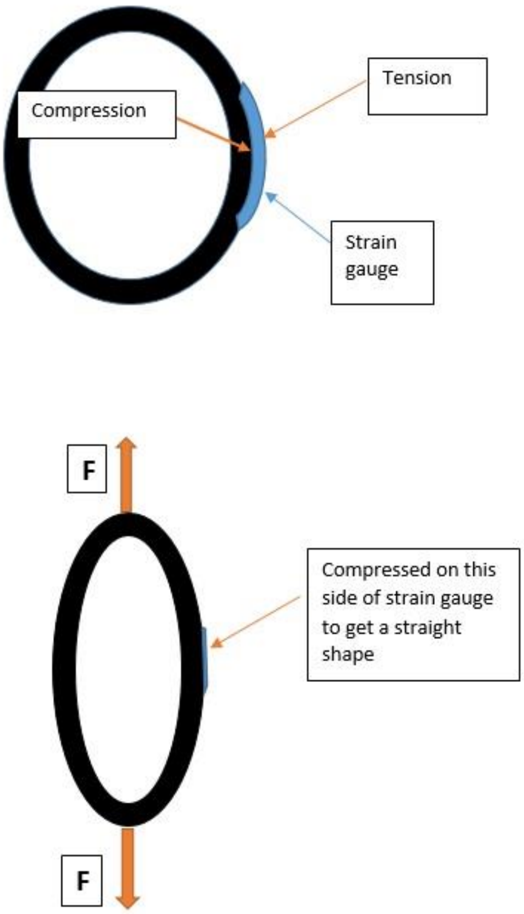

Figure 46 Illustration showing the behavior of a strain gauge attached to a circular test piece

8.5 Determining the transverse Young's modulus

The transverse Young's modulus was found to be 6.3 GPa. This is somewhat low compared to the corresponding modulus for the Hexel T300/914 which was considered a good approximation for the composite material used to make the tubes. In addition, it is 50 % lower than what the calculations predicted. The voids present in the tube may have affected the modulus by taking the space of the matrix in the composite. The transverse modulus is generally lower than the longitudinal because the matrix takes up more load than the fibers in this direction. By having voids, the matrix volume fraction is lowered causing the material to have lower transverse Young's modulus. This is most likely the main cause of the deviation in the results.

9 Conclusion

This thesis investigated how small diameter filament wound tubes could withstand external pressure. Experimental tests were conducted and compared to simulation results from an FEA. Input parameters for the transverse and longitudinal Young's modulus were obtained from experimental tests and implemented in the analysis.

9.1 Production method

The filament winding method was used to make the tubes in this thesis. Using two layers of plastic film and then heating the tube before extracting it from the mandrel turned out to be successful. This production method gave good quality tubes, with some voids as expected.

9.2 Finding the transverse and longitudinal Young's modulus

The compression tests done on a hoop wound tube gave a transverse Young's modulus of 6.3 GPa. This result is lower than predicted from the transverse modulus Equation 6. However, voids present in the tubes were not taken into consideration by this equation. The difference that occurred between the values is probably caused by these voids.

The transverse Young's modulus was found using the split disc method. This method was simple to use and gave good results matching quite well with the calculated values. Smaller strain gauges would be preferred to minimize the compressive effect caused by the radius of the test piece.

9.3 External pressure tests compared to FEA

The finite element analysis predicted buckling at 244 bar. This was much higher than the experimental results, which give an average buckling value of approximately 160 bar. It was assumed that the initial failure of the tube was caused by fiber fracture on the top and bottom ply due to hoop stresses.

Obtaining a higher buckling value with the FEA is not surprising as the analysis models a close to perfect case, which is not achievable in reality. It is difficult to take into account all of the imperfections present in a real tube using FEA. Two methods were used to try to add an imperfection to the tube in the analysis. An ovality of 0.46% was added to the tube manually and deformation modes from the linear buckling analysis were imported to the Riks analysis. Both methods gave the same result.

The strain readings obtained by the external pressure tests showed poor match with the strain values from the FEA when making a comparison at the same pressure. A better match was found in the strain values at non-matching pressures. If a higher pressure is considered in the FEA, there is a better match for the strains.

9.4 Further work

The experimental tests in this thesis resulted in interesting findings on the behavior of carbon fiber tubes with optical fibers. For further work, it is proposed to collect a larger set of experimental data before any final conclusions can be made regarding such tubes. Further, to gain more information about the behavior of small diameter composite tubes, a recommendation is to create and test tubes with different layup, wall thickness, diameter and length. To find the optimal layups, the optimization code suggested by Tanguy Messager, Mariusz Pyrz, Bernard Gineste and Pierre Cauchot [23] can be studied. To achieve more accurate results in the FEA, new methods for implementing imperfections and modeling other non-linear factors affecting the performance of the tube should be investigated. A more complete input data set should be found, determining all of the elastic properties as well as the Poisson's ratio. To obtain more successful strain readings from the pressure tests, a system to protect the fibers during the tests should be made.

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Appendix A

Strain graphs comparing experimental pressure test with analytical analysis

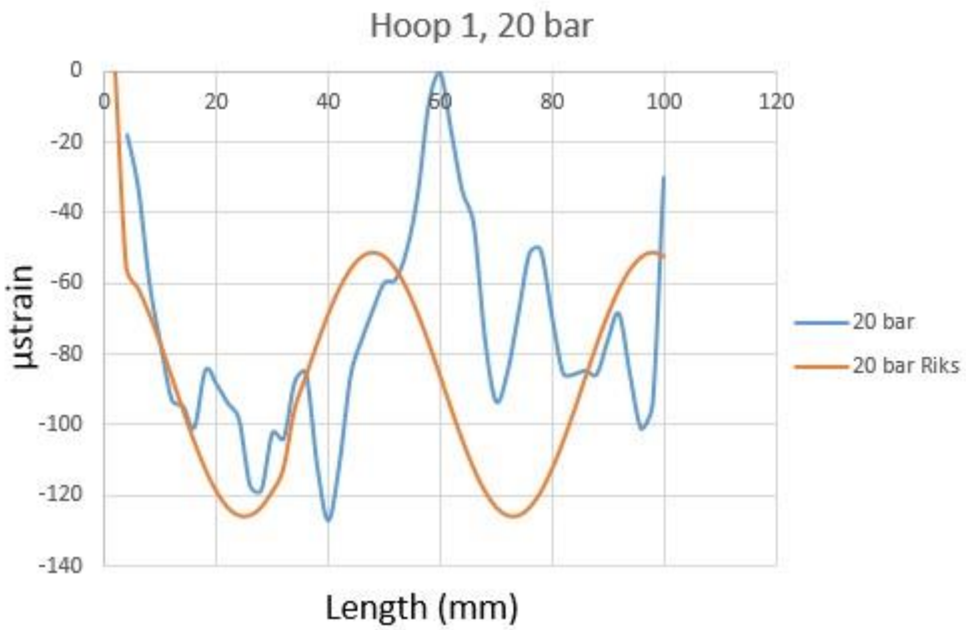

Figure A1 Comparing strain at 20 bar in hoop 1

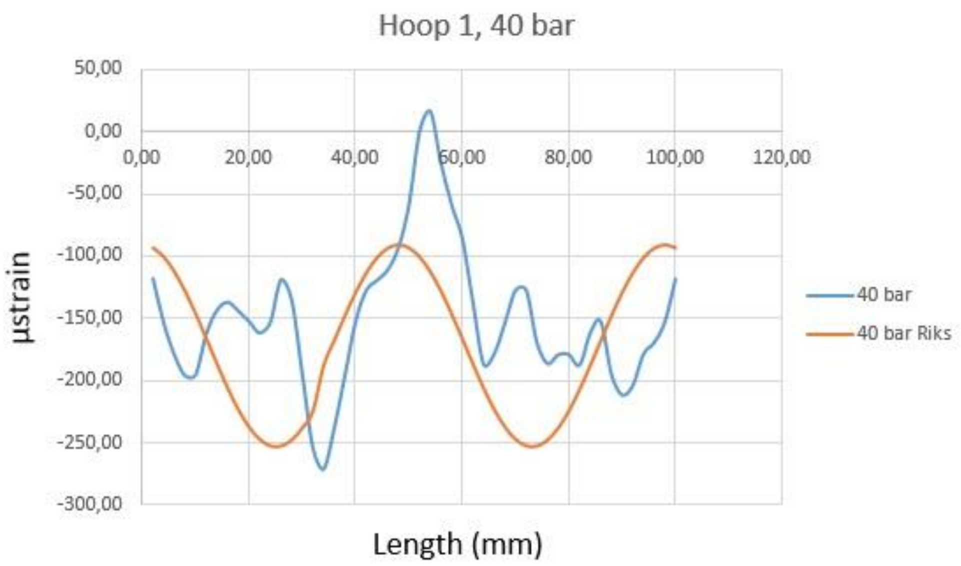

Figure A2 Comparing strain at 40 bar in hoop 1

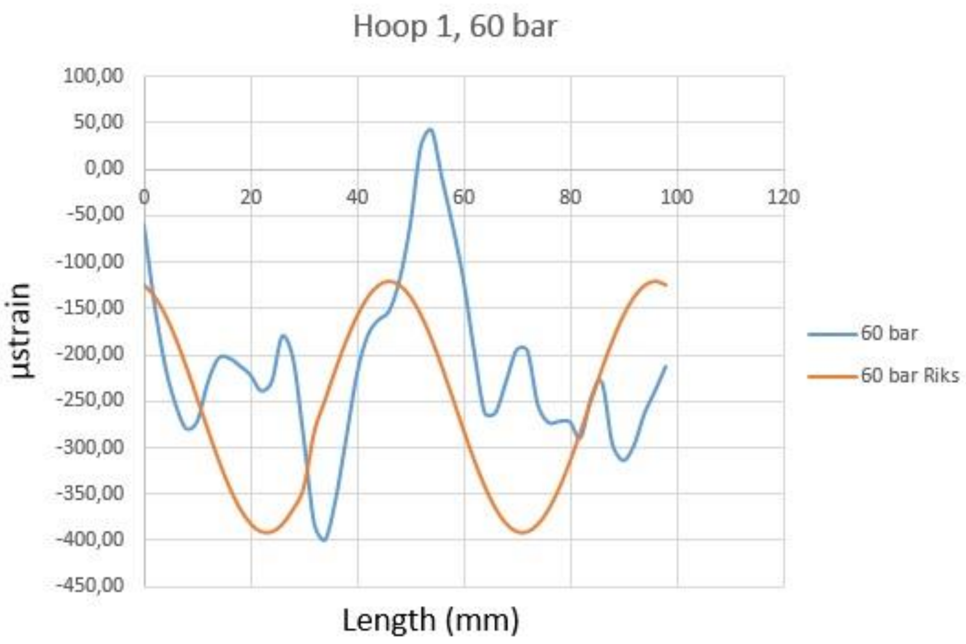

Figure A3 Comparing strain at 60 bar in hoop 1

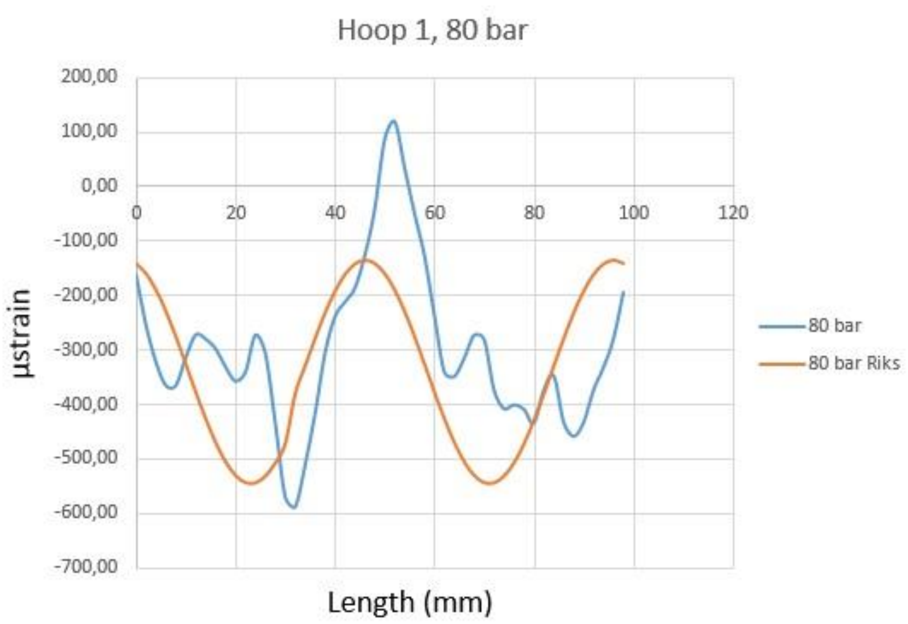

Figure A4 Comparing strain at 80 bar in hoop 1

Figure A5 Comparing strain at 100 bar in hoop 1

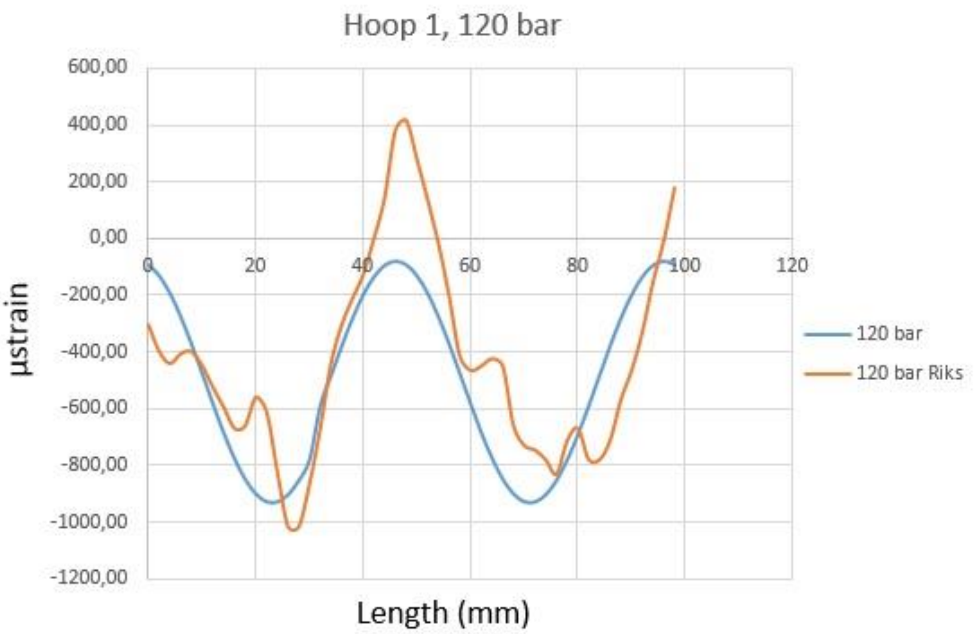

Figure A6 Comparing strain at 120 bar in hoop 1

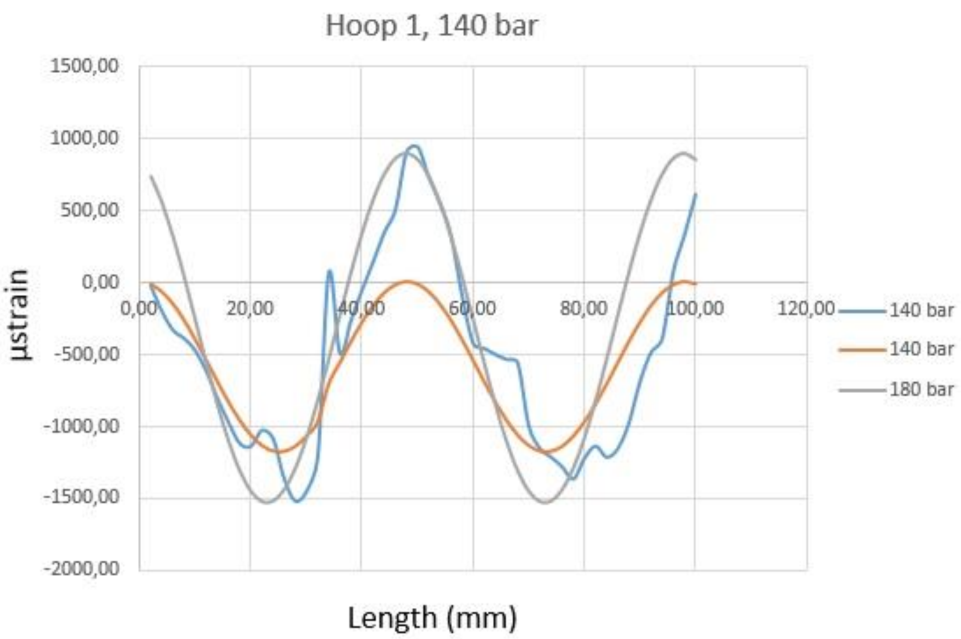

Figure A7 Comparing strain at 140 bar from test with 140 and 180 bar in Riks

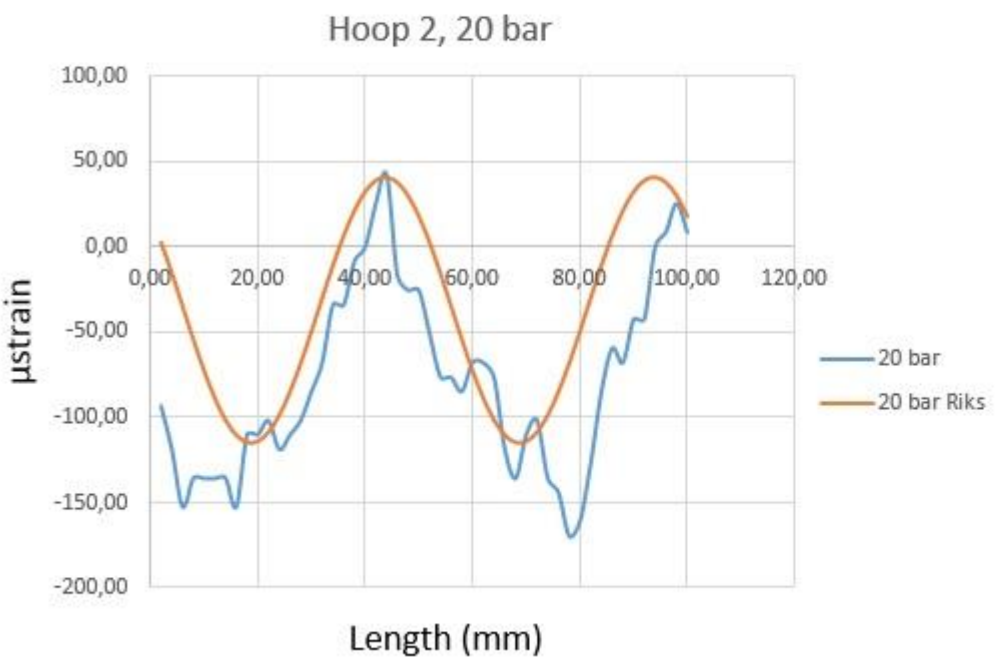

Figure A8 Comparing strain at 20 bar in hoop 2

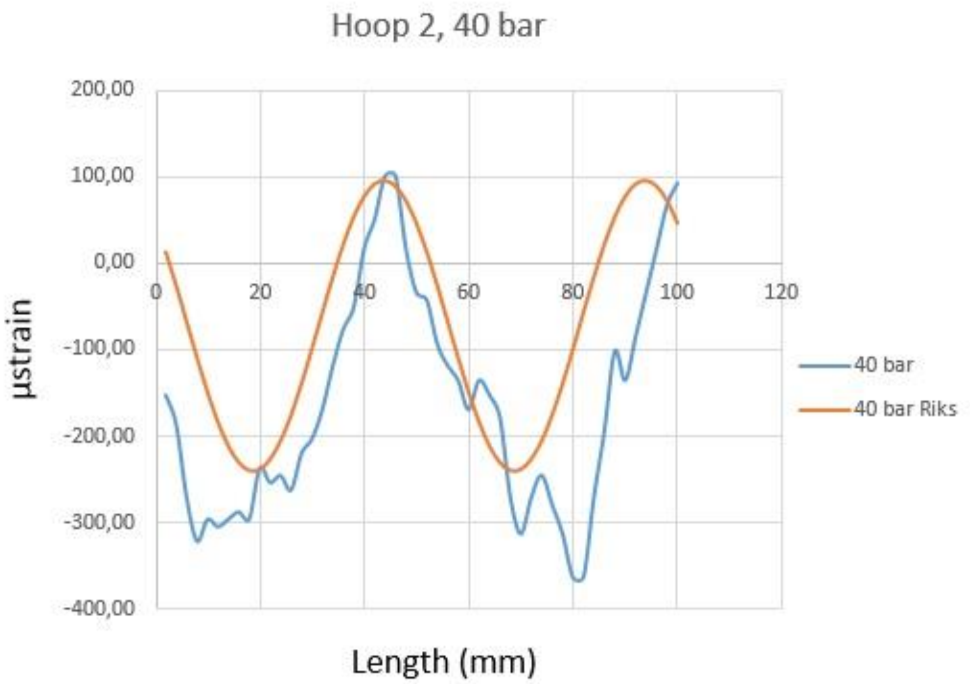

Figure A9 Comparing strain at 40 bar in hoop 2

Figure A10 Comparing strain at 60 bar in hoop 2

Figure A11 Comparing strain at 80 bar in hoop 2

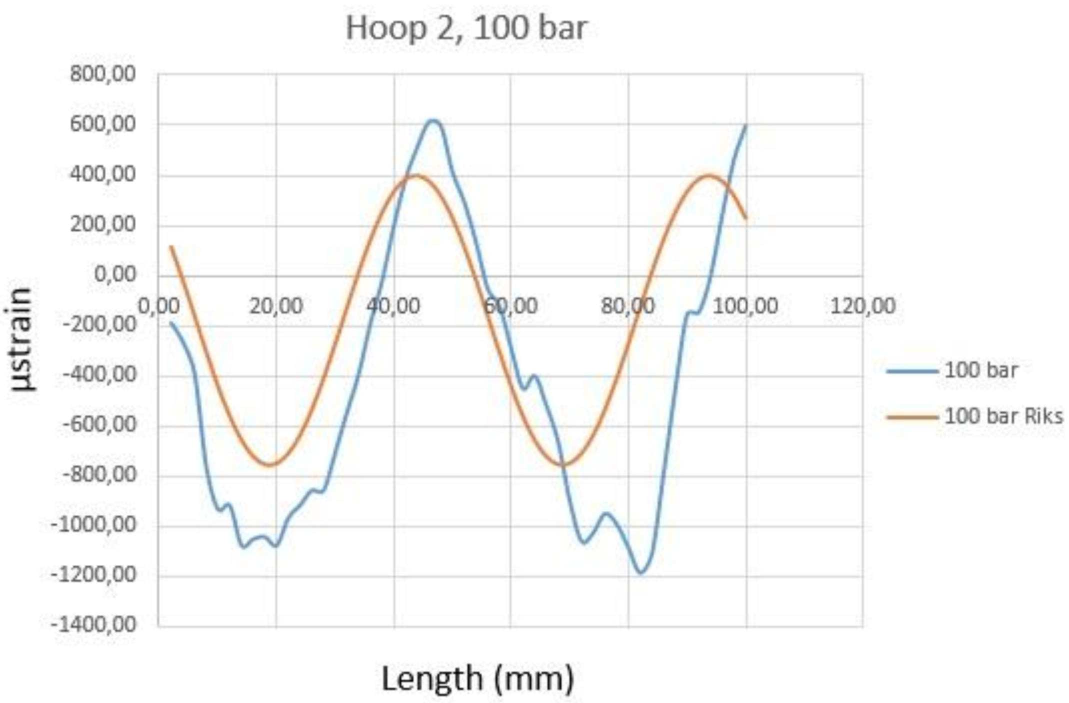

Figure A12 Comparing strain at 100 bar in hoop 2

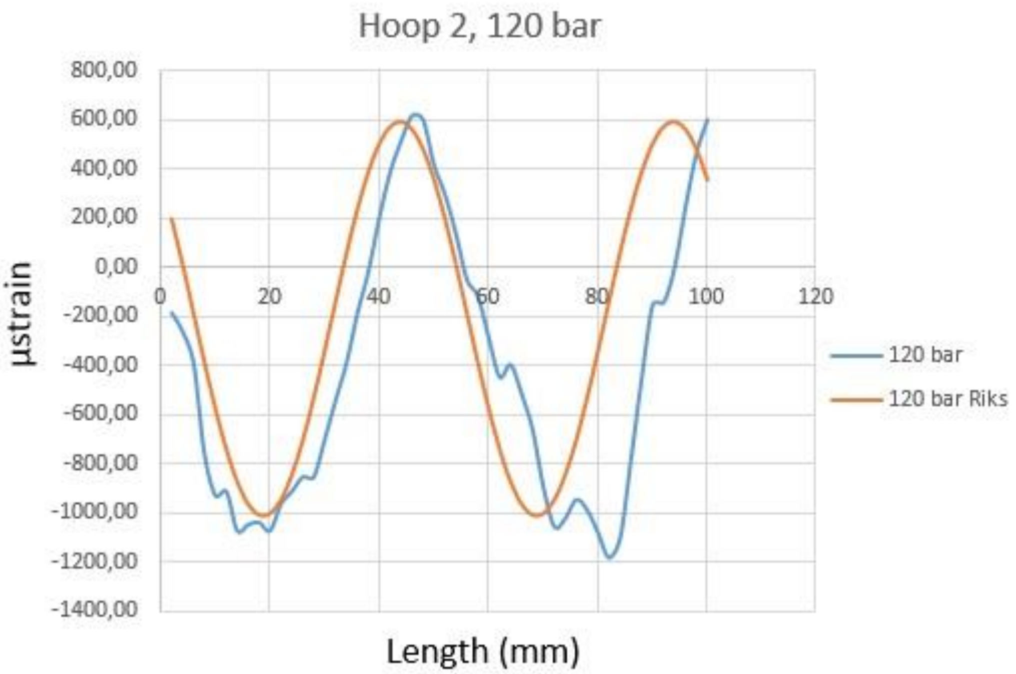

Figure A13 Comparing strain at 120 bar in hoop 2

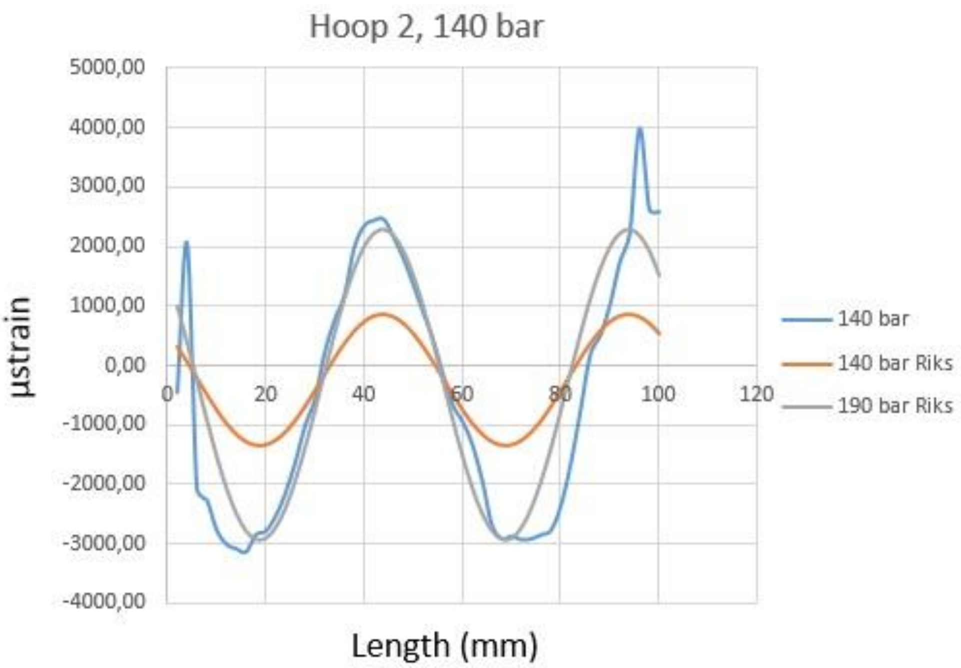

Figure A14 Comparing strain at 140 bar from test with 140 and 190 bar from Riks in hoop 2

Figure A15 Comparing strain at 20 bar in hoop 3

Figure A16 Comparing strain at 40 bar in hoop 3

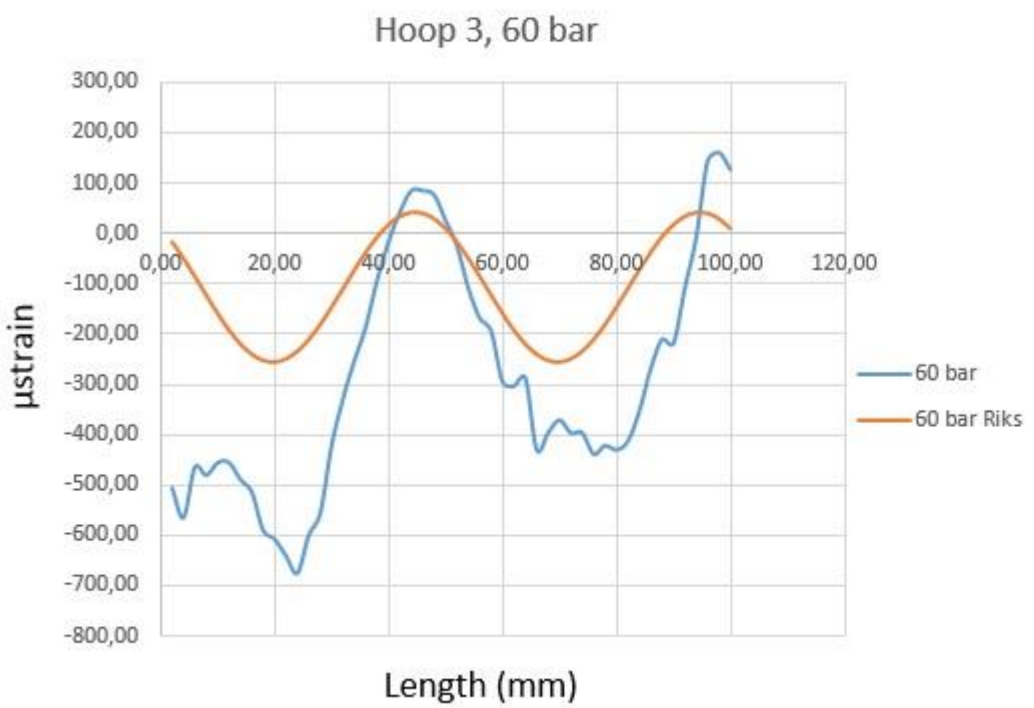

Figure A17 Comparing strain at 60 bar in hoop 3

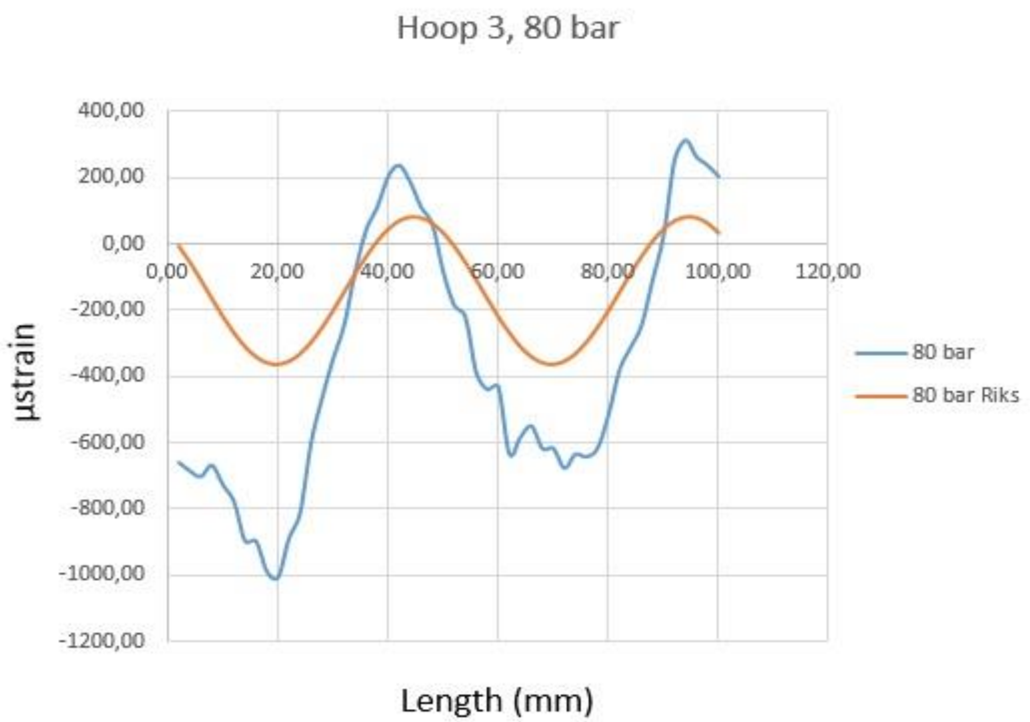

Figure A18 Comparing strain at 80 bar in hoop 3

Figure A19 Comparing strain at 100 bar in hoop 3

Figure A20 Comparing strain at 120 bar in hoop 3

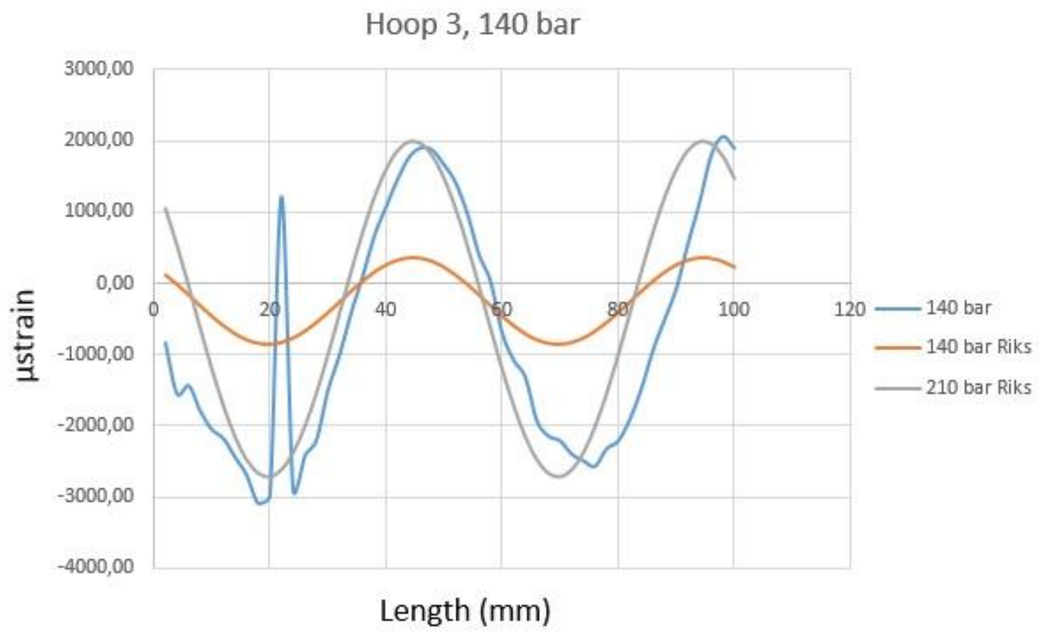

Figure A21 Comparing strain at 140 bar from test with 140 and 210 bar from Riks in hoop 3

Appendix B

Transverse Young's modulus graphs

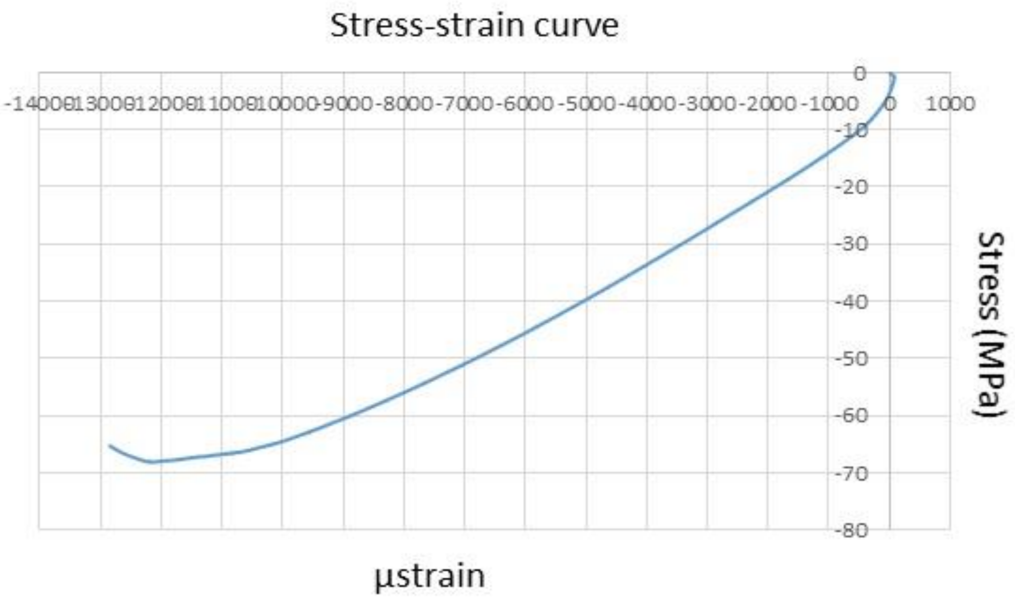

Figure B1 Stress-strain curve sample 1

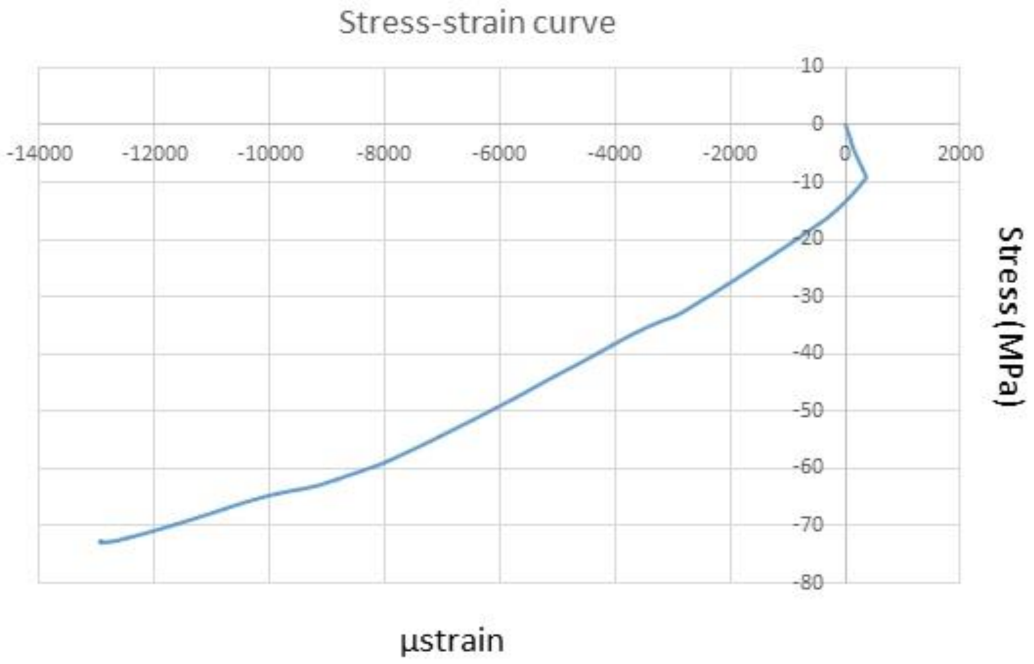

Figure B2 Stress-strain curve sample 3

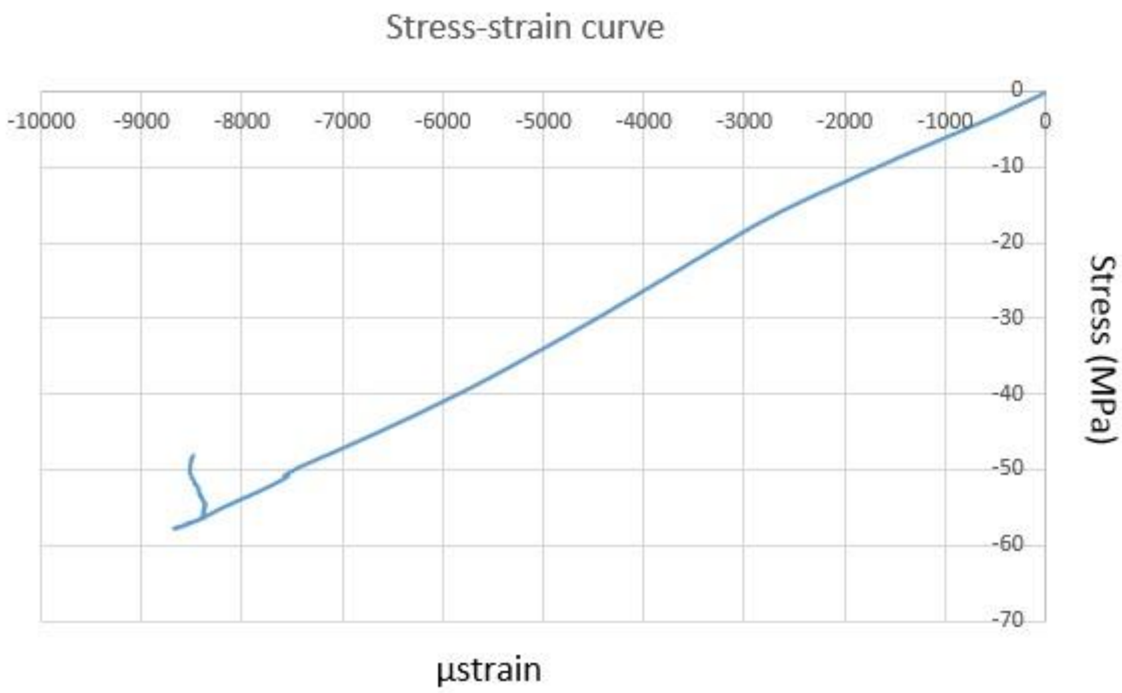

Figure B3 Stress-strain curve sample 4

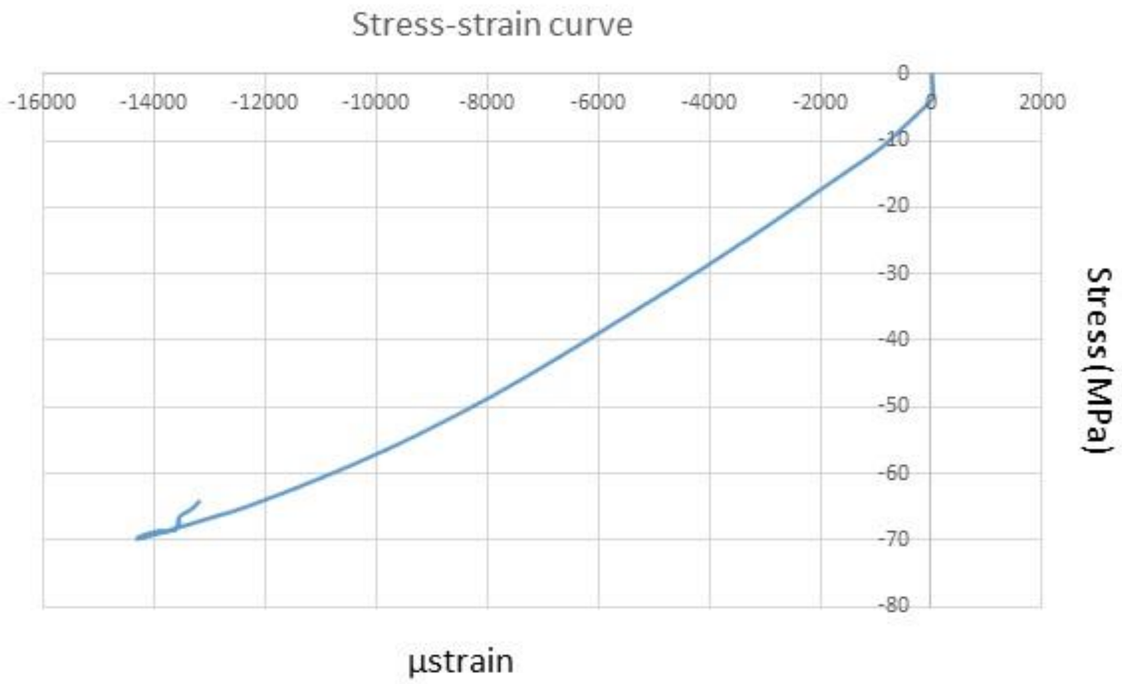

Figure B4 Stress-strain curve sample 5

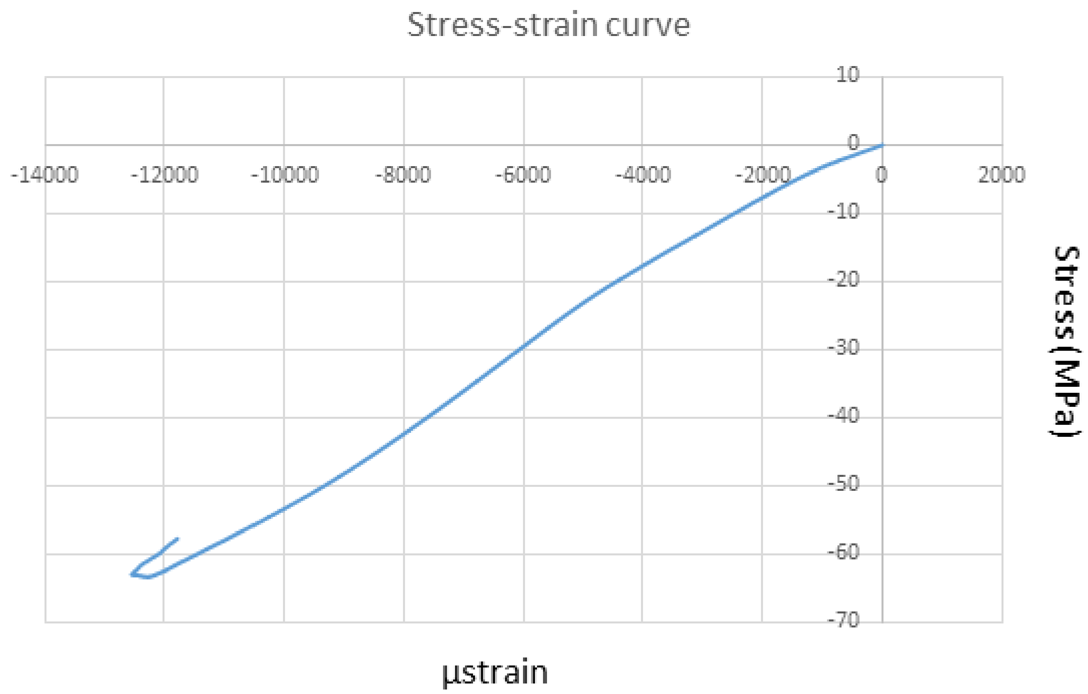

Figure B5 Stress-strain curve sample 6

Appendix C

Longitudinal Young's modulus graphs

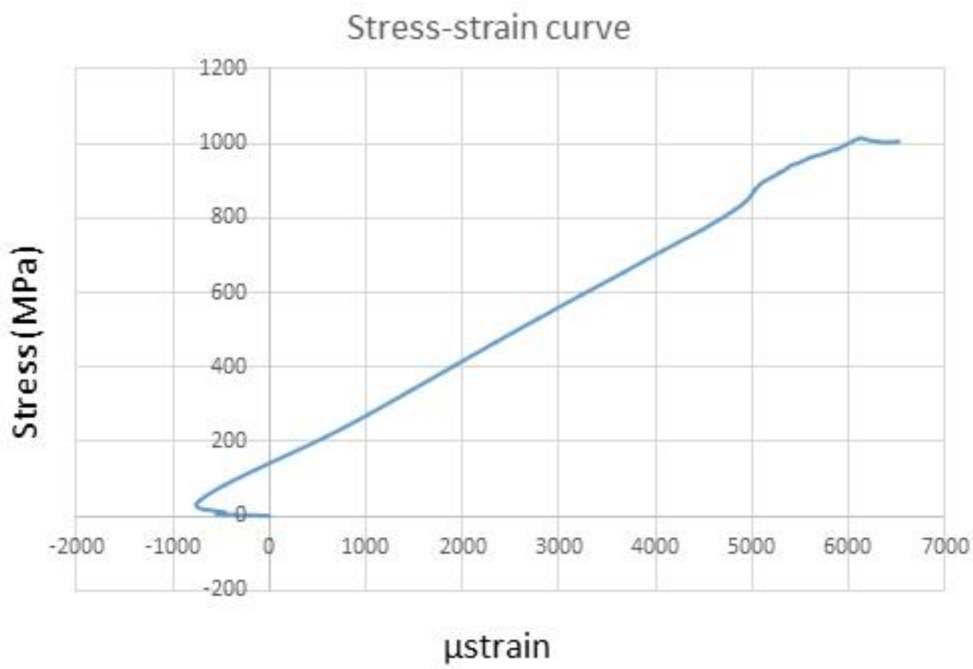

Figure C1 Stress-strain curve for sample 1

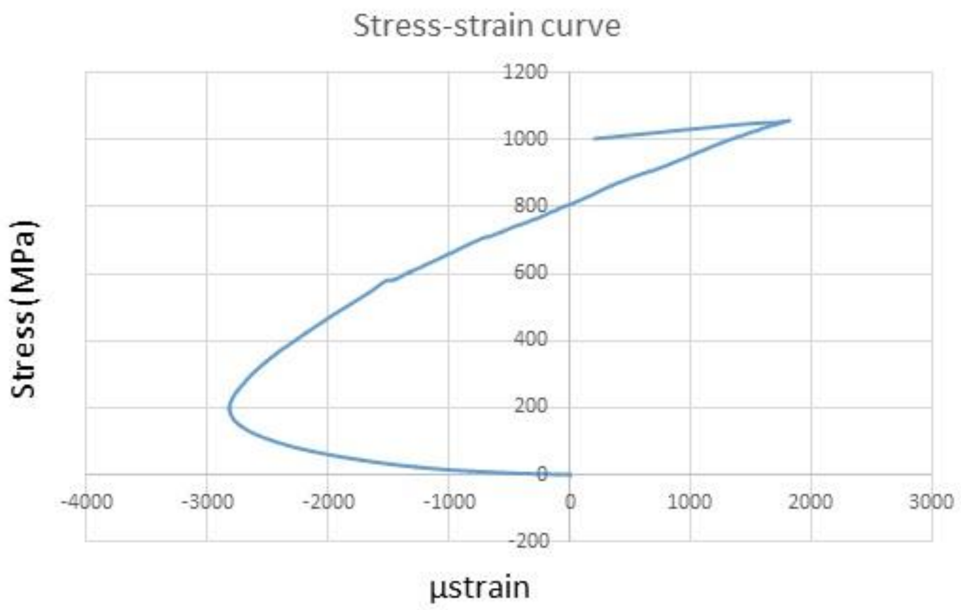

Figure C2 Stress-strain curve for sample 2

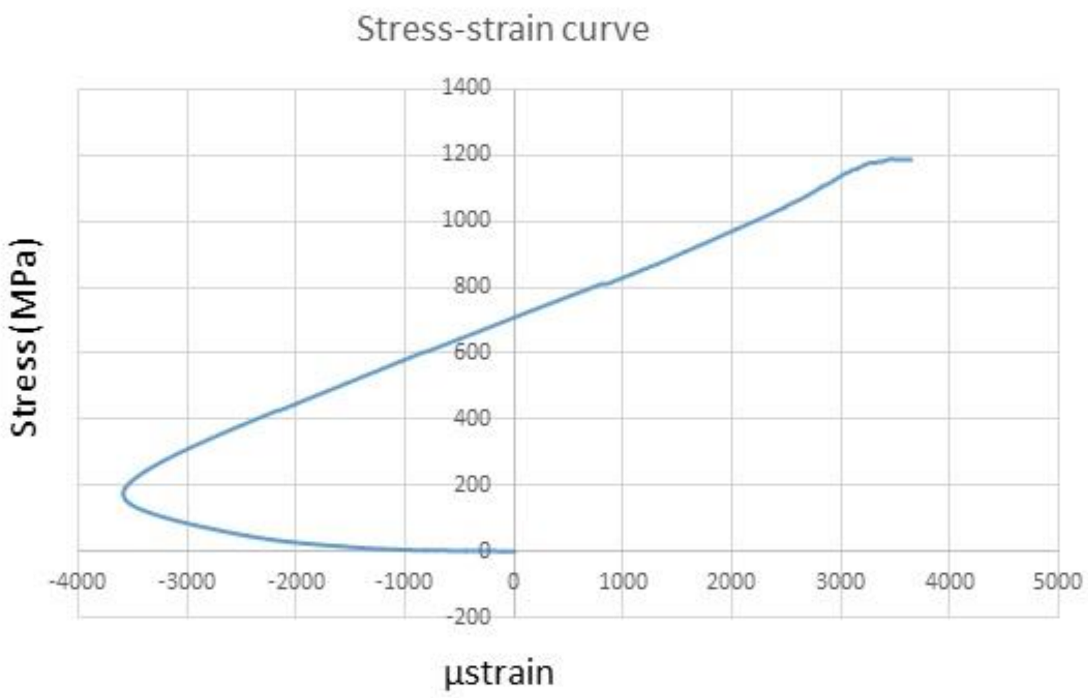

Figure C3 Stress-strain curve for sample 3

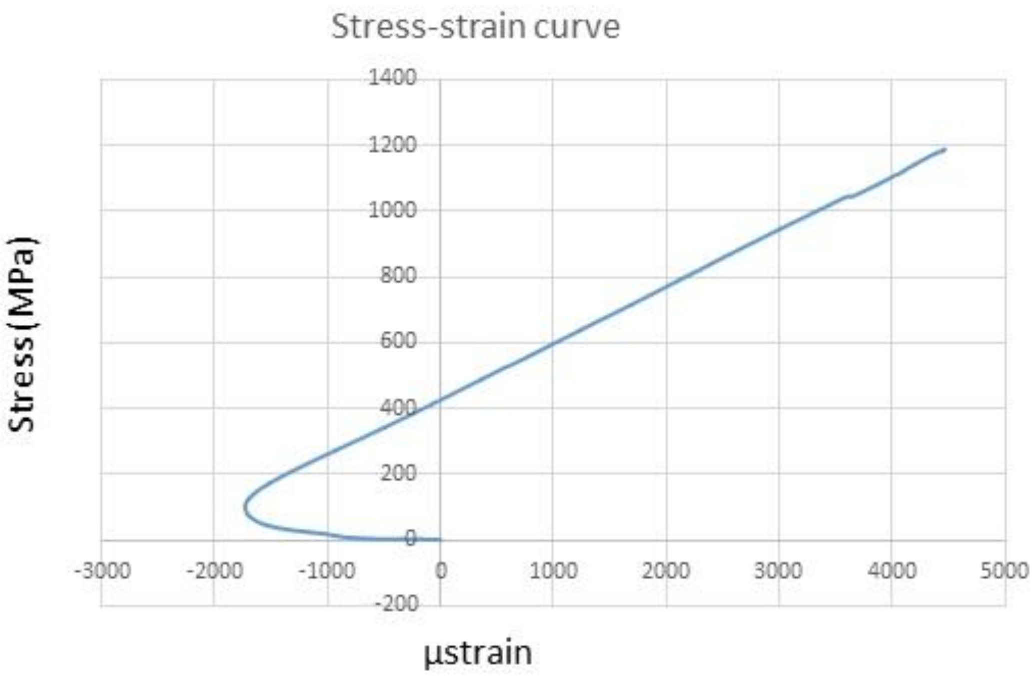

Figure C4 Stress-strain curve for sample 4

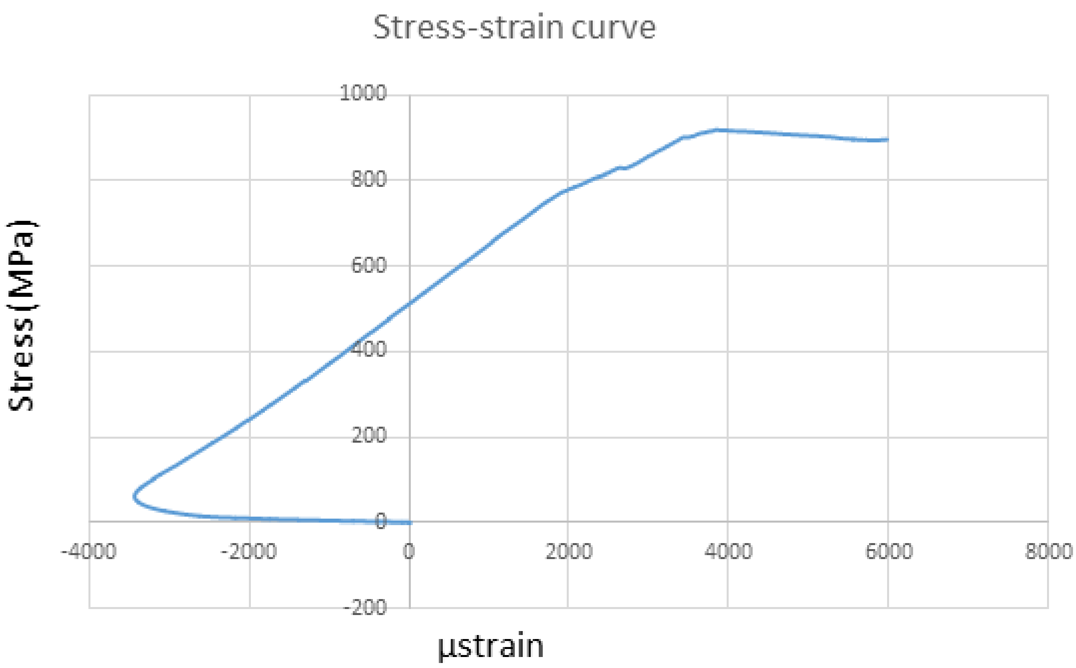

Figure C5 Stress-strain curve for sample 5

Appendix D

Pressure tests graphs

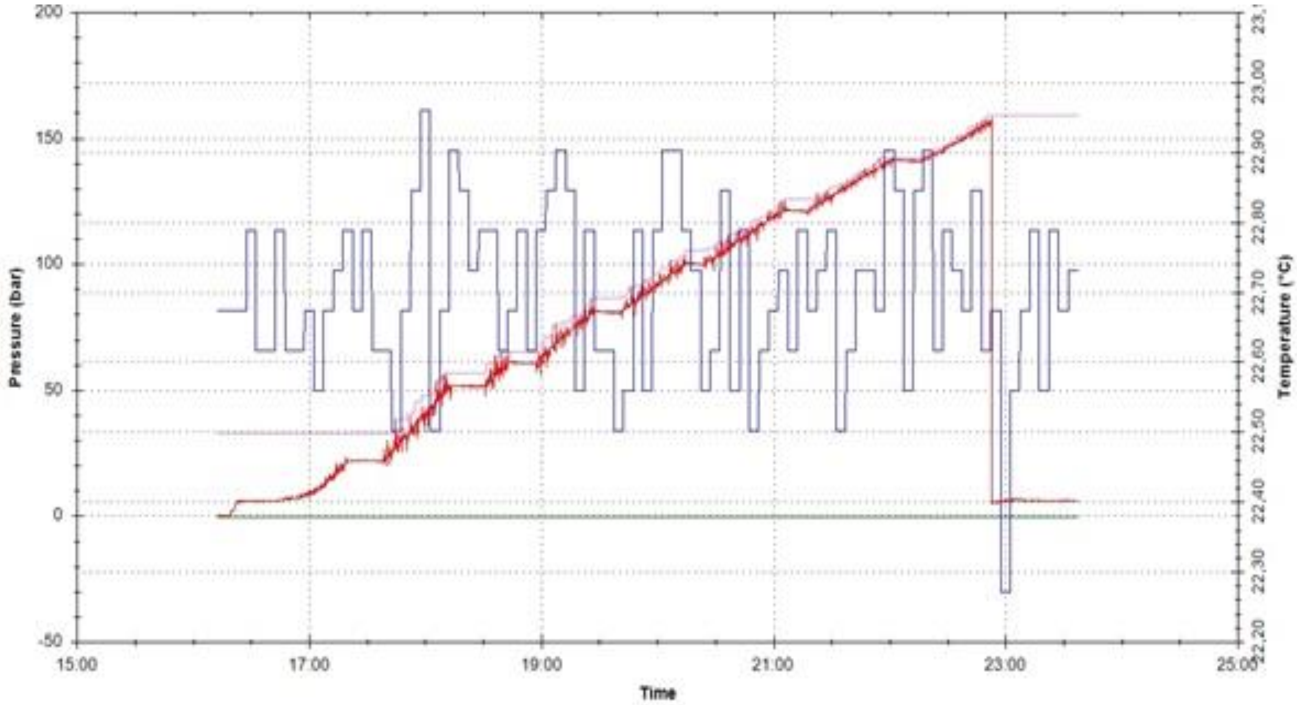

Figure D1 Pressure graph for test 1

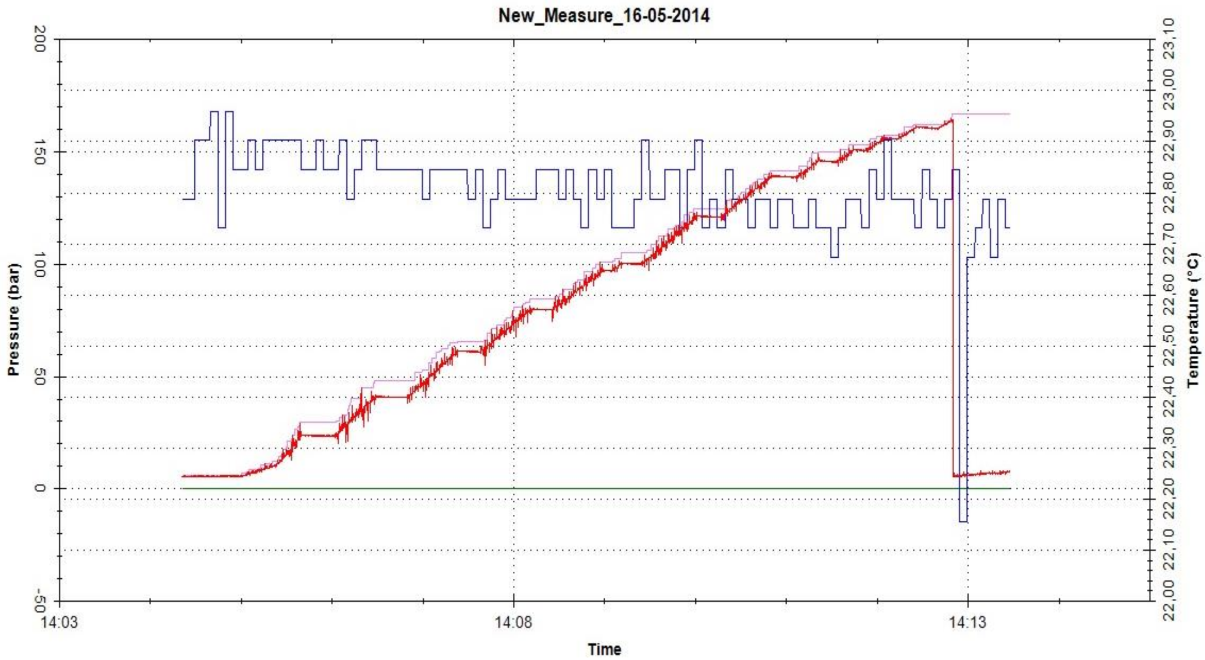

Figure D2 Pressure graph for test 2

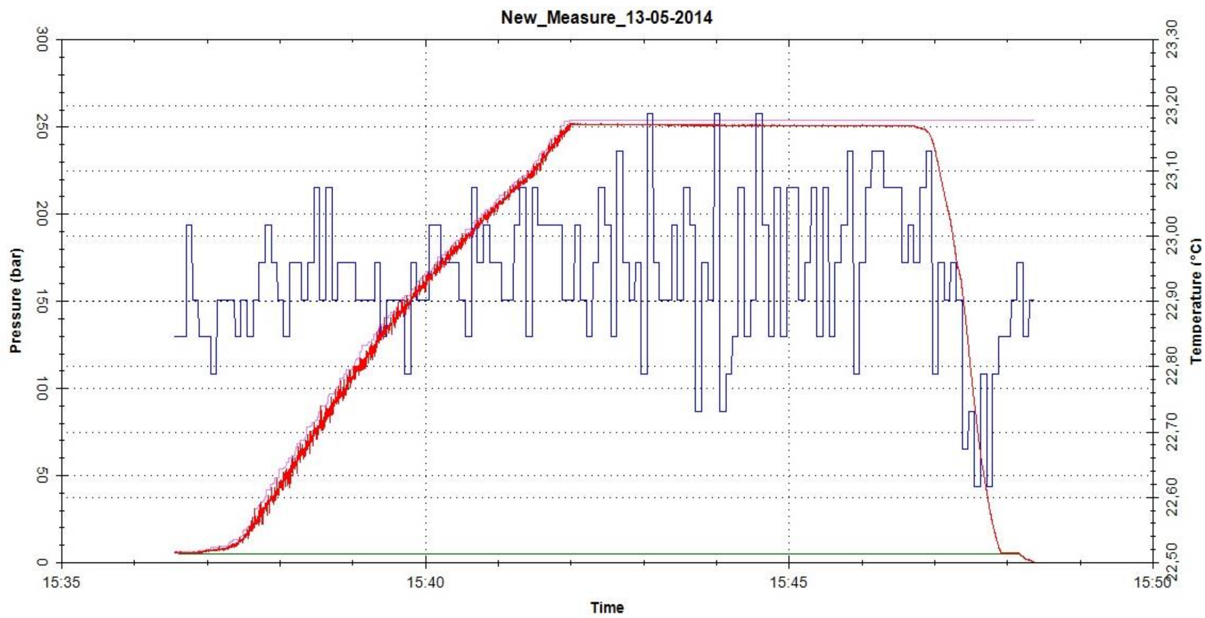

Figure D3 Pressure test before real testing to see if the T-piece can withstand high pressure

Appendix E

Health, safety and environment forms

Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid
Safety and Quality Evaluation of Activities in the Laboratory and Workshop

NTNU

Perleporten

1 Identifikasjon - *Identification*	**Dokumentnr. - *Document no.*:**	
Kundenavn – *Customer name*	Prosjektnavn – *Master thesis*	Projektnr. – *Project no.*
Beskrivelse av arbeid – *Split disc test*		Dato – *20.05.2014*

2 Projekt – *Team*			
Prosjektleder og organisasjon – *Project manager and organisation*	Andreas Echtermeyer	Ansvarlig for instrumentering – *Responsible for instrumentation.*	Emir Dzubur
Leiestedsansvarlig – *Laboratory responsible*	Emir Dzubur	Operatør – *Operator*	Emir Dzubur
Auditør for sikkerhets og kvalitetsgjennomgang – *Auditer for safety check*	Emir Dzubur	Ansvarlig for styring av forsøk – *Responsible for running the experiment.*	Emir Dzubur
Ansvarlig for eksperimentelt faglig innhold – *Responsible for experimental and scientific content*	Emir Dzubur	Ansvarlig for logging av forsøksdata – *Responsible for logging and storing experimental data*	Emir Dzubur
Ansvarlig for dimensjonering av last og trykkpåkjente komponenter – *Reponsible for dimensioning load bearing and pressurized components*	Emir Dzubur	Ansvarlig for montering av testrigg – *Responsible for building the rig*	Emir Dzubur

3 Viktig!! – *Important!!*	J: Ja – *Yes* / N: Nei - *No*
Er arbeidsordren signert? – *Is the work order signed?*	
Har operatøren nødvendig kurs/trening i bruk av utstyret? - *Has the operator the required courses/training on the equipment?*	J
Har operatøren sikkerhetskurs? (påbudt) – *Has the operator followed the safety courses? (mandatory)*	J
Kan jobben gjøres alene? - *Can the work be done alone?*	N
- Dersom ja, er det med visse forbehold (for eksempel, må bruke alarm, ha avtale med noen som kommer innom med jevne mellomrom eller lignende). Dette må vurderes i Seksjon 5. *If yes, the work may have to be done under special conditions (e. g. must use the alarm, have agreement with somebody coming back periodically or similar). This shall be evaluated in Section 5.*	

4.1 Sikkerhet – *Safety* (Testen medfører – *The test contains*)			J: Ja – *Yes* / N: Nei - *No*
Stor last – *Big loads*	N	Brannfare – *Danger of fire*	N
Tunge løft – *Heavy lifting*	N	Arbeid i høyden – *Working at heights*	N
Hengende last – *Hanging load*	N	Hydraulisk trykk – *Hydraulic pressure*	J
Gasstrykk – *Gas pressure*	N	Vanntrykk – *Water pressure*	N
Høy temperatur – *High temperature*	N	Lav temperatur – *Low temperature*	N
Deler i høy hastighet – *Parts at high velocity*	N	Farlige kjemikalier – *Dangerous chemicals*	N
Sprutakselerasjon ved brudd – *Sudden acceleration at fracture/failure*	N	Forspente komponenter – *Pre-tensioned components*	J
Farlig støv – *Dangerous dust*	N	Kraftig støy – *Severe noise*	N
Klemfare – *Danger of pinching*	N	Roterende deler – *Rotating parts*	N

4.2 Påkrevet verneustyr – *Required safety equipment*			J: Ja – *Yes* / N: Nei - *No*
Briller (påbudt) – *Glasses (mandatory)*	J	Vernesko – *Safety shoes*	N
Hjelm – *Helmet*	N	Hansker – *Gloves*	N
Skjerm – *Screen*	J	Visir – *Visir*	N
Hørselsvern – *Ear protection*	J	Løfteredskap – *Lifting equipment*	N
Yrkessele, fallsele, etc. – *Harness ropes, other measures to prevent falling down.*	N		

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Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU
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5.1 Beskrivelse av aktivitet – *Description of the activity (see Appendix)*

Vurdering skal være basert på en skriftlig prosedyre for bruk av maskinen. I enkelte tilfeller kan prosedyre bli beskrevet direkte i tabellen nedenfor.

The evaluation shall be based on a written operating procedure for the machine. For simple cases the procedure can be directly described in the tables below.

Nr.	Beskrivelse av aktivitet – *Description of activity*	Fare - *Danger*	Lov, forskrift o.l. – *Legal requirements*	Prosedyre nr. – *Procedure no.*	Sannsynlighet – *Probability*	Konsekvens –*Consequence*	Risiko – *Risk*
1	Sette inn testbit i testmaskinen						
2	Testing	Bolt ryker, test bit ryker			3	C	C3

5.2 Korrigerende Tiltak – *Corrective Actions*

Nr.	Korrigerende tiltak – Corrective action	Sannsynlighet – *Probability*	Konsekvens – *Consequence*	Risiko – *Risk*	Utført dato – *Date of action*
1					
2	Verneutstyr, Beskyttelses skjermer rundt hele testmaskinen	3	A	A3	

Sikkerhets og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU
Perleporten

5.3 Feilkilder – *Reasons for mistakes/errors*

Sjekkliste: Er følgende feilkilder vurdert? – Check list: Is the following considered? J: Ja – *Yes* / N: Nei - *No*

Tap av strøm – *Loss of electricity*	J	Overspenning – *Voltage surge*	N
Elektromagnetisk støy – *Electromagnetic noise*	N	Manglende aggregatkapasitet av hydraulikk – *Insufficient power of the machine*	N
Jordfeil – *Electrical earth failure*	N	Vannsprut – *Water jet*	N
Ustabilt trykk av hydraulikk/kraft – *Unstable pressure or hydraulic force*	N	Tilfeldig avbrudd av hydraulikk/kraft – *Unintended interruption of power supply*	J
Last-/ forskyvnings grenser etablert ? – *Are load and displacement limits established?*	J	Lekkasjer (slanger/koblinger, etc.) – *Leakage of pipes, hoses, joints, etc.*	J
Mulige påvirkninger fra andre aktiviteter – *Possible interference from other activities*	N	Mulige påvirkninger på andre aktiviteter – *Possible interference towards other activities*	N
Problemer med datalogging og lagring – *Troubles in loading and storage*	N	Brann i laboratoriet – *Fire in the laboratory*	J

6 Kalibreringsstatus for utstyr – *Calibration of equipment*

(ex: load cell, extensometer, pressure transducer, etc)

I.D.	Utstyr - *Equipment*	Gyldig til (dato) – *Valid until (date)*
	Strekklapper	

7 Sporbarhet – *Tracebility*

Eksisterer – Is there	J: Ja – *Yes* / N: Nei - *No*
Er alle prøvematerialene kjente og identifiserbare? – *Are all experimental materials known and traceable?*	J
Eksisterer det en plan for markering av alle prøvene? – *Is there a plan for marking all specimens?*	J
Er dataloggingsutstyret identifisert? – *Is the data aquisition equipment identified?*	J
Er originaldata lagret uten modifikasjon? – *Are the original data stored safely without modification?*	J
Eksisterer det en backup-prosedyre? – *Is there a back-up procedure for the data (hard disk crash)?*	J
Eksisterer det en plan for lagring av prøvestykker etter testing? – *Is there a plan for storing samples after testing?*	J
Eksisterer en plan for avhending av gamle prøvestykker? – *Is there a plan for disposing of old samples?*	J

8 Kommentarer – *Comments*

9 Signaturer – *Signatures*

Godkjent (dato/sign) – Approved (date/signature)

Prosjektleder – *Project leader*	Verifikatør – *Verifier*	Godkjent – *Approved by*
Emir Dzubur	[illegible]	[illegible]

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Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid *Safety and Quality Evaluation of Activities in the Laboratory and Workshop*	NTNU **Perleporten**

1 Identifikasjon - *Identification*	**Dokumentnr. - *Document no.*:**	
Kundenavn – *Customer name*	Prosjektnavn – *Master thesis*	Projektnr. – *Project no.*
Beskrivelse av arbeid – *Compression test of tubes*		Dato – *Date* 23.04.2014

2 Projekt - *Team*

Prosjektleder og organisasjon – *Project manager and organisation*	Andreas Echtermeyer	Ansvarlig for instrumentering – *Responsible for instrumentation.*	Emir Dzubur
Leiestedsansvarlig – *Laboratory responsible*	Emir Dzubur	Operatør – *Operator*	Emir Dzubur
Auditør for sikkerhets og kvalitetsgjennomgang – *Auditer for safety check*	Emir Dzubur	Ansvarlig for styring av forsøk – *Responsible for running the experiment.*	Emir Dzubur
Ansvarlig for eksperimentelt faglig innhold – *Responsible for experimental and scientific content*	Emir Dzubur	Ansvarlig for logging av forsøksdata – *Responsible for logging and storing experimental data*	Emir Dzubur
Ansvarlig for dimensjonering av last og trykkpåkjente komponenter – *Reponsible for dimensioning load bearing and pressurized components*	Emir Dzubur	Ansvarlig for montering av testrigg – *Responsible for building the rig*	Emir Dzubur

3 Viktig!! – *Important!!*	J: Ja – *Yes* / N: Nei - *No*
Er arbeidsordren signert? – *Is the work order signed?*	
Har operatøren nødvendig kurs/trening i bruk av utstyret? - *Has the operator the required courses/training on the equipment?*	J
Har operatøren sikkerhetskurs? (påbudt) – *Has the operator followed the safety courses? (mandatory)*	J
Kan jobben gjøres alene? - *Can the work be done alone?*	N
- Dersom ja, er det med visse forbehold (for eksempel, må bruke alarm, ha avtale med noen som kommer innom med jevne mellomrom eller lignende). Dette må vurderes i Seksjon 5. *If yes, the work may have to be done under special conditions (e. g. must use the alarm, have agreement with somebody coming back periodically or similar). This shall be evaluated in Section 5.*	

4.1 Sikkerhet – *Safety* (Testen medfører – *The test contains*)			J: Ja – *Yes* / N: Nei - *No*
Stor last – *Big loads*	N	Brannfare – *Danger of fire*	N
Tunge løft – *Heavy lifting*	N	Arbeid i høyden – *Working at heights*	N
Hengende last – *Hanging load*	N	Hydraulisk trykk – *Hydraulic pressure*	J
Gasstrykk – *Gas pressure*	N	Vanntrykk – *Water pressure*	N
Høy temperatur – *High temperature*	N	Lav temperatur – *Low temperature*	N
Deler i høy hastighet – *Parts at high velocity*	N	Farlige kjemikalier – *Dangerous chemicals*	N
Sprutakselerasjon ved brudd – *Sudden acceleration at fracture/failure*	N	Forspente komponenter – *Pre-tensioned components*	J
Farlig støv – *Dangerous dust*	N	Kraftig støy – *Severe noise*	N
Klemfare – *Danger of pinching*	N	Roterende deler – *Rotating parts*	N

4.2 Påkrevet verneustyr – *Required safety equipment*			J: Ja – *Yes* / N: Nei - *No*
Briller (påbudt) – *Glasses (mandatory)*	J	Vernesko – *Safety shoes*	J
Hjelm – *Helmet*	N	Hansker – *Gloves*	N
Skjerm – *Screen*	J	Visir – *Visir*	N
Hørselsvern – *Ear protection*	N	Løfteredskap – *Lifting equipment*	N
Yrkessele, fallsele, etc. – *Harness ropes, other measures to prevent falling down.*	N		

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Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU
Perleporten

5.1 Beskrivelse av aktivitet – *Description of the activity (see Appendix)*

Vurdering skal være basert på en skriftlig prosedyre for bruk av maskinen. I enkelte tilfeller kan prosedyre bli beskrevet direkte i tabellen nedenfor.

The evaluation shall be based on a written operating procedure for the machine. For simple cases the procedure can be directly described in the tables below.

Nr.	Beskrivelse av aktivitet – *Description of activity*	Fare - *Danger*	Lov, forskrift o.l. – *Legal requirements*	Prosedyre nr. – *Procedure no.*	Sannsynlighet – *Probability*	Konsekvens –*Consequence*	Risiko – *Risk*
1	Fix tubes						
2	Testing	Rør ryker og skyter deler			2	B	B2

5.2 Korrigerende Tiltak – *Corrective Actions*

Nr.	Korrigerende tiltak – Corrective action	Sannsynlighet – *Probability*	Konsekvens – *Consequence*	Risiko – *Risk*	Utført dato – *Date of action*
1					
2	Verneutstyr og skjerm	2	A	A2	

Sikkerhets og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU Perleporten

5.3 Feilkilder – *Reasons for mistakes/errors*

Sjekkliste: Er følgende feilkilder vurdert? – Check list: Is the following considered? J: Ja – *Yes* / N: Nei - *No*

Tap av strøm – *Loss of electricity*	J	Overspenning – *Voltage surge*	N
Elektromagnetisk støy – *Electromagnetic noise*	N	Manglende aggregatkapasitet av hydraulikk – *Insufficient power of the machine*	N
Jordfeil – *Electrical earth failure*	N	Vannsprut – *Water jet*	N
Ustabilt trykk av hydraulikk/kraft – *Unstable pressure or hydraulic force*	N	Tilfeldig avbrudd av hydraulikk/kraft – *Unintended interruption of power supply*	J
Last-/ forskyvnings grenser etablert ? – *Are load and displacement limits established?*	J	Lekkasjer (slanger/koblinger, etc.) – *Leakage of pipes, hoses, joints, etc.*	J
Mulige påvirkninger fra andre aktiviteter – *Possible interference from other activities*	N	Mulige påvirkninger på andre aktiviteter – *Possible interference towards other activities*	N
Problemer med datalogging og lagring – *Troubles in loading and storage*	N	Brann i laboratoriet – *Fire in the laboratory*	J

6 Kalibreringsstatus for utstyr – *Calibration of equipment*

(ex: load cell, extensometer, pressure transducer, etc)

I.D.	Utstyr - *Equipment*	Gyldig til (dato) – *Valid until (date)*
1	Strain gauges	

7 Sporbarhet – *Tracebility*

Eksisterer – Is there	J: Ja – *Yes* / N: Nei - *No*
Er alle prøvematerialene kjente og identifiserbare? – *Are all experimental materials known and traceable?*	J
Eksisterer det en plan for markering av alle prøvene? – *Is there a plan for marking all specimens?*	J
Er dataloggingsutstyret identifisert? – *Is the data aquisition equipment identified?*	J
Er originaldata lagret uten modifikasjon? – *Are the original data stored safely without modification?*	J
Eksisterer det en backup-prosedyre? – *Is there a back-up procedure for the data (hard disk crash)?*	J
Eksisterer det en plan for lagring av prøvestykker etter testing? – *Is there a plan for storing samples after testing?*	J
Eksisterer en plan for avhending av gamle prøvestykker? – *Is there a plan for disposing of old samples?*	J

8 Kommentarer – *Comments*

9 Signaturer – *Signatures*

Godkjent (dato/sign) – Approved (date/signature)

Prosjektleder – *Project leader*	Verifikatør – *Verifier*	Godkjent – *Approved by*
Emir Dzubur		

Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

Safety and Quality Evaluation of Activities in the Laboratory and Workshop

NTNU

Perleporten

1 Identifikasjon - *Identification*	**Dokumentnr. - *Document no.*:**	
Kundenavn – *Customer name*	Prosjektnavn – *Master thesis*	Projektnr. – *Project no.*
Beskrivelse av arbeid – *Description of job* *External pressure testing of composite tubes*		Dato – *Date* *18.03.2014*

2 Projekt – *Team*

Prosjektleder og organisasjon – *Project manager and organisation*	Andreas Echtermeyer	Ansvarlig for instrumentering – *Responsible for instrumentation.*	Emir Dzubur
Leiestedsansvarlig – *Laboratory responsible*	Emir Dzubur	Operatør – *Operator*	Emir Dzubur
Auditør for sikkerhets og kvalitetsgjennomgang – *Auditer for safety check*	Emir Dzubur	Ansvarlig for styring av forsøk – *Responsible for running the experiment.*	Emir Dzubur
Ansvarlig for eksperimentelt faglig innhold – *Responsible for experimental and scientific content*	Emir Dzubur	Ansvarlig for logging av forsøksdata – *Responsible for logging and storing experimental data*	Emir Dzubur
Ansvarlig for dimensjonering av last og trykkpåkjente komponenter – *Reponsible for dimensioning load bearing and pressurized components*	Emir Dzubur	Ansvarlig for montering av testrigg – *Responsible for building the rig*	Emir Dzubur

3 Viktig!! – *Important!!*	J: Ja – *Yes* / N: Nei - *No*
Er arbeidsordren signert? – *Is the work order signed?*	
Har operatøren nødvendig kurs/trening i bruk av utstyret? - *Has the operator the required courses/training on the equipment?*	J
Har operatøren sikkerhetskurs? (påbudt) – *Has the operator followed the safety courses? (mandatory)*	J
Kan jobben gjøres alene? - *Can the work be done alone?*	N
- Dersom ja, er det med visse forbehold (for eksempel, må bruke alarm, ha avtale med noen som kommer innom med jevne mellomrom eller lignende). Dette må vurderes i Seksjon 5. *If yes, the work may have to be done under special conditions (e. g. must use the alarm, have agreement with somebody coming back periodically or similar). This shall be evaluated in Section 5.*	

4.1 Sikkerhet – *Safety* (Testen medfører – *The test contains*)			J: Ja – *Yes* / N: Nei - *No*
Stor last – *Big loads*	N	Brannfare – *Danger of fire*	N
Tunge løft – *Heavy lifting*	N	Arbeid i høyden – *Working at heights*	N
Hengende last – *Hanging load*	J	Hydraulisk trykk – *Hydraulic pressure*	N
Gasstrykk – *Gas pressure*	N	Vanntrykk – *Water pressure*	J
Høy temperatur – *High temperature*	N	Lav temperatur – *Low temperature*	N
Deler i høy hastighet – *Parts at high velocity*	N	Farlige kjemikalier – *Dangerous chemicals*	N
Sprutakselerasjon ved brudd – *Sudden acceleration at fracture/failure*	N	Forspente komponenter – *Pre-tensioned components*	N
Farlig støv – *Dangerous dust*	N	Kraftig støy – *Severe noise*	J
Klemfare – *Danger of pinching*	J	Roterende deler – *Rotating parts*	N

4.2 Påkrevet verneustyr – *Required safety equipment*			J: Ja – *Yes* / N: Nei - *No*
Briller (påbudt) – *Glasses (mandatory)*	J	Vernesko – *Safety shoes*	N
Hjelm – *Helmet*	N	Hansker – *Gloves*	J
Skjerm – *Screen*	J	Visir – *Visir*	N
Hørselsvern – *Ear protection*	J	Løfteredskap – *Lifting equipment*	N
Yrkessele, fallsele, etc. – *Harness ropes, other measures to prevent falling down.*	N		

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Sikkerhets- og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid

NTNU
Perleporten

5.1 Beskrivelse av aktivitet – *Description of the activity (see Appendix)*

Vurdering skal være basert på en skriftlig prosedyre for bruk av maskinen. I enkelte tilfeller kan prosedyre bli beskrevet direkte i tabellen nedenfor.

The evaluation shall be based on a written operating procedure for the machine. For simple cases the procedure can be directly described in the tables below.

Nr.	Beskrivelse av aktivitet – *Description of activity*	Fare - *Danger*	Lov, forskrift o.l. – *Legal requirements*	Prosedyre nr. – *Procedure no.*	Sannsynlighet – *Probability*	Konsekvens –*Consequence*	Risiko – *Risk*
1	Sette på optiske fiber	Sterkt lim			1	A	A1
2	Sette røret i Autoclaven	Kontaktskader ved nedheising av topplokk			2	B	B2
3	Trykktesting	T-fitting ikke tåler det høye trykket			4	C	C4
4		Slanger ryker			4	C	C4

5.2 Korrigerende Tiltak – *Corrective Actions*

Nr.	Korrigerende tiltak – Corrective action	Sannsynlighet – *Probability*	Konsekvens – *Consequence*	Risiko – *Risk*	Utført dato – *Date of action*
1	Verneutstyr				
2					
3	T-fitting laget for høyt trykk, vegg satt mellom autoclaven og personer	1	C	C1	
4	Godkjente slanger	1	C	C1	

Sikkerhets og kvalitetsgjennomgang av laboratorietester og verkstedsarbeid	NTNU Perleporten

5.3 Feilkilder – *Reasons for mistakes/errors*

Sjekkliste: Er følgende feilkilder vurdert? – Check list: Is the following considered? J: Ja – *Yes* / N: Nei - *No*

Tap av strøm – *Loss of electricity*	J	Overspenning – *Voltage surge*	N
Elektromagnetisk støy – *Electromagnetic noise*	N	Manglende aggregatkapasitet av hydraulikk – *Insufficient power of the machine*	N
Jordfeil – *Electrical earth failure*	N	Vannsprut – *Water jet*	J
Ustabilt trykk av hydraulikk/kraft – *Unstable pressure or hydraulic force*	J	Tilfeldig avbrudd av hydraulikk/kraft – *Unintended interruption of power supply*	J
Last-/ forskyvnings grenser etablert ? – *Are load and displacement limits established?*	N	Lekkasjer (slanger/koblinger, etc.) – *Leakage of pipes, hoses, joints, etc.*	J
Mulige påvirkninger fra andre aktiviteter – *Possible interference from other activities*	N	Mulige påvirkninger på andre aktiviteter – *Possible interference towards other activities*	N
Problemer med datalogging og lagring – *Troubles in loading and storage*	N	Brann i laboratoriet – *Fire in the laboratory*	J

6 Kalibreringsstatus for utstyr – *Calibration of equipment*

(ex: load cell, extensometer, pressure transducer, etc)

I.D.	Utstyr - *Equipment*	Gyldig til (dato) – *Valid until (date)*
	Trykkmåler	
	Optiske fiber	Erfaring fra lab

7 Sporbarhet – *Tracebility*

Eksisterer – Is there	J: Ja – *Yes* / N: Nei - *No*
Er alle prøvematerialene kjente og identifiserbare? – *Are all experimental materials known and traceable?*	J
Eksisterer det en plan for markering av alle prøvene? – *Is there a plan for marking all specimens?*	J
Er dataloggingsutstyret identifisert? – *Is the data aquisition equipment identified?*	J
Er originaldata lagret uten modifikasjon? – *Are the original data stored safely without modification?*	J
Eksisterer det en backup-prosedyre? – *Is there a back-up procedure for the data (hard disk crash)?*	J
Eksisterer det en plan for lagring av prøvestykker etter testing? – *Is there a plan for storing samples after testing?*	N
Eksisterer en plan for avhending av gamle prøvestykker? – *Is there a plan for disposing of old samples?*	J

8 Kommentarer – *Comments*

9 Signaturer – *Signatures*

Godkjent (dato/sign) – Approved (date/signature)

Prosjektleder – *Project leader*	Verifikatør – *Verifier*	Godkjent – *Approved by*
Emir Dzubur		AGH 18/3/2014

NTNU HMS	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet: **Dato: 05.02.2014**

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon)**: Emir Dzubur, Andreas Echtermeyer**
(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave student Emir Dzubur. Tittel på oppgaven: Modelling and testing of sm diameter composite tubes under hydrostatic pressure

Er oppgaven rent teoretisk? (JA/NEI)**:** *«JA» betyr at veileder innestår for at oppgaven ikke inneholder noen aktiviteter som krever risikovurdering. Dersom «JA»: Beskriv kort aktiviteteten i kartleggingskjemaet under. Risikovurdering trenger ikke å fylles ut.*

Signaturer: *Ansvarlig veileder:* AAE *Student:* Emir Dzubur

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	FEM analyser	Emir Dzubur				
2	Oppgaveskriving	Emir Dzubur				
3	Lage rør med Filament Winding machine	Emir Dzubur, Andreas Echtermeyer	Filament winding kurs, user manual	Sensorer som stopper maskinen da de blir brutt, Verneutstyr		
4	Testing	Emir Dzubur		Verneutstyr		

NTNU	Risikovurdering	Utarbeidet av	Nummer	Dato
HMS		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av		Erstatter
		Rektor		01.12.2006

Enhet:

Dato: 05.02.2014

Linjeleder:

Deltakere ved kartleggingen (m/ funksjon):
(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Risikovurderingen gjelder hovedaktivitet: Masteroppgave student Emir Dzubur. Tittel på oppgaven.

Signaturer: *Ansvarlig veileder:* *Student:* Emir Dzubur

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet	Vurdering av konsekvens:				Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
			(1-5)	Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)		
1	FEM analyser	Nakke, rygg, håndledd og andre skader som er relatert til å jobbe på PC.	2	B				2B	
2	Oppgaveskriving	Nakke, rygg, håndledd og andre skader som er relatert til å jobbe på PC.	2	B				2B	
3a	Lage rør med Filament Winding macine	Skade ved uheldig kontakt med maskinen.	1	C				1C	
3b		Søle på utstyr eller gulv	2			C		2C	Dekke til gulv og utstyr som har størst risiko for søl. Orden på laben
3c		Kjemikalie søl på menneske	2	B					Bruke hansker og annet verneutstyr. Orden i laben
4	Testing	Kontakt med testmaskin, øyeskader	3	C				3C	Verneutstyr

Sannsynlighet vurderes etter følgende kriterier:

Probability shall be evaluated using the following criteria:

Svært liten Very unlikely 1	Liten Unlikely 2	Middels Probable 3	Stor Very Probable 4	Svært stor Nearly certain 5
1 gang/50 år eller sjeldnere *– Once per 50 years or less*	1 gang/10 år eller sjeldnere *– Once per 10 years or less*	1 gang/år eller sjeldnere *– Once a year or less*	1 gang/måned eller sjeldnere *– Once a month or less*	Skjer ukentlig *– Once a week*

Konsekvens vurderes etter følgende kriterier:

Consequence shall be evaluated using the following criteria:

Gradering *– Grading*	Menneske *– Human*	Ytre miljø, Vann, jord og luft *– Environment*	Øk/materiell *– Financial/Material*	Omdømme *– Reputation*
E Svært Alvorlig *– Very critical*	Død – Death	Svært langvarig og ikke reversibel skade *– Very prolonged, non-reversible damage*	Drifts- eller aktivitetsstans >1 år. *– Shutdown of work >1 year.*	Troverdighet og respekt betydelig og varig svekket *– Trustworthiness and respect are severely reduced for a long time.*
D Alvorlig *– Critical*	Alvorlig personskade. Mulig uførhet. *– May produce fatality/ies*	Langvarig skade. Lang restitusjonstid *– Prolonged damage. Long recovery time.*	Driftsstans > ½ år Aktivitetsstans i opp til 1 år *– Shutdown of work 0,5-1 year.*	Troverdighet og respekt betydelig svekket *– Trustworthiness and respect are severely reduced.*
C Moderat *– Dangerous*	Alvorlig personskade. *– Permanent injury, may produce serious health damage/sickness*	Mindre skade og lang restitusjonstid *– Minor damage. Long recovery time*	Drifts- eller aktivitetsstans < 1 mnd *– Shutdown of work < 1 month.*	Troverdighet og respekt svekket *– Troverdighet og respekt svekket.*
B Liten *– Relatively safe*	Skade som krever medisinsk behandling *– Injury that requires medical treatment*	Mindre skade og kort restitusjonstid *– Minor damage. Short recovery time*	Drifts- eller aktivitetsstans < 1uke *– Shutdown of work < 1 week.*	Negativ påvirkning på troverdighet og respekt *– Negative influence on trustworthiness and respect.*
A Siker - Safe	Injury that requires first aid	Insignificant damage. Short recovery time	Shutdown of work < 1day	

Risikoverdi = Sannsynlighet X Konsekvenser

Beregn risikoverdi for menneske. IPM vurderer selv om de i tillegg beregner risikoverdi for ytre miljø, økonomie/ material og omdømme. I så fall beregnes disse hver for seg.

Risk = Probability X Consequence

Calculate risk level for humans. IPM shall evaluate itself if it shall calculate in addition risk for the environment, economic/material and reputation. If so, the risks shall be calculated separately.

KONSEKVENS						
	Svært alvorlig	E1	E2	E3	E4	E5
	Alvorlig	D1	D2	D3	D4	D5
	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært stor
		SANNSYNLIGHET				

Prinsipp over akseptkriterium. Forklaring av fargene som er brukt i risikomatrisen.

Farge		Beskrivelse
Rød		Uakseptabel risiko. Tiltak skal gjennomføres for å redusere risikoen.
Gul		Vurderingsområde. Tiltak skal vurderes.
Grønn		Akseptabel risiko. Tiltak kan vurderes ut fra andre hensyn.

Til Kolonnen "Korrigerende Tiltak":

Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs sannsynlighetsreduserende tiltak foran skjerpende beredskap, dvs konsekvensreduserende tiltak.

For Column "Corrective Actions"

Corrections can influence both probability and consequence. Prioritize actions that can prevent an event from happening.

Oppfølging:

Tiltak fra risikovurderingen skal følges opp gjennom en handlingsplan med ansvarlige personer og tidsfrister.

Follow Up

Actions from the risk evaluation shall be followed through by an action plan with responsible persons and time limits.

Etterarbeid #

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