NTNU
Norwegian University of
Science and Technology

# Buckling due to External Pressure of Tubes Measured by Rayleigh Optical Backscatter Reflectometry.

Enrique Martin de Saavedra Navarro

Mechanical Engineering
Submission date: July 2017
Supervisor: Nils Petter Vedvik, MTP
Co-supervisor: José Ignacio Linares Hurtado, Comillas Pontifical University - ICAI

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

## Abstract

This master's thesis should focus on measuring the buckling suffered by tubes from external pressure. The technique to be studied, is Rayleigh optical backscatter reflectometry (OBR), which through swept wavelength interferometry, measures backscatter as a function of length with high resolution optical fibers. It offers continuous monitoring of strain and temperature along these fibers. Used in Structural Health Monitoring (SHM) as a regular early measurement analysis for possible accidents and dangerous states, this technique have been improved for the last 30 years, getting the same accuracy as current devices working in the same field. The main structure of the thesis will be divided into three blocks, with different objectives.

The first one, analytical and numerical study, explains through simulations in Abaqus CAE Software, the behavior of different tubes exposed to external pressure, giving non-critical values and other information that is quite important for future studies. FEA analysis is the main focus of this part. Therefore, non-critical values are quite high, allowing us to test different situations without not much restrictive limitations.

The second one, experimental study, is responsible of obtaining signals, strain profiles and values regarding deformation due to pressure applied on experimental tubes in the laboratory of the department in which the thesis is being developed. In order to do that, information obtained in previous block will be helpful, and Luna OBR Software is the program which will give us every needed data for a conclusion. Trial and error is the best method used in this part because of the several amount of ideas and possibilities that appear at doing these experiments. Lots of problems and factors that quite significant have been found and should be studied in future developments.

The last one should be an analysis of the results obtained in both last parts, the methods used to get those results, and an analysis of sensibility. Thoughts and statement here will be the basis of the conclusions that must have this thesis about the Rayleigh OBR technique regarding case results, methods and future studies recommendations. Therefore, by this simple study, it can be said that this technique has so much potential not only for SHM, but for other areas too, being a really good focus for future studies.

# Preface

This master's thesis has been developed at the Department of Mechanical and Industrial Engineering, part of the Faculty of Engineering Science, at Norwegian University of Science and Technology, Trondheim, in the period of Autumn/Spring 2016/2017. It is the final step of a Double Master in Industrial Engineering and in Business Administration (MII+MBA) studied at Comillas Pontifical University, Madrid, Spain.

I would like to thank to my supervisor, Nils Petter Vedvik, who guide me since the first moment in the department, and to Andrea Steinert, Higher Executibe Officer of the department for helping me with everything I needed regarding documents for validating the master's thesis.

Thanks also to all the people I have met during this year, both inside and outside the university, for making this time a fantastic experience for me. One more time, thank you.

*I hereby declare that this is an independent work according to the exam regulations of the Norwegian University of Science and Technology (NTNU).*

Trondheim, 23 of July 2017

Enrique Martín de Saavedra Navarro

# Contents


Abstract ..... III

Preface ..... V

Contents ..... VII

List of figures ..... IX

List of tables ..... XI

1. Introduction and project approach ..... 1

2. State of the art – technology description ..... 1

3. Description of the developed model ..... 3

3.1. Objectives ..... 3
3.2. Specifications and resources ..... 5
3.3. Analytical and numerical study ..... 8
3.4. Experimental study ..... 19
3.4.1. Preparing the optical fiber ..... 19
3.4.2. Obr v3.10.1 luna technologies software ..... 25
3.4.3. Experimental study with polypropylene tubes ..... 27
3.4.4. Experimental study with polyvinyl chloride rings ..... 35
3.4.5. Experimental study with polyvinyl chloride tubes ..... 55

4. Analysis of results ..... 63

4.1. Results of base case ..... 63
4.1.1. First test of the first set up with pvc ring (regular tape) ..... 65
4.1.2. Second test of the first set up with pcv ring (regular tape) ..... 66
4.1.3. Second set up with pvc ring (industrial tape) ..... 66
4.1.4. First test of the first set up with pvc tube (regular tape) ..... 67
4.1.5. Second test of the first set up with pvc tube (regular tape) ..... 67
4.2. Analysis of sensitivity ..... 68

5. Conclusions ..... 71

5.1. Conclusions on the methodology ..... 71
5.2. Conclusions on the results ..... 72
5.3. Recommendations for future studies ..... 73

Bibliography ..... 76

Annexes ..... I

List of annexes ..... I

# List of figures

Figure 1 Rayleigh OBR technique ........ 2

Figure 2 Abaqus CAE Software ........ 5

Figure 3 OBR Luna Technologies Software ........ 6

Figure 4 Optical measurement fiber from OFS ........ 7

Figure 5 Linear buckling simulation results ........ 9

Figure 6 Non-linear buckling simulation results ........ 10

Figure 7 Implicit dynamic simulation results ........ 10

Figure 8 Model 1.0 – Linear buckling simulation ........ 12

Figure 9 Model 1.0 – Non-linear buckling simulation (linear) ........ 13

Figure 10 Model 1.0 – Non-linear buckling simulation (process) ........ 14

Figure 11 Model 1.0 – Non-linear buckling simulation (result) ........ 15

Figure 12 Model 1.0 – Non-linear buckling simulation (displacement diagram) ........ 15

Figure 13 Model 1.0 – Implicit dynamic simulation (before breakdown) ........ 16

Figure 14 Model 1.0 – Implicit dynamic simulation (after breakdown) ........ 17

Figure 15 Model 1.0 – Implicit dynamic simulation (breakdown step time) ........ 17

Figure 16 Equipment used for optical fiber splicing ........ 20

Figure 17 Quality control of fiber tips in Fitel S178 fiber splicer device ........ 23

Figure 18 Spliced fibers in Fitel S178 fiber splicer device ........ 24

Figure 19 Reference signal from tube through OBR technique ........ 25

Figure 20 Strain profile signal from tube through OBR technique ........ 26

Figure 21 Polypropylene tube used in experimental study ........ 27

Figure 22 First adhesion done with cyanoacrylate adhesive ........ 28

Figure 23 Results of the first adhesion with cyanoacrylate adhesive ........ 29

Figure 24 Industrial tape used ........ 30

Figure 25 First set up of the experimental study with PP tubes ........ 31

Figure 26 Signal from the first set up of the experimental study with PP tubes ........ 32

Figure 27 Second set up of the experimental study with PP tubes ........................................ 33
Figure 28 Signals from the second set up of the experimental study with PP tubes................ 34
Figure 29 Polyvinyl chloride tubes used in experimental study ............................................ 36
Figure 30 First set up in a PVC ring for experimental study ................................................. 37
Figure 31 Regular tape used................................................................................................. 37
Figure 32 Pressure point at 0 and 90 degrees........................................................................ 38
Figure 33 Pressure point at 180 and 270 degrees.................................................................. 39
Figure 34 Pressure application problem................................................................................ 40
Figure 35 Signals from the first set up of the experimental study with PVC ring at 0 and 90 degrees................................................................................................................................ 41
Figure 36 Signals from the first set up of the experimental study with PVC ring at 180 and 270 degrees......................................................................................................................... 42
Figure 37 New optical fiber set up ........................................................................................ 43
Figure 38 Signals from the second set up of the experimental study with PVC ring at 0 and 90 degrees................................................................................................................................ 45
Figure 39 Signals from the second set up of the experimental study with PVC ring at 180 and 270 degrees......................................................................................................................... 46
Figure 40 Industrial tape with transverse reinforcements used.............................................. 47
Figure 41 Third set up in a PVC ring for experimental study................................................ 48
Figure 42 Signals from the third set up of the experimental study with PVC ring at 0 and 90 degrees................................................................................................................................ 49
Figure 43 Signals from the third set up of the experimental study with PVC ring at 180 and 270 degrees......................................................................................................................... 50
Figure 44 Second signals from the second set up of the experimental study with PVC ring at 0 and 90 degrees.................................................................................................................... 52
Figure 45 Second signals from the second set up of the experimental study with PVC ring at 180 and 270 degrees............................................................................................................. 53
Figure 46 Measuring failure due to repetitive deformations.................................................. 54
Figure 47 Polyvinyl chloride tube used in experimental study.............................................. 56

Figure 48 First set up in a PVC tube for experimental study .................................................. 57

Figure 49 Signals from the first set up of the experimental study with PVC tube at 0 and 90 degrees .......................................................................................................... 58

Figure 50 Signals from the first set up of the experimental study with PVC tube at 180 and 270 degrees .......................................................................................................... 59

Figure 51 Signals from the second set up of the experimental study with PVC tube at 0 and 90 degrees .......................................................................................................... 60

Figure 52 Signals from the second set up of the experimental study with PVC tube at 180 and 270 degrees .......................................................................................................... 61

Figure 53 Displacement-time diagram from Abaqus CAE Software for Model 1.0 ............... 64

Figure 54 Pre-model of pressure chamber .................................................................. 74

## List of tables

Table 1 Analytical and numerical results ..................................................................... 18

Table 2 Expanded analytical and numerical results I ................................................ II

Table 3 Expanded analytical and numerical results II .............................................. III

Table 4 Signal values from first PVC ring set up (regular tape) first test ................................IV

Table 5 Signal values from second PVC ring set up (industrial tape) ...................................... V

Table 6 Signal values from first PVC ring set up (regular tape) second test ........................... VI

Table 7 Signal values from first PVC tube set up (regular tape) ...........................................VII

Table 8 Signal values from second PVC tube set up (regular tape)...................................... VIII

# 1. Introduction and project approach

This master thesis work shall investigate how tubes behave when submerged and how optical fibers can be used as a health monitoring system or test data acquisition system for such applications utilizing Rayleigh Optical Backscatter Reflectometry (OBR from now on). Tubes that operate in high external pressure environments with composite tubes include drilling risers, drill strings and flow line at subsea installations.

The fiber optical sensor technology based on Rayleigh backscatter enables continuous strain measurements along the fiber length which provides a versatile mean to characterize the buckling mode shape during pressurization. Previous works have demonstrated its capacity and potential on composite tubes, and also identified a need for further investigation.

However, for the reasons shown in the next section, this master thesis work shall focus on the study of more simple tubes, mainly PVC and steel tubes.

# 2. State of the art – Technology description

Optical fibers are the main transmission medium in data networks due to the ability to send a large amount of data over a long distance with similar speeds to radio or cable, through light pulses that are completely confined, propagated and then transmitted inside by reflection angles according to Snell’s law. They have the great advantage of not being sensitive to electromagnetic interference which make them perfect for telecommunications.

Nowadays, and for the past 30 years, they have been used for Structural Health Monitoring (SHM) as a regular measurement analysis with the purpose of detecting signals of accidents or dangerous states at an early stage, avoiding casualties as well as providing maintenance. Along these years, the technique has been developed, getting the same accuracy as current standard strain gauges and extensometers.

The OBR technique uses swept wavelength interferometry, measuring Rayleigh backscatter as a function of length with high resolution optical fibers. It offers continuous monitoring of strain and temperature along these fibers. External actions, strain changes in this case, deform spectral and temporal aspects of the Rayleigh backscatter pattern. This shifts can be represented by a distribution as shown in Figure 1. Changes in sensor spacing, gage length and region measured through the software used, help us to get a better analysis of the shifts due to deformations and strain shifts.

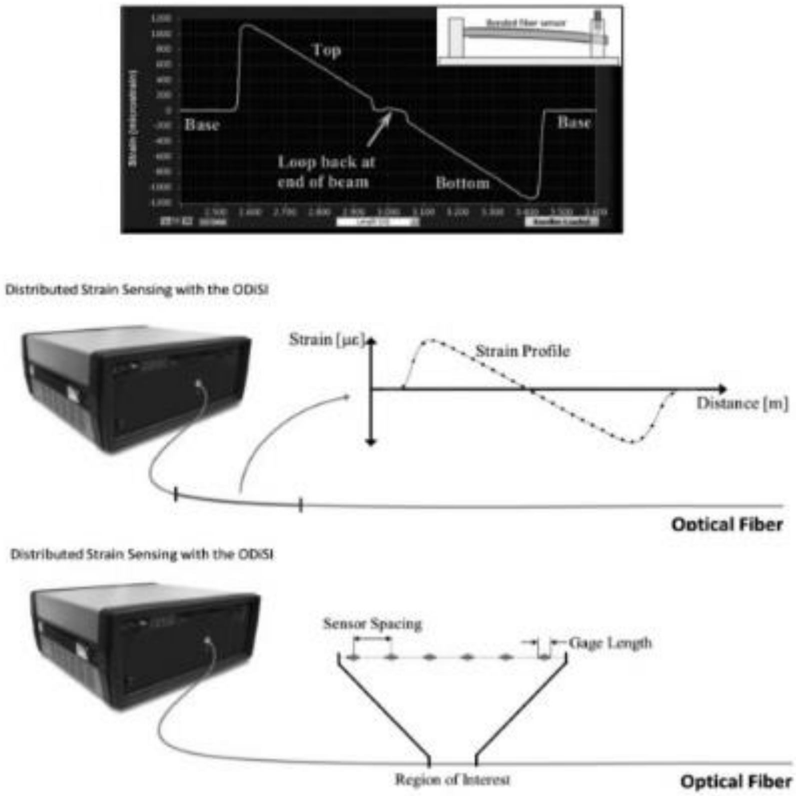


*Figure 1 Rayleigh OBR technique*

Authors such as Leung (2001), Li (2004) and Villalba & Casas (2012) have shown and summarized the potential, research and development of this technique in SHM. Materials such as composite, steel and aluminum have both a smooth surface where the bonding of the fiber is easily carried out, and a continuous strain field that the OBR can follow without limitations at high levels of deformation. Currently, this technique is being used in cracking, deformation and damage detection as well as temperature leakage (FRAN14).

As we can see in Figure 1, when applying deformation in the surface where the fiber is attached, the strain profile is changed due to tension and compression that appear in the surface and that the fiber follows. This shift is then showed in the computer program, in the form of a sine wave where the tension is represented above the reference profile and the compression below. The figure represents the strains along the area of fiber that is affected.

In previous thesis of this same study, tubes made of composite materials were analyzed, but lots of unknown errors made really difficult to state a conclusion. This is why in this work, more simple materials are going to be studied, such as PVC and/or stainless steel.

# 3. Description of the developed model

In this section, the procedure of the whole work is going to be exposed in the best way possible in order to get a better understanding. Subsections such as objectives, specifications, numerical data and methodologies are some of the main points that are going to show the basis of this thesis. In each of the subsections, information will be detailed and will be accompanied by necessary numerical data, tables and figures obtained along the whole process.

Afterward, an analysis of these data and results, and the consequent conclusion, will be made.

## 3.1. Objectives

As I have explained in the first part of the thesis, a study of the behavior of tubes under external pressure will be done, measuring helpful data with Rayleigh OBR. For that, we have to take into account a number of main objectives, or steps, that should be achieved, which are the following ones:

- <u>Analytical and numerical study (FEA analysis):</u> in this first part of the thesis work, decision making, learning of the necessary computer programs, information searching and simulation models, among others, are the start line of the project. Results and data obtained from this part will be essential for the correct accomplishment of the following objectives.

- Risk Assessment: mandatory activity to perform in order to achieve the level of security needed to work safely in the laboratories of the department where the experimental work will be done. A document regarding the information of this assessment is attached at the last part of this thesis.

- Experimental study: measures and data taken from a real application of the OBR equipment in a tube under external pressure. Thanks to the information obtained in the analytical and numerical study, we should have a range of measures and materials for the tubes in order to work properly in the laboratory, avoiding damage to the equipment and ourselves.

- Analysis of results: regarding the experience and data achieved through both numerical and experimental studies, we get into the results, compare each other, and make sensitivity analysis. Once all of that is done, a final conclusion of the application of the OBR to real behavior measure of tubes under external pressure scenarios will be made.

To sum up, the main objective of this thesis is to dictate, in our opinion and experience through measures and data, if Rayleigh OBR could be used in real cases, its advantages and disadvantages, and if it should continue to be studied and developed.

## 3.2. Specifications and resources

Even before starting with the analytical and numerical study, some aspects of the project were established given the equipment, materials, software and other available resources in the facilities. Most important ones are explained below:

- <u>Abaqus CAE v6.14.1 Software:</u> is a software used for finite element analysis and computer-aided engineering (WIKI17). This program will be learned and used in the first part of the project, the analytical and numerical study. Simulations of tubes with different measures, materials and pressures will be made with this software regarding FEA analysis. Data obtained will be collected in Table 1 in the analytical and numerical study section. Figure 2 shows a regular PVC tube designed in the program after simulation.

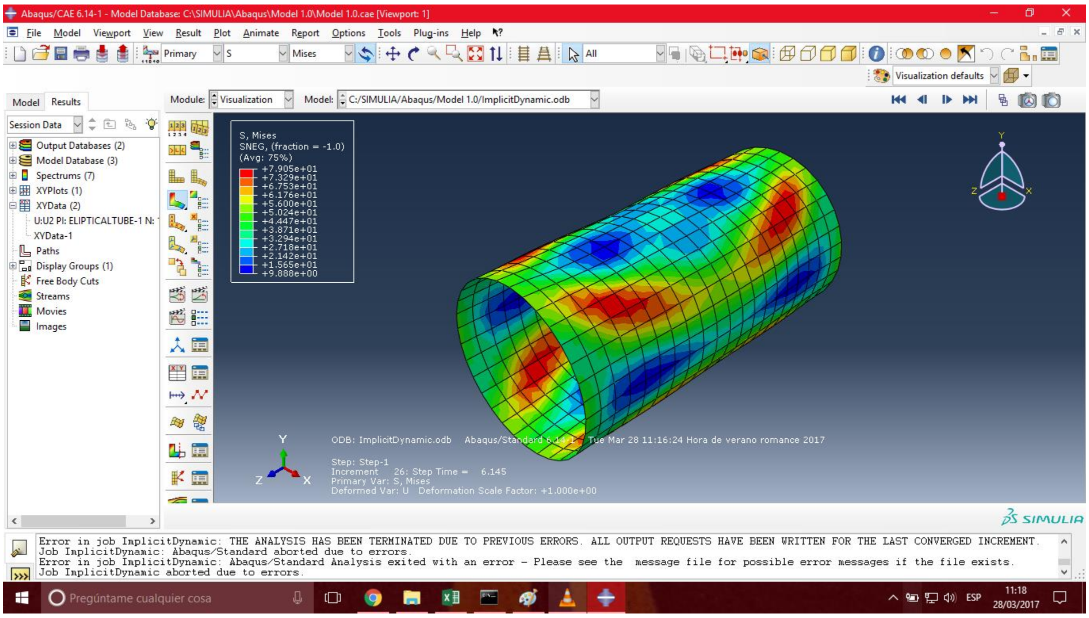


*Figure 2 Abaqus CAE Software*

- <u>OBR v3.10.1 Luna Technologies Software:</u> computer program that receive the information measured by the optical fiber, and with the OBR hardware, translate the signal into numerical data and graphics that are shown in the computer. Figure 3 shows a signal detected from the deformation measured in one tube.


*Figure 3 OBR Luna Technologies Software*

- <u>Polypropylene (PP), polyvinyl chloride (PVC) and stainless steel tubes:</u> tube materials available in the laboratory to work with. As explained before, we wanted to work with simple materials in order to get results from basic scenarios and use them as basis for future studies.

- <u>Optical measurement fiber from Optical Fiber Cable and Connectivity Solutions OFS:</u> fiber shown in Figure 4. It is the one used in all the experimental work with the different tubes and methods explained in following sections.


*Figure 4 Optical measurement fiber from OFS*

Most of the specifications were established in order to avoid damage to the OBR hardware while measuring, it is expensive equipment and safety measures should be taken into account. The results in the analytical and numerical study are also to avoid this, as we it will be explained later. Anyway, in this thesis, every studied result and case did not compromise the structure of the device.

There are some other resources, most of them tools, which are going to be explained later on in the experimental study, for the preparation of the measurement fiber.

## 3.3. Analytical and numerical study

At the beginning of the project, most of the main points, objectives, specifications and resources, already explained in sections above, are decided in the first weekly meetings between supervisor and student. The main objective of the thesis should focus on how the fiber with the OBR equipment measures buckling and deformation, and how functional this can be applied to real cases. For that, the structure of the work was divided in three parts: analytical study, experimental study and analysis of results. Although some resources and specifications were established at the beginning of the project, some others were specified along the studies. Once the basic structure was clear, we can start with the main work.

In this first part, a Finite Element Analysis of the tubes is carried out, and Abaqus CAE Software is the program used in order to do that. It is necessary to say that a few lessons were needed to learn how to program the software and run some simulations, but it was not a big deal. The focus of this analysis was divided in two ends: study the behavior of tubes with different design measures and materials under external homogeneous pressure both before and after the critical pressure and the consequent breakdown; and obtain the critical pressures of each different tubes. With that information we also could have an approximation of how much pressure we could apply to the different tubes in the experimental study without breaking the tubes and the fiber inside, avoiding damage to the OBR equipment.

Now, it is important to explain how this FEA simulations are done in the program. First of all, we have two main specifications since the beginning of the study: all the tubes, although they have different measures, have the same material properties, this is, PVC (density of 1.2 g/cm3; Poisson coefficient of 0.35; Young module of 3000 MPa); and that for every single tube, three different simulations are going to be programmed and tested. These are:

Linear buckling simulation: in this case the tube model has a cross section represented by a perfect circumference. This simulation will give us important data such as the linear critical pressure and the number of “slopes” just before the breakdown. Figure 5 shows the result of this kind of test.

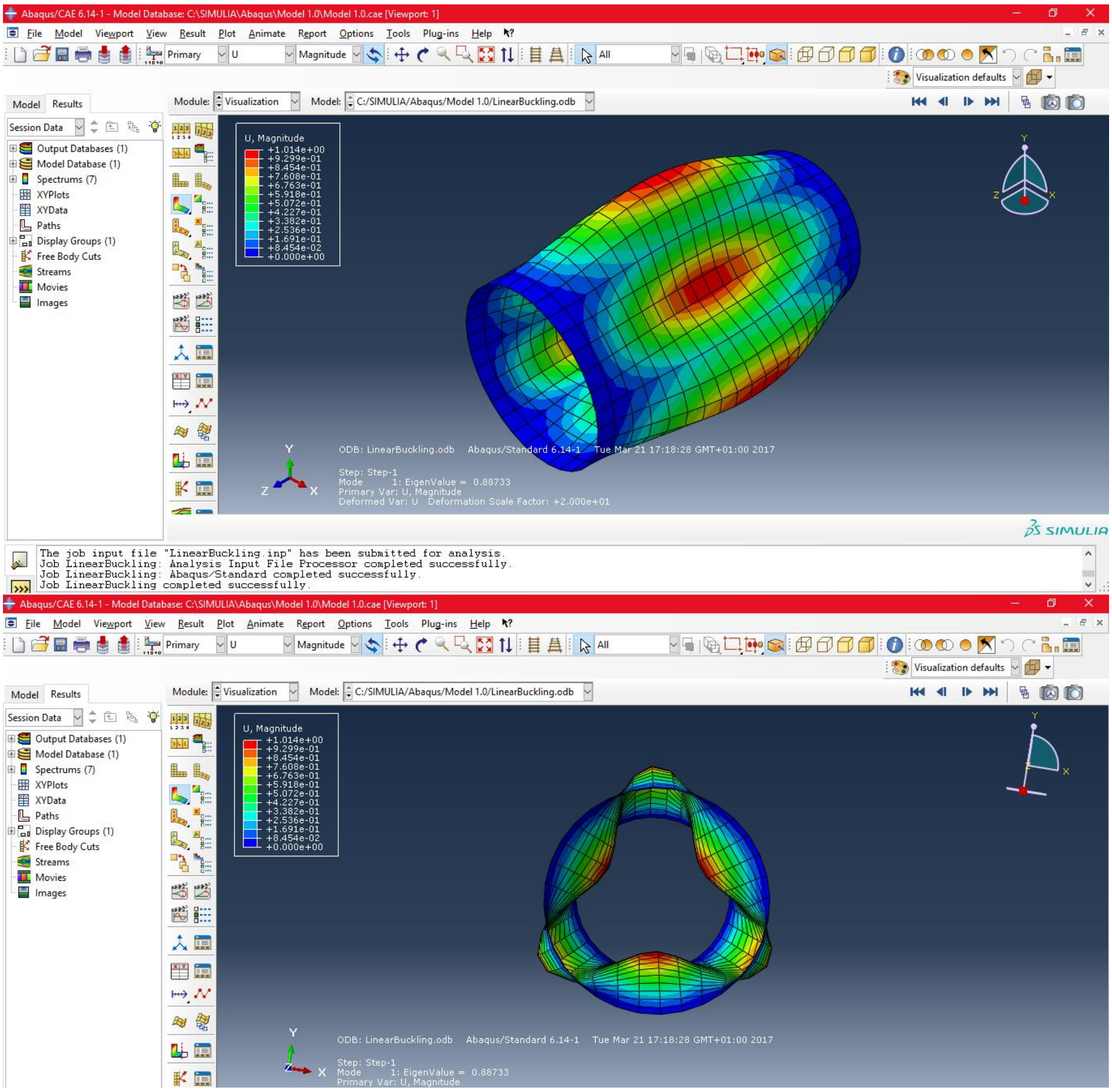


*Figure 5 Linear buckling simulation results*

Non-linear buckling simulation: in this case, the cross section of the model is not a perfect circumference, it has a very little deviation, getting an ellipse. This is done trying to simulate the deformations and other factors that the real tube has due to process of manufacturing, nothing is perfect after all. With this, we obtain the non-linear critical pressure. Figure 6 shows the result of this kind of test.

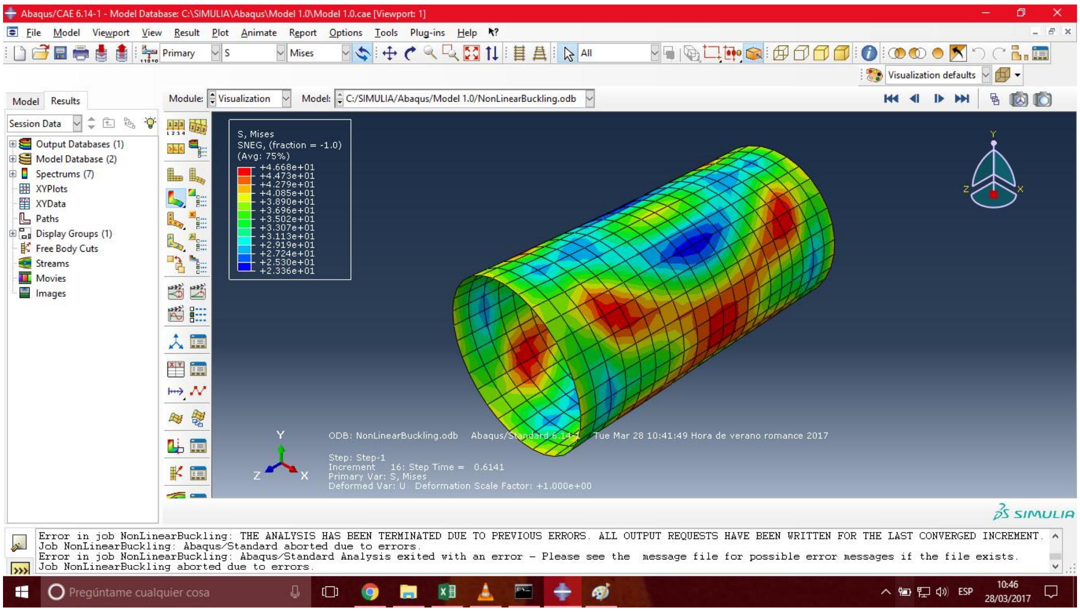


*Figure 6 Non-linear buckling simulation results*

Implicit dynamic simulation: this third type of test is also valid to see the behavior of the tube after the breakdown and that the critical pressure here is similar to the one obtained in the non-linear buckling simulation. It is important to say that this test does not always work depending on the model, as it is explained later in the respective models, but however, we are only interested in the critical pressure and not in the post-buckling behavior, so this is not a big problem. Figure 7 shows the result of this kind of test.

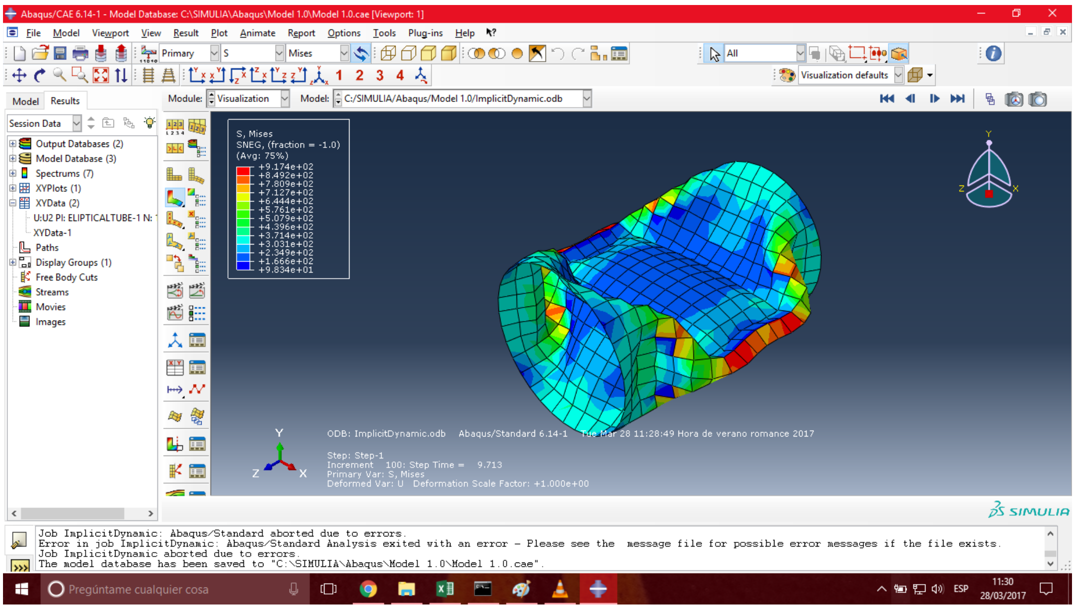


*Figure 7 Implicit dynamic simulation results*

Once the three types of simulations are clear, a deep analysis of the model test is explained in the following paragraphs. As it is a general process, only the first model it is shown for the description. However, the rest of the models are explained in order to show some problems during the analysis, and every data obtained, with measures and properties of each model, is collected in Table 1 later.

Starting with the first model/first submodel (Model 1.0 – LinearBuckling in Table 1), the design measures are easy to implement in the program, it is relatively intuitive in this aspect. It is a tube with a length of 200 mm, diameter of 50 mm and thickness of 3 mm. Some restrictions and boundary conditions must be set in order to get a correct simulation, similar to the experimental case. These boundary conditions consist of, in the cross section of each end, the points belonging to the tube must have the same displacement and rotation as the point in the center of the cross section, an imaginary point which we call Reference Point (RP) in the program. In this RP is where we are going to point the equivalent axial force due to the external pressure, explained later in this section. Regarding restrictions, displacements and rotations in every axis in both ends of the tube are forbidden, but displacement of one end in the direction of the longitudinal axis of the tube is allowed.

Now, in order to start the simulation, we apply pressure of 1 MPa homogeneously through the surface of the model, and an equivalent axial force, in the RP of the end which is allowed to move along the longitudinal axis of the tube, of 7850 N. Then we run the simulation with a number of requested eigenvalues of 4 and 100 iterations (data for all the models), obtaining and eigenvalues of 0.8873 and 3 slopes as shown in Figure 8.

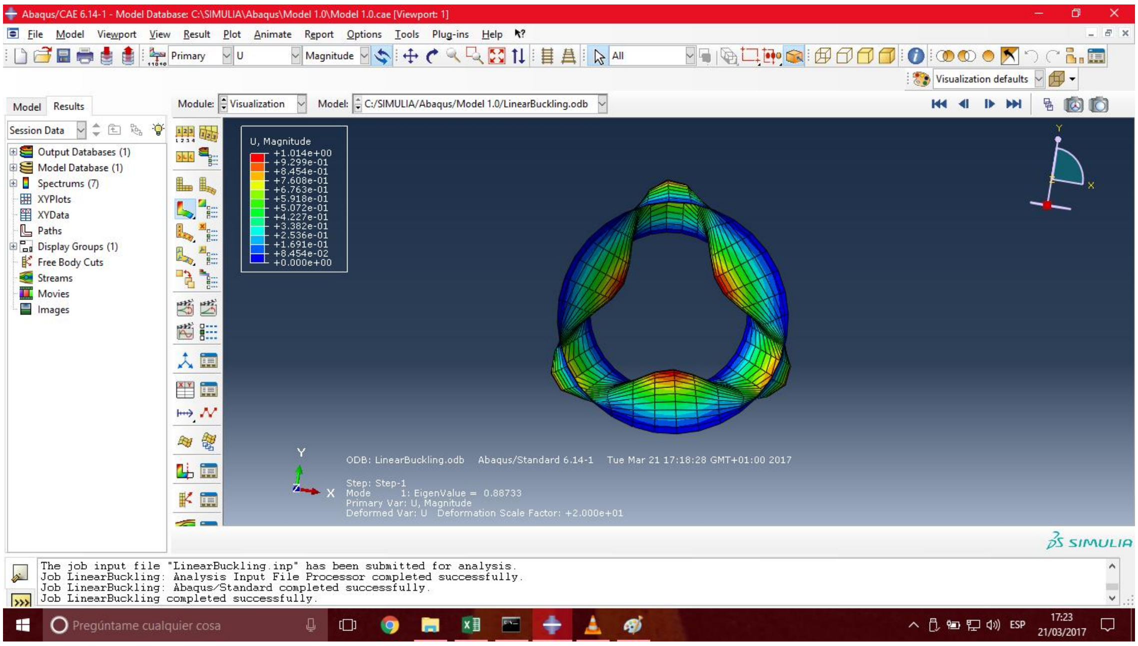


*Figure 8 Model 1.0 – Linear buckling simulation*

With that values, we get a linear critical pressure of 0.8873 MPa, but as we explained before, the linear simulation is not really accurate, due to lack of imperfections and deformations. In order to get more realistic data, we proceed with the non-linear simulation.

In this model (Model 1.0 – NonLinearBuckling in Table 1), dimensions of the tube change, making the cross section of the tube an ellipse instead of a circle. Other data remains the same. First of all, a linear simulation is tested with this model to see if it works, and we get the structure shown in Figure 9 with different scale factors.

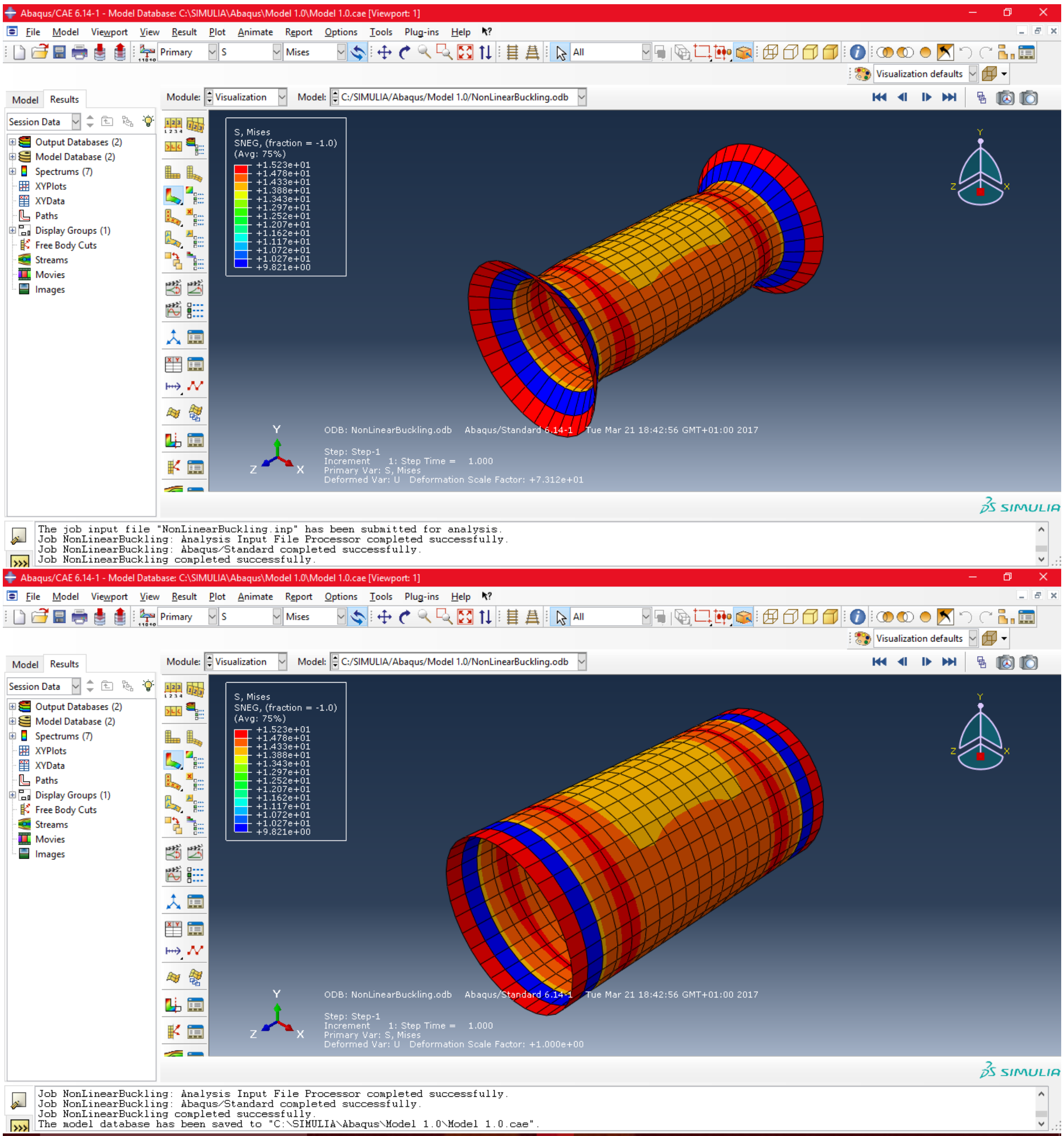


*Figure 9 Model 1.0 – Non-linear buckling simulation (linear)*

As we can see, these are not the results we are looking for, but this was only a test to see if the model works properly, so now we run the same model but with non-linear simulation. The deal with this process is that we do not obtain the results in the first try, and in some cases, even in the second try. In this process we have to increase the pressure and the consequent equivalent axial force after each test until we get the breakdown in the tube. Regarding our project, and as shown in Table 1, we increase the pressure by multiplying by two each time. The process can be seen in Figure 10 below.

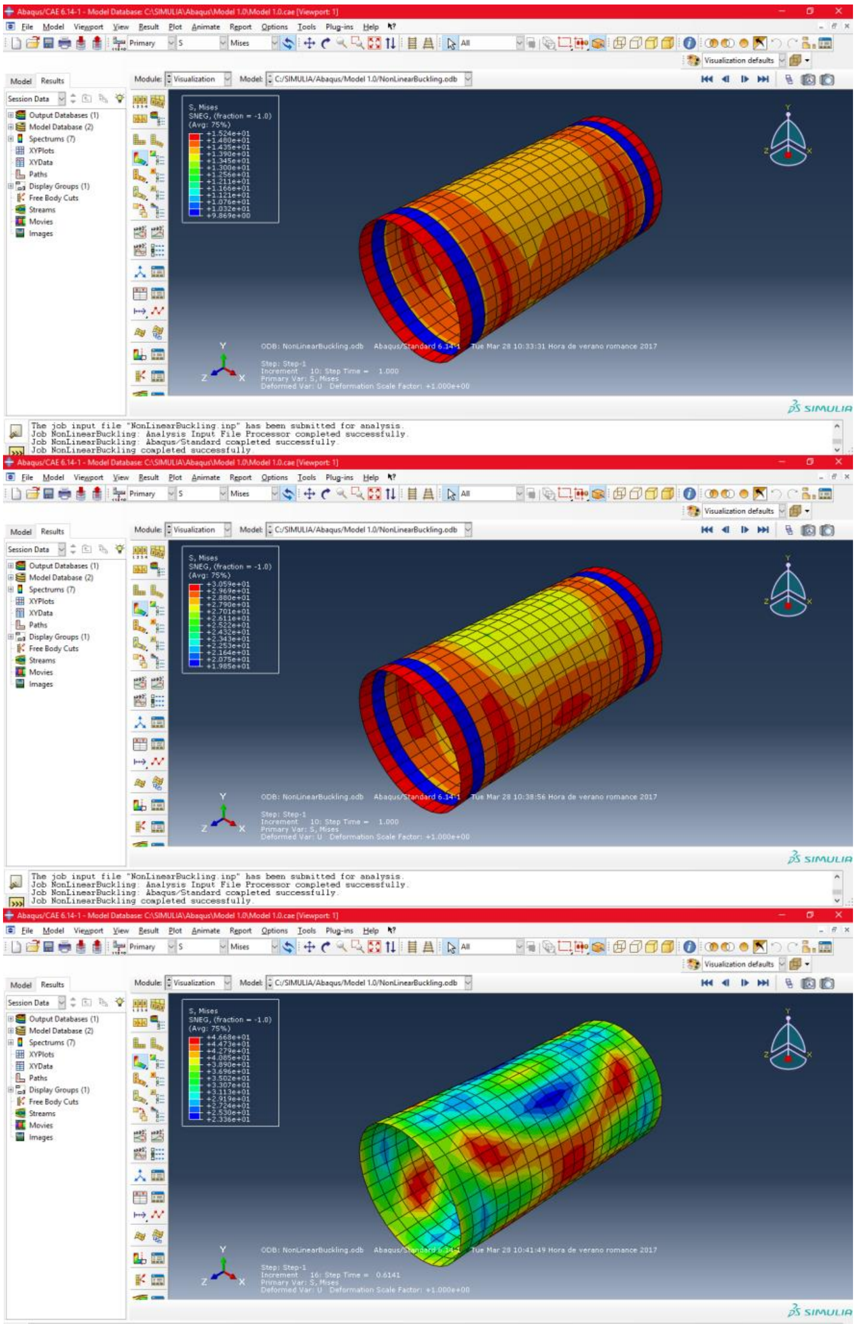

*Figure 10 Model 1.0 – Non-linear buckling simulation (process)*

As we can see now in Figure 11, the breakdown happens at the third simulation, with a pressure of 4 MPa and an equivalent axial force of 31400 N. This with the data obtain in the program (step time of 0.6141), give us a non-linear critical pressure of 2.4564 MPa. This value is higher than the linear one because of the deformation applied in the model at the beginning, this means, due to the ellipse-shape of the model, the forces needed to break the tube are higher than the necessary ones to break a perfect circle-shape tube. So, at the moment the data looks good. Figure 12 shows the displacement of one point in the middle section, in

Y-axis direction along the time. We can see there also, how at step time 0.61 approximately, the tube breaks.

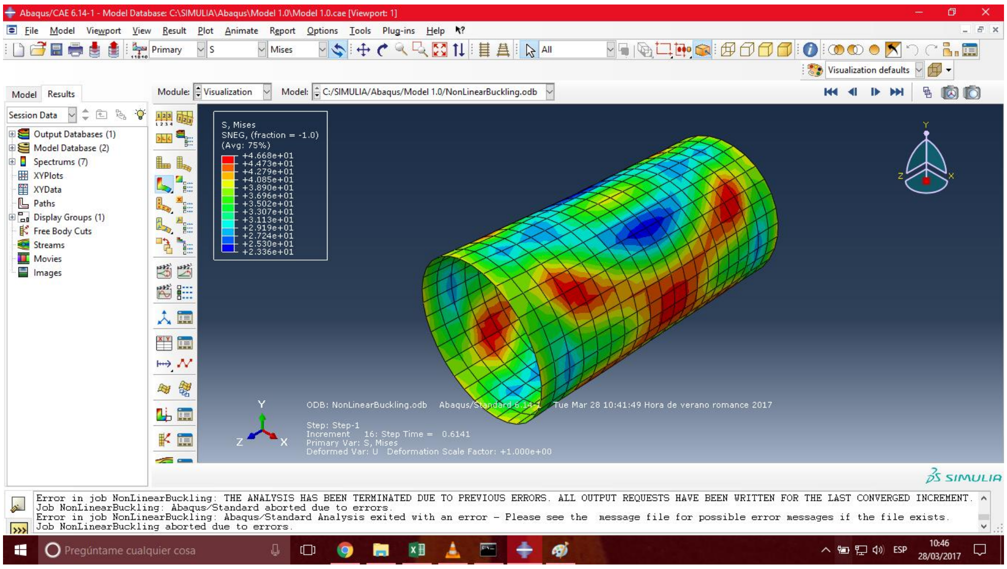


*Figure 11 Model 1.0 – Non-linear buckling simulation (result)*

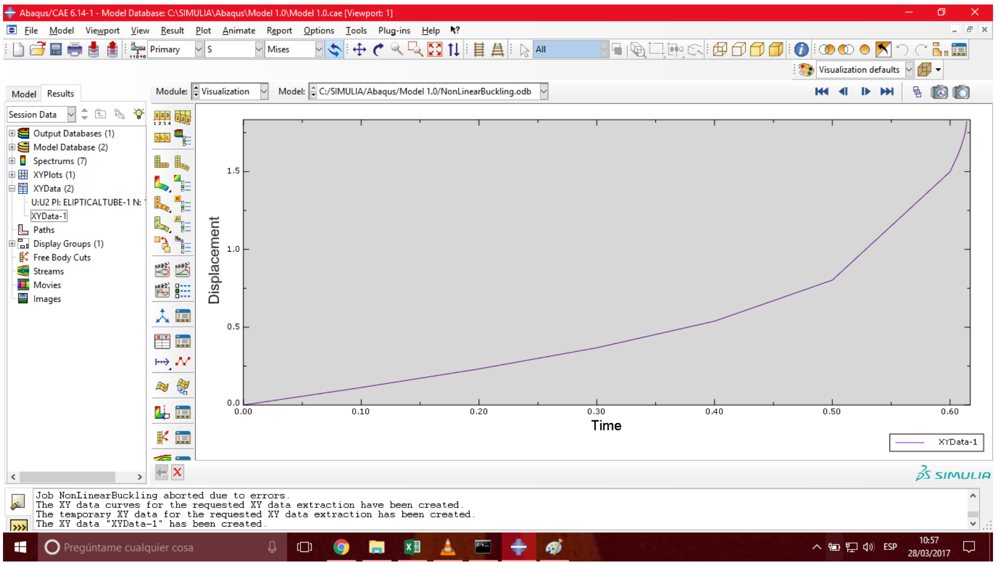


*Figure 12 Model 1.0 – Non-linear buckling simulation (displacement diagram)*

At last, we run the implicit dynamic simulation from the data and model obtained in the non-linear simulation. To get a better perspective of the behavior post-buckling here, and given the fact that we are not going to get nothing important from this part, we can increase the density of the material in this test. Figures 13, 14 and 15 show the structures obtained from this simulation. In this particular process, we can see the development of the tube along the time and as shown in Figure 15 the breakdown happens in the step time 6.151 and give us a pressure of 2.4604 MPa, pretty similar to the data obtained in the non-linear section, which is really good for this analysis.

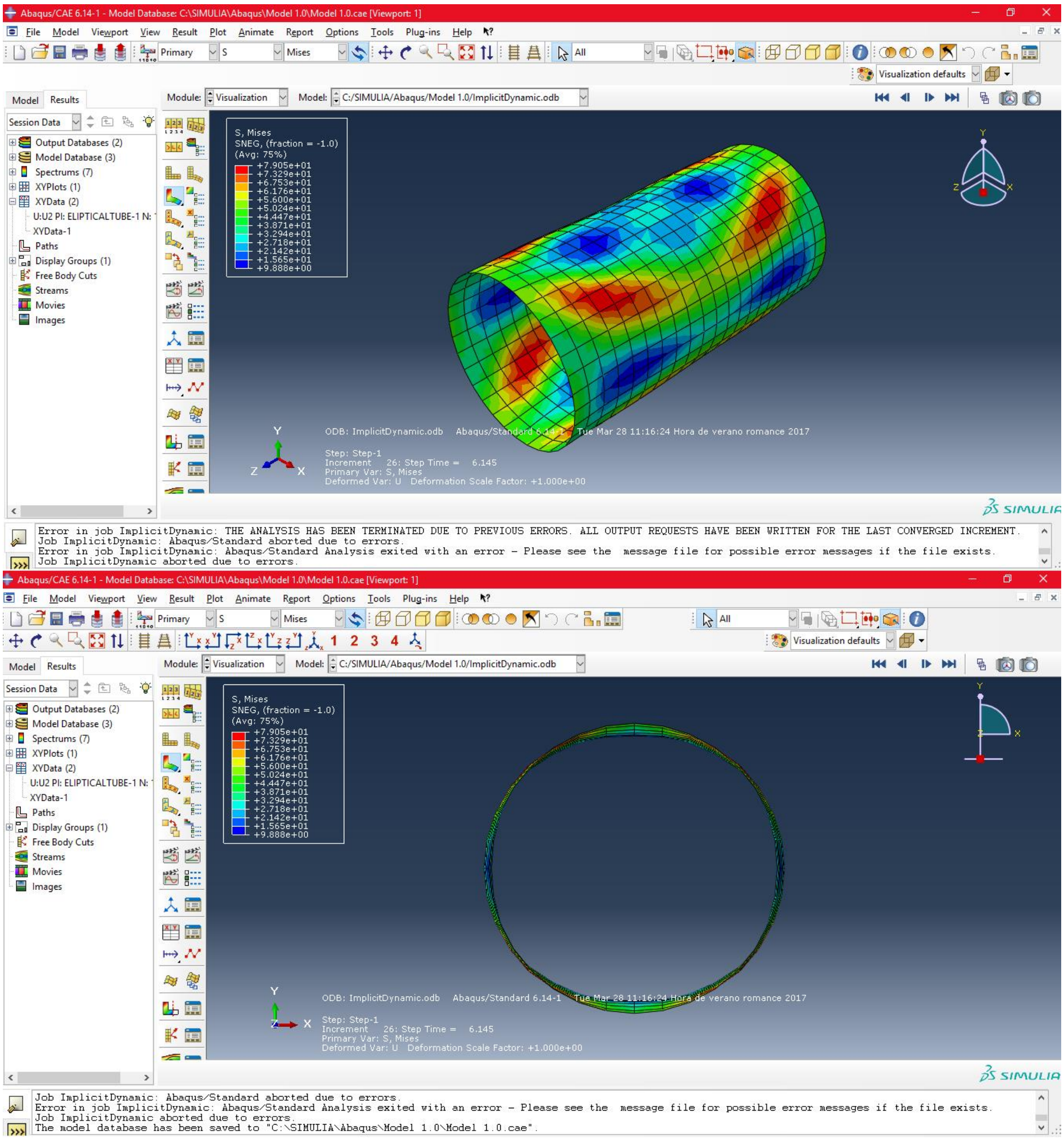


*Figure 13 Model 1.0 – Implicit dynamic simulation (before breakdown)*

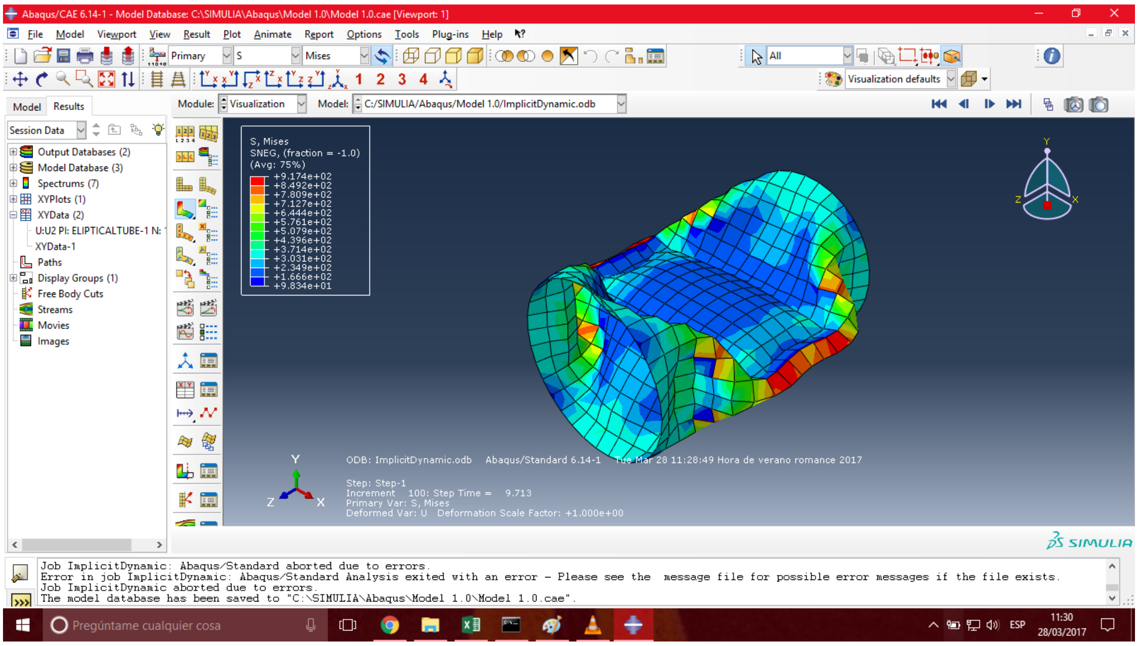


*Figure 14 Model 1.0 – Implicit dynamic simulation (after breakdown)*

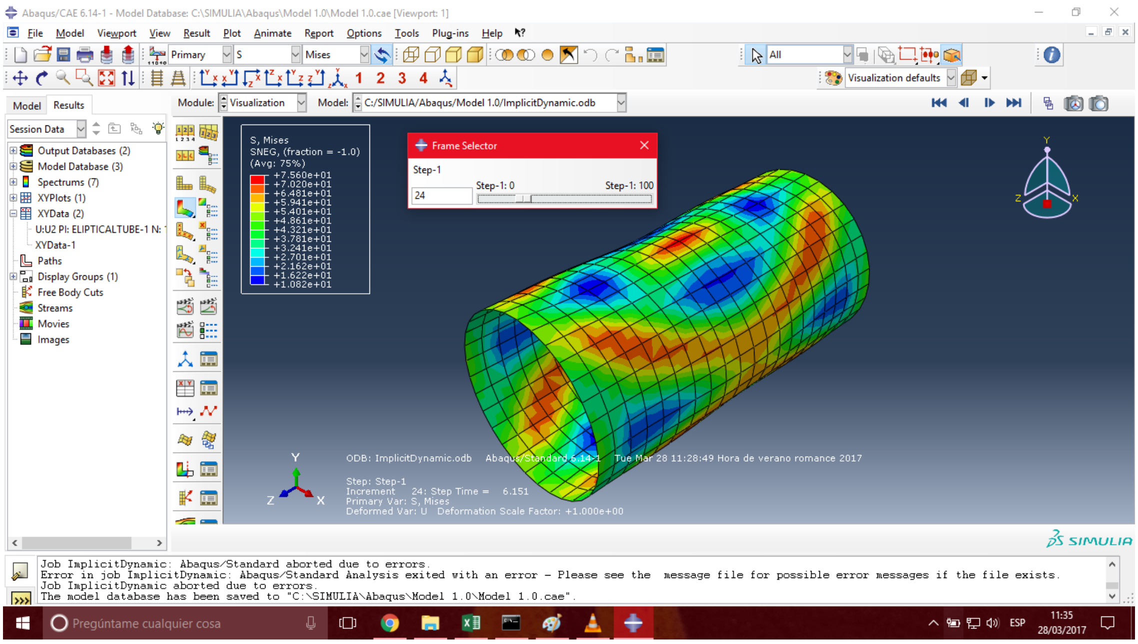


*Figure 15 Model 1.0 – Implicit dynamic simulation (breakdown step time)*

This is the whole process carried out for all the models that were analyzed with the software. Here below, Table 1 shows every model with their dimensions, external pressures and results. It is important to remember the following data is the same for every model along the analytical and numerical study: density of 1.2 g/cm3, Young module of 3000 MPa, Poisson coefficient of 0.35, 4 eigenvalues requested and 100 iterations maximum. A more informative version of the table can also be found at the section Annexes as Annex 1.

| Model - Submodel | Material | L [mm] | R [mm] | t [mm] | P [Mpa] | F [N] | Linear P [MPa] | Slopes | Step time | Non-Linear P [MPa] |
|---|---|---|---|---|---|---|---|---|---|---|
| Model 1.0 - LinearBuckling | PVC | 200 | 50 | 3 | 1 | -7850 | 0,88733 | 3 | | |
| Model 1.0 - NonLinearBuckling | PVC | 200 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | 2 | -15700 | | | | |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | 4 | -31400 | | | 0,6141 | 2,4564 |
| Model 1.0 - ImplicitDynamic | PVC | 200 | 50,1/49,9 | 3 | 4 | -31400 | | | | |
| Model 1.0 - ImplicitDynamic | PVC | 200 | 50,1/49,9 | 3 | 4 | -31400 | | | 6,151 | 2,4604 |
| Model 2.0 - LinearBuckling | PVC | 400 | 50 | 3 | 1 | -7850 | 0,51188 | 2 | | |
| Model 2.0 - NonLinearBuckling | PVC | 400 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 2.0 - NonLinearBucklingON | PVC | 400 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 2.0 - NonLinearBucklingON | PVC | 400 | 50,1/49,9 | 3 | 2 | -15700 | | | 0,2441 | 0,4882 |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | 2 | -15700 | | | | |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | 2 | -15700 | | | | |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | | | | | | |
| Model 3.0 - LinearBuckling | PVC | 100 | 50 | 3 | 1 | -7850 | 1,7505 | 4 | | |
| Model 3.0 - NonLinearBuckling | PVC | 100 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | 1 | -7850 | | | | |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | 2 | -15700 | | | | |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | 4 | -31400 | | | | |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | 8 | -62800 | | | | |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | 16 | -125600 | | | 0,6298 | 10,0768 |
| Model 3.0 - ImplicitDynamic | PVC | 100 | 50,1/49,9 | 3 | 16 | -125600 | | | 6,013 | 9,6208 |
| Model 4.0 - LinearBuckling | PVC | 200 | 25 | 3 | 1 | -7850 | 2,1625 | 2 | | |
| Model 4.0 - NonLinearBuckling | PVC | 200 | 25,1/24,9 | 3 | 1 | -7850 | | | | |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | 1 | -7850 | | | | |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | 2 | -15700 | | | | |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | 4 | -31400 | | | 0,525 | 2,1 |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | 4 | -31400 | | | | |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | 4 | -31400 | | | | |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | | | | | | |
| Model 5.0 - LinearBuckling | PVC | 200 | 100 | 3 | 1 | -7850 | 0,32729 | 5 | | |
| Model 5.0 - NonLinearBuckling | PVC | 200 | 100,1/99,9 | 3 | 1 | -7850 | | | | |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | 1 | -7850 | | | | |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | 2 | -15700 | | | | |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | 4 | -31400 | | | | |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | 8 | -62800 | | | 0,8283 | 6,6264 |
| Model 5.0 - ImplicitDynamic | PVC | 200 | 100,1/99,9 | 3 | 8 | -62800 | | | 8,909 | 7,1272 |

*Table 1 Analytical and numerical results*

Comments regarding these information will be done in following sections. However, obtained critical pressures are essential to see how much pressure we can apply to experimental tubes in the laboratory without breaking them with the OBR fiber attached, and what models can we test due to limitations of the equipment. Taking a look at the table, we can see that the highest value is 10.0768 MPa (100 bar approximately), which it is high enough to assure safety of the structure and the equipment in the experimental work. It is not the same case for model 2, which have a critical pressure of 0.4882 MPa, forcing us to be really careful at testing this tube.

One appointment to make, and commented also in analysis of results section, is that critical pressure values are indirectly proportional to the ratio between length and radius of the tube tested, as can be confirmed in Table 1.

## 3.4. Experimental study

In the experimental work is where the main focus of the thesis will be allocated, which is to see how good optical fibers can be used as a health monitoring system or test data acquisition system utilizing Rayleigh OBR. This means that in the next paragraphs, a description of the whole process that allows us to measure strains profiles in the tubes, thanks to the OBR technology, will be explained thoroughly. This process consists of several steps that have to be continuously repeated in a cycle until we get the best measures. Iterations contain four main steps: preparation of the fiber, attachment of the fiber to the tube, deformation of the tube and measurement of the strain profiles.

But before doing nothing, a risk assessment of experimental activities should be performed. In this one, possible safety issues are exposed due to the activities that have to be done in the laboratory related to the thesis, analyzing the level of danger to the people in the environment regarding probability and intensity. Also, safety measures and regulations are imposed by the student itself in order to avoid these problems. In this case, given the fact that the experimental work does not require the control of heavy equipment and materials, dangers and issues are not a big deal. However, the risk assessment was done, and the main document is shown at the end of the thesis in the section Annexes as Annex 2.

### 3.4.1. Preparing the optical fiber

Once safety regulations are in order, the real experimental work should start. At the beginning, the optical fiber needs some preparation and splicing steps in order to get ready and attach it to the tube. In this part, we will see every equipment needed to do that and the steps required.

First of all, equipment and stuff needed for this splicing process should be named, as shown in Figure 16.


*Figure 16 Equipment used for optical fiber splicing*

- Supports.
- Fiber pressure weights.
- Fitel S325 fiber cleaver.
- Fiber stripper.
- Fitel S178 fiber splicer.
- Splice protection tubes.
- Cleaning spray.
- Lint free cloths.
- PTFE sheets.
- Cyanoacrylate adhesive.
- Tape.
- Lighter.

Pigtails, measurement fiber and protective coated fiber is also needed for the experimental work. The optical fiber used is the one showed in Figure 4, and the rest of the materials are supplied by the laboratory. Now, the whole splicing process is explained:

- Clean the table or surface where the process is going to take place. The fiber is very sensitive and the minimum dirt particle or defect in the surface can damage the fiber or affect the measurement.

- Cut one long enough piece of measurement fiber from the roll showed in Figure 4, between 1.5 and 2 meter should be enough. Be careful with the fiber, its small thickness could make it difficult to see while working and you could lose it or break it in the process.

- Pick one of the pigtails with long enough protective coated fiber. Try to take a look in case that there are damages to the fiber.

- Place one of the splice tubes over the protective coated fiber before doing anything. This is a really important steps and easily forgettable. If you forget this and splice the fibers, it could be really difficult to insert the splice tube later, making us, in the worst case, to start the process again.

- Pick the optical fiber and, with the lighter, burn lightly fast two centimeters approximately of the tip of the fiber. Then use a piece of lint free cloth with a small quantity of cleaning spray, to softly clean the burnt part of the measurement fiber. Try it between three and five times until the burnt layer has disappeared and you hear a squeaking sound, indicating that is ready. If removing the burnt part results kind of difficult, you may have burnt it with more intensity than required, so just cut the burnt part, and repeat this step until you get used to it.

- Regarding the protective coated fiber, the preparation is similar to the one explained for the optical one. In this case, instead of burn the two centimeters, you have to use the fiber stripper to remove two centimeters of protective coat of the tip of the fiber. Then, just clean it in the same way as the step before.

- Using now Fitel S325 fiber cleaver, we cut just a small portion of the cleaned tips of each fiber, between 5 and 8 mm approximately. The device has several slots where you can place the fiber according to the thickness, so make sure to place correctly each one of them. Also make sure to give a clean and perpendicular cut in both fibers.

- Place the fibers inside the Fitel S178 fiber splicer device. Just open the tape and place each one of the fibers in their right place according to their thickness. Be careful with two things: the whole fiber inside the device has to be in the slots, so make sure that at the moment that you close the tape, it does not cut or hit the fiber, use the magnetic tapes to help you; and the tip of the fibers has to be placed quite carefully between the "V" shape supports and the two opposing needles. If you close the tape now, you can see in the screen of the device the aspect of the tips after the preparation. They should look like in Figure 17 below. You can use this advantage in previous steps to make sure the quality of the cut before going on with the process.


*Figure 17 Quality control of fiber tips in Fitel S178 fiber splicer device*

Now, press the green button and the device will start to line up the fibers and to splice them. If the quality or the angle of the cut is not appropriate, the device will tell you before the splicing step. It is advisable to retire the fiber and cut it again. If there is no problem, the device will splice them and you will get a result similar to the one shown in Figure 18.


*Figure 18 Spliced fibers in Fitel S178 fiber splicer device*

It is the turn of the splice tube that we insert before. Open the tape, and apply a slight tension while opening the magnetics tapes, given the fact that they move when opened, so we need to avoid possible fractures. Slid the splice tube over the union of the fibers and place the set in the heating chamber. The process will start the moment you shut the cover.

When finished, open the cover, retire the set, and softly blow on the splice tube until it turns out opaque. Then you can check for errors and imperfections with the help of the OBR equipment.

The fiber is now ready for the experimental study.

### 3.4.2. OBR v3.10.1 Luna Technologies Software

It is necessary also to explain how the software and hardware works, before going into the measures. The hardware is really easy. Just plug the pigtail of the fiber into the OBR device, once you have cleaned it to avoid obstacles when the lasers goes through the fiber at the moment of measure. The software instead, needs a little bit more of explanation. First of all, we need a reference to compare signals between before and during pressure application. This reference must be taken twice, and without any pressure applied to the tube. We take two measures of the reference just in case one of them does not work properly, so we can avoid just to repeat whole process and to waste time. The signal should be something very similar to the one shown in Figure 19. Then we must upload the reference file to the program so we can continue with the test.


*Figure 19 Reference signal from tube through OBR technique*

Once it is uploaded to the program, it is now a matter of where and how much pressure is going to be applied. During the deformation, we just need to take another measure with the software, but this time, we will compare this signal with the reference, and obtain a profile of strains derived from that comparison, shown in Figure 20.

The signal has two positive and two negatives waves, representing the parts of the tube which are in compression and which ones are in tension, given the case that the external pressure is applied in two opposite sides of the section of the tube with bar clamps. This is the best way to identify the effectiveness of the OBR technique in a simple method. The software also give the possibility to obtain another profiles such as temperature. It also allow us to manipulate some parameters of the measurement in order to get a good view of the signal. These parameters are the sensing range (m), gage length (cm) and sensor spacing (cm), which are represented in Figure 1, and can be modified in the left part of the software as seen in Figure 20.


*Figure 20 Strain profile signal from tube through OBR technique*

The software also allows to keep data information about the values obtained in the signal. In this case, the most important values are the values of strain obtained in each measure according to each one of the points measured. This data is collected through the whole experimental study, commented in the section about analysis of results, and showed in the Annexes.

### 3.4.3. Experimental study with polypropylene tubes

Idea now is to try different ways of adhering the optical fiber to a tube made of polypropylene, 300 mm length, 110 mm diameter and 3.4 mm thickness. The one used for the experiments with this material is shown in Figure 21, where we can make sure of the measures and the material that it is made of.


*Figure 21 Polypropylene tube used in experimental study*

First thing to do is to try if the optical fiber work in the way we want, this means, when applying pressure to the tube, changes in the strain profile appears in the program. So, to make it easier, we just attached the fiber over the outside surface of the tube. This problem with the difficulty of the attachment to the inside surface will be commented later in this section. Regarding ways of adhesion, also a problem to be commented later on, we started with the cyanoacrylate adhesive shown in Figure 16 in the previous part. It is a very quick adhesive, it takes almost 10 seconds to dry, so it need to be manipulated with precaution. In order to avoid accidents, just have close to you PTFE sheets, also shown in Figure 16. This first try, and its results, can be seen in Figures 22 and 23.

*Figure 22 First adhesion done with cyanoacrylate adhesive*

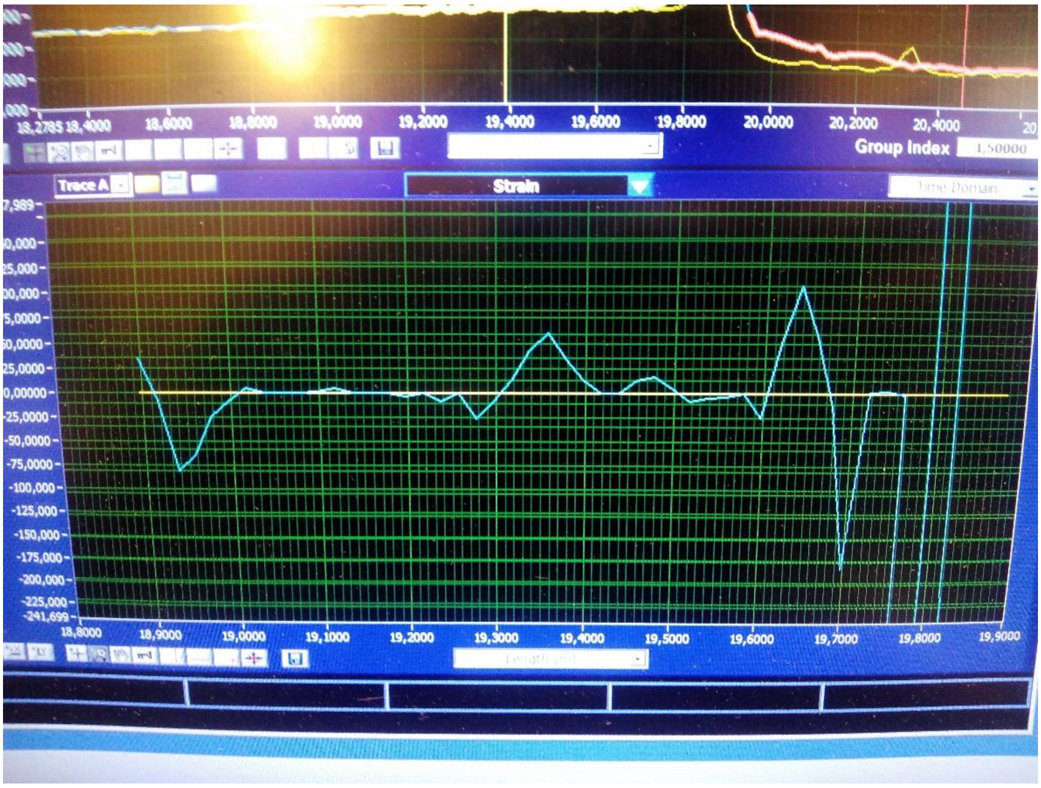


*Figure 23 Results of the first adhesion with cyanoacrylate adhesive*

Regardless the fact that the signal is everything but a sine wave, as it is expected to be later in a deeper study, and as commented at the beginning of the paper, we can see a proper signal caused by the deformation due to external pressure on the tube and measured by the optical fiber through the OBR equipment and software. So with that in mind, we can start now with the main experiments.

At the first moment, we have two main problems to face in this study. The first one is what kind of adhesive is going to be used to stick the fiber to the inside surface of the tube. Taking a look through the laboratory, different kind of tapes and adhesives were found. The thing here is that, at the beginning, the efficiency of the tapes was not quite trustworthy and this is the reason: Rayleigh OBR is a technique really sensitive, so we want the optical fiber to stick as much as possible to the surface to detected minimum changes in the structure under external pressures. For this reason, it is obvious that the cyanoacrylate adhesive were the first thought resource to meet this goal, so we have it this way.

The other main point to face, is how it could be possible to place the fiber inside the tube and stick it in a way that it would be positioned as close as possible to the center of the tube, regarding length, and as concentric as possible to the section of the tube. This is only a problem of this particular experimental study, I mean, in real cases, tubes would be much bigger and there would be no problem placing the fiber, but here, the diameter of the experimental tube just allows to get one hand inside, with quite difficult control operations.

*Figure 24 Industrial tape used*

So, for the first try, cyanoacrylate adhesive shown in Figure 16, and industrial tape shown in Figure 24, just for reinforcement, were used. For the placement of the fiber, a piece of paper which height was half of the tube's length, and which length was enough to make one roll inside the tube, was cut so we could have a reference where easily place the measurement fiber. Some pieces of tape are set over the fiber just to fix it, making easier to attach it after with the adhesive to the surface. More industrial tape help to reinforce the whole set up, which can be seen in Figure 25.

*Figure 25 First set up of the experimental study with PP tubes*

Then, pressure was applied with bar clamps form the laboratory in two opposite sides of the tube, at middle height. With this way of applying the pressure we can easily figure out which parts are deformed by compression or tension, and compare it to the signals in the OBR software. Now, following the procedures explained before, we measure the deformations and get the signal shown in Figure 26 below.


*Figure 26 Signal from the first set up of the experimental study with PP tubes*

The result is nothing similar to a sine wave showed in Figure 20 that it is supposed to be. So, an analysis of the signal is done in order to know what is happening. To start, we should know that with a diameter of 110 mm, the length of the fiber that should be important is about 346 mm approximately, depending on how you have placed the fiber inside the tube. Given the fact that the fiber ends at 19.80 m according to Figure 26 (significant shift reached at this point in the superior signal), the waves should start between 19.30 and 19.50 m (maybe the end of the fiber is overlapping with the rest of itself when turning a whole circle inside the tube). In this case we can see that, apart from having small waves before that point, we also have more waves than it is supposed to. After some thoughts, the most probable reason that could explain this bad result is the method used to stick the optical fiber. It is true that the cyanoacrylate adhesive can work properly in lots of cases, but not in this one in which we have almost none space to maneuver the fiber and the adhesive at the same time. Apart from that, its properties were not the best ones because we discover that it is a bit brittle, especially in this case where the deformations are big enough, making the fiber to detect these fractures and avoiding the important information we want.

So, now we forget about the cyanoacrylate adhesive and focus only in the tape. By sticking the fiber with adhesive before, we need to retire it and replace it for another new one. However, we also try to solve the problem of the few space we have to manipulate inside the tube by using a small piece of paper where we can attach the fiber to, then form a kind of ring and place it inside the tube. This method also allows us to retire the set up with the fiber totally intact and change it to another tube or for another fiber, which make a decrease in the time needed for the experiment. The whole set up is now shown in Figure 27.

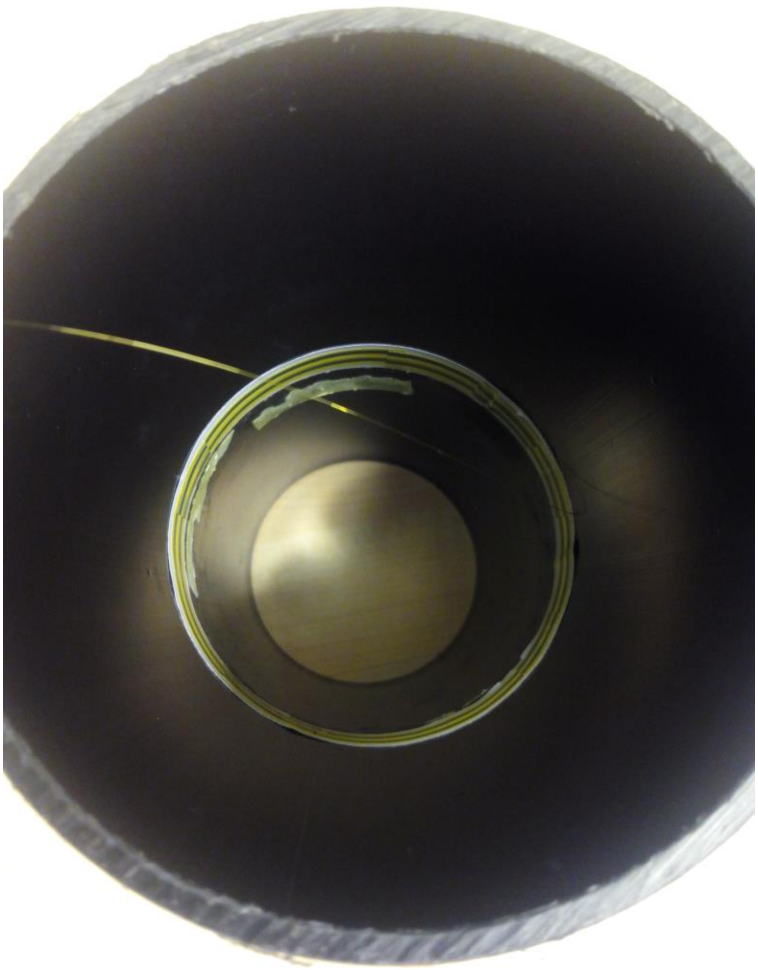

*Figure 27 Second set up of the experimental study with PP tubes*

Applying pressure in the same way as before we get the signals form Figure 28.


*Figure 28 Signals from the second set up of the experimental study with PP tubes*

In this case we can better see now the sine nature of the deformation signal, with two positives and two negatives waves, although they are not as symmetrical as it should be. However, there are two different signals because, once we noticed that the shape was getting better, we decided to apply external pressure with the clamps at two different positions. If you imagine the section of the tube as a circle, the first signal correspond to external pressure applied on one point and the second signal correspond to external pressure applied on another point that is placed 90 degrees from the previous one. It makes senses because where we have tension in one signal (positive waves), we have compression in the second one (negative waves). However, this description of the points of pressure will be deeper explained later. It is also important to say that the last wave of each signal seems to be cut, they are not completely represented. This will be commented later with the PVC tubes.

It almost seems like we have a winner for this thesis, but after other measures, failures started to appear in the signals. Additional waves like in signals from the first set up, Figure 26, are examples of this failures. Sometimes, there was not even changes in the strain profile in some points through the optical fiber. It was easy to realize that the problem was due to the constant retirement and placement and deformation process of the paper ring with the fiber attached. The paper at the beginning could properly follow even the minimum deformation of the inner side of the tube, but after a few more tests, the shape of the paper would weaken, losing the ability to properly adapt to the surface. So, another way to place the fiber should be thought.

### 3.4.4. Experimental study with polyvinyl chloride rings

Due to several test already performed in the PP tube, it was thought that it would be time to change the tube, and even use another material for itself. At the beginning of the project the most sounded material was the PVC so, two tubes of this material, 2000 mm length, were bought and brought to the laboratory. Their diameter and thickness are 110 and 3.2 mm respectively, as shown in Figure 29.


*Figure 29 Polyvinyl chloride tubes used in experimental study*

At first time, they were thought to be cut in pieces of same length as the PP tubes used before, but, instead of doing that, we decided to cut pieces of 30 mm height each one, kind of rings shown in Figure 30, in order to avoid already known space maneuver problems at the beginning. However, pieces of 300 mm were cut too, for later tests.

For the first set up, regular tape, shown in Figure 31, was used, just to see the possibilities of other adhesives. Additionally to the ease of place now the tape with the fiber inside the ring, the transparency of the regular tape allows you to place the fiber completely straight in the middle along the tape, and consequently, along the inner side of the ring. You can see the set up also in Figure 30 below.

*Figure 30 First set up in a PVC ring for experimental study*

*Figure 31 Regular tape used*

As we have mentioned before, it would be useful to have a system to identify each signal regarding where the pressure has been applied. In order to do that, the following figures, will determine the different positions of the pressure and the nomenclature they will have from now on. Figures 32 and 33, represents the points of application at 0 and 90 degrees, 180 and 270 degrees respectively, regarding the fixed black part of the bar clamp. The point of reference in the ring is located at 225 degrees, where the optical fiber enters in the ring.

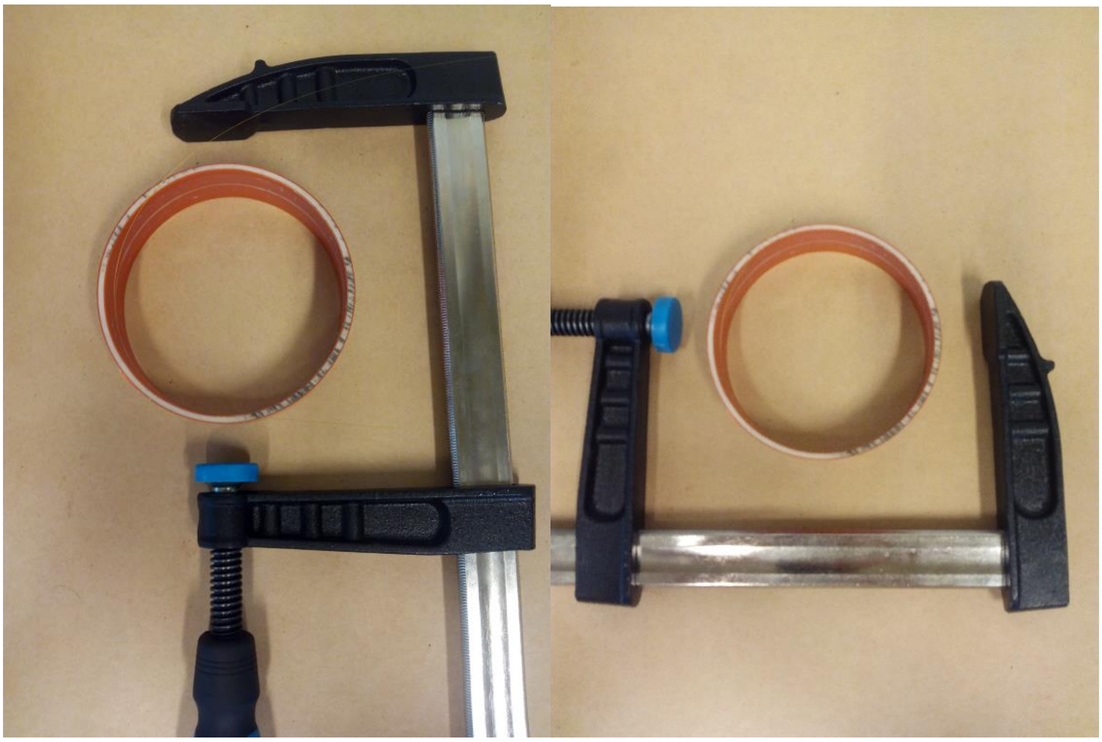

*Figure 32 Pressure point at 0 and 90 degrees*

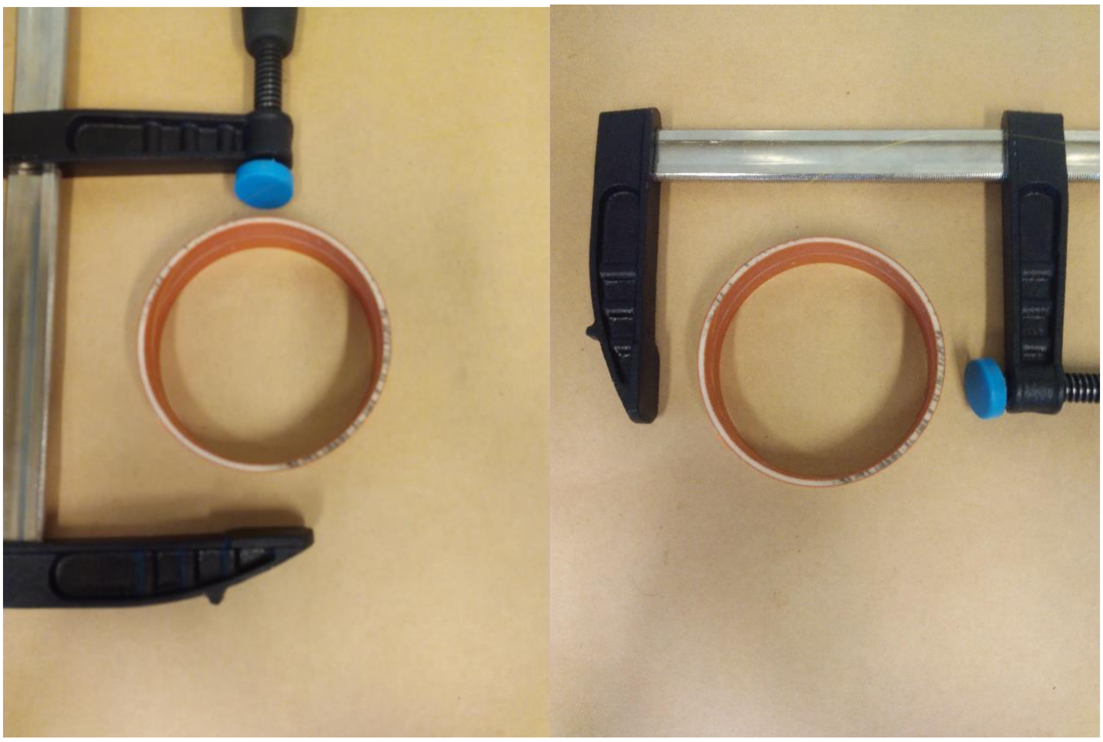

*Figure 33 Pressure point at 180 and 270 degrees*

With this method, the measures should appear in the following order. At points 0 and 180 degrees, the fiber enters the ring and find a compression region, followed by a tension one, then compression and finally, tension again, reaching after the end fiber. This means that in the signal obtained from these points, a negative wave should appear at the beginning, followed by a positive one, then a negative and finally, positive again. The opposite case happens with measures at points 90 and 270 degrees. From now on, this system will be the reference for the rest of the measures and data collected.

Given the fact that the pressure is applied in both opposite sides of the tubes thanks to the bar clamp used, it seems useless and repetitive to take measures at 0 and 180 degrees because they would be similar. The same would happen with 90 and 270 degrees. But, apart from the fact that is really good in this case to have the most quantity of numerical data, the clamp used in this experiment has an inconvenient. Although it will allow to apply pressure in opposite sides of the tube, the two parts of the tool that are in contact with the tube are quite different. While the fixed part is completely flat and does not give problems, the other part is not as flat as the first one, neither it is fixed, it is a moving part thought to be adapted to the surface that it is making contact with. In our case, we are dealing with a circular surface, this means, that the pressure vector created by this part is probable to not be normal to the surface, neither parallel to the pressure vector originated by the fixed part of the clamp. This problem will follow until the end of the experimental study, just making slight differences in the waves of the sine signal that is supposed to be symmetrical. Figure 34 shows this kind of problem.

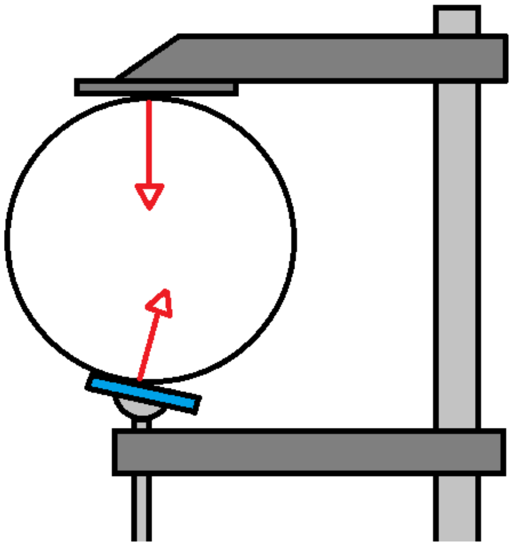

*Figure 34 Pressure application problem*

However, for the main focus of this project, this obstacle is not big enough to deal with before collecting the data. So, with that in mine, we proceed to measure deformation in the set up explained before. The results are the following ones.


*Figure 35 Signals from the first set up of the experimental study with PVC ring at 0 and 90 degrees*

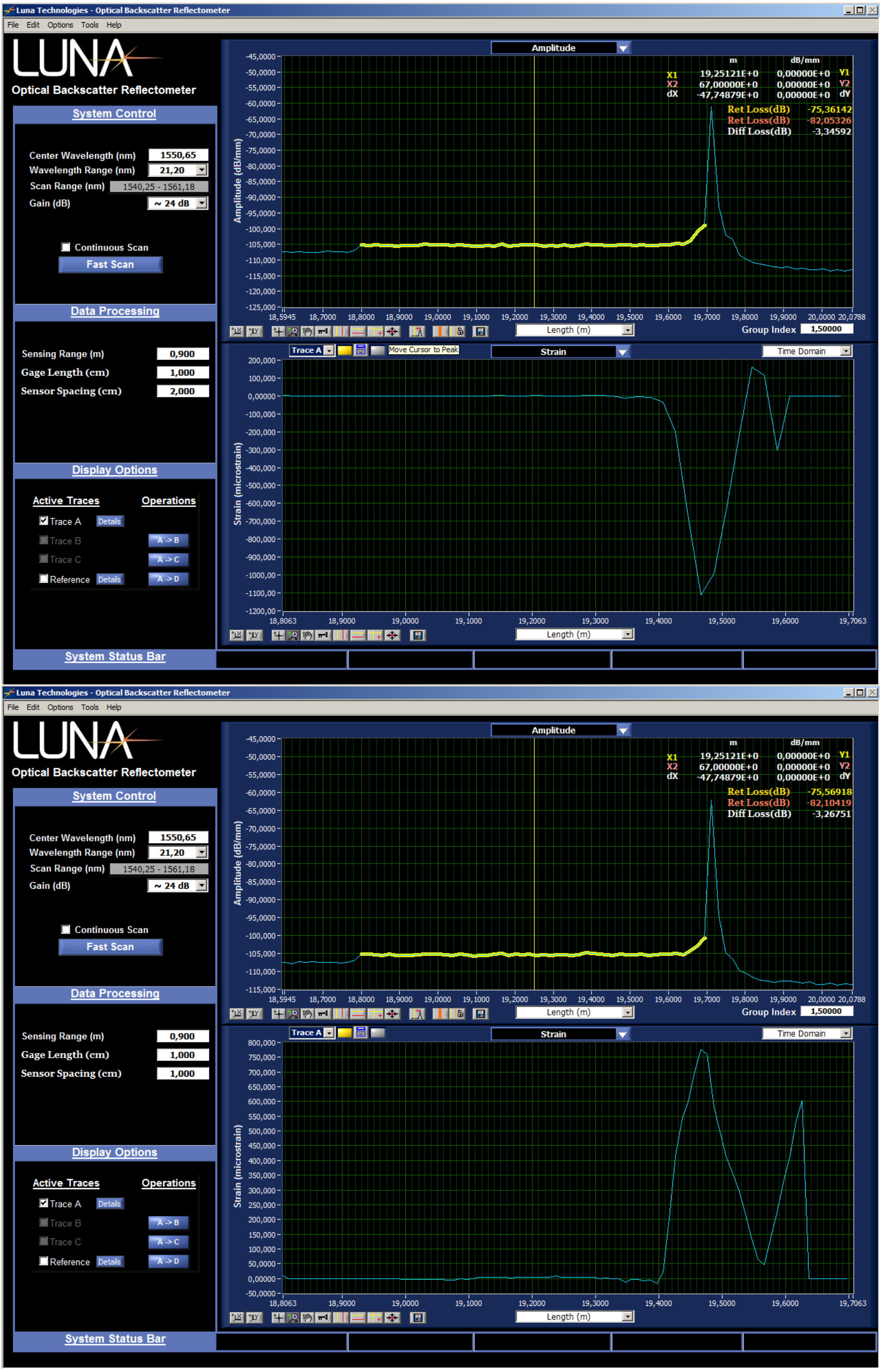


*Figure 36 Signals from the first set up of the experimental study with PVC ring at 180 and 270 degrees*

Even in this new set up, we almost keep with the sine signals, and according to the system explained before, measures at 0 and 180 degrees start with compression (negative waves) while measures at 90 and 270 degrees start with tension (positive waves). But, an almost new problem appears again. Remember the section measuring deformations in PP tubes, in which the last wave in each signal, looked incomplete. In this case, we have reached a point where the last wave is not represented at all, increasing the difficulty of analyzing these results. Getting deeper in this problem, we find out that the optical fiber, with the OBR technique, has a little inconvenient, that is, the measures at the last region of the fiber (between the last 50 and 100 mm of the fiber end) are not registered by the software, and is where the extremely high peak of the superior signal in the screen appears, indicating the end of the measurement fiber. So, the basic solution is, at the time of placing the tape and the fiber inside the ring or tube, a piece of fiber end should have left without attaching it to the surface in order to get a complete strain profile. Figure 37 shows the new set up, mandatory for the rest of experiments. As you can see from the picture, a piece of fiber end (we decided that it should be 100 mm approximately to be sure) has left without attachment.

*Figure 37 New optical fiber set up*

Having prepared the new set up, we proceed to take the measures, getting the results from Figures 38 and 39.

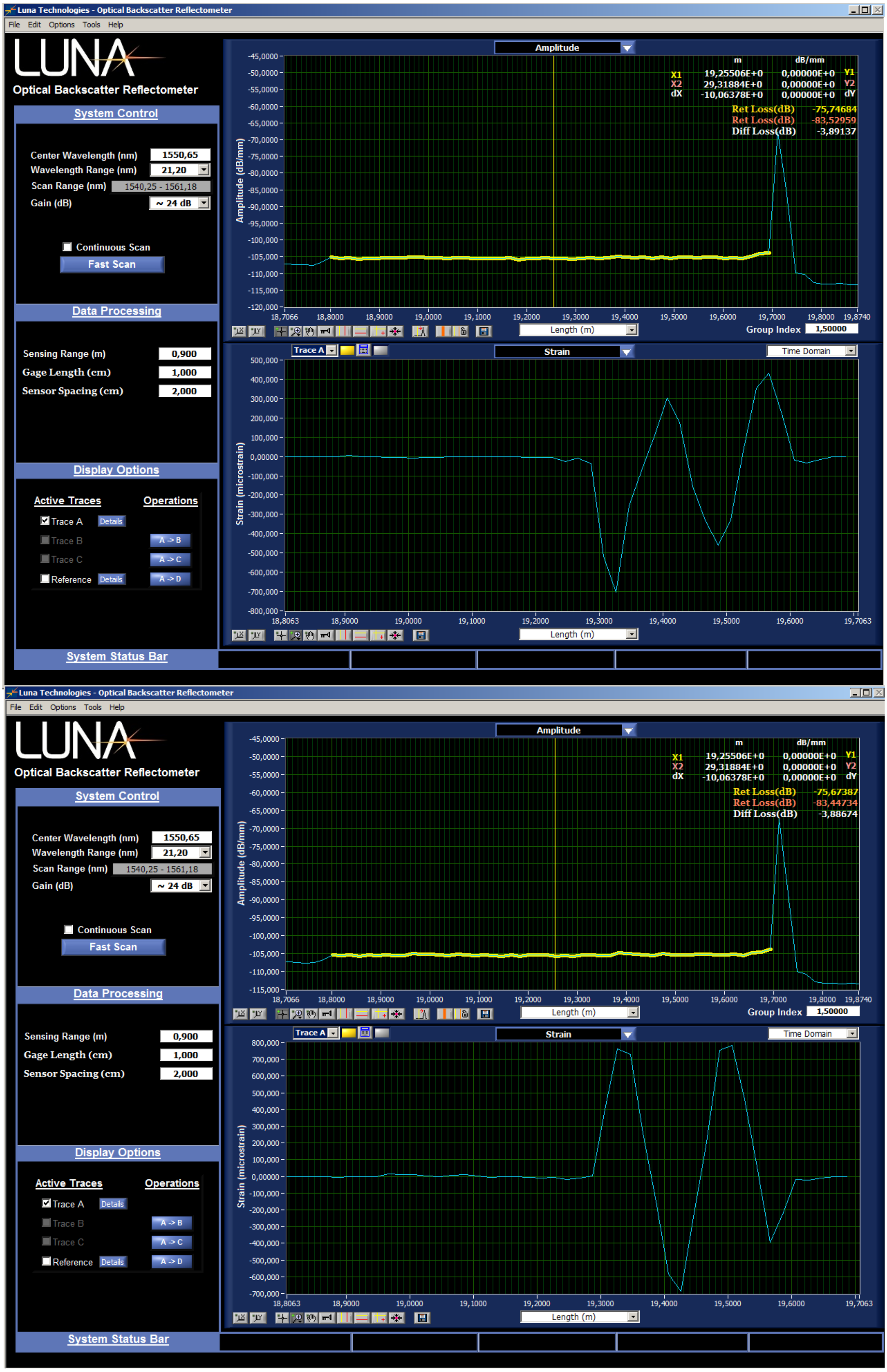


*Figure 38 Signals from the second set up of the experimental study with PVC ring at 0 and 90 degrees*

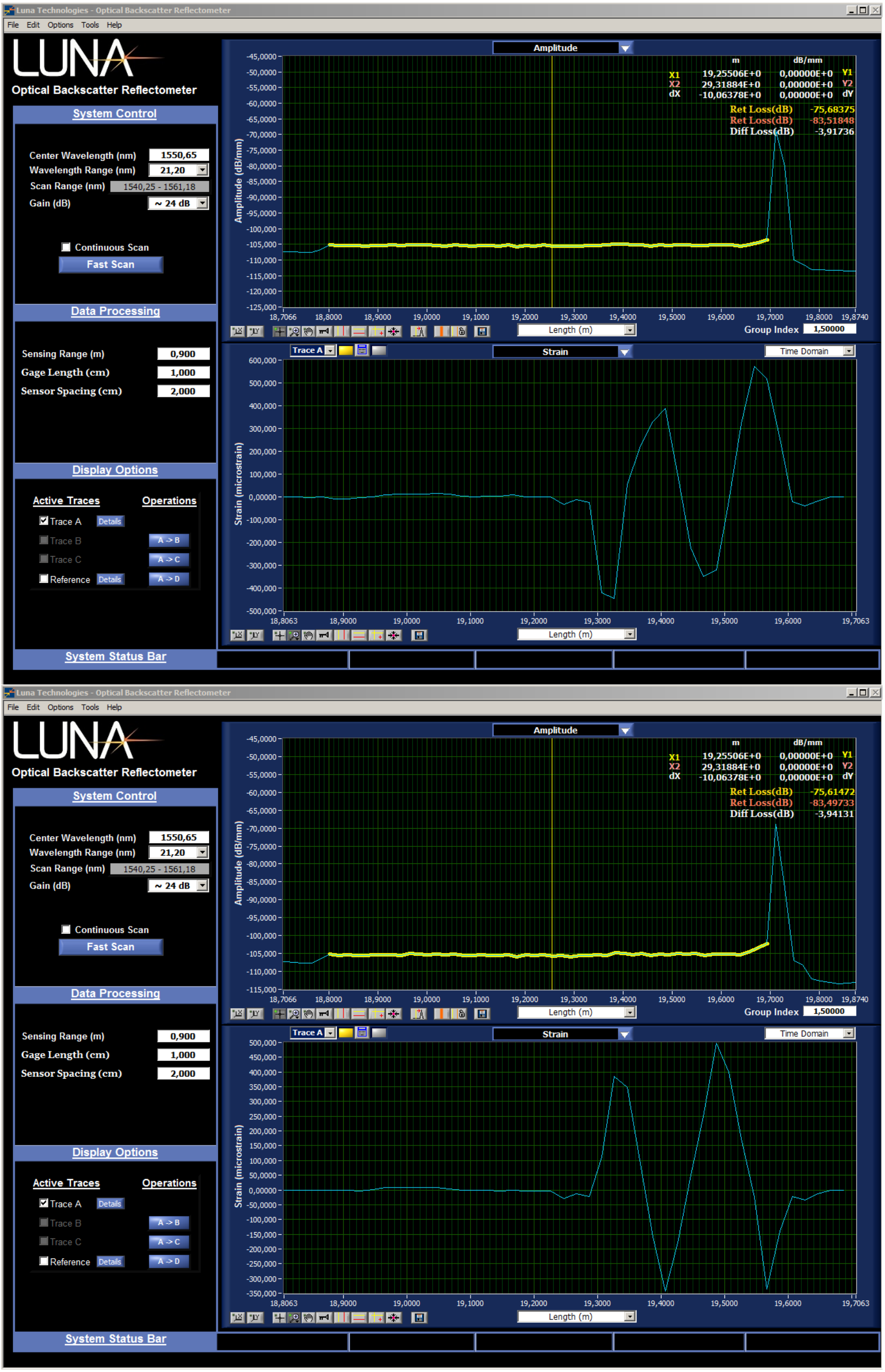


*Figure 39 Signals from the second set up of the experimental study with PVC ring at 180 and 270 degrees*

Finally we get to obtain a complete sine signal of the deformation due to the external pressure applied and according to the system explained before. If there is something more to improve, it would be try other methods of attachment, just to reach similarity between the waves. In order to get to that goal, we try now with another kind of industrial tape, the one shown in Figure 40.


*Figure 40 Industrial tape with transverse reinforcements used*

This new tape has transverse reinforcements that could be expected to improve efficiency in most of the real cases where it can be implemented, but for this experiment, it is expected two things. The first one, is to stick better to the surface and get more similar signals, which is really an improvement. The second one, is to deform the signal due to the transverse reinforcements. However, it worth to try.

*Figure 41 Third set up in a PVC ring for experimental study*

The new set up can be seen in Figure 41, and the results of the measurement process, in Figures 42 and 43.

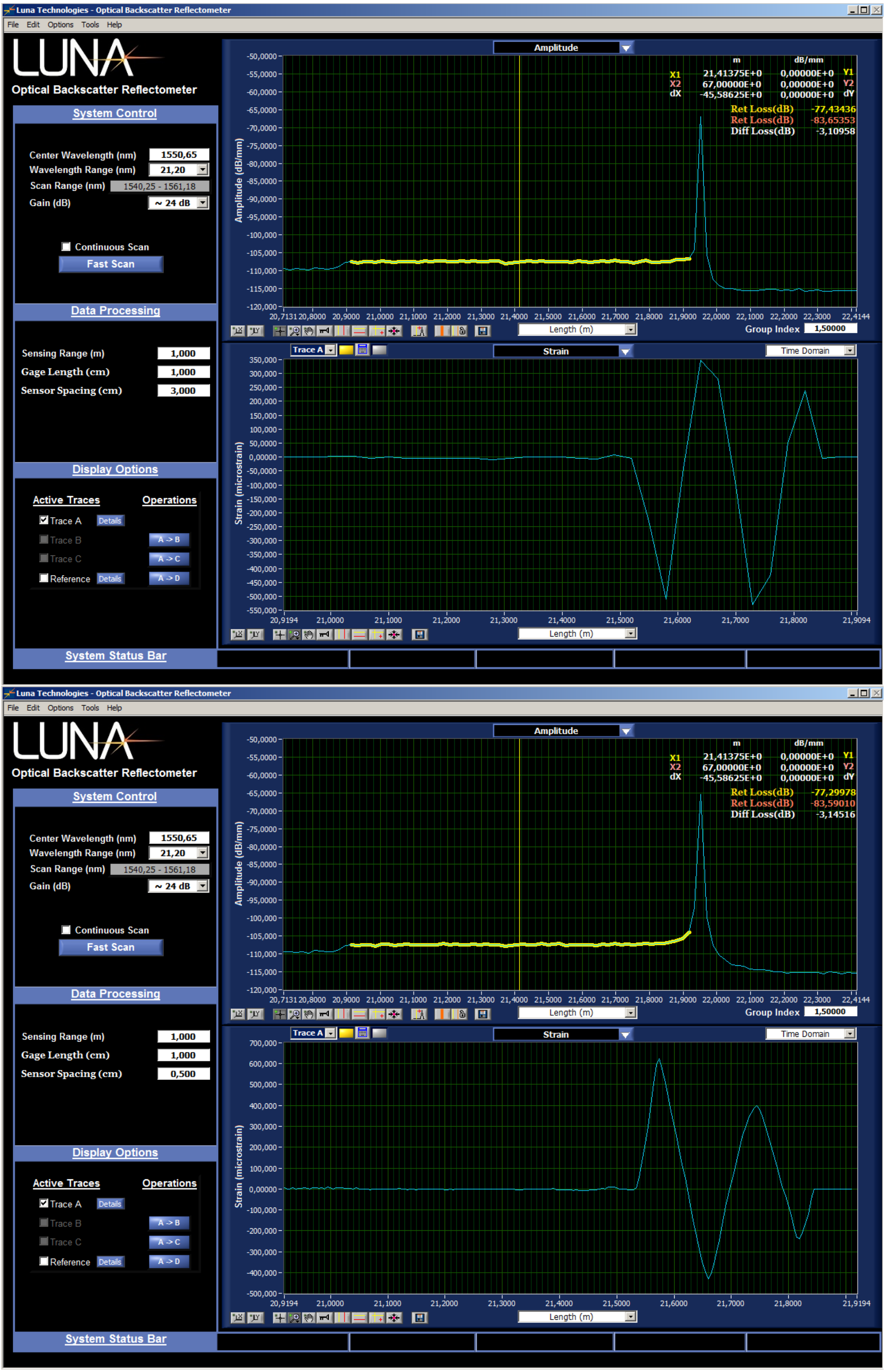


*Figure 42 Signals from the third set up of the experimental study with PVC ring at 0 and 90 degrees*

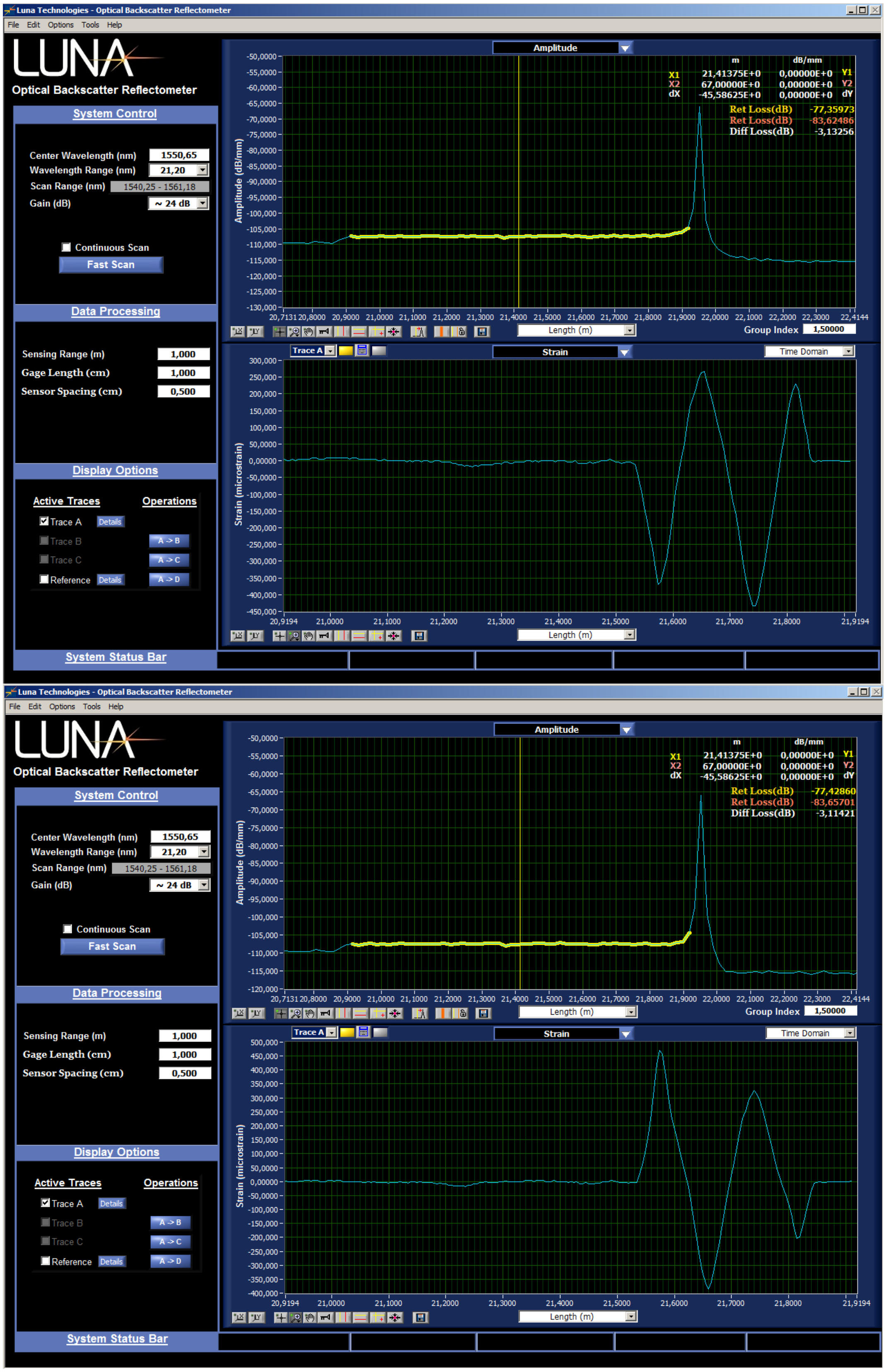


*Figure 43 Signals from the third set up of the experimental study with PVC ring at 180 and 270 degrees*

Comparing results with the second set up, we can say that the signals at points 0 and 180 degrees improve while signals at points 90 and 270 degrees get worse. This is something more or less expected due to the advantages and disadvantages commented before regarding transversal reinforcements of the tape. However, these are good results too.

In order to start getting more accurate analysis and conclusions, we test the second set up again, and as expected, we find out a new problem. Figures 44 and 45 shows improved results of this set up, but the big deal is in Figure 46, where after measuring deformations again and again, errors start to appear.

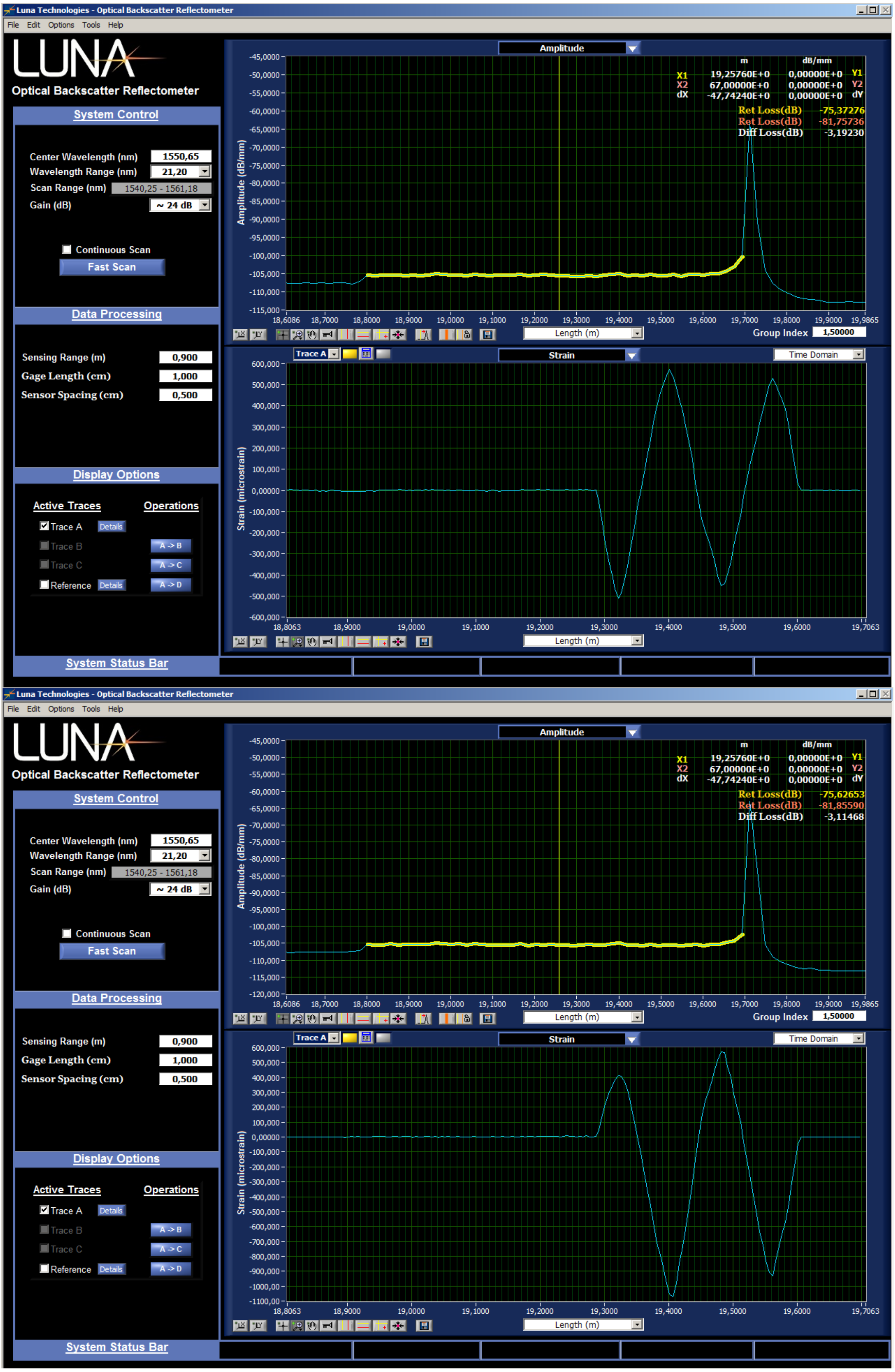


*Figure 44 Second signals from the second set up of the experimental study with PVC ring at 0 and 90 degrees*

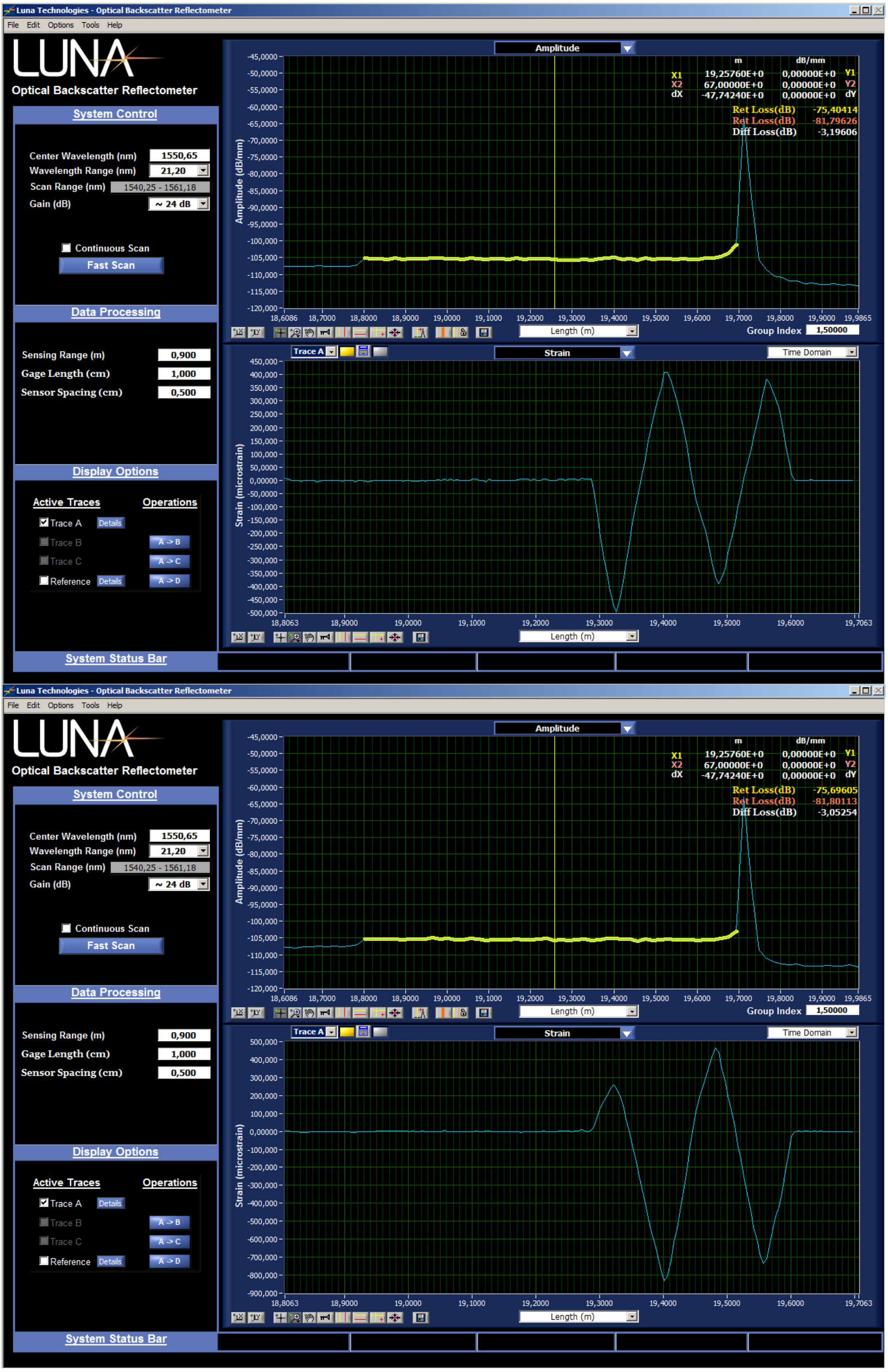


*Figure 45 Second signals from the second set up of the experimental study with PVC ring at 180 and 270 degrees*

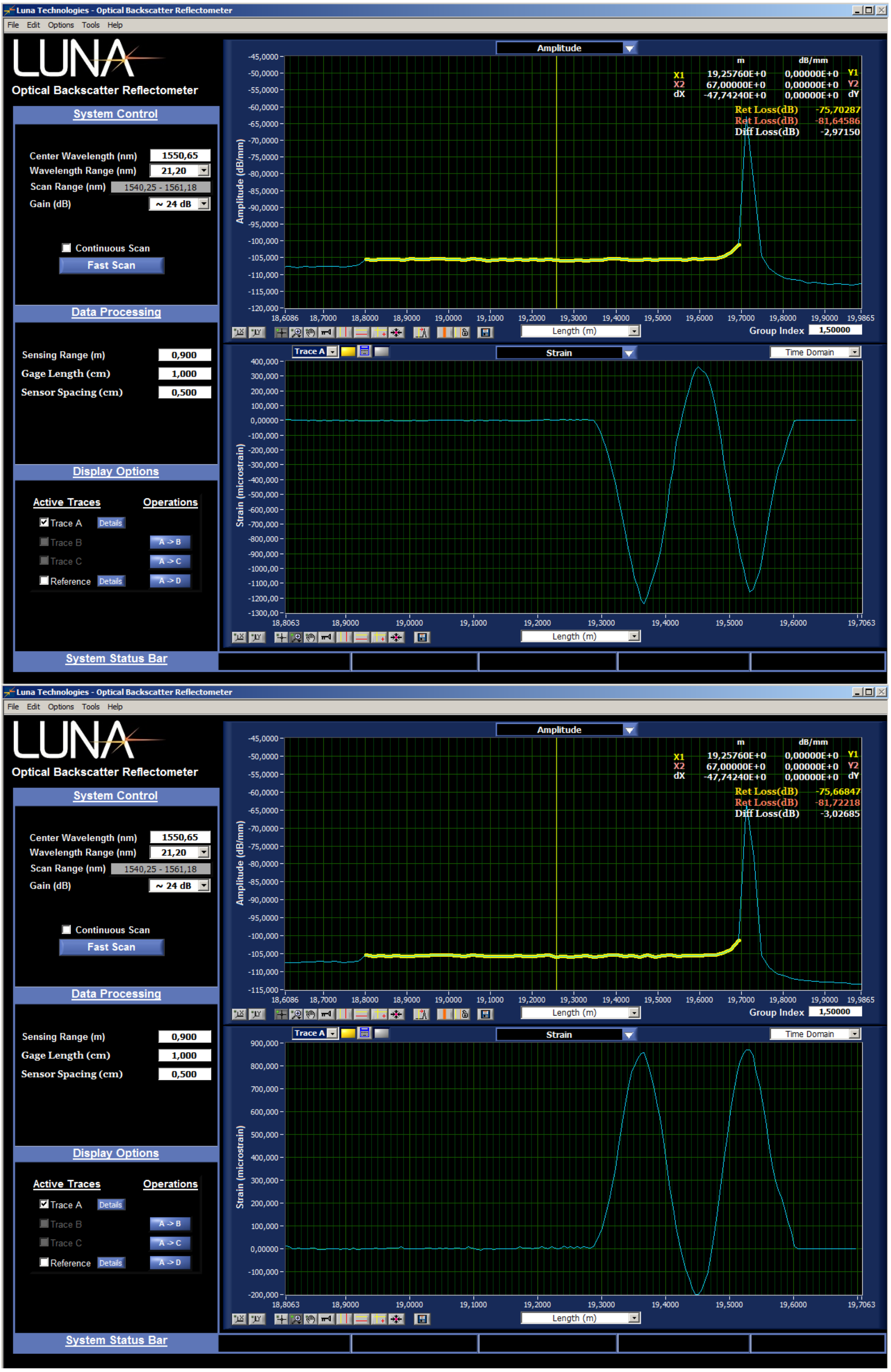

*Figure 46 Measuring failure due to repetitive deformations*

As we can see from the figures, the signals have improved since the first time tested, although they still lack a bit of similarity. This could just happen because the process where you attach the fiber to the ring is not automated, you do it with your bare hands, so there are a lot of factors that change between one test and another, and consequently, the signals change too. But, the important problem to address, is the one showed in Figure 46. At first look, it seems like we came back to the original problem where we miss one of the waves, but when checking the set up, a piece of fiber have been left without attaching, and that the fiber was not broken, was a fact confirmed by the OBR software. After a while trying to find out the source of the problem, some idea was almost certain. For the measuring process, it takes a while (a few seconds) to get the signal processed, analyzed and then saved in a file, and for every test before, the clamps were left applying the deformation during this processes while it should has been applying pressure only when the software is obtaining the signal. The result is that after a few tests in the same tube or ring, some deformations are kept by the tested tube and so, when testing again, it lose similarity between the waves, up to the point of even lose one of the waves (compression or tension), depending on the pressure application point. This conclusion is in part responsible for the lack of similarity in the rest of graphics obtained before this point. In order to mitigate this problem, at least a mayor part of it, from now on, the clamp will be applying pressure just while the software is recording the signal. Once we have it, we retire the clamp and proceed with the analysis and saving of the data.

### 3.4.5. Experimental study with polyvinyl chloride tubes

After those tests with different ring set ups, it is time to experiment with the tubes we said before at the beginning of the previous section. These tubes have the same diameter, thickness and material as the rings used before, but they have a length of 300 mm. Figure 47 shows the PVC tube use for this section.

*Figure 47 Polyvinyl chloride tube used in experimental study*

Although both of the tapes used in previous section properly work, we decided to use here the transparent one for one simple reason. Given the fact that the problem of such small space to maneuver the tape with the fiber inside the tube has come back, the transparency of that industrial tape allow us to see some marks inside the tube, that we have painted before, so we can place the fiber inside correctly, this means, in the center and concentric to the cross section of the tube. Another advantage of the transparent regular tape is that we can see at every moment along the attachment process, where the fiber is placed or if it is still fixed to the tape or not. This is really useful since the few space inside the tube and the long length of tape with fiber attached to it, can make result in problems such as the separation of both fiber and tape in the process. Knowing that, the new set up is built and show in Figure 48 below.

*Figure 48 First set up in a PVC tube for experimental study*

Coming back to the pressure process, we obtain the signals shown in Figures 49 and 50. As we can see, the strain profiles are completely different from the ones obtained in the PVC rings, even they lose some of the waves in the signals. Without knowing the reason of this issue, we run another test with another measurement fiber due to the possibility that the first one was broken or damaged. Figures 51 and 52 show the signals of this second set up test.

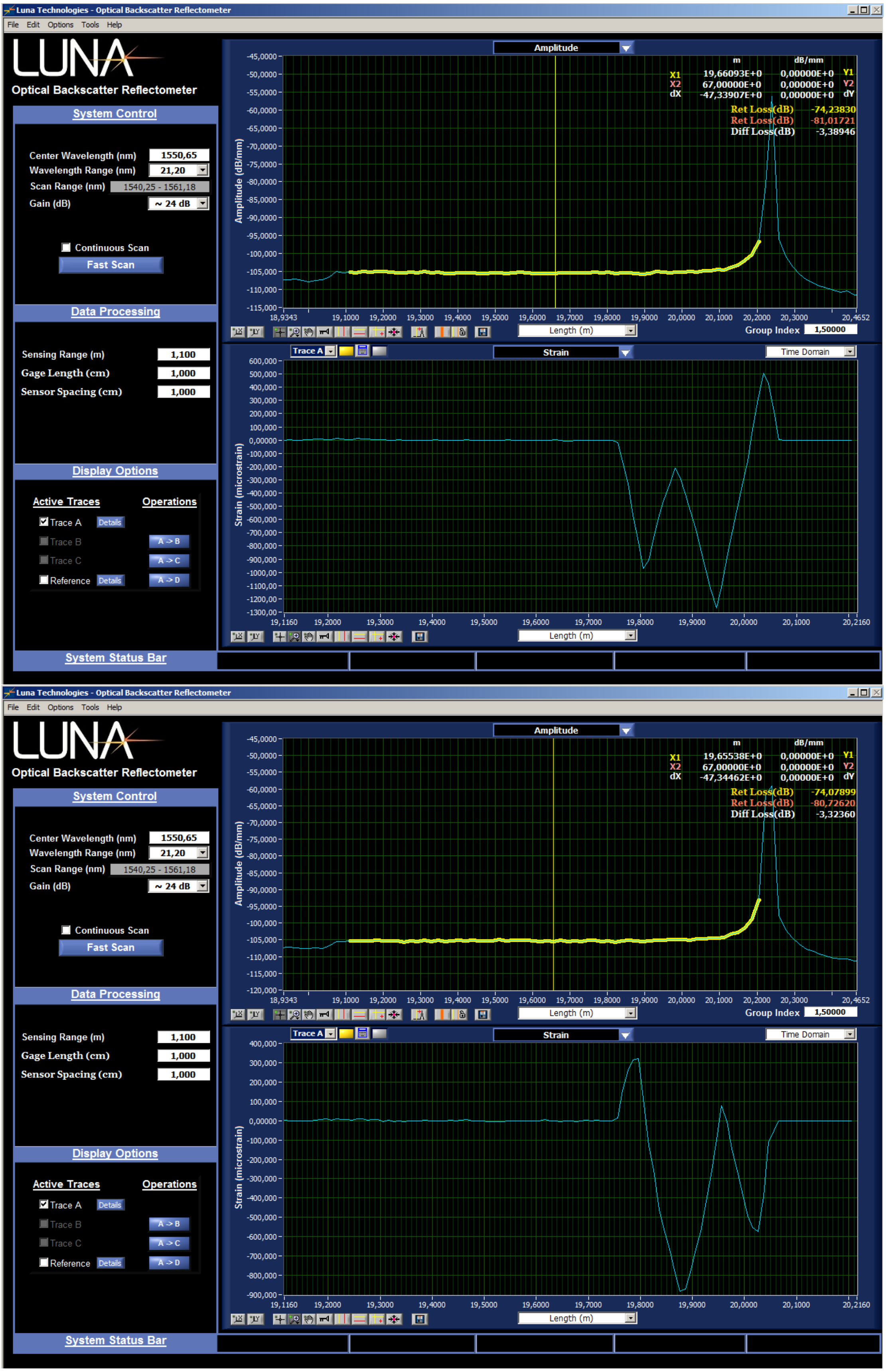


*Figure 49 Signals from the first set up of the experimental study with PVC tube at 0 and 90 degrees*


*Figure 50 Signals from the first set up of the experimental study with PVC tube at 180 and 270 degrees*


*Figure 51 Signals from the second set up of the experimental study with PVC tube at 0 and 90 degrees*

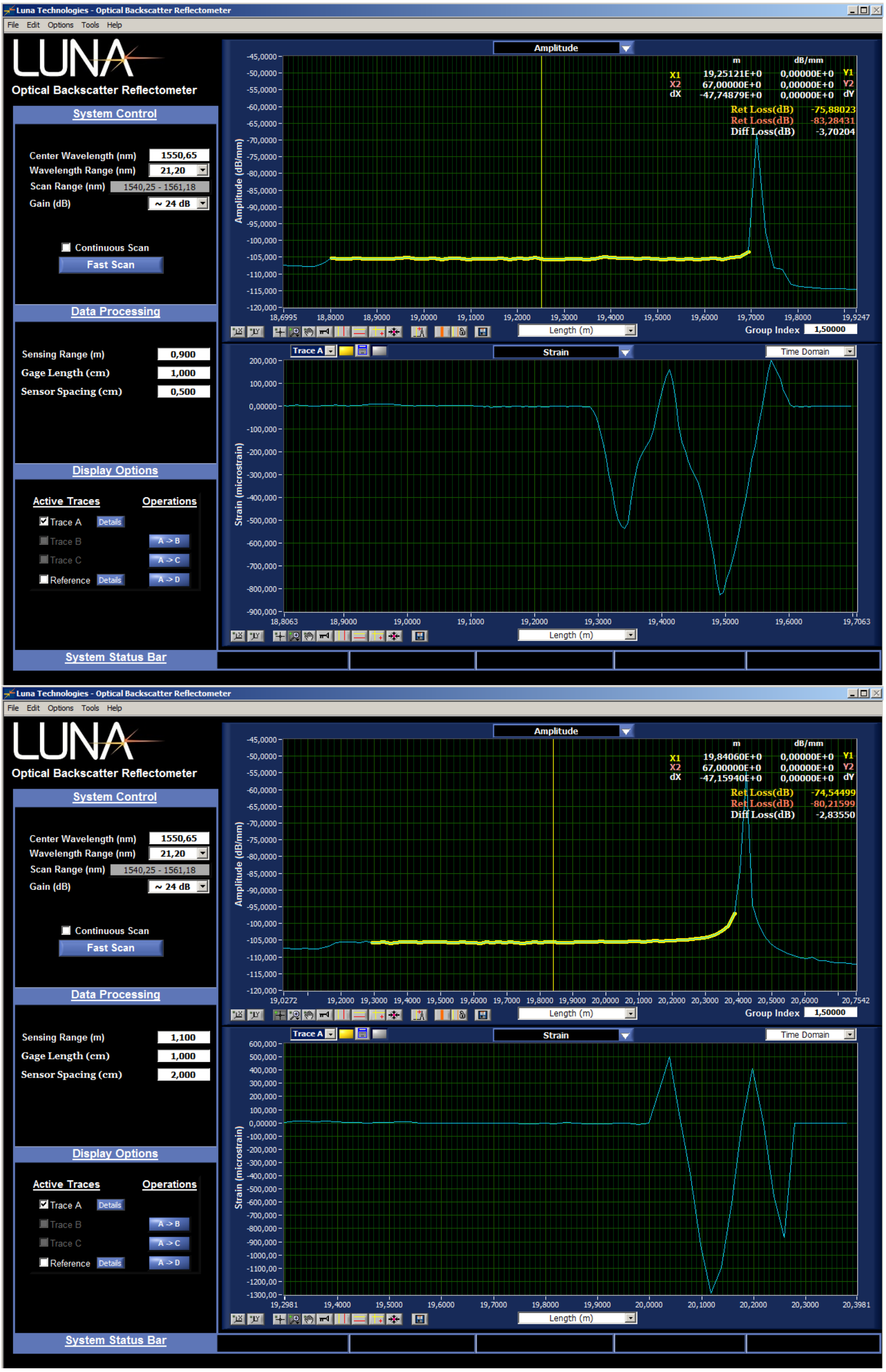


*Figure 52 Signals from the second set up of the experimental study with PVC tube at 180 and 270 degrees*

We can say few things of these tests. First of all, it is true that the signals improve in the second set up, maybe the reason is a failure in the fiber used for the first set up, or it could be too that the attachment process was better in the second try than in the first one. However, we are going to refer now to the second test, that is because, several more experiments were tried between the first one and the second one shown, but the signals from Figures 51 and 52 were the best one we could obtain. From them, it is obvious that we have a big difference between compression and tension values, the first ones are so much bigger at any pressure point applied. Also, it seems to have lack of similarity, but stronger between compression waves than tension ones. This could happen because we are testing tubes now, and a lot more factors are taking into account than in the PVC rings experiment.

There have been, and there are, so many identified problems along the experimental study, as well as advantages for this OBR technique. Those will be commented and studied in following chapters with the help of numerical data obtained in each test along this work. The tables with the numerical data will be found in the Annexes.

# 4. Analysis of results

Regarding previous sections, we have been able to see a process divided in several steps where the failures or the problems of one of them, gave birth to then next. Signals, strain profiles and tables with numerical data have been obtained and recollected to make a deep study of them, in order to get some conclusions of the OBR technique, which is the main focus of this project. Advantages, disadvantages, aspects to improve, developments, future studies, applications to real cases etc. are points of discussion that should naturally born from the information in previous section and the studies that are going to be done.

This is the aim of this chapter, make connection between the experimental work and the conclusions of the OBR technique, by analyzing the graphical and numerical information obtained and collected. In order to do that, we will divide this analysis of results in two main parts, being so results of the base case, in which signals will be commented regarding numerical values and shapes, and analysis of the sensitivity, where we will try to figure out how the measures are influenced by different factors.

## 4.1. Results of base case

Analysis of the numerical and graphical results obtained in the whole study will be commented in this section, which is divided into two main focuses, like the previous chapter: analytical and numerical study and experimental study.

Taking a look at Tables 2 and 3 in the Annexes section of this project, data from tubes with different measures has been collected, focusing in the non-critical pressures values, which are the ones whose are going to tell us until which point we can test the tubes later in the experimental study. Given the fact that, in this experimental work, both PP and PVC tubes are of similar measures, being so, length of 300 mm, diameter of 110 mm and thickness of 3 mm approximately, the most important data needed from the analytical and numerical study is the non-critical pressure of the Models 1.0 and 2.0, with lengths of 200 and 400 mm respectively. Considering that the tube from Model 2.0 is too long for resist the pressure that could be applied in the laboratory to get good results, we support the data form Model 1.0, representing the tubes used later in the experimental analysis. Figure 53 shows the displacement of one point in the middle of the tube while the software is applying external pressure up to the non-critical pressure, which can be seen from Tables 2 and 3 that occurs at 2.4564 MPa (even a little bit less due to the longer length of the tested tube). This means, looking at Figure 55, that the maximum displacement of one point in the middle of the tube is about 17.5 mm before it breaks. This value is taken into account for the experimental study, in order to not damage or break the OBR equipment while testing.

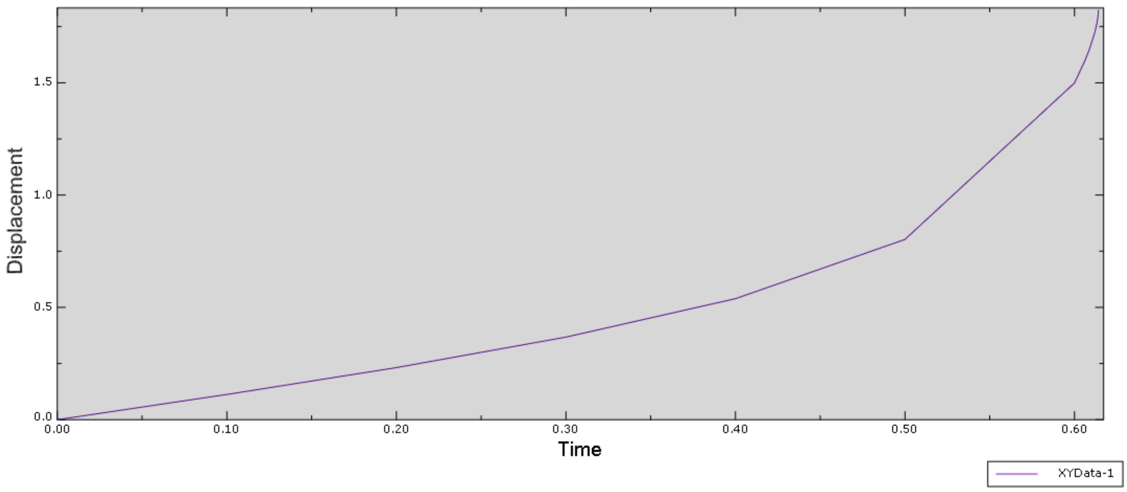


*Figure 53 Displacement-time diagram from Abaqus CAE Software for Model 1.0*

Regarding experimental results, it is useless to analyze data and graphics from the first set ups due to errors and problems that were appearing while we tried to obtain the first complete sine wave. This is why, we should focus on the results from the first PVC ring forward. In order to do that we are going to split these signals into two parts: data from the PVC rings and data from the PVC tubes.

If you remember what it was explained in previous chapters, two kind of tapes were used for this experiment with PVC rings. Starting with the regular transparent tape, Tables 4 and 5 show the numerical values of the signals referred to the experiments with PVC rings and regular transparent tape, both first test and second respectively. In the tables, both for PVC rings and for PVC tubes, values are shown for each one of the four points of pressure application, having each one of them, a first column with values of length (mm) referring to the exact point in the fiber, and a second column representing the values of the strain (microstrains). To make easier the task of analyze the results, tables collect just the numerical values of the piece of optical fiber which is influenced by the deformations due to the external pressure applied, this means, values that are part of the sin waves in the graphics obtained along the experimental study. One thing more to highlight is that the pressure control is too difficult to deal with, due to the clamp used, we cannot apply a certain value of external pressure. However, as we can see in all of the tables, the values of strain are really small (remember that they are in microstrains), and comparing with the maximum value of displacement before breakthrough obtained in the analytical study, we do not need to worry about this aspect when applying pressure with the bar clamp. So, instead of analyzing the strain values of each wave we are going to focus in other aspects such as similarity between them and quality of the measure. In order to do that, comments of each signal will be done by advantages and disadvantages analysis.

As is was said, we are going to start with the PVC rings and regular tape attachment. In this set up, two tests are analyzed. Several tests were made between them, but the important ones are the first one and the last one, just to not fill this work with only tables and tables of data. Apart from that, they are quite similar, so there is no meaning in doing that. Then, the PVC ring with industrial tape will be commented comparing with the regular tape. Finally, an analysis of the results of the PVC tubes will be done.

### 4.1.1. First test of the first set up with PVC ring (regular tape)

This set up is the first one in showing the shape of a sine wave, and it is not as bad as we can thought it would be. In points 90 and 270 degrees we have quite good similarity between waves of same type of deformation (compression or tension), the problem is that there are difference in values comparing positive and negative waves, being so, values for tension are higher than values for compression, although quite small difference, just about 100-150 microstrains. Regarding points 0 and 180 degrees, even having the complete signal, we lack of similarity both between same deformation waves and between positive and negative waves. This is weird given the fact that only happens to these two points of application and not to the whole set of signals. For the moment, we only can confirm that the optical fiber measures slight higher values in tension regions rather than compression regions.

### 4.1.2. Second test of the first set up with PCV ring (regular tape)

In this case, the problem described before is solved, not so sure how. It could be just a matter of the attachment of the fiber, or that the fiber was in bad conditions. In points 0 and 180 degrees, we have quite the perfect similarity between all the waves, with just small difference of 50 microstrains. These values are really good, and it is supposed to get this similarity in all the signals in order to say that the experimental work has been successful. In points 90 and 270 degrees, now we have higher values in compression than in tension regions. As we have explained in previous sections, one of the main problems that we have with this signals, is that between measure and measure, lots of deformations are suffered by the tube, and some of them are kept by it. This means that, when measuring the following pressure point, one of the two kinds of deformation will get higher values than the other. In order to do that, in a perfect world. We should have as many tubes as measures that are going to be done, and not like this case in which we use one or two tubes for all the possible measures. This will be commented also in the conclusion section, as it is a really important point in this thesis. However, the results have improved since the first test.

### 4.1.3. Second set up with PVC ring (industrial tape)

Regarding this case, the only important thing to remember is the transversal reinforcements that the tape has, being cause of mayor part of the changes here comparing to the regular tape. In points 0 and 180 degrees, we have a similar problem remembering previous set ups, being so, higher values in compression than in tension, about 150-200 microstrains, something more significant than before. In points 90 and 270 degrees, we observe a relevant decrease in the values as we go through the fiber in both kind of deformations. It is not sure that the industrial tape used has something to do with this due to the fact that it only affect to half of the measures and not for the whole set of signals. So it could be again the quality of the attachment. However the pros and cons, comparing to the regular tape, it has more disadvantages for one reason: the transparency and smaller size of the regular tape make easier to control the attachment process. This is why, regular tape is decided to be used later in the PVC tubes.

### 4.1.4. First test of the first set up with PVC tube (regular tape)

In this first test done with a PVC tube, results are really bad as we can see from Figures 49 and 50, and Table 7. Given the fact that some of the errors are in the next test too, but with better results, the comments will be made in the following analysis in order to not repeat the information.

### 4.1.5. Second test of the first set up with PVC tube (regular tape)

A quick look into Figures 51 and 52, and Table 8, make us notice that the optical fiber get higher values in compression rather than in tension, and with really significant differences up to 700-800 microstrains. Another aspect to take into account is that the difference between tension waves are smaller than the ones for compression waves (100 and 300-400 respectively). These facts can be explain through sources explained before such as deformations kept by the tube from one measure to another, and problems at the moment of attaching the optical fiber to the inner surface of the tube. But, it could be explained also for a new reason, being so, that we are working now with tubes and not rings. In the rings, the surface that is in contact with the clamp has almost the same length, so the pressure can be equally applied, obtaining such good signals as commented before. But, working with tubes, the surface that is in contact with the clamp is just a little region in the middle of the tube, so the pressure do not work as well as in the rings, we have much more material opposing to the deformation. Also, if you can remember, we have the inconvenient of the bar clamp used, not only here but in the rest of the tests, regarding the moving part that makes difficult to properly apply pressure, observed in Figure 34.

All of this will be remembered in the conclusions section.

## 4.2. Analysis of sensitivity

As it has been commented at the beginning of this chapter, there are some factor that will influenced the measures obtained in the experimental work. Through the whole analytical and experimental study, these factors have been appearing, so most of them have been identified in the experimental work than in the analysis of results. In this section, these factors and how they interact with the signals will be analyzed as well as possible.

Attachment method: since the beginning of the experimental study, many methods to attach the fiber to the inside of the structure were tested. First, cyanoacrylate adhesive was used, hoping that the attachment would be almost perfect. The thing here is that the adhesive, once it is dry, is kind of weak facing deformations, especially in compression regions, so it brittles in some points and the fiber follows it, obtaining more waves from the adhesive than form the tube. This method is then rejected, giving chance to the regular and industrial tapes. As we could see before, tape has so many advantages besides the fact that the signals obtained are so much better. They are easily place inside the structure, even you can stick the fiber to the tape before place it inside it. The tapes have demonstrated that they perfectly stick to the surface and allows the fiber to get most of the deformations caused in the tube. Among them, the industrial one, due to the transversal reinforcements, the measures could be a little bit worse than the case with regular tape, but however, both of them get good signals.

Pressure application method: in this project, the pressure was applied with a bar clamp, which has the inconvenient we have explained before, and that it is showed in Figure 34. The moving part making contact with the surface, apply proper pressure but maybe not in the direction it should. This is translated in lack of similarity between waves, sometimes more relevant than others, just depending on how well the bar clamp is used. In order to get better signals, the pressure should be applied with both fixed parts, creating pressure vectors of same direction but different senses. Another method to improve the signals, is to apply uniformly pressure along the whole surface, a different case for improving this thesis that will be commented in the section regarding recommendations for future studies.

Pressure applied: several tests that have been done in the laboratory show that the optical fiber get better results when the deformation is small, this means, pressure applies is low. When this pressures is increased, the fiber tends to get higher values from one of the deformation types, usually from compression, increasing the lack of similarity. In order to obtain proper strain profiles then is advisable to apply low levels of pressure, also helping to reduce the deformations kept later by the tube from one measure to another one, problem which cause also errors in the signals.

Structure tested: as we have explained before, the pressure applied in rings cause quite good profiles due to the few surface opposing to the deformation. In the case of the tubes, more material is making harder the uniform deformation, which give us worse signals. It is not something that affect the analysis of the project itself, because we are focusing on tubes among themselves, so it is more a problem to face in future studies about this technique. Tubes offer many more factors affecting the signals than simple rings.

Deformation time: regarding the condition of the tested tube between measures, if the clamp is applying pressure between one measure and another one, the tube will probably keep some of this deformation, making the following measure to produce signals in which the values of compression or tension (depending on the case measured before) decrease. This will decrease the similarity between the waves. It is confirmed that when using the clamp only when the software is processing the deformations, the signals are better for the next measurement.

Software parameters: inside OBR Luna Software, there are three parameters that can be manipulated in order to get more or less values, and more or less understandable profiles. These parameters are three, sensor spacing, gage length and region measured. It is important to change these values with frequency in the same measured signal, just not for getting a good looking and better profile, but also for having the chance to discover other waves or problems in the fiber that could not be seen without the preselected values of the software.

# 5. Conclusions

At last, final comments regarding different aspects of the thesis that has been developed in every chapter, will be done in this section. These conclusions are mainly opinions of mine from the experience I have acquired performing experimental test through the whole work, and from the data obtained by doing these tests. Lots of these aspects have been explained in previous chapters as needed, so the main focus of the following paragraphs is to collect and briefly comment those points. In order to do that, three different blocks group all of the conclusions depending on their natures, being so, conclusions on the methodology, conclusions on the results and recommendations for future studies.

## 5.1. Conclusions on the methodology

This part is focused on what have happened while the project went forward, this means, on the chosen method to develop this thesis in order to get the results and analyze them. First of all is important to say that, although it has been done to assure the integrity and safety of the OBR equipment, the analytical and numerical study does not seem to have a relevant role in this thesis, given the fact also that we only have tested one of the models later in the experimental work. However, this does not mean that it is useless. In the last part of this chapter, recommendations for future studies, this analysis will have more importance, as I will explain some procedures and aspects that should be deeply performed to achieve better results on the advantages of using this OBR technique in real scenarios.

Regarding experimental study methodology, there are three main points that need to be discussed in this section.

By one hand, the reduced diameter of the tubes tested was one of the main problems of this thesis, and so, source of imperfections in most of the signals obtained. One option would be to increase the diameter of the tubes that we bought for the experiment, so we could place the fiber inside without relative difficulties, and according to Table 1, increasing the diameter increase the non-critical pressure, so we do not need to worry about limitations at applying the external pressure. However, this is not a critical issue for the main objective of the project because, in real cases, tubes have a higher diameter in most of the cases. In the cases that this is not true, advanced equipment should be used, and it can be an aspect for future studies.

By other hand, in order to get the desired sine signals, the method used to apply the pressure was just using a bar clamp for the laboratory. It was a good idea before beginning the process, but the problem described with the moving part, makes difficult to analyze correctly some signals. Although the tests are better or worse between each other due to this, the error just depend on how good you can place the moving part respect to the fixed part. However, another method could be thought to avoid this issue such as using heavy equipment to apply pressure in both opposite sides, which give us also control on how much pressure we apply, another aspect of the methodology that could have helped us to analyze the results in a much better way.

Finally, it is important to say that not everything went wrong. The trial and error method that we used along the project to study different ways of attach the fiber to the inner surface of the structure, allows us to detect which resources are better to get this right or what materials are easier for the optical fiber to measure. From my point of view, the study about OBR technique here has been done in a simple way to detect these factors that should be solved in order to apply more advanced techniques and complex resources, but it is promising how it can be used to detect deformations, imperfections and prevent malfunctions in structures of high importance.

## 5.2. Conclusions on the results

As we have seen in the previous chapter, there are some factors that affect the quality of the results obtained by the OBR Software. In this project, most of them have been identified, but it was difficult to deal with some of them due to limitations regarding resources, equipment and ability.

However, most of the results are quite good and show a great potential for what the optical fiber can be used to. With the PVC rings, we could confirm that the optical fiber can get almost perfect signals of what is going on with the deformation of the structure due to external pressure, while regarding PVC tubes, the signals are not as good. These does not mean that the technique does not have the required properties to meet the expectations that are thought for it, but instead, is the implementation the main problem. As we saw in the analysis of results section, the signals for PVC tubes are in the way to get the strain profiles that it should be, but according to the factors mentioned in analysis of sensibility, there are issues that should be solved in order to get the rightful measures.

From my point of view, given the fact that this study was carried out in a simple way to identify the main problems that could drive to worst situations in the future, we have reached a simple goal, being so, obtain completed strain profiles according to the theory to a great extent. Therefore, it can be said that the results obtained here are quite great and useful for future references.

## 5.3. Recommendations for future studies

At last, so many points of this section have made reference to future opportunities and present limitations, being this project a simple study which it is supposed to be a reference for an upcoming development of the Rayleigh OBR technique. This section will explain what are some of those procedures and aspects that should be considered for following studies, in other words, future recommendations.

The first one is referred to the pressure application method. While using a bar clamp to get a simple sine wave, in some real cases, external pressure come from many different points and different directions, sometimes all at the same time. For this analysis, the measures obtained by the bar clamp set up its completely useless. Instead of that, advanced equipment such as an autoclave device, could simulate these scenarios, getting measures much more similar to the real world. If we need first to take it to a smaller case, depending on the resource availability, we can design a pressure chamber, that adapted to the tested structure, could been filled by water or air at a predefined pressure, which give us also control and more numerical data, and simulate for example the tubes that have been studied in this project. Figure 54 shows an example of what a pressure chamber could look like.

*Figure 54 Pre-model of pressure chamber*

Other recommendations for future studies are bigger diameter for the tubes, in order to get easier control of the attachment process; increase of the number of different materials that the tubes are made of, for example stainless steel, so more information on how the fiber and attachment methods work with those materials; testing of one tube for each fiber and point of pressure application, avoiding the problem in which the tube kept some deformations from one measure to another; use of different kinds of liquid adhesives that does not brittle while deforming, maybe they are as good as it was thought at the beginning, even better than used tapes; attachment of the optical fiber on the outside of the tube with protective materials covering, in cases where the diameter of the tube does not allow the placement inside even with advanced equipment; implementation of more than one fiber for the same tube, so we can supervise the condition of the tube in various points, even at real time, something possible through the OBR Software; implementation of the optical fiber in other structures with non-circular section etc.

As we can see, there are so many possibilities of testing this technique in different situations and in different ways, being this in part, why this method has a great potential of development and application not only in the structure monitoring, as commented in the state-of-the-art chapter.

# Bibliography


[FRAN14] Frangopol, Dan and Tsompanakis, Yiannis, “Maintenance and Safety of Aging Infrastructure”, CRC Press, October 2014.

[WIKI17] Wikipedia, “Abaqus FEA”, Online [https://en.wikipedia.org/wiki/Abaqus], last edited on 23 May 2017.

# Annexes

## List of annexes


| | |
|---|---|
| Expanded analytical and numerical study results I | I |
| Expanded analytical and numerical study results II | II |
| Signal values from first PVC ring set up (regular tape) first test | III |
| Signal values from second PVC ring set up (industrial tape) | IV |
| Signal values from first PVC ring set up (regular tape) second test | V |
| Signal values from first PVC tube set up (regular tape) | VI |
| Signal values from second PVC tube set up (regular tape) | VII |
| Risk assessment | VIII |

| Model - Submodel | Material | Length [mm] | Radius [mm] | Thickness [mm] | Instance Type | Density [g/cm3] | Young [MPa] | Poisson | Eigenvalues requested | Max. Iterations |
|---|---|---|---|---|---|---|---|---|---|---|
| Model 1.0 - LinearBuckling | PVC | 200 | 50 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - NonLinearBuckling | PVC | 200 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - NonLinearBucklingON | PVC | 200 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - ImplicitDynamic | PVC | 200 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 1.0 - ImplicitDynamic | PVC | 200 | 50,1/49,9 | 3 | Dependent | 12,00 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - LinearBuckling | PVC | 400 | 50 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - NonLinearBuckling | PVC | 400 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - NonLinearBucklingON | PVC | 400 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - NonLinearBucklingON | PVC | 400 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | Dependent | 12,00 | 3000 | 0,35 | 4 | 100 |
| Model 2.0 - ImplicitDynamic | PVC | 400 | 50,1/49,9 | 3 | Dependent |  | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - LinearBuckling | PVC | 100 | 50 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBuckling | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - NonLinearBucklingON | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 3.0 - ImplicitDynamic | PVC | 100 | 50,1/49,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - LinearBuckling | PVC | 200 | 25 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - NonLinearBuckling | PVC | 200 | 25,1/24,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - NonLinearBucklingON | PVC | 200 | 25,1/24,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | Dependent | 12,00 | 3000 | 0,35 | 4 | 100 |
| Model 4.0 - ImplicitDynamic | PVC | 200 | 25,1/24,9 | 3 | Dependent |  | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - LinearBuckling | PVC | 200 | 100 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - NonLinearBuckling | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - NonLinearBucklingON | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |
| Model 5.0 - ImplicitDynamic | PVC | 200 | 100,1/99,9 | 3 | Dependent | 1,20 | 3000 | 0,35 | 4 | 100 |

*Table 2 Expanded analytical and numerical results I*

| Model - Submodel | Pressure [MPa] | EquivalentAxialForce [N] | Eigenvalue | Slopes | Linear Pressure [MPa] | Work? | Step time | Non-Linear Pressure [MPa] | Step |
|---|---|---|---|---|---|---|---|---|---|
| Model 1.0 - LinearBuckling | 1 | -7850 | 0,88733 | 3 | 0,88733 | Yes | | | |
| Model 1.0 - NonLinearBuckling | 1 | -7850 | | | | No | | | |
| Model 1.0 - NonLinearBucklingON | 1 | -7850 | | | | No | | | |
| Model 1.0 - NonLinearBucklingON | 2 | -15700 | | | | No | | | |
| Model 1.0 - NonLinearBucklingON | 4 | -31400 | | | | Yes | 0,6141 | 2,4564 | |
| Model 1.0 - ImplicitDynamic | 4 | -31400 | | | | No | | | |
| Model 1.0 - ImplicitDynamic | 4 | -31400 | | | | Yes | 6,151 | 2,4604 | 24/100 |
| Model 2.0 - LinearBuckling | 1 | -7850 | 0,51188 | 2 | 0,51188 | Yes | | | |
| Model 2.0 - NonLinearBuckling | 1 | -7850 | | | | No | | | |
| Model 2.0 - NonLinearBucklingON | 1 | -7850 | | | | No | | | |
| Model 2.0 - NonLinearBucklingON | 2 | -15700 | | | | Yes | 0,2441 | 0,4882 | |
| Model 2.0 - ImplicitDynamic | 2 | -15700 | | | | No | | | |
| Model 2.0 - ImplicitDynamic | 2 | -15700 | | | | No | | | |
| Model 2.0 - ImplicitDynamic | | | | | | No | | | |
| Model 3.0 - LinearBuckling | 1 | -7850 | 1,7505 | 4 | 1,7505 | Yes | | | |
| Model 3.0 - NonLinearBuckling | 1 | -7850 | | | | No | | | |
| Model 3.0 - NonLinearBucklingON | 1 | -7850 | | | | No | | | |
| Model 3.0 - NonLinearBucklingON | 2 | -15700 | | | | No | | | |
| Model 3.0 - NonLinearBucklingON | 4 | -31400 | | | | No | | | |
| Model 3.0 - NonLinearBucklingON | 8 | -62800 | | | | No | | | |
| Model 3.0 - NonLinearBucklingON | 16 | -125600 | | | | Yes | 0,6298 | 10,0768 | |
| Model 3.0 - ImplicitDynamic | 16 | -125600 | | | | Yes | 6,013 | 9,6208 | 43/43 |
| Model 4.0 - LinearBuckling | 1 | -7850 | 2,1625 | 2 | 2,1625 | Yes | | | |
| Model 4.0 - NonLinearBuckling | 1 | -7850 | | | | No | | | |
| Model 4.0 - NonLinearBucklingON | 1 | -7850 | | | | No | | | |
| Model 4.0 - NonLinearBucklingON | 2 | -15700 | | | | No | | | |
| Model 4.0 - NonLinearBucklingON | 4 | -31400 | | | | Yes | 0,525 | 2,1 | |
| Model 4.0 - ImplicitDynamic | 4 | -31400 | | | | No | | | |
| Model 4.0 - ImplicitDynamic | 4 | -31400 | | | | No | | | |
| Model 4.0 - ImplicitDynamic | | | | | | No | | | |
| Model 5.0 - LinearBuckling | 1 | -7850 | 0,32729 | 5 | 0,32729 | Yes | | | |
| Model 5.0 - NonLinearBuckling | 1 | -7850 | | | | No | | | |
| Model 5.0 - NonLinearBucklingON | 1 | -7850 | | | | No | | | |
| Model 5.0 - NonLinearBucklingON | 2 | -15700 | | | | No | | | |
| Model 5.0 - NonLinearBucklingON | 4 | -31400 | | | | No | | | |
| Model 5.0 - NonLinearBucklingON | 8 | -62800 | | | | Yes | 0,8283 | 6,6264 | |
| Model 5.0 - ImplicitDynamic | 8 | -62800 | | | | Yes | 8,909 | 7,1272 | 28/28 |

*Table 3 Expanded analytical and numerical results II*

| Point 0 | | Point 90 | | Point 180 | | Point 270 | |
|---|---|---|---|---|---|---|---|
| Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] |
| 1,927E+04 | -8,508E+00 | 1,927E+04 | -8,233E+00 | 1,927E+04 | -1,284E+01 | 1,927E+04 | -1,268E+01 |
| 1,929E+04 | -3,816E+01 | 1,929E+04 | 4,501E+00 | 1,929E+04 | -2,533E+01 | 1,929E+04 | -2,116E+01 |
| 1,931E+04 | -5,179E+02 | 1,931E+04 | 3,991E+02 | 1,931E+04 | -4,201E+02 | 1,931E+04 | 1,105E+02 |
| 1,933E+04 | -7,046E+02 | 1,933E+04 | 7,644E+02 | 1,933E+04 | -4,459E+02 | 1,933E+04 | 3,862E+02 |
| 1,935E+04 | -2,553E+02 | 1,935E+04 | 7,303E+02 | 1,935E+04 | 5,489E+01 | 1,935E+04 | 3,482E+02 |
| 1,937E+04 | -7,223E+01 | 1,937E+04 | 2,588E+02 | 1,937E+04 | 2,165E+02 | 1,937E+04 | 1,021E+02 |
| 1,939E+04 | 1,104E+02 | 1,939E+04 | -1,487E+02 | 1,939E+04 | 3,311E+02 | 1,939E+04 | -1,572E+02 |
| 1,941E+04 | 3,016E+02 | 1,941E+04 | -5,863E+02 | 1,941E+04 | 3,866E+02 | 1,941E+04 | -3,437E+02 |
| 1,943E+04 | 1,781E+02 | 1,943E+04 | -6,879E+02 | 1,943E+04 | 9,765E+01 | 1,943E+04 | -1,785E+02 |
| 1,945E+04 | -1,572E+02 | 1,945E+04 | -2,208E+02 | 1,945E+04 | -2,250E+02 | 1,945E+04 | 5,105E+01 |
| 1,947E+04 | -3,316E+02 | 1,947E+04 | 2,037E+02 | 1,947E+04 | -3,483E+02 | 1,947E+04 | 2,505E+02 |
| 1,949E+04 | -4,583E+02 | 1,949E+04 | 7,556E+02 | 1,949E+04 | -3,224E+02 | 1,949E+04 | 4,968E+02 |
| 1,951E+04 | -3,272E+02 | 1,951E+04 | 7,855E+02 | 1,951E+04 | -1,717E+01 | 1,951E+04 | 3,993E+02 |
| 1,953E+04 | 2,564E+01 | 1,953E+04 | 4,626E+02 | 1,953E+04 | 3,224E+02 | 1,953E+04 | 1,740E+02 |
| 1,955E+04 | 3,527E+02 | 1,955E+04 | 3,424E+01 | 1,955E+04 | 5,735E+02 | 1,955E+04 | -2,539E+01 |
| 1,957E+04 | 4,335E+02 | 1,957E+04 | -3,949E+02 | 1,957E+04 | 5,181E+02 | 1,957E+04 | -3,353E+02 |
| 1,959E+04 | 2,210E+02 | 1,959E+04 | -2,165E+02 | 1,959E+04 | 2,547E+02 | 1,959E+04 | -1,403E+02 |
| 1,961E+04 | -2,099E+01 | 1,961E+04 | -1,704E+01 | 1,961E+04 | -2,084E+01 | 1,961E+04 | -2,110E+01 |

*Table 4 Signal values from first PVC ring set up (regular tape) first test*

| Point 0 | | Point 90 | | Point 180 | | Point 270 | |
|---|---|---|---|---|---|---|---|
| Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] |
| 2,153E+04 | -4,362E+00 | 2,155E+04 | 4,553E+00 | 2,155E+04 | -1,258E+01 | 2,155E+04 | -3,906E+00 |
| 2,156E+04 | -2,290E+02 | 2,155E+04 | 5,553E+01 | 2,155E+04 | -4,656E+01 | 2,155E+04 | 2,543E+01 |
| 2,159E+04 | -5,097E+02 | 2,156E+04 | 1,484E+02 | 2,156E+04 | -9,324E+01 | 2,156E+04 | 6,820E+01 |
| 2,162E+04 | -4,257E+01 | 2,156E+04 | 2,204E+02 | 2,156E+04 | -1,402E+02 | 2,156E+04 | 1,151E+02 |
| 2,165E+04 | 3,478E+02 | 2,157E+04 | 2,972E+02 | 2,157E+04 | -1,788E+02 | 2,157E+04 | 1,700E+02 |
| 2,168E+04 | 2,807E+02 | 2,157E+04 | 4,033E+02 | 2,157E+04 | -2,246E+02 | 2,157E+04 | 2,422E+02 |
| 2,171E+04 | -8,931E+01 | 2,158E+04 | 5,055E+02 | 2,158E+04 | -2,636E+02 | 2,158E+04 | 3,315E+02 |
| 2,174E+04 | -5,310E+02 | 2,158E+04 | 5,948E+02 | 2,158E+04 | -3,227E+02 | 2,158E+04 | 4,205E+02 |
| 2,177E+04 | -4,242E+02 | 2,159E+04 | 6,240E+02 | 2,159E+04 | -3,695E+02 | 2,159E+04 | 4,713E+02 |
| 2,180E+04 | 5,050E+01 | 2,159E+04 | 5,772E+02 | 2,159E+04 | -3,608E+02 | 2,159E+04 | 4,582E+02 |
| 2,183E+04 | 2,374E+02 | 2,160E+04 | 5,093E+02 | 2,160E+04 | -3,190E+02 | 2,160E+04 | 3,783E+02 |
| 2,186E+04 | -4,178E+00 | 2,160E+04 | 4,421E+02 | 2,160E+04 | -2,843E+02 | 2,160E+04 | 3,018E+02 |
| | | 2,161E+04 | 3,739E+02 | 2,161E+04 | -2,295E+02 | 2,161E+04 | 2,376E+02 |
| | | 2,161E+04 | 3,147E+02 | 2,161E+04 | -1,654E+02 | 2,161E+04 | 1,952E+02 |
| | | 2,162E+04 | 2,548E+02 | 2,162E+04 | -9,309E+01 | 2,162E+04 | 1,569E+02 |
| | | 2,162E+04 | 1,827E+02 | 2,162E+04 | -4,725E+01 | 2,162E+04 | 1,143E+02 |
| | | 2,163E+04 | 1,193E+02 | 2,163E+04 | -3,276E-01 | 2,163E+04 | 7,177E+01 |
| | | 2,163E+04 | 5,076E+01 | 2,163E+04 | 5,061E+01 | 2,163E+04 | 2,149E+01 |
| | | 2,164E+04 | -2,085E+01 | 2,164E+04 | 1,106E+02 | 2,164E+04 | -1,740E+01 |
| | | 2,164E+04 | -9,798E+01 | 2,164E+04 | 1,610E+02 | 2,164E+04 | -8,100E+01 |
| | | 2,165E+04 | -1,656E+02 | 2,165E+04 | 1,864E+02 | 2,165E+04 | -1,482E+02 |
| | | 2,165E+04 | -2,249E+02 | 2,165E+04 | 2,119E+02 | 2,165E+04 | -2,043E+02 |
| | | 2,166E+04 | -2,888E+02 | 2,166E+04 | 2,419E+02 | 2,166E+04 | -2,715E+02 |
| | | 2,166E+04 | -3,480E+02 | 2,166E+04 | 2,637E+02 | 2,166E+04 | -3,229E+02 |
| | | 2,167E+04 | -3,991E+02 | 2,167E+04 | 2,671E+02 | 2,167E+04 | -3,656E+02 |
| | | 2,167E+04 | -4,291E+02 | 2,167E+04 | 2,339E+02 | 2,167E+04 | -3,860E+02 |
| | | 2,168E+04 | -4,079E+02 | 2,168E+04 | 2,042E+02 | 2,168E+04 | -3,610E+02 |
| | | 2,168E+04 | -3,606E+02 | 2,168E+04 | 1,739E+02 | 2,168E+04 | -3,144E+02 |
| | | 2,169E+04 | -3,010E+02 | 2,169E+04 | 1,397E+02 | 2,169E+04 | -2,636E+02 |
| | | 2,169E+04 | -2,464E+02 | 2,169E+04 | 1,015E+02 | 2,169E+04 | -2,160E+02 |
| | | 2,170E+04 | -1,739E+02 | 2,170E+04 | 7,196E+01 | 2,170E+04 | -1,533E+02 |
| | | 2,170E+04 | -8,507E+01 | 2,170E+04 | 2,565E+01 | 2,170E+04 | -8,013E+01 |
| | | 2,171E+04 | -2,570E+01 | 2,171E+04 | -2,562E+01 | 2,171E+04 | -2,560E+01 |
| | | 2,171E+04 | 2,536E+01 | 2,171E+04 | -7,246E+01 | 2,171E+04 | 2,094E+01 |
| | | 2,172E+04 | 7,656E+01 | 2,172E+04 | -1,185E+02 | 2,172E+04 | 6,756E+01 |
| | | 2,172E+04 | 1,357E+02 | 2,172E+04 | -1,529E+02 | 2,172E+04 | 1,232E+02 |
| | | 2,173E+04 | 1,912E+02 | 2,173E+04 | -1,995E+02 | 2,173E+04 | 1,740E+02 |
| | | 2,173E+04 | 2,507E+02 | 2,173E+04 | -2,629E+02 | 2,173E+04 | 2,249E+02 |
| | | 2,174E+04 | 2,973E+02 | 2,174E+04 | -3,312E+02 | 2,174E+04 | 2,551E+02 |
| | | 2,174E+04 | 3,353E+02 | 2,174E+04 | -3,734E+02 | 2,174E+04 | 2,883E+02 |
| | | 2,175E+04 | 3,612E+02 | 2,175E+04 | -4,036E+02 | 2,175E+04 | 3,100E+02 |
| | | 2,175E+04 | 3,867E+02 | 2,175E+04 | -4,330E+02 | 2,175E+04 | 3,264E+02 |
| | | 2,176E+04 | 3,990E+02 | 2,176E+04 | -4,334E+02 | 2,176E+04 | 3,144E+02 |
| | | 2,176E+04 | 3,819E+02 | 2,176E+04 | -4,077E+02 | 2,176E+04 | 2,928E+02 |
| | | 2,177E+04 | 3,486E+02 | 2,177E+04 | -3,605E+02 | 2,177E+04 | 2,589E+02 |
| | | 2,177E+04 | 2,972E+02 | 2,177E+04 | -3,099E+02 | 2,177E+04 | 2,121E+02 |
| | | 2,178E+04 | 2,501E+02 | 2,178E+04 | -2,549E+02 | 2,178E+04 | 1,698E+02 |
| | | 2,178E+04 | 2,041E+02 | 2,178E+04 | -2,040E+02 | 2,178E+04 | 1,321E+02 |
| | | 2,179E+04 | 1,572E+02 | 2,179E+04 | -1,534E+02 | 2,179E+04 | 8,882E+01 |
| | | 2,179E+04 | 1,107E+02 | 2,179E+04 | -1,014E+02 | 2,179E+04 | 4,656E+01 |
| | | 2,180E+04 | 6,357E+01 | 2,180E+04 | -4,257E+01 | 2,180E+04 | 1,727E+01 |
| | | 2,180E+04 | 8,705E+00 | 2,180E+04 | 1,725E+01 | 2,180E+04 | -1,670E+01 |
| | | 2,181E+04 | -3,419E+01 | 2,181E+04 | 7,244E+01 | 2,181E+04 | -4,735E+01 |
| | | 2,181E+04 | -8,077E+01 | 2,181E+04 | 1,318E+02 | 2,181E+04 | -8,027E+01 |
| | | 2,182E+04 | -1,273E+02 | 2,182E+04 | 1,786E+02 | 2,182E+04 | -1,151E+02 |
| | | 2,182E+04 | -1,869E+02 | 2,182E+04 | 2,084E+02 | 2,182E+04 | -1,659E+02 |
| | | 2,183E+04 | -2,332E+02 | 2,183E+04 | 2,291E+02 | 2,183E+04 | -2,035E+02 |
| | | 2,183E+04 | -2,382E+02 | 2,183E+04 | 2,161E+02 | 2,183E+04 | -1,996E+02 |
| | | 2,184E+04 | -2,082E+02 | 2,184E+04 | 1,694E+02 | 2,184E+04 | -1,651E+02 |
| | | 2,184E+04 | -1,702E+02 | 2,184E+04 | 1,188E+02 | 2,184E+04 | -1,232E+02 |
| | | 2,185E+04 | -1,185E+02 | 2,185E+04 | 7,221E+01 | 2,185E+04 | -7,198E+01 |
| | | 2,185E+04 | -4,638E+01 | 2,185E+04 | 1,264E+01 | 2,185E+04 | -3,370E+01 |
| | | 2,186E+04 | -4,105E-01 | 2,186E+04 | -9,682E-01 | 2,186E+04 | -4,642E+00 |

*Table 5 Signal values from second PVC ring set up (industrial tape)*

| Point 0 | | Point 90 | | Point 180 | | Point 270 | |
|---|---|---|---|---|---|---|---|
| Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] |
| 1,929E+04 | 4,706E-01 | 1,929E+04 | 4,109E+00 | 1,929E+04 | 4,644E+00 | 1,929E+04 | 4,433E+00 |
| 1,929E+04 | -5,521E+01 | 1,929E+04 | 4,654E+01 | 1,929E+04 | -4,263E+01 | 1,929E+04 | 3,001E+01 |
| 1,930E+04 | -1,525E+02 | 1,930E+04 | 1,487E+02 | 1,930E+04 | -1,313E+02 | 1,930E+04 | 8,893E+01 |
| 1,930E+04 | -2,505E+02 | 1,930E+04 | 2,211E+02 | 1,930E+04 | -2,121E+02 | 1,930E+04 | 1,355E+02 |
| 1,931E+04 | -3,318E+02 | 1,931E+04 | 2,932E+02 | 1,931E+04 | -2,932E+02 | 1,931E+04 | 1,698E+02 |
| 1,931E+04 | -3,988E+02 | 1,931E+04 | 3,439E+02 | 1,931E+04 | -3,527E+02 | 1,931E+04 | 1,996E+02 |
| 1,932E+04 | -4,669E+02 | 1,932E+04 | 3,868E+02 | 1,932E+04 | -4,158E+02 | 1,932E+04 | 2,338E+02 |
| 1,932E+04 | -5,097E+02 | 1,932E+04 | 4,122E+02 | 1,932E+04 | -4,713E+02 | 1,932E+04 | 2,590E+02 |
| 1,933E+04 | -4,883E+02 | 1,933E+04 | 4,081E+02 | 1,933E+04 | -4,973E+02 | 1,933E+04 | 2,420E+02 |
| 1,933E+04 | -4,204E+02 | 1,933E+04 | 3,694E+02 | 1,933E+04 | -4,501E+02 | 1,933E+04 | 2,038E+02 |
| 1,934E+04 | -3,437E+02 | 1,934E+04 | 3,018E+02 | 1,934E+04 | -3,821E+02 | 1,934E+04 | 1,446E+02 |
| 1,934E+04 | -2,632E+02 | 1,934E+04 | 2,123E+02 | 1,934E+04 | -3,144E+02 | 1,934E+04 | 6,840E+01 |
| 1,935E+04 | -1,743E+02 | 1,935E+04 | 9,756E+01 | 1,935E+04 | -2,383E+02 | 1,935E+04 | 1,783E-01 |
| 1,935E+04 | -8,114E+01 | 1,935E+04 | 4,165E+00 | 1,935E+04 | -1,618E+02 | 1,935E+04 | -7,643E+01 |
| 1,936E+04 | -1,679E-01 | 1,936E+04 | -1,059E+02 | 1,936E+04 | -9,791E+01 | 1,936E+04 | -1,529E+02 |
| 1,936E+04 | 8,512E+01 | 1,936E+04 | -2,423E+02 | 1,936E+04 | -3,366E+01 | 1,936E+04 | -2,466E+02 |
| 1,937E+04 | 1,614E+02 | 1,937E+04 | -3,481E+02 | 1,937E+04 | 2,100E+01 | 1,937E+04 | -3,190E+02 |
| 1,937E+04 | 2,383E+02 | 1,937E+04 | -4,585E+02 | 1,937E+04 | 8,111E+01 | 1,937E+04 | -4,029E+02 |
| 1,938E+04 | 3,227E+02 | 1,938E+04 | -5,774E+02 | 1,938E+04 | 1,486E+02 | 1,938E+04 | -4,797E+02 |
| 1,938E+04 | 3,989E+02 | 1,938E+04 | -7,133E+02 | 1,938E+04 | 2,078E+02 | 1,938E+04 | -5,650E+02 |
| 1,939E+04 | 4,625E+02 | 1,939E+04 | -7,897E+02 | 1,939E+04 | 2,634E+02 | 1,939E+04 | -6,287E+02 |
| 1,939E+04 | 5,012E+02 | 1,939E+04 | -8,704E+02 | 1,939E+04 | 3,057E+02 | 1,939E+04 | -6,961E+02 |
| 1,940E+04 | 5,437E+02 | 1,940E+04 | -9,811E+02 | 1,940E+04 | 3,479E+02 | 1,940E+04 | -7,815E+02 |
| 1,940E+04 | 5,731E+02 | 1,940E+04 | -1,053E+03 | 1,940E+04 | 4,073E+02 | 1,940E+04 | -8,320E+02 |
| 1,941E+04 | 5,390E+02 | 1,941E+04 | -1,074E+03 | 1,941E+04 | 4,080E+02 | 1,941E+04 | -8,028E+02 |
| 1,941E+04 | 4,881E+02 | 1,941E+04 | -9,810E+02 | 1,941E+04 | 3,778E+02 | 1,941E+04 | -7,179E+02 |
| 1,942E+04 | 4,328E+02 | 1,942E+04 | -8,450E+02 | 1,942E+04 | 3,400E+02 | 1,942E+04 | -6,199E+02 |
| 1,942E+04 | 3,738E+02 | 1,942E+04 | -7,345E+02 | 1,942E+04 | 2,977E+02 | 1,942E+04 | -5,396E+02 |
| 1,943E+04 | 3,056E+02 | 1,943E+04 | -6,155E+02 | 1,943E+04 | 2,502E+02 | 1,943E+04 | -4,416E+02 |
| 1,943E+04 | 2,295E+02 | 1,943E+04 | -4,673E+02 | 1,943E+04 | 1,959E+02 | 1,943E+04 | -3,314E+02 |
| 1,944E+04 | 1,483E+02 | 1,944E+04 | -3,054E+02 | 1,944E+04 | 1,318E+02 | 1,944E+04 | -2,124E+02 |
| 1,944E+04 | 3,409E+01 | 1,944E+04 | -1,486E+02 | 1,944E+04 | 5,916E+01 | 1,944E+04 | -9,356E+01 |
| 1,945E+04 | -5,486E+01 | 1,945E+04 | 4,410E+00 | 1,945E+04 | -1,724E+01 | 1,945E+04 | 2,551E+01 |
| 1,945E+04 | -1,353E+02 | 1,945E+04 | 1,279E+02 | 1,945E+04 | -7,236E+01 | 1,945E+04 | 1,102E+02 |
| 1,946E+04 | -1,910E+02 | 1,946E+04 | 2,375E+02 | 1,946E+04 | -1,190E+02 | 1,946E+04 | 1,914E+02 |
| 1,946E+04 | -2,376E+02 | 1,946E+04 | 3,055E+02 | 1,946E+04 | -1,610E+02 | 1,946E+04 | 2,505E+02 |
| 1,947E+04 | -2,801E+02 | 1,947E+04 | 3,649E+02 | 1,947E+04 | -1,912E+02 | 1,947E+04 | 3,013E+02 |
| 1,947E+04 | -3,394E+02 | 1,947E+04 | 4,544E+02 | 1,947E+04 | -2,549E+02 | 1,947E+04 | 3,653E+02 |
| 1,948E+04 | -4,037E+02 | 1,948E+04 | 5,141E+02 | 1,948E+04 | -3,096E+02 | 1,948E+04 | 4,163E+02 |
| 1,948E+04 | -4,500E+02 | 1,948E+04 | 5,730E+02 | 1,948E+04 | -3,649E+02 | 1,948E+04 | 4,668E+02 |
| 1,949E+04 | -4,419E+02 | 1,949E+04 | 5,692E+02 | 1,949E+04 | -3,910E+02 | 1,949E+04 | 4,419E+02 |
| 1,949E+04 | -3,989E+02 | 1,949E+04 | 4,752E+02 | 1,949E+04 | -3,698E+02 | 1,949E+04 | 3,525E+02 |
| 1,950E+04 | -3,398E+02 | 1,950E+04 | 4,036E+02 | 1,950E+04 | -3,354E+02 | 1,950E+04 | 2,842E+02 |
| 1,950E+04 | -2,632E+02 | 1,950E+04 | 2,930E+02 | 1,950E+04 | -2,760E+02 | 1,950E+04 | 1,993E+02 |
| 1,951E+04 | -1,872E+02 | 1,951E+04 | 1,996E+02 | 1,951E+04 | -2,208E+02 | 1,951E+04 | 1,190E+02 |
| 1,951E+04 | -1,192E+02 | 1,951E+04 | 1,059E+02 | 1,951E+04 | -1,702E+02 | 1,951E+04 | 3,427E+01 |
| 1,952E+04 | -2,929E+01 | 1,952E+04 | -3,383E+01 | 1,952E+04 | -1,058E+02 | 1,952E+04 | -7,203E+01 |
| 1,952E+04 | 5,101E+01 | 1,952E+04 | -1,531E+02 | 1,952E+04 | -4,673E+01 | 1,952E+04 | -1,574E+02 |
| 1,953E+04 | 1,189E+02 | 1,953E+04 | -2,590E+02 | 1,953E+04 | 8,608E+00 | 1,953E+04 | -2,503E+02 |
| 1,953E+04 | 1,869E+02 | 1,953E+04 | -3,864E+02 | 1,953E+04 | 5,917E+01 | 1,953E+04 | -3,482E+02 |
| 1,954E+04 | 2,507E+02 | 1,954E+04 | -5,179E+02 | 1,954E+04 | 1,106E+02 | 1,954E+04 | -4,370E+02 |
| 1,954E+04 | 3,184E+02 | 1,954E+04 | -6,323E+02 | 1,954E+04 | 1,613E+02 | 1,954E+04 | -5,347E+02 |
| 1,955E+04 | 3,823E+02 | 1,955E+04 | -7,262E+02 | 1,955E+04 | 2,166E+02 | 1,955E+04 | -5,988E+02 |
| 1,955E+04 | 4,371E+02 | 1,955E+04 | -8,321E+02 | 1,955E+04 | 2,634E+02 | 1,955E+04 | -6,794E+02 |
| 1,956E+04 | 5,012E+02 | 1,956E+04 | -9,089E+02 | 1,956E+04 | 3,315E+02 | 1,956E+04 | -7,342E+02 |
| 1,956E+04 | 5,307E+02 | 1,956E+04 | -9,298E+02 | 1,956E+04 | 3,817E+02 | 1,956E+04 | -7,094E+02 |
| 1,957E+04 | 5,052E+02 | 1,957E+04 | -8,325E+02 | 1,957E+04 | 3,691E+02 | 1,957E+04 | -6,365E+02 |
| 1,957E+04 | 4,628E+02 | 1,957E+04 | -7,307E+02 | 1,957E+04 | 3,355E+02 | 1,957E+04 | -5,432E+02 |
| 1,958E+04 | 4,329E+02 | 1,958E+04 | -6,496E+02 | 1,958E+04 | 3,098E+02 | 1,958E+04 | -4,711E+02 |
| 1,958E+04 | 3,860E+02 | 1,958E+04 | -5,693E+02 | 1,958E+04 | 2,715E+02 | 1,958E+04 | -4,161E+02 |
| 1,959E+04 | 3,013E+02 | 1,959E+04 | -4,461E+02 | 1,959E+04 | 2,041E+02 | 1,959E+04 | -3,228E+02 |
| 1,959E+04 | 2,036E+02 | 1,959E+04 | -3,060E+02 | 1,959E+04 | 1,398E+02 | 1,959E+04 | -2,213E+02 |
| 1,960E+04 | 1,065E+02 | 1,960E+04 | -1,701E+02 | 1,960E+04 | 7,627E+01 | 1,960E+04 | -1,188E+02 |
| 1,960E+04 | 2,955E+01 | 1,960E+04 | -4,201E+01 | 1,960E+04 | 2,132E+01 | 1,960E+04 | -2,522E+01 |
| 1,961E+04 | 5,121E-01 | 1,961E+04 | 4,188E-01 | 1,961E+04 | 7,899E-01 | 1,961E+04 | 5,121E-01 |

*Table 6 Signal values from first PVC ring set up (regular tape) second test*

| Point 0 | | Point 90 | | Point 180 | | Point 270 | |
|---|---|---|---|---|---|---|---|
| Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] |
| 1,976E+04 | -1,734E+01 | 1,976E+04 | 1,304E+01 | 1,976E+04 | -1,270E+01 | 1,976E+04 | 8,154E+00 |
| 1,977E+04 | -1,570E+02 | 1,977E+04 | 1,568E+02 | 1,978E+04 | -2,674E+02 | 1,977E+04 | 1,615E+02 |
| 1,978E+04 | -3,268E+02 | 1,978E+04 | 2,593E+02 | 1,980E+04 | -6,622E+02 | 1,978E+04 | 2,764E+02 |
| 1,979E+04 | -5,646E+02 | 1,979E+04 | 3,139E+02 | 1,982E+04 | -6,331E+02 | 1,979E+04 | 3,188E+02 |
| 1,980E+04 | -7,725E+02 | 1,980E+04 | 3,229E+02 | 1,984E+04 | -3,818E+02 | 1,980E+04 | 2,123E+02 |
| 1,981E+04 | -9,721E+02 | 1,981E+04 | 1,150E+02 | 1,986E+04 | -2,505E+02 | 1,981E+04 | 1,258E+01 |
| 1,982E+04 | -9,088E+02 | 1,982E+04 | -1,316E+02 | 1,988E+04 | -2,376E+02 | 1,982E+04 | -1,736E+02 |
| 1,983E+04 | -7,391E+02 | 1,983E+04 | -2,547E+02 | 1,990E+04 | -3,649E+02 | 1,983E+04 | -3,691E+02 |
| 1,984E+04 | -5,651E+02 | 1,984E+04 | -4,583E+02 | 1,992E+04 | -5,736E+02 | 1,984E+04 | -5,983E+02 |
| 1,985E+04 | -4,458E+02 | 1,985E+04 | -5,647E+02 | 1,994E+04 | -8,447E+02 | 1,985E+04 | -7,178E+02 |
| 1,986E+04 | -3,357E+02 | 1,986E+04 | -6,619E+02 | 1,996E+04 | -9,850E+02 | 1,986E+04 | -8,279E+02 |
| 1,987E+04 | -2,124E+02 | 1,987E+04 | -7,901E+02 | 1,998E+04 | -6,624E+02 | 1,987E+04 | -9,596E+02 |
| 1,988E+04 | -2,803E+02 | 1,988E+04 | -8,833E+02 | 2,000E+04 | -3,612E+02 | 1,988E+04 | -9,681E+02 |
| 1,989E+04 | -4,116E+02 | 1,989E+04 | -8,703E+02 | 2,002E+04 | 7,464E-01 | 1,989E+04 | -8,704E+02 |
| 1,990E+04 | -5,351E+02 | 1,990E+04 | -7,854E+02 | 2,004E+04 | 4,159E+02 | 1,990E+04 | -7,643E+02 |
| 1,991E+04 | -6,713E+02 | 1,991E+04 | -6,626E+02 | 2,006E+04 | 1,868E+02 | 1,991E+04 | -6,412E+02 |
| 1,992E+04 | -8,238E+02 | 1,992E+04 | -5,738E+02 | 2,008E+04 | -8,521E-01 | 1,992E+04 | -5,390E+02 |
| 1,993E+04 | -9,936E+02 | 1,993E+04 | -4,158E+02 | | | 1,993E+04 | -3,780E+02 |
| 1,994E+04 | -1,138E+03 | 1,994E+04 | -2,800E+02 | | | 1,994E+04 | -2,205E+02 |
| 1,995E+04 | -1,270E+03 | 1,995E+04 | -9,773E+01 | | | 1,995E+04 | -1,683E+01 |
| 1,996E+04 | -1,112E+03 | 1,996E+04 | 7,658E+01 | | | 1,996E+04 | 4,903E+00 |
| 1,997E+04 | -8,871E+02 | 1,997E+04 | -4,646E+00 | | | 1,997E+04 | -1,356E+02 |
| 1,998E+04 | -7,091E+02 | 1,998E+04 | -1,445E+02 | | | 1,998E+04 | -2,888E+02 |
| 1,999E+04 | -5,137E+02 | 1,999E+04 | -2,591E+02 | | | 1,999E+04 | -4,164E+02 |
| 2,000E+04 | -3,436E+02 | 2,000E+04 | -3,693E+02 | | | 2,000E+04 | -5,390E+02 |
| 2,001E+04 | -1,611E+02 | 2,001E+04 | -4,924E+02 | | | 2,001E+04 | -6,580E+02 |
| 2,002E+04 | 8,076E+01 | 2,002E+04 | -5,520E+02 | | | 2,002E+04 | -7,175E+02 |
| 2,003E+04 | 3,146E+02 | 2,003E+04 | -5,731E+02 | | | 2,003E+04 | -6,372E+02 |
| 2,004E+04 | 5,055E+02 | 2,004E+04 | -3,904E+02 | | | 2,004E+04 | -3,736E+02 |
| 2,005E+04 | 4,249E+02 | 2,005E+04 | -1,106E+02 | | | 2,005E+04 | -1,443E+02 |
| 2,006E+04 | 2,163E+02 | 2,006E+04 | -5,085E+01 | | | 2,006E+04 | -5,962E+01 |
| 2,007E+04 | 5,013E+00 | 2,007E+04 | -3,379E-01 | | | 2,007E+04 | -4,837E+00 |

*Table 7 Signal values from first PVC tube set up (regular tape)*

| Point 0 | | Point 90 | | Point 180 | | Point 270 | |
|---|---|---|---|---|---|---|---|
| Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] | Length [mm] | Strain [microstrain] |
| 1,929E+04 | -2,695E-02 | 2,000E+04 | 4,231E+00 | 1,929E+04 | -4,207E+00 | 2,000E+04 | -1,431E-01 |
| 1,929E+04 | -1,706E+01 | 2,002E+04 | 3,224E+02 | 1,929E+04 | -1,676E+01 | 2,002E+04 | 2,462E+02 |
| 1,930E+04 | -5,082E+01 | 2,004E+04 | 5,730E+02 | 1,930E+04 | -4,613E+01 | 2,004E+04 | 5,005E+02 |
| 1,930E+04 | -9,722E+01 | 2,006E+04 | 1,441E+02 | 1,930E+04 | -8,894E+01 | 2,006E+04 | 3,797E+01 |
| 1,931E+04 | -1,656E+02 | 2,008E+04 | -2,675E+02 | 1,931E+04 | -1,492E+02 | 2,008E+04 | -3,864E+02 |
| 1,931E+04 | -2,334E+02 | 2,010E+04 | -8,068E+02 | 1,931E+04 | -2,168E+02 | 2,010E+04 | -9,215E+02 |
| 1,932E+04 | -3,223E+02 | 2,012E+04 | -1,167E+03 | 1,932E+04 | -2,978E+02 | 2,012E+04 | -1,291E+03 |
| 1,932E+04 | -3,867E+02 | 2,014E+04 | -9,510E+02 | 1,932E+04 | -3,650E+02 | 2,014E+04 | -1,095E+03 |
| 1,933E+04 | -4,674E+02 | 2,016E+04 | -3,571E+02 | 1,933E+04 | -4,419E+02 | 2,016E+04 | -6,109E+02 |
| 1,933E+04 | -5,309E+02 | 2,018E+04 | 1,150E+02 | 1,933E+04 | -5,011E+02 | 2,018E+04 | 1,078E+00 |
| 1,934E+04 | -5,645E+02 | 2,020E+04 | 5,101E+02 | 1,934E+04 | -5,269E+02 | 2,020E+04 | 4,116E+02 |
| 1,934E+04 | -5,815E+02 | 2,022E+04 | 6,489E-01 | 1,934E+04 | -5,351E+02 | 2,022E+04 | -3,711E-01 |
| 1,935E+04 | -5,908E+02 | 2,024E+04 | -4,071E+02 | 1,935E+04 | -5,135E+02 | 2,024E+04 | -5,562E+02 |
| 1,935E+04 | -5,562E+02 | 2,026E+04 | -7,642E+02 | 1,935E+04 | -4,203E+02 | 2,026E+04 | -8,660E+02 |
| 1,936E+04 | -4,715E+02 | 2,028E+04 | -8,894E-01 | 1,936E+04 | -3,230E+02 | 2,028E+04 | 2,239E-01 |
| 1,936E+04 | -3,911E+02 | | | 1,936E+04 | -2,547E+02 | | |
| 1,937E+04 | -3,527E+02 | | | 1,937E+04 | -2,206E+02 | | |
| 1,937E+04 | -3,226E+02 | | | 1,937E+04 | -1,951E+02 | | |
| 1,938E+04 | -2,931E+02 | | | 1,938E+04 | -1,739E+02 | | |
| 1,938E+04 | -2,587E+02 | | | 1,938E+04 | -1,486E+02 | | |
| 1,939E+04 | -1,955E+02 | | | 1,939E+04 | -1,019E+02 | | |
| 1,939E+04 | -1,273E+02 | | | 1,939E+04 | -4,225E+01 | | |
| 1,940E+04 | -5,121E+01 | | | 1,940E+04 | 2,530E+01 | | |
| 1,940E+04 | 1,232E+01 | | | 1,940E+04 | 7,674E+01 | | |
| 1,941E+04 | 7,661E+01 | | | 1,941E+04 | 1,276E+02 | | |
| 1,941E+04 | 1,364E+02 | | | 1,941E+04 | 1,617E+02 | | |
| 1,942E+04 | 8,048E+01 | | | 1,942E+04 | 1,186E+02 | | |
| 1,942E+04 | -2,952E+01 | | | 1,942E+04 | 2,949E+01 | | |
| 1,943E+04 | -1,484E+02 | | | 1,943E+04 | -8,097E+01 | | |
| 1,943E+04 | -2,338E+02 | | | 1,943E+04 | -1,572E+02 | | |
| 1,944E+04 | -2,717E+02 | | | 1,944E+04 | -1,957E+02 | | |
| 1,944E+04 | -3,188E+02 | | | 1,944E+04 | -2,380E+02 | | |
| 1,945E+04 | -3,607E+02 | | | 1,945E+04 | -2,799E+02 | | |
| 1,945E+04 | -3,859E+02 | | | 1,945E+04 | -3,013E+02 | | |
| 1,946E+04 | -4,157E+02 | | | 1,946E+04 | -3,309E+02 | | |
| 1,946E+04 | -4,674E+02 | | | 1,946E+04 | -3,825E+02 | | |
| 1,947E+04 | -5,177E+02 | | | 1,947E+04 | -4,331E+02 | | |
| 1,947E+04 | -5,902E+02 | | | 1,947E+04 | -5,054E+02 | | |
| 1,948E+04 | -6,619E+02 | | | 1,948E+04 | -5,820E+02 | | |
| 1,948E+04 | -7,388E+02 | | | 1,948E+04 | -6,582E+02 | | |
| 1,949E+04 | -8,620E+02 | | | 1,949E+04 | -7,732E+02 | | |
| 1,949E+04 | -9,000E+02 | | | 1,949E+04 | -8,278E+02 | | |
| 1,950E+04 | -8,571E+02 | | | 1,950E+04 | -8,151E+02 | | |
| 1,950E+04 | -8,028E+02 | | | 1,950E+04 | -7,646E+02 | | |
| 1,951E+04 | -7,562E+02 | | | 1,951E+04 | -7,216E+02 | | |
| 1,951E+04 | -7,002E+02 | | | 1,951E+04 | -6,663E+02 | | |
| 1,952E+04 | -6,536E+02 | | | 1,952E+04 | -6,159E+02 | | |
| 1,952E+04 | -5,774E+02 | | | 1,952E+04 | -5,434E+02 | | |
| 1,953E+04 | -5,135E+02 | | | 1,953E+04 | -4,757E+02 | | |
| 1,953E+04 | -4,417E+02 | | | 1,953E+04 | -4,079E+02 | | |
| 1,954E+04 | -3,566E+02 | | | 1,954E+04 | -3,230E+02 | | |
| 1,954E+04 | -2,678E+02 | | | 1,954E+04 | -2,333E+02 | | |
| 1,955E+04 | -2,083E+02 | | | 1,955E+04 | -1,744E+02 | | |
| 1,955E+04 | -1,318E+02 | | | 1,955E+04 | -9,768E+01 | | |
| 1,956E+04 | -5,105E+01 | | | 1,956E+04 | -2,091E+01 | | |
| 1,956E+04 | 2,565E+01 | | | 1,956E+04 | 6,396E+01 | | |
| 1,957E+04 | 8,524E+01 | | | 1,957E+04 | 1,398E+02 | | |
| 1,957E+04 | 1,695E+02 | | | 1,957E+04 | 1,995E+02 | | |
| 1,958E+04 | 1,914E+02 | | | 1,958E+04 | 1,782E+02 | | |
| 1,958E+04 | 1,658E+02 | | | 1,958E+04 | 1,492E+02 | | |
| 1,959E+04 | 1,316E+02 | | | 1,959E+04 | 1,145E+02 | | |
| 1,959E+04 | 8,115E+01 | | | 1,959E+04 | 6,781E+01 | | |
| 1,960E+04 | 5,046E+01 | | | 1,960E+04 | 3,832E+01 | | |
| 1,960E+04 | 1,293E+01 | | | 1,960E+04 | 8,538E+00 | | |
| 1,961E+04 | 3,483E-01 | | | 1,961E+04 | -3,827E+00 | | |

*Table 8 Signal values from second PVC tube set up (regular tape)*

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

**Enhet:** **Department of Mechanical and Industrial Engineering** **Dato: 24/05/2017**

**Linjeleder:**

**Deltakere ved kartleggingen** (m/ funksjon)**: Nils Petter Vedvik, Enrique Martín de Saavedra Navarro**
*(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)*

**Kort beskrivelse av hovedaktivitet/hovedprosess:** Buckling due to external pressure of tubes measured by Rayleigh optical backscatter reflectometry.

**Er oppgaven rent teoretisk?** (JA/NEI)**:** *NEI*

**Signaturer:** *Ansvarlig veileder:* *Student:*

| ID nr. | Aktivitet/prosess | Ansvarlig | Eksisterende dokumentasjon | Eksisterende sikringstiltak | Lov, forskrift o.l. | Kommentar |
|---|---|---|---|---|---|---|
| 01 | Implementation of the fiber inside the tube. | Student | - | Teflon paper and acetone. | - | - |
| 02 | Manufacturing of parts and structures. | Student | - | Safety glasses, | - | - |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

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

**Enhet:** **Department of Mechanical and Industrial Engineering** **Dato: 24/05/2017**

**Linjeleder:**

**Deltakere ved kartleggingen (m/ funksjon): Nils Petter Vedvik, Enrique Martín de Saavedra Navarro**
*(Ansv. Veileder, student, evt. medveiledere, evt. andre m. kompetanse)*

**Risikovurderingen gjelder hovedaktivitet:** Buckling due to external pressure of tubes measured by Rayleigh optical backscatter reflectometry.

**Signaturer:** *Ansvarlig veileder:* *Student:*

| 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) | | |
| 01 | Implementation of the fiber inside the tube. | Stick yourself to other objects or to yourself. | 2 | B | - | - | - | B2 | Awareness of the properties of adhesives used. Use of teflon paper to prevent. Use of acetone to unstick. |
| 02 | Manufacturing of parts and structures. | Flying rest of material getting into the eye. | 3 | C | - | - | - | C3 | Use of safety glasses. |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

## Sannsynlighet vurderes etter følgende kriterier:

| Svært liten<br>1 | Liten<br>2 | Middels<br>3 | Stor<br>4 | Svært stor<br>5 |
|---|---|---|---|---|
| 1 gang pr 50 år eller sjeldnere | 1 gang pr 10 år eller sjeldnere | 1 gang pr år eller sjeldnere | 1 gang pr måned eller sjeldnere | Skjer ukentlig |

## Konsekvens vurderes etter følgende kriterier:

| Gradering | Menneske | Ytre miljø<br>Vann, jord og luft | Øk/materiell | Omdømme |
|---|---|---|---|---|
| **E**<br>**Svært Alvorlig** | Død | Svært langvarig og ikke reversibel skade | Drifts- eller aktivitetsstans >1 år. | Troverdighet og respekt betydelig og varig svekket |
| **D**<br>**Alvorlig** | Alvorlig personskade.<br>Mulig uførhet. | Langvarig skade. Lang restitusjonstid | Driftsstans > ½ år<br>Aktivitetsstans i opp til 1 år | Troverdighet og respekt betydelig svekket |
| **C**<br>**Moderat** | Alvorlig personskade. | Mindre skade og lang restitusjonstid | Drifts- eller aktivitetsstans < 1 mnd | Troverdighet og respekt svekket |
| **B**<br>**Liten** | Skade som krever medisinsk behandling | Mindre skade og kort restitusjonstid | Drifts- eller aktivitetsstans < 1uke | Negativ påvirkning på troverdighet og respekt |
| **A**<br>**Svært liten** | Skade som krever førstehjelp | Ubetydelig skade og kort restitusjonstid | Drifts- eller aktivitetsstans < 1dag | Liten påvirkning på troverdighet og respekt |

**Risikoverdi = Sannsynlighet x Konsekvens**
Beregn risikoverdi for Menneske. Enheten vurderer selv om de i tillegg vil beregne risikoverdi for Ytre miljø, Økonomi/materiell og Omdømme. I så fall beregnes disse hver for seg.

**Til kolonnen "Kommentarer/status, forslag til forebyggende og korrigerende tiltak":**
Tiltak kan påvirke både sannsynlighet og konsekvens. Prioriter tiltak som kan forhindre at hendelsen inntreffer, dvs. sannsynlighetsreduserende tiltak foran skjerpet beredskap, dvs. konsekvensreduserende tiltak.

# MATRISE FOR RISIKOVURDERINGER ved NTNU

| | | | | | | |
|---|---|---|---|---|---|---|
| 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. |