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Innovative Impact Protection and Monitoring System for Composite Pressure Vessels

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Preface

This masters thesis was carried out in the spring of 2015 at NTNU at the department of product development and materials. As composite pressure vessels are becoming more widely used it is crucial to ensure safe and predictable use of such vessels. Impacted composites in particular are difficult to assess and current standards normally unsuitable for composites. This thesis aims to develop a system for impact protection and impact detection for composite pressure vessels. Further this thesis is intended for professors, master/PhD students and industry professionals with a particular interest in composite pressure vessels.

During this thesis composite pipes have been manufactured and promising technologies and protection materials have been experimentally tested. Based on these tests, a prototype was developed that was able to protect the composite from impact and measure the location and to some extent the magnitude of the impact. This prototype is a proof of concept for an impact protection system.

On a less serious note: After hours upon days of blood, sweat and tears at the frontier of science, a functional prototype was assembled and tested. As one famously said: “Success is the sum of small efforts, repeated day in and day out.” This thesis is the sum of many small battles. Some battles were easy; as the testing of protection materials. Others were hard; the impact detection system. Yet other battles were lost, like the composite pressure testing. Although the battles were long and strenuous, the author prevailed and can now present a functional prototype of an impact protection and detection system.

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Paul A. Kopperud

Acknowledgment

First and foremost I would like to thank my two supervisors, Andreas Echtemeyer and Nils Petter Vedvik for their invaluable help and advice during the work on this thesis. I would like to thank Martin Skaar and Vadim Khentalov for the productive collaboration on both production and testing of the composites pipes. Thanks also to Carl Magnus Midtbø for his help with the filament winding machine.

I would also like to thank all inhabitants of my office 230 and the unique atmosphere that has both been of great help and great distraction for my thesis. The people of 230 have made the writing of my thesis enjoyable and fun. Great thanks to Eivind Haarberg, Sigmund Tronvoll, Vadim Khentalov, Martin Welle Skaar, Sigbjørn Aukland and Christian Finnstrøm. A special thanks to Eivind Haarberg for his moral support and assistance.

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Last but definitely not least I would like to thank Jennifer A. Sweeting for all her help, encouragements and patience with me during the writing of my thesis.

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Summary and Conclusions

Impact behavior and resistance of composite structures are difficult to predict. For composite pressure vessels, where failure can be fatal, impact protection and detection is particularly important. This thesis aims to render high pressure composite vessels safer to use with regards to impact. Three main objectives were identified; Firstly, finding an effective impact protection method and material. Secondly, developing a low cost impact detection system. Lastly, find an approach to estimate the severity of damage in an impacted composite vessel. Adopting an experimental approach, each objective was investigated separately before combining them into a final prototype.

For the protective material, a material-search was conducted where cross-linked Polyvinyl Chloride foam (X-PVC), Polyethylene terephthalate foam (PET) and Low-density polyethylene foam (LDPE) were chosen and impact tested. X-PVC was identified as the most promising impact absorption material for protection of composite pressure vessels.

The low cost solution for impact detection was developed by taking advantage of the elastic wave induced in the composite material during an impact. Instrumenting the pressure vessel with simple piezo elements and an accelerometer together with a low cost processor, allowed detection of the elastic waves and the origin of the impacts on a composite tube.

Residual strain in the composite after impact was tested in an attempt to assess impact damage. Optical fiber strain measurements were conducted to register the residual strain after impact. Elevated strains were found and correlation between impact damage and the residual strain was identified.

As a proof of concept, a final prototype was built, satisfying the main objectives; The protective material was able to fully protect the impacted pipe as no visible damage was detected. The low cost piezo element was able to detect the imposed impacts and residual strain measurement in the composite indicated a low level of damage as well as predicting the location of damage.

Sammendrag og konklusjon

Kompositter er komplekse materialer og deres motstand mot støt er vanskelig å forutsi. For trykktanker i kompositt, hvor svikt kan bli fatalt, er støtbeskyttelse og deteksjon spesielt viktig. Denne masteroppgavens mål er å gjøre trykktanker i kompositt tryggere å bruke. Tre hovedmål er satt opp; finne en effektiv beskyttelsesmetode og passende material, utvikle en lav-kost støt-deteksjonsløsning og finne en metode for skadeevaluering for støtskadede kompositt tanker. Hvert delmål ble undersøkt ekspirementellt hvorpå løsningene satt sammen til en endelig prototype.

For den beskyttende løsningen ble det foretatt et materialsøk hvor kryssbundet polyvinylklorid skum, Polyethylenterephthalat skum og lav-tetthets polyetylen ble valgt og testet eksperimentellt. Kryssbundet polyvinylklorid ble valgt som det mest lovende materialet for beskyttelse av trykktanker i kompositt.

Lav-kost løsningen ble utviklet for å utnytte den elastiske bølgen som blir indusert i komposittmaterialet ved et støt. Ved å bruke Piezo elementer og et akselerometer, koblet til en lav-kost mikrokontroller kunne den elastiske bølgen og støtlokasjon påvises.

Restspenningene i kompositten etter støt ble undersøkt for å vurdere skadeomfang. Fiberoptiske tøyningsmålinger ble gjennomført for å kartlegge restspenninger i komposittprøven etter støt. Forhøyede tøyningsverdier ble påvist og korrelasjon mellom støtskade og restspenninger ble registrert.

Den utviklede prototypen tilfredstillte hovedmålene og er dermed en konsuptuell verifikasjon. Beskyttelsesmaterialet beskyttet komposittstrukture og ingen visuell skade ble detektert. Lav-kost løsningen detekterte støt og restspenningsløsningen påviste begrenset skade samtidig som å indikere støtlokasjon.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

Over the last three decades the use of composite materials has increased exponentially. Weight reduction, shape optimization, superior mechanical properties, chemical resistance and several other factors have promoted its use. Composite materials were for many years regarded as "high-tech" and have primarily been used in the aerospace industry. In recent years however, several other industries have employed composites, ranging from automotive to gas storage systems. With the great versatility of composite materials comes also great complexity. Specifically the impact behavior and resistance of composite structures are difficult to predict and has been of great focus in the scientific community over the last decade. This is particularly important for composite pressure vessels where impact damage could result in fatal accidents.

Problem Formulation

The overall challenge this thesis aims to investigate and resolve, is to render high pressure composite vessels safer to use with regards to impact. Firstly, impacts in composites are difficult to detect. Secondly, because of the many failure modes of composites, impact damage is difficult to assess. Lastly, impacts can induce internal damage which may not be visible on external surfaces. This implies that composite pressure vessels could sustain damage that goes undetected, rendering the vessel as potentially dangerous and health hazardous. It also implies that if damage was detected there is great uncertainty regarding the extent of damage and whether the pressure vessel is still safe to use. Low velocity impacts especially, such as dropped tools etc. induce such damage, and will be used as the main load case. Today, most composite pressure vessels are inspected visually and if cracks and other signs of impact damage are detected, the vessel is scrapped. Some experimental research exists that attempts to detect and evaluate damage for a composite pressure vessel. These solutions are complex and expensive thus only applicable for high-end industries. Additionally, even if a prediction of the residual strength is possible, who would take responsibility for the reliability of the predicted value? Since this is a health and safety issue, predicted values must be extensively tested and verified. There exists a grey zone between an undamaged pressure vessel and a fully damaged (unusable) pressure vessel, as there are most likely no stakeholders that would want to take responsibility for the integrity of the vessel with the technologies available at present. Therefore more research and perhaps different approaches are needed in this field.

There are three main areas of focus for this thesis. This thesis aims firstly to protect composite pressure vessel from impact. Secondly it aims to develop a low-cost solution for impact detection that could be used throughout the whole cost-range of composite pressure vessels. Lastly it aims to evaluate the impact and attempt to approximate the sustained damage in the composite vessel which would provide the user with an indication as to whether the vessel is safe to use.

In summary the objectives of this thesis are

1. Find an effective impact protection method and material
2. Develop a low cost impact detection system
3. Find a way to assess damage in composites after impact

1.2 The concept of an impact protection system

As mentioned above, this thesis aims to find solutions that will protect, detect and evaluate impacted pressure vessels. A protective structure outside the pressure vessel could mitigate any impacts induced onto the pressure vessel. Another system would register impact events and notify an operator that an impact event has occurred. Ultimately a third component or system could assess the damage induced in the composite pressure vessel and advice the operator whether the pressure vessel is safe to use. All these components together make up the "impact protection system" as shown in figure 1.1 which will be referred to throughout this thesis.

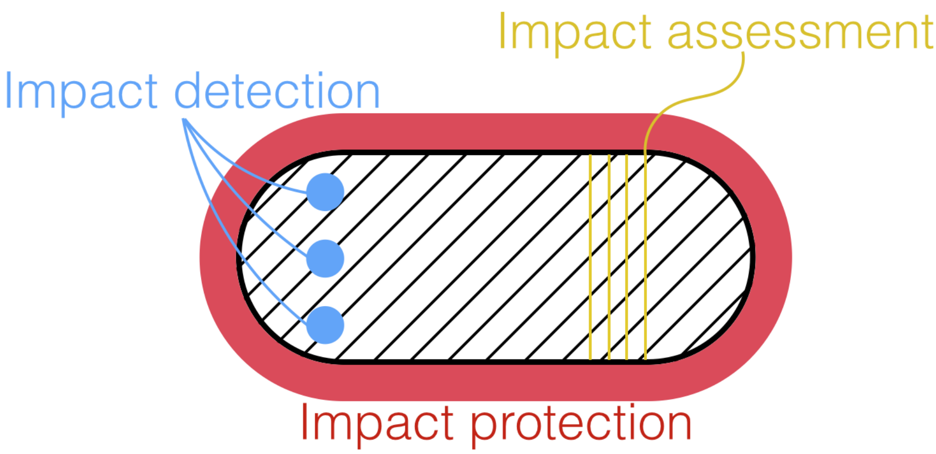


Figure 1.1: Impact protection system

1.3 Limitations

There are some limitations to this thesis. Economic limitation does not allow procurement of expensive services, materials and sensing equipment. Therefore in terms of high-cost items this thesis was limited to the current inventory at NTNU.

1.4 Approach

This thesis will begin with the examination of the current field of research regarding detection and protection of composite pressure vessels through an extended literature review. On the basis of the information found in the review, promising technologies and methods will be evaluated and tested experimentally. Experiments will comprise of drop weight impact testing and pressure testing on self-manufactured composite specimens. The experimental data will then be used as a basis for development and testing of a preliminary prototype.

1.5 Structure of the Report

The structure of the report is based on the natural developmental progression of a prototype, thus involving investigation of current technology, preliminary testing of each chosen concept, and development of a functional prototype.

Chapter 2 consists of the literature review where relevant research is described and evaluated. Chapter 2 is a summary of the full review that can be found in appendix B. This review provides an overview of current research and development on impact detection and protection of composite pressure vessels.

Chapter 3 describes production of composite specimens as well as preliminary experiments of the test-rig and protection materials.

Chapter 4 describes the experimental testing of the technology found promising in the literature review. Each technology is tested experimentally to investigate limitations and prepare for the construction of a prototype.

Chapter 5 summarizes the pressure tests of composite pipes. The full description of the conducted pressure-test and sealing methods attempted are outlined in appendix C.

Chapter 6 describes the development and testing of the impact protection system. Technologies tested in chapter 4 are implemented into one system and tested.

Chapter 7 contains the discussion, summary and conclusion for this thesis as well as recommendations for further work.

Chapter 2

Literature Review

In order to gain an overview of the existing research and development, a study of the existing literature on the subject was conducted. The purpose of this chapter is to outline the extent of current research related to impact protection and impact detection on pressurized composite vessels. In addition this chapter identifies how this thesis can contribute by integrating protection and detection in a single system. This literature review differs from most reviews because of the need for a wide overview of current research. Whereas most reviews only seek to emphasize and support theories used in the thesis, this literature review seeks to overview current technology on the field of impact protection and detection in composite pressure vessels.

2.1 Search matrix

As a tool to gain a preliminary overview of current research a search matrix was constructed. A search matrix will summarize how many articles or papers are present in a database, upon being matched with chosen key words.. As seen from table 2.1 and table 2.2 14 papers were chosen from the search regarding impact detection and 6 papers chosen from research regarding impact protection. The selection of papers was done by prioritizing subjects that could be related to composite pressure vessels and by filtering for duplicates (both exact duplicates and by topic) and for non relevant results. For a complete list of chosen articles see appendix B.

Table 2.1: Search matrix for impact detection technology and techniques

	Key words	**Results**	**Key words**	**Results**	**Key words**	**Results**	**Used**
Bibsys NTNU Library	Impact composite	63	impact composite pressure	3			0
Google Scholar (Year 2000-)	impact composite pressure vessel	29500	impact composite pressure vessel detection	17600	impact composite fibre pressure vessel detection monitoring	17300	4
Scopus (2000-)	Impact composite pressure	2001	composite pressure vessel impact	179			7
Compendex (2000-) (Journal & Conference)	Impact composite pressure	3772	composite pressure vessel impact	57			3

While searching for articles and papers on impact detection and protection for composite pressure vessels it quickly became obvious that there was a fairly limited amount of relevant research in this field. As seen from the search matrix there were few articles relevant to this thesis compared to the number of results in the search. What also became apparent was that within the defined search area no previous work had been done on combining impact protection and detection. Therefore a separate search for impact protection materials with a primary focus on foams was conducted to widen

Table 2.2: Search matrix for impact protection materials and techniques

	Key Words	Results	Key Words	Results	Key Words	Results	Used
Bibsys NTNU Library	Impact Foam	4					0
Google Schoolar	Energy Absorbing Material Low Velocity Impact Foam Overview	19100	Allintext: Energy Absorbing Material Low Velocity Impact Foam Overview	3340	Allintext: Energy Absorbing Material Low Velocity Impact Foam Overview -composites -sandwich	1830	4
Scopus	Impact Foam	4498	Impact Foam Material Low Velocity	212	Impact Foam Material Low Velocity -sandwich	101	0
Compendex	Impact Foam Protection Energy Absorption	117	Impact Foam Protection Energy Absorption Low Velocity	63			2

the literature review scope. Foam was focused on due to the great variety of suitable foam materials for impact protection. There were several studies regarding impact detection in composite vessels and some studies regarding impact protection materials. However no studies combined these two and studied the effects of impact protection on the ability of impact detection.

2.2 Findings

Since there are no current studies on the combination of impact protection and detection the literature review is divided into two parts; impact detection and impact protection.

2.2.1 Impact protection articles

Today there are many applications both in consumer products and in engineering that utilize impact protection. Consumer products like helmets, elbow/knee pads as well as running shoes, all provide impact protection through different principles. For engineering purposes however the impact energies vary significantly over a wide range of applications, everything from micro-impacts to ballistic protection. This literature review will examine research on impact absorbing materials and principles relevant for the protection of composite pressure vessels that could mitigate low velocity impacts. As mentioned in section 2.1 6 articles were chosen through the search. A summary of each article can be found in appendix B.

From the articles, we can obtain an overview of the current knowledge and research regarding protection materials for composites within the selected scope. It is apparent that a large portion of the research available is focused on vehicle and pedestrian safety in public traffic. Collapsible profiles and polymeric foams are used in vehicle bumpers. Most articles available are therefore tailored to that particular application. A smaller portion of the studies found are focused on high velocity impacts. These studies are mostly involving protection from projectiles or shrapnel for military purposes. For this thesis which is focused on low velocity impacts on composite pressure vessels none of the articles found are directly relevant. One can conclude that within the chosen search scope there are no relevant studies regarding impact protection of *composite pressure vessels*. However in the chosen articles there are many relevant principles, tools and materials that provide guidance for the development of a pressure vessel protection system.

One of the major research areas that was identified through this analysis is Finite Element models and analysis of protection materials during impact. During the last two centuries there has been great advances in computational methods for material analysis. Researchers have drawn upon these new possibilities to achieve a deeper understanding of material behavior under impact loading. Several papers describe the development of advanced and complex computational models for impact protection materials. Although it is not within the scope for this thesis, it is very likely that these models can be used to select an optimum impact material and configuration to protect composite pressure vessels under impact loading when developing an impact protection system.

The second area of focus within the search-scope is thin walled structures and their ability to absorb impacts. Extruded profiles predominantly made out of aluminum are impacted to map their effectiveness under impact loading. Optimization in both shape and wall thickness are conducted to find the best design. Although these profiles are mainly used as compression zones for automotive vehicles they could be considered for other purposes, such as absorbing impacts on composite pressure vessels.

Another area that researchers have investigated is the true impact performance of different cellular foams. Using energy-absorption diagrams, force-displacement/time measurements and other techniques researchers have been able to describe how different foams, both different materials and different densities, have different responses. Some foams are relatively brittle and will have other energy absorption modes than ductile foams. These are all aspects that will be important for the selection of a protective material for composite pressure vessels.

2.2.2 Impact detection and analysis

As described in section 2.1 several studies cover impact detection in composite materials. A small number of papers also cover impact detection in composite pressure vessels. 16 papers were found within the given search scope that provide an overview of current research regarding impact detection and residual strength in composites and composite pressure vessels.

In appendix B the author has summarized the chosen articles that describe the area of research regarding impact detection and analysis for composite pressure vessels. In line with the exponential increase of composite use over the last two decades, and the complexity of composite structures, there has been an accelerated interest in the field of structural health monitoring. In composite pressure vessels where impacts are considered to be one of the most detrimental modes of damage, health monitoring is mainly focused around impact detection and analysis. There are two main technologies that have been identified as the main focus within the search scope for impact detection and analysis for composite structures. One technology uses optical fibers to measure changes in reflective light within the fiber, thus enabling calculations of strain and temperature - among other measurements. The main advantage of this technology is the ability to measure the change in strain field in the composite material after an impact. The second takes advantage of the vibrations generated by either an impact or by a controllable frequency generator. The vibration response in the composite structure is measured, predominantly by piezo elements and will indicate damage and enable analysis of the changed physical properties of the component.

Another comprehensive area of research is understanding composite material behavior under impact loading and their corresponding failure modes. As described section 1.1, composite materials are complex and difficult to approximate, therefore several studies have been conducted to construct virtual finite element models that can describe composites under impact loading. Failure modes and progressive failure analysis in particular have been investigated in-depth to enable accurate determination of residual strength after impact in composites. Some of the studies found have been able to predict damage with relatively high accuracy using advanced models. However several challenges remains in order to apply these models to approximate residual strength in impacted composite structures. It is not within the scope of this thesis, it is however the main focus of my colleague's master thesis [1] with whom the author has collaborated.

In addition to these techniques identified by a literature review, other techniques were identified in the author's project thesis. These include ultra-sound, X-ray, Thermography and Eddy Current which are all used for damage evaluation in composites. These are all techniques that would provide the user with a relatively accurate damage assessment of a composite structure. In the project thesis however, it was concluded that these technologies require substantial framework to function and are both space and weight consuming. Additionally these techniques did not appear with the chosen search scope for the literature review. Conclusively these technologies will not be considered as viable options for applications in this thesis. On the other hand, fibre measurements, vibration measurements and conventional strain gauges have been highlighted as feasible options. These three techniques will be investigated and described in more detail in section 4.1 Experimental equipment and measurement tools.

2.3 Summary

From this literature review the author believes than an introductory overview of the current research field regarding impact protection and detection for composite pressure vessels has been achieved. By summarizing the two main fields of protection and detection it has become apparent that there are most likely no studies that cover protection and detection and how they interact. Promising technologies have been identified that take advantage of the change in strain in the composite after impact and change in vibration response. Additionally there are no studies within the search scope that cover low-cost solutions for impact detection in composite pressure vessels. This literature review has emphasized the need for further investigation of impact detection in combination with a protective layer. With the lack of any articles on the subject, it has also highlighted the need for a simple and low cost solution for impact detection. These are all aspects that this thesis will investigate further.

Chapter 3

Preliminary impact testing

In various industries today one can find several principles for impact protection. Many different technologies and materials are utilized to absorb the impact energy and protect the underlying structure. However as described in section 2 there has been limited research and no widely known commercially available solutions found for impact protection of composite pressure-vessels. Therefore this thesis will examine the effectiveness of different protection materials as well as testing the interaction between protective structures and damage detection systems. Preliminary testing was therefore conducted to evaluate different protection materials to identify the most promising for composite pressure-vessel protection.

In order to quantify the material's ability to withstand impact, several drop tests were conducted. Firstly this allowed us to construct a drop test rig that can be used for further experiments. Secondly it allows for rigorous testing of the test rig to identify potentials for improvement. Lastly and most importantly it will provide the author with an indication of which energy absorption material is most effective and what absorption mechanisms govern an impact on conventional materials. However before testing could be conducted composite test specimens had to be manufactured.

3.1 Production of test specimens

Composite test specimens were produced by the author in collaboration with two other master students (Martin Welle Skaar and Vadim Khentalov). This allowed us to control the quality and properties of the test-material. All composite specimens were made from glass fibre E-glass [2]. Carbon fibre is more common in large pressurized composite tanks for high pressure systems and could be used, however glass fibre poses less challenges in terms of production, handling, machining, post production inspection and health hazards.

3.1.1 Composite plates

For the preliminary testing of potential protection materials, a large amount of tests were necessary to ensure accurate readings by avoiding statistical variations. Hence a high volume of test specimens were needed. In cooperation with my supervisor, Andreas Echtemeyer, it was decided to use composite plates as a substitute for composite tubes or composite pressure vessels for these experiments. Based on the fact that a pressure vessel with high internal pressure will give a minimal amount of structural damping during an impact, it was believed that the impact response and damage pattern of a back-supported composite plate would be very similar to that of a pressurized composite tube (Figure 3.1). As a rough test of this assumption a simple FEM-analysis

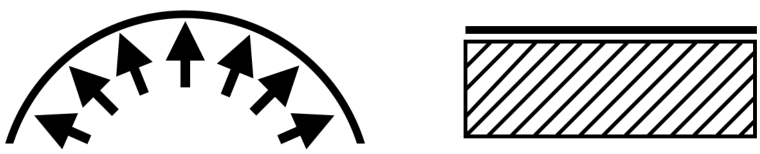


Figure 3.1: Difference in support, Pipe vs Plate

was conducted simulating the deflection in a composite tube with a 90,90,0,0,90,90 layup (typical pressure vessel layup) and internal pressure of 0-400 bar in 100bar increments. Figure 3.2 shows displacement vs applied energy for a static indentation of *one* node. As a reference; the chosen impact energy of 42 joules (2,9kg from 1500mm in section 3.4.1) is plotted in purple. As seen in the illustration the deflection in an un-pressurized pipe at 42 joules is 10mm. With increasing internal pressure the deflection at 42 joules decreases, and at 400 bar internal pressure the deflection was 4,5mm. This deflection is comparably large, cannot be neglected and does not directly support the assumption of using a plate as a substitute for a pipe. However, several aspects need to be taken into consideration. Firstly, since dynamic effects are not taken into account, inertia etc. it will yield a smaller deflection. Secondly the indentation was in one node, not an impactor shape, thus the deflection would also be reduced by introducing a real impactor shape. Lastly, in commercial composite high pressure tanks, wall thickness and operational pressure is significantly higher which further stiffens the system. Therefore one can assume that a composite plate can be used as a sufficient substitute in the preliminary testing.

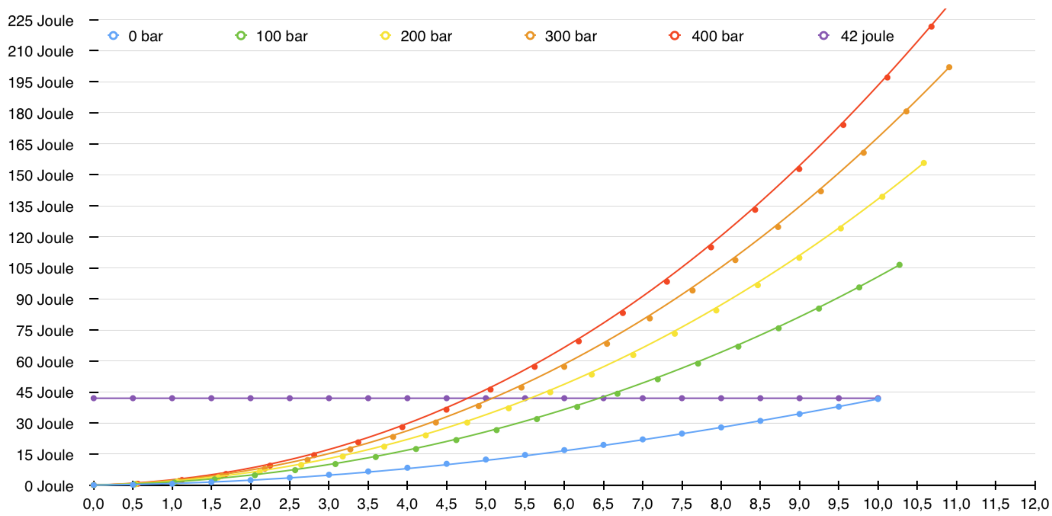


Figure 3.2: Results from FEM analysis, Joules on Y-axis, mm deflection on X-axis

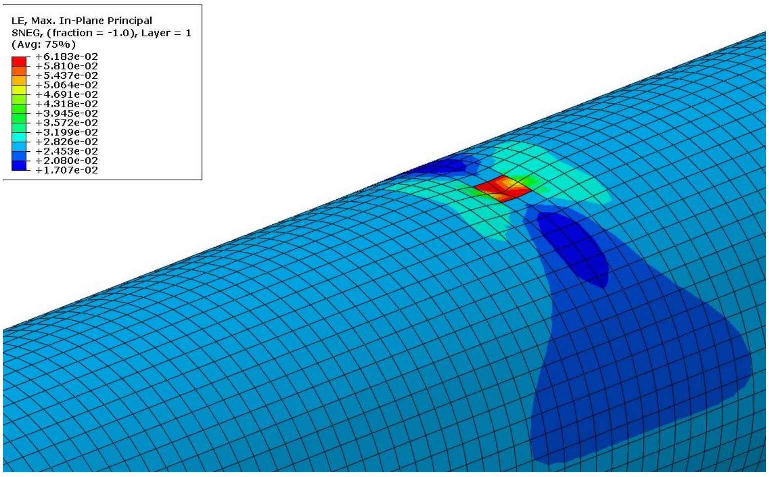


Figure 3.3: FEM model used to calculate deflection

The composite plates for this thesis were manufactured by vacuum infusion of glass fibre sheets[2] with a +-45 degree orientation infused with an Epoxy resin[3]. By stretching the fibre sheets before infusion a higher angle was achieved to attempt an angle closer to the optimal angle for pressure vessels +-55 degrees (see equation 3.6). Epoxy resin was drawn through the fibers by a vacuum pump. After the fibre was fully saturated with epoxy, the inlet and outlet hoses were clamped to maintain a vacuum and left for 24 hours to cure. The finished composite plate was then cut into smaller sheets, one for each impact test. Quality verification of the composite plate was conducted by visual inspection. By letting light pass through the plate one can easily spot impurities like air bubbles and other weakening factors. Upon inspection (Figure 3.6) no trapped air, impurities or other faults were found.

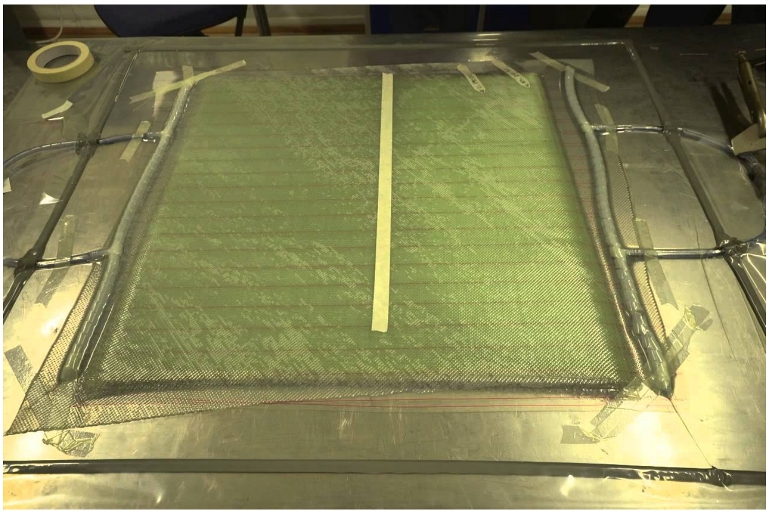


Figure 3.4: Vacuum Infusion of glass fibre composite plate

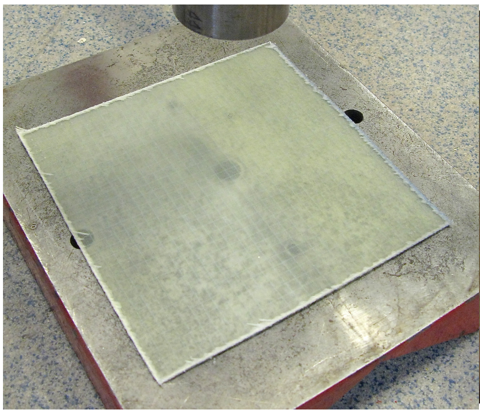


Figure 3.5: Cutout composite plate

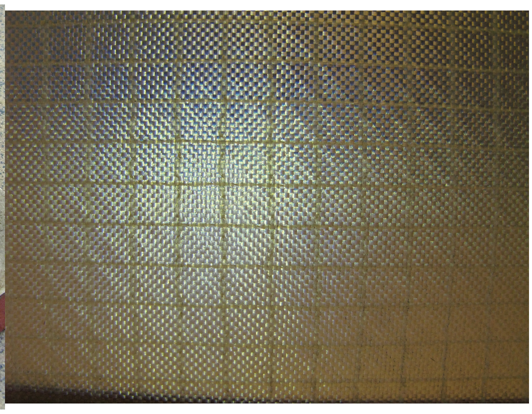


Figure 3.6: Visual inspection

3.1.2 Composite Tubes

For further testing a structure with similar mechanical properties to that of a pressure vessel is needed to ensure accurate test results. Therefore glass fibre composite tubes were produced by filament winding[4]. To determine the fibre layup of the composite tube one must calculate the forces acting on a pressurized composite tube. Firstly a simplification of the stress state in a pressurized tube yields the following:

- P=internal pressure
- r=radius of the pipe
- t=thickness of the pipe
- σ_l=longitudinal / axial stress
- σ_h=circumferential / hoop stress

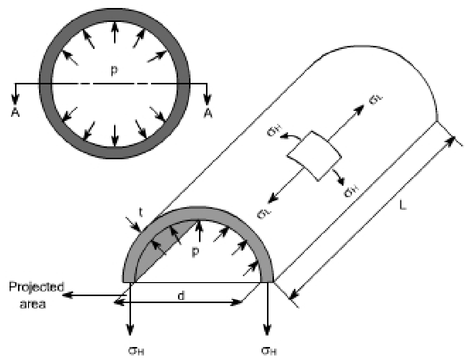


Figure 3.7: Pipe with internal pressure

$$\sigma_l = \text{(Force on axial section)/(axial Area)} = \frac{P\pi r^2}{2\pi r t} = \frac{Pr}{2t} \tag{3.1}$$

$$\sigma_h = \text{(Force on hoop section)/(hoop Area)} = \frac{P2rl}{2lt} = \frac{Pr}{t} \tag{3.2}$$

Combining 3.1 and 3.2 it is apparent that the hoop stresses are twice as high as in the axial direction. Therefore the fibers in the composite tube must be wound in such an angle that the hoop strength is double the axial strength. There are two main approaches to achieve this property and in this thesis both have been used in production of specimens. The first approach is to wind a multiple of three layers, two layers in the hoop direction (90 degrees) and one in the axial direction (0 degrees). The second method is to find a constant winding angle such that the resulting hoop strength : axial strength ratio is 2:1. Whereas the first method requires no calculations, the latter requires some approximations. To calculate the winding angle to achieve a 2:1 strength ratio we used a method called "Netting analysis". This analysis assumes that the epoxy (commonly called the matrix) does not carry any load. Further it is also assumed that the bending and shear stiffness of the composite tube is zero.

- T = tension in fibres
- n = number of fibres transmitting tension T
- α = winding angle

$$\sigma_h = nT\cos\alpha\frac{Pr}{t} \tag{3.3}$$

$$\sigma_l = nT\sin\alpha\tan\alpha\frac{Pr}{2t} \tag{3.4}$$

Calculating the stress balance $\sigma_h : \sigma_l$ we now get:

$$\frac{\sigma_h}{\sigma_l} = \frac{nT\cos\alpha\frac{Pr}{t}}{nT\sin\alpha\tan\alpha\frac{Pr}{2t}} = \frac{\cos\alpha}{\sin\alpha\tan\alpha\frac{1}{2}} = \frac{2}{(\tan\alpha)^2} \tag{3.5}$$

Therefore the optimal winding angle for pressurized composite tubes is:

$$\alpha = \arctan(\sqrt{2}) = 54.7 \tag{3.6}$$

After determining the optimal winding angle we proceeded to manufacture the pipe. The winding procedure, sectioning and strengthening considerations are described in detail in appendix F. In order to strengthen the end of the pipe sections a layer of +-45° fibre mats were added onto the pipe as seen in figure 3.8. This was to ensure failure in the pressurized pipe rather than at the boundaries during pressure testing.

Figure 3.8: +- 55° Pipe in curing oven, note fibre patches distributed along the pipe

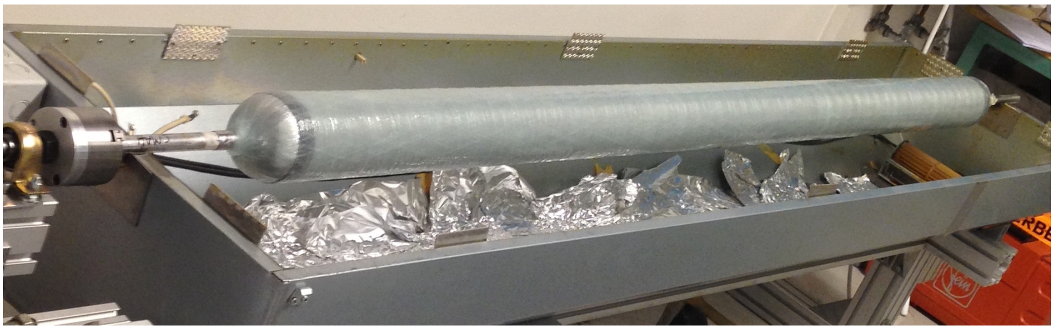


Figure 3.9: 90-0-90 ° pipe in curing oven

After cutting the pipe into the predetermined lengths a burn off test as well as a microscopy analysis was done to verify the material quality and properties to ensure that the test specimens were up to industry standards.

3.1.3 Burn-off test

A burn-off test is used to determine the volume fraction of fibers in the composite where high volume fractions are desirable. Industrial pressure vessels usually have a volume fraction between 50% and 60% [5]. Samples are heated to a temperature of 500 degrees Celsius to burn off the epoxy. By weighing the samples before and after the burn-off combined with the material density of the two components, the volume fraction can be determined by the following formula:

$$X_f = \frac{V_f}{V_{total}} = \frac{V_f}{V_m + V_f} = \frac{m_f/\rho_f}{m_m/\rho_m + m_f/\rho_f} = \frac{\frac{m_{total}-m_m}{\rho_f}}{\frac{m_m}{\rho_m} + \frac{m_{total}-m_m}{\rho_f}} \tag{3.7}$$

For the +-55° filament wound pipe the fiber volume fraction was determined to be:

$$\frac{\frac{m_{total}-m_m}{\rho_f}}{\frac{m_m}{\rho_m} + \frac{m_{total}-m_m}{\rho_f}} = \frac{\frac{118-38}{2,55}}{\frac{38}{1,19} + \frac{118-38}{2,55}} = 0,496 \tag{3.8}$$

For the 90-0-90 filament wound pipe the fiber volume fraction was determined to be:

$$\frac{\frac{m_{total}-m_m}{\rho_f}}{\frac{m_m}{\rho_m} + \frac{m_{total}-m_m}{\rho_f}} = \frac{\frac{16,78}{2,55}}{\frac{7,81}{1,19} + \frac{16,78}{2,55}} = 0,501 \tag{3.9}$$

With a volume fraction of 50% we can conclude that the volume fraction is approximately what is expected in the industry.

3.1.4 Microscopy analysis

The microscopy analysis is used to determine the layer thicknesses of the different filament wounded layers. This provides input to a potential FEM (Finite Element Method) analysis[1]. Further it is used to identify voids, impurities and other detrimental factors. The microscopy also allowed identification of regions in the material with significantly lowered fiber volume fraction that could be a cause of failure in future tests.

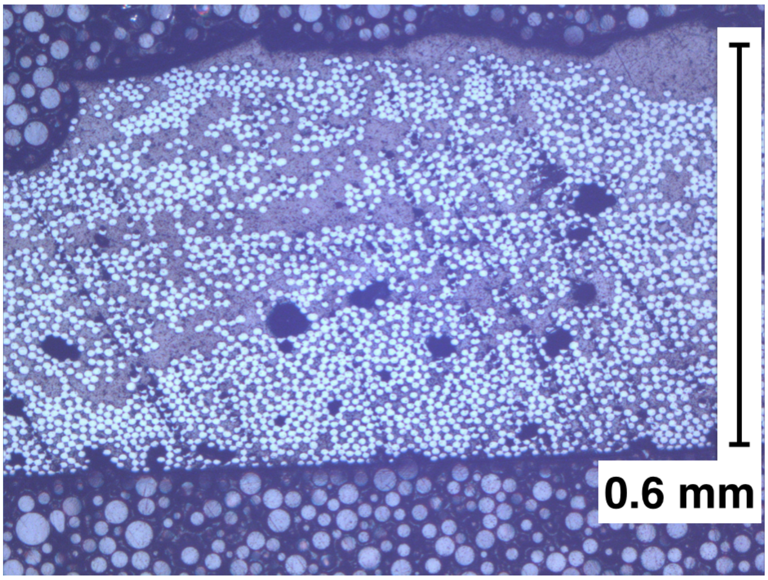


Figure 3.10: Microscopy image of the produced +-55° pipe

From the microscopy it was concluded that fibre distribution was satisfactory, the layer thickness was relatively constant and the void fraction was at a low 1,9% (see figure F.8 in appendix F). Laminate thickness was 0,6mm for the +-55° pipe and 2,68mm for the 0-90-0 ° pipe. It was therefore concluded that the produced pipes were applicable as substitutes for commercial available pipes.

3.2 Drop test rig

An impact is essentially energy transfer from one object with relative velocity to another. The impact occurs at the point of physical contact between the objects. From the perspective of impact protection the most important factors are peak force, energy transferred, shape of the objects and energy transfer time. Peak force during impact is besides impact energy the most important factor that determines the extent of damage in an impact. The impact force can be determined by the impactor shape, impact energy, energy transfer time, impacted material and boundary conditions. These are all variables that one should be able to control. By controlling *drop height, impactor shape, directional guidance, rebounce and energy loss* during drop, and by using the same support-structure in every test, it is believed that a relatively accurate impact scenario can be simulated.

Drop height determines the amount of energy in the impact by equation 3.10. Drop height was adjusted by a nylon (aliphatic polyamide) rope with markings for specific drop heights. This provided flexibility and adjustments could be done quickly.

$$U = mgh, \quad \text{m=mass of object [kg], g=gravitational acceleration, h=drop height} \tag{3.10}$$

Equation 3.10 is a simplification that builds on the following assumptions:

1. Air resistance during impactor flight is neglected
2. Friction in flight and during release is neglected
3. All energy from the impactor is transferred to the impacted body

Impactor shape is a very important factor. Firstly it determines the area of contact during impact thus determining the contact-pressure or impact force (which are transient). Secondly it will strongly influence penetration depth into a protective layer. For the experiments in this thesis a rounded impactor was chosen (Figure 3.12). This hemispherical impactor shape is commonly used and is found to yield high impact forces compared to other typical shapes. [6]

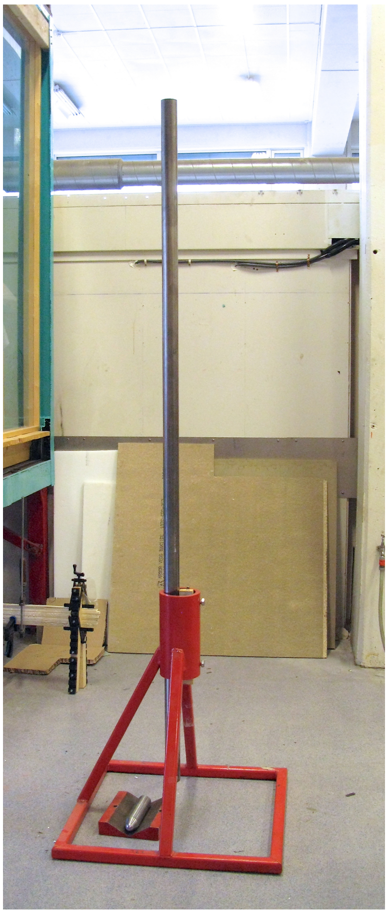


Figure 3.11: The impact testing rig used for impact experiments

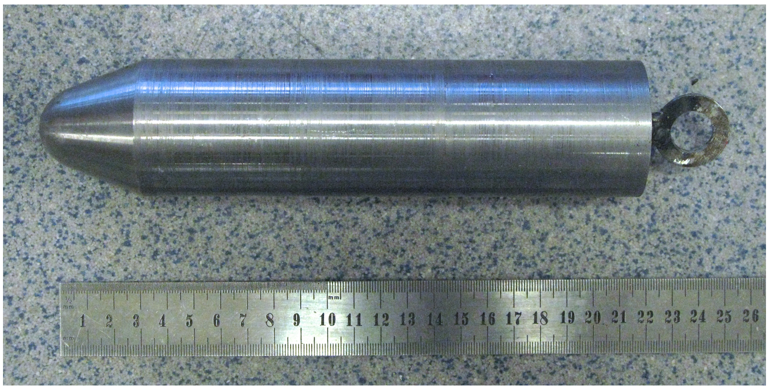


Figure 3.12: The hemispherical impactor used in this thesis, weight=2903 g

Directional guidance is important to ensure that the impactor is aligned and hits the desired point of impact. For the setup used in these experiments, a steel pipe was used to guide the impactor.

Rebounce refers to the undesired second impact when the impactor is returned due to elastic response from the impacted object. If not prevented the second impact will add more energy to the impacted zone thus adding an element of uncertainty. In these experiments rebounce was avoided by adjusting the length of the drop-rope so that only small adjustments waere needed to prevent a rebounce during the impact sequence. This method proved to be effective yet very simple.

Energy loss refers to the uncertainty due to loss of kinetic energy through friction or fluid dynamic resistance during the impact sequence. An estimation of potential losses for the constructed setup is shown below in equation 3.11.

$$E_{initial} - E_{loss} = E_{initial} - E_{dynamic} - E_{friction} = mgh - \frac{1}{2}\rho v^2 CAh - mgsin(\theta)\mu h \tag{3.11}$$

Assumptions:

- h=maximum drop hight for the rig = 2 meters
- v=maximum velocity of impactor = $\sqrt{2gh}$
- m=mass of impactor = 2.903 kg
- C= drag coefficient for cylinder = 0.82
- A= area of impactor cylinder = $\pi 0.03^2$ = $0.0028m^2$
- ρ = density of air at sea level= 1.3 $\frac{kg}{m^3}$
- μ = coefficient of friction in a steel - steel interface = 0.5
- angle of misalignment that generates friction = θ = 1 degree

The ratio $E_{loss}/E_{initial}$ will yield the percentage of loss of the total energy. (Note that in these calculations values that maximizes energy loss are chosen and is considered a worst case scenario.)

$$\% \text{ loss} = \frac{E_{loss}}{E_{initial}} = \frac{\frac{1}{2}\rho v^2 CAh + mgsin(\theta)\mu h}{mgh} = \frac{\rho hCA + msin(\theta)\mu}{m} =$$

$$\frac{(1.3 \times 2 \times 0.82 \times 0.0028 + 2.903 \times \sin(1) \times 0.5)100}{2.903} = \tag{3.12}$$

$$\frac{(0.00597 + 0.0253)100}{2.903} = 1.08\%$$

Equation 3.12 shows that the estimated maximum/worst case energy loss is 1 percent of the total energy. Also note that the largest energy loss is through wall-friction between the guiding pipe and the impactor. By minimizing the angle of misalignment θ we have significantly reduced energy loss. By leveling the drop guidance pipe we can with good accuracy assume that energy losses can be neglected.

3.3 Choice of material

There are several conventional energy absorbent materials commercially available today. Polymeric foams, aluminum crash structures described in Chapter 2. During the author's project thesis [7], several design requirements for a protective layer covering a composite pressure vessel used for transportation were derived. Using these design requirements one can limit the amount of options available in material selection[7]. The design requirements are:

1. Low weight
2. High energy absorption
3. Permanent indentation after impact
4. Possible to manufacture in circular shape (malleability)
5. Low cost compared to the total pressure vessel system

The *weight* of the material needs to be minimal due to the fact that composite pressure vessels are used to reduce weight for the pressure system. Therefore the chosen material for impact protection should not add significant weight to a pressure storage system. *Energy absorption* is the material's ability to dissipate energy under impact loading. By choosing a material with high energy absorption, less material and therefore less space is needed to accommodate the protective structure. Energy absorption is governed by the compressive strength and elongation to failure. Thus a ductile material with high strength would be the optimum material in terms of energy absorption.[8] *Permanent indentation* after impact is not an obvious requirement. There are two modes of impact result for foams; permanent and non-permanent indentation. Non-permanent indentation foams will be able to absorb multiple impacts, where as permanent indentation foams allows the user to quickly identify the impact location for inspection. For the purpose of protection composite pressure vessels it is assessed that multiple high energy impacts are unlikely thus location determination receives precedence. The *Malleability* together with the method of production are also important properties that governs the choice of material. In order to protect a pressure vessel the material needs to be shaped to fit the dimensions of the vessel. Therefore it is important to choose a material that can feasibly be formed into cylindrical shapes. Lastly it is important to ensure a *low price* for the protection system to be feasible economically and appealing for the industry.

A short study was conducted to investigate different materials in relation to the five different selection criteria mentioned above. Using CES material management software [9] a material search was built to accommodate the chosen criteria. Firstly the search was limited by price; less than 200 NOK per Kg. Then energy absorption at compressive failure per density was plotted against density alone (Figure 3.13). Energy absorption was approximated by multiplying compressive strength with the compressive strain at failure. Then by dividing by density the calculation would yield the weight to compressive energy absorption ratio. The search highlights different materials that would be feasible as protection materials for a composite pressure vessel. In particular PVC-foam, PET-foam and Polystyrene-foam have promising mechanical properties compared to density. This search gives a strong indication of what materials would be suitable for impact protection, however further testing is needed to validate the protection material performance.

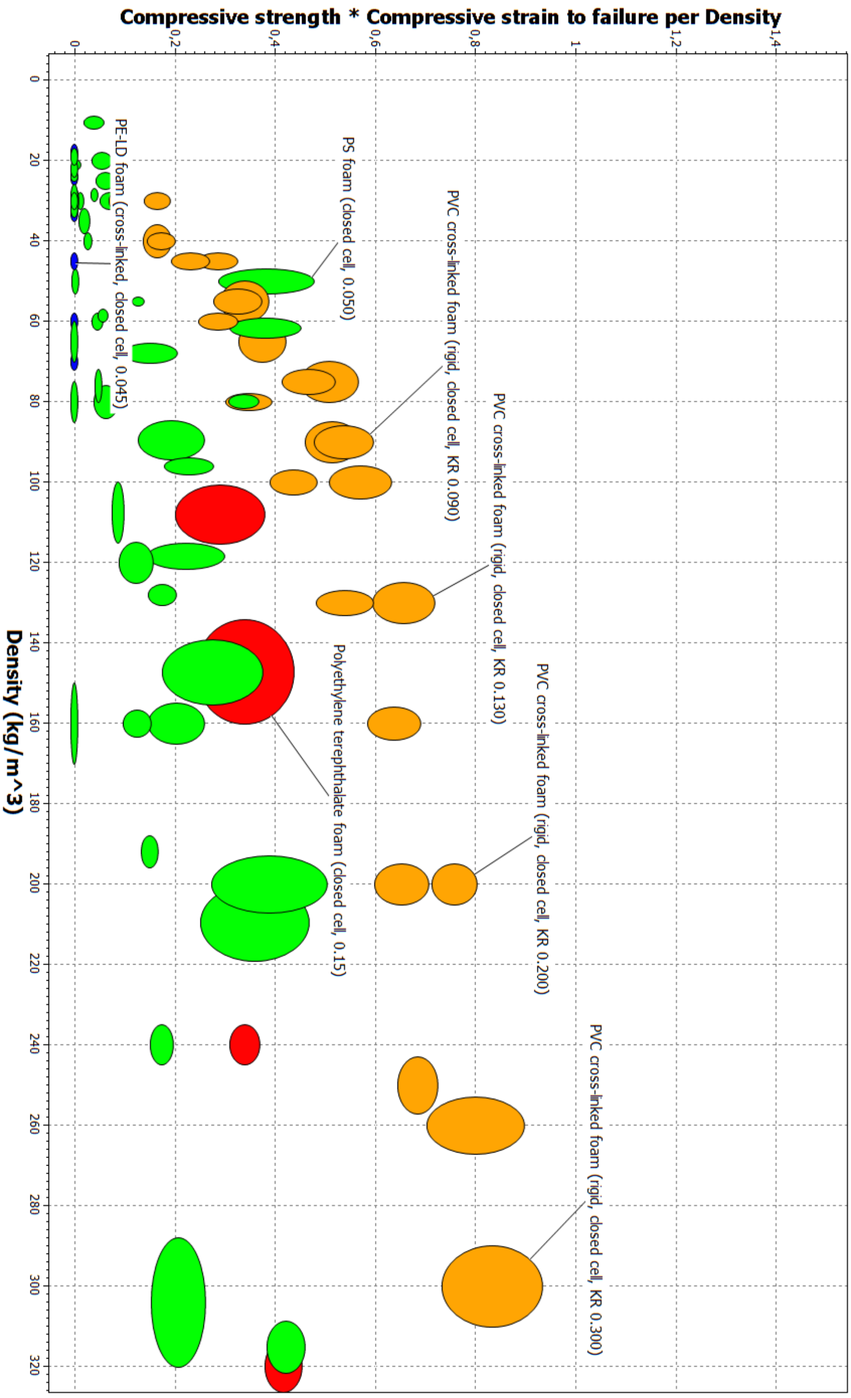


Figure 3.13: Material search plot using CES material management

3.4 Impact resistance protective materials

This section will outline the experiments conducted to investigate a selection of conventional impact protection materials for the purpose of protecting an underlying composite structure.

3.4.1 Determination of impact energy

To be able to distinguish between the different materials it is important to find an impact energy that will create significant damage to the protection material without destruction of the protected composite structure. It is also important that the test impact energy reflects the levels of impact energy found on pressure vessels in service. From equation 3.10 we can vary both impactor weight and drop height to achieve the desired impact energy. From a practical point of view it requires less effort to adjust the drop height. Therefore in these experiments only drop height was adjusted to tune impact energy according to the desired impact scenario.

In order to determine a drop height that yields significant and visible damage, drop tests were done from 300mm to 1800mm with 300mm increments on glass fibre composite plates without protection. From table 3.1 one can identify delamination failure at low drop heights and fiber failure at higher drops. It is desirable to be able to prevent both, thus both should be present to allow determination of the effectiveness of different protection materials. While a drop height of 1800mm created massive fiber failure and partial penetration of the plate, 1300mm created limited fibre failure, 1500mm created delimitation and fiber failure without significant penetration. Additionally this drop height with the chosen impactor is equivalent to an impact energy of 42 joules. This impact energy corresponds to a typical dropped-tool-impact which is regarded as one of the most probable low velocity impact for pressure vessels. Therefore 1500mm was chosen for further materials testing.

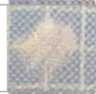
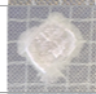
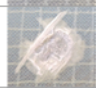
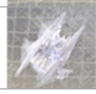
Drop height	Delamination diameter	Fiber failure diameter	Image (scaled to fit)
300mm	4.5 mm	0 mm	
600mm	8 mm	2 mm	
900mm	12 mm	5 mm	
1200mm	17 mm	8.5 mm	
1500mm	20 mm	10 mm	
1800mm	24 mm	18.5 mm	

Table 3.1: Table of impact tests to determine drop height for future experiments

3.4.2 Determination of foam material thickness

To further test whether the chosen impact height would yield a distinguishable damage pattern, several foam materials and thicknesses were tested to find the optimal for further testing. For these experiments Low density poly ethylene (LDPE) foam, Cross-linked Polyvinyl Chloride (X-PVC) foam and Polyethylene terephthalate (PET) foam were tested. X-PVC and PET were highlighted by the material search (figure 3.13), where as LD-PE was tested as a reference to test the assumptions in the materials search. As for the previous experiments in section 3.4.1 the same composite plate specimens were used as a substitute for composite pipes. This allowed for a large volume of tests and each material thickness was tested three times. The drop tests are shown in table 3.2.

While conducting the test it quickly became apparent that neither LDPE nor PET met the design criteria for the impact protection material, thus these materials would most likely not be suitable for the application of impact protection. In the case of LDPE it firstly did not suffer permanent indentation after impact. Secondly LDPE had very low energy absorption as seen from table 3.2 where the penetration depth is equal to the

Protective material	Dropheight [mm]	protection thickness [mm]	Damage diameter [mm]	Penetration depth [mm]	Weight [g] (All plates 100x100mm)
X-PVC	1500	50	0	15	72,8
X-PVC	1500	40	0	15	58,2
X-PVC	1500	30	0	15	43,7
X-PVC	1500	20	0	12	29,1
X-PVC	1500	17	0	10	24,8
X-PVC	1500	13	0	13	18,9
X-PVC	1500	10	9	10*	14,6
LDPE	1500	35	13	35*	14,0
LDPE	1500	70	10	70*	28,0
PET	1500	20	6	20*	20,1
PET	1500	50	0	45	50,3

Table 3.2: Table of impact experiments to test protection material impact resistance * Penetration depth is equal to or grater than material thickness

material thickness in all cases. In the case of PET it displayed a more promising behavior than LDPE. From table 3.2 PET has successfully protected the underlying composite plate at a thickness of 50mm. PET also satisfies several of the design requirements especially since it is a thermo-plastic and can easily be shaped around a vessel. However its brittleness is a major weakness that renders it difficult to use in a pressure vessel protection design. As seen from figure 3.14 the only material left after impact are the collapsed cells of the PET foam. The rest of the material was broken into small pieces and scattered away from the impactor. This further emphasizes the need for a ductile compressive behavior. This material would therefore most likely not be suitable for protection. X-PVC on the other hand displayed excellent protection capabilities. Firstly X-PVC required small thicknesses to successfully protect the underlying surface. Secondly the plates behaved in a ductile manner thus not breaking under impact loading. This means that the impact location can be determined accurately by investigating the foam indentation contrary to that of the PET. Lastly the weight required to fully protect the underlying structure can be evaluated from table 3.2. It shows that PET requires more than double the weight to successfully protect the structure. Based on these aspects X-PVC was chosen for further use in this thesis.

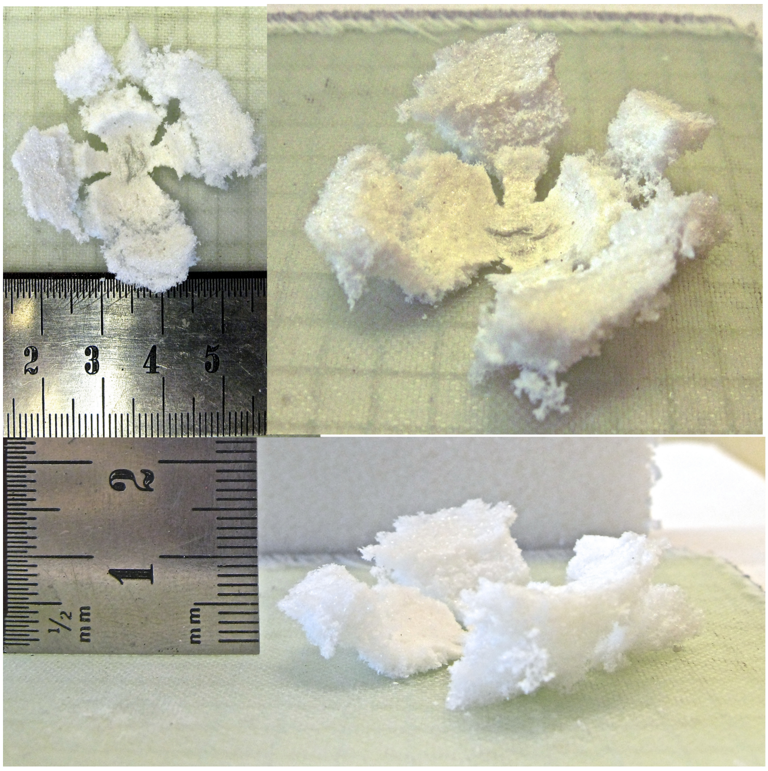


Figure 3.14: PET plate after impact

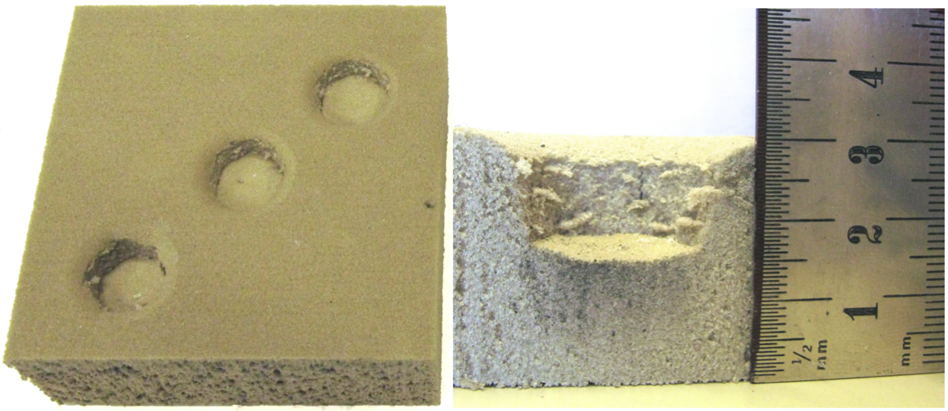


Figure 3.15: X-PVC plate after impact

Chapter 4

Impact Detection and Impact Assessment

Impact detection, along with the protective energy absorbent material, is the most important component in an impact protection system. For the system as a whole to be effective, the impact detection system must be able to detect impacts while covered by the protective layer. Therefore it is important to find the optimal configurations so that these two core functions (protection and detection) do not interfere with each other. This chapter will outline the development and experiments to find the optimal protection and detection layout to maximise the effectiveness of both.

Impact detection and assessment can be achieved with a myriad of different technologies and techniques. From the literature review in section 2.2.2 the principle technologies are outlined. This chapter will investigate the promising impact assessment techniques found from the literature review, namely Optical Backscatter Reflectometry and conventional strain gauges. This chapter will also describe a new solution for impact detection with a primary focus on low cost.

4.1 Experimental Equipment and Measurement Tools

The literature review has highlighted the opportunities with conventional strain gauges, Optical Backscatter Reflectometry and Piezo (vibration) sensors. Based on this analysis these three techniques will be be tested experimentally to determine their effectiveness. This section summarizes all equipment and measuring tools used for impact detection and assessment in this thesis.

4.1.1 Optical Backscatter Reflectometry

Optical Backscatter Reflectometry (OBR) is a measuring technique utilising Rayleigh backscatter in an optical fibre attached to the test specimen. The device emits a Laser-pulse through the fibre and measures the “echo” from that pulse. Combined with a reference reading, changes in the backscatter is translated into strain, temperature change etc. More specifically OBR uses a technique called Optical Frequency Domain Reflectometry (OFDR). This technique uses a high resolution solid state tunable laser that transmits a stepped sine-wave through the fibre and the backscatter is recorded by a interferometer as a function of frequency. The strain along the fibre is then calculated from the change in frequency between the emitted and the backscattered signal. This technique has been used on optical fibres up to a length of 2km. The technology also has a spatial resolution down to 10 μm at shorter measurement lengths.

The disadvantage of an OBR measurement system is the sample rate. Measurements can take between 2 and 30 seconds, being mainly dependent on the selected frequency range but also the measurement length. For our application a sampling rate of 0.5Hz or lower is not suitable for real time impact detection. However, our hypothesis is that the residual strain in the composite after an impact is measurable with the high resolution of the OBR. If the residual strains after impact can be detected, a distributed network of optical fibers could potentially be able to determine impact location and severity. This hypothesis is tested in section 4.4.1.

In this thesis the OBR measurement system used is the OBR4600 manufactured by Luna

Technologies with a maximum measurement distance of 30 meter (at 10 μm resolution) and 70 meter (at 20 μm resolution) [10]. To obtain the strain measurements from an experiment, all recorded files are loaded into a data interpreter software (OBR Desktop). The final output can either be a screen capture of the measurement software for simple measurements or strains can be exported into a comma separated text-file for extensive analysis. The optical fibre used is a standard 160 μm silica tele communications cable [11]. To prepare the specimens for measurement, the fibre is glued to the specimen at the desired measurement locations.

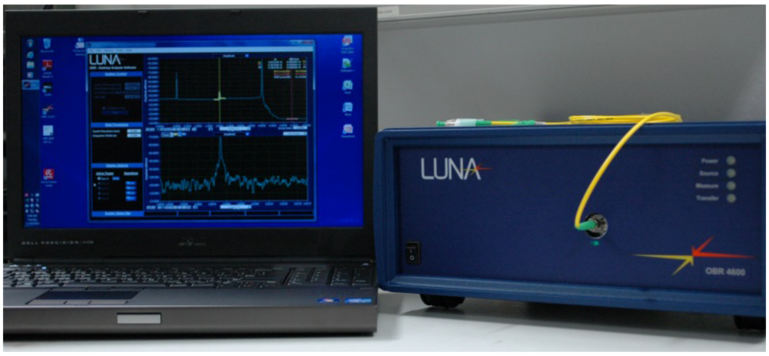


Figure 4.1: The OBR measurement and recording setup

4.1.2 Conventional Strain Gauges

Conventional strain gauges are essentially conductors embedded into a foil that upon deformation changes the electrical resistance thus enabling a strain measurement. Where the OBR can measure strain over long distances and along a fiber, the conventional strain gauge only gives the strain in a single location. The spatial resolution of a strain gauge is normally between 2 and 10 mm which is 10^2 times larger compared to the OBR. In addition, compared to the OBR a large amount of conventional strain gauges are needed to cover the same area as one optical fibre for OBR. The main advantage of the conventional strain gauge is the sampling rate. With sampling rates up to 9600Hz it is likely that an impact cycle can be recorded. This would allow for more accurate evaluation of an impact event.

The strain gauges used in this thesis were manufactured by Tokyo Sokki Kenkyujo with a gauge factor of 2.13 and and resistance of 120 Ω. They were connected by a Spider8 data acquisition unit and recorded in HBM Catman easy recording software. Output is a comma separated text file or a csv-file with the data-set containing strain and time measurements.

Figure 4.2: The Strain gauge used in this thesis

4.1.3 Low Cost Solution

Both the strain gauge (and in particular) the OBR require relatively expensive and space consuming equipment. Therefore it would be desirable to find low cost solutions that could be used for a large variety of composite pressure systems. Simple prototyping sensors provide alternative impact detection that could be both low cost and space efficient. In this thesis both piezo electric sensors and accelerometers are investigated to develop an alternative low cost impact detection system.

A piezo electric sensor generates a voltage when deformed. As a fun-fact: "piezo" originates from greek, meaning "squeeze". Technically a piezo consists of ceramic or single crystal materials that have a linear electromechanical relationship between mechanical and electrical state. This material is commonly attached to a metal base and wires for connection. Piezo sensors are used for a variety of measurements; pressure, temperature, strain, force and vibration. By recording the voltage fluctuations in a piezo element it is believed that an impact can be detected. The piezo elements used in this thesis are ST006 Bitsbox piezo transducers, 23mm diameter and 30V maximum driving signal.[12]

An accelerometer is a sensor that measures true acceleration. True meaning that a stationary accelerometer would read 1g or ≈ 9,81 m/s^2 in the vertical axis and zero in the other. Conceptually an accelerometer is a damped mass on a spring. Under acceleration the mass is displaced to the point where an equilibrium is reached between the spring acceleration and the external acceleration. The measured displacement then yields the acceleration. Accelerometers are used for a large variety of applications. For the application specific for this thesis, it will measure acceleration during an impact thus the directional sensitivity of such a sensor is an important factor. The accelerometer used in this thesis is a 3-axis accelerometer; ADXL 335 on a GY-61 brake out board.[13]

A micro controller can be used to power and read the piezo and accelerometer sensors and correlate them into a single system. For this thesis the Arduino micro controller will be used. Arduino is a hardware and software open source company that provides micro controller boards and the software required. The boards have a small processor, digital and analog I/O pins that can be connected to numerous sensors and circuits. The board used in this thesis is an Arduino Uno [14]. The Arduino allows the user to connect several sensors and communicates via a serial communication interface (including USB).

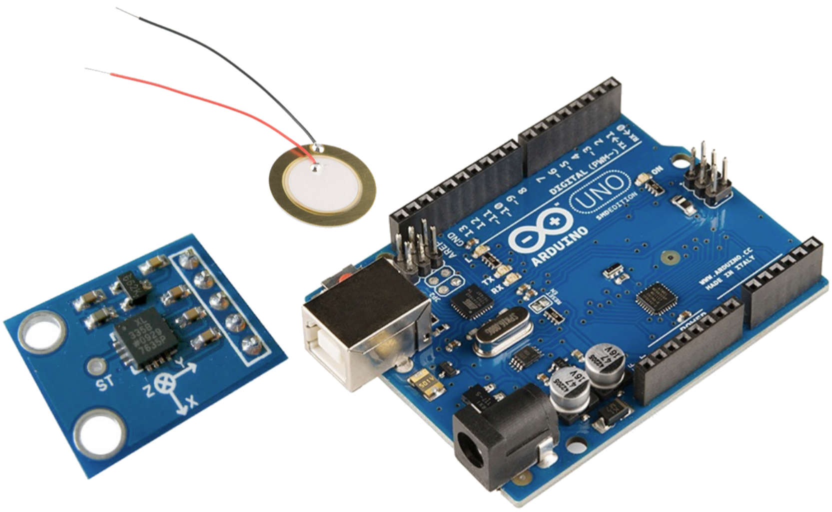


Figure 4.3: The Arduino Uno micro controller, peizo element and accelerometer used

4.2 Impact Wave propagation in composites

An impact induces structural waves in the receiving material. In order to attempt wave based impact detection using piezo elements, one should understand how these waves are induced and which propagation wave modes can be detected. An impact to the plate induces guided waves called Lamb waves. These typically refer to elastic waves in a solid plate where particle motion is either mostly along the plate-plane (S_0) or mostly perpendicular to the plate (A_0). Lamb waves are dispersive, meaning that their velocity is dependent on their frequency. However, for the fundamental longitudinal wave (S_0) the velocity is approximately constant when the wave length is much larger than the plate thickness. Equations 4.1 and 4.2 describe the phase velocity for (S_0) in a composite as a function of the components of the in plane laminate stiffness matrix A, the density ρ and the plate thickness h. Assuming wave length, λ » h.

$$C_{pe,x} = \sqrt{\frac{A_{xx}}{\rho h}} \tag{4.1}$$

$$C_{pe,y} = \sqrt{\frac{A_{yy}}{\rho h}} \tag{4.2}$$

For the fundamental flexural mode (A_0), where the particles move mostly perpendicular to the plate, the phase velocity is approximated as follows.

$$C_{pf,x} = \sqrt[4]{\frac{D_{xx}}{\rho h}}\sqrt{\omega} \tag{4.3}$$

$$C_{pf,y} = \sqrt[4]{\frac{D_{yy}}{\rho h}}\sqrt{\omega} \tag{4.4}$$

Where D is the flexural stiffness of the laminate and ω is the angular wave frequency. Since the flexural wave velocity is frequency dependent, one scan expect a large spectrum of wave velocities. In the case of an impact, a very wide spectrum of frequencies can be excited.

Considering the plate deformation profile for the two fundamental lamb wave modes, a surface mounted piezo element will most likely detect a flexural wave (A_0) which consists of large out-of-plane deformations. Piezo elements are able to detect deformations of the element it self. When the plane of the piezo element is parallel to that of the wave (S_0), the piezo element, due to its limited sensitivity, might not be able to detect small out-of-plane displacements by this longitudinal mode. However for the flexural wave (A_0), the piezo will most likely be able to provide a significant output voltage.

For the composite pipe with a +-55 degree layup the in plane stiffness and the flexural stiffness is:

$$A = \begin{bmatrix} 18,24 & 14,34 & 0 \\ 14,34 & 31,99 & 0 \\ 0 & 0 & 13,95 \end{bmatrix} [GPa - mm] \quad B = \begin{bmatrix} 2,189 & 1,721 & 0 \\ 1,721 & 3,839 & 0 \\ 0 & 0 & 1,675 \end{bmatrix} [GPa - mm^3] \tag{4.5}$$

One can now calculate the expected low frequency in-plane wave for the composite tube using the density from the burn-off test ($\rho = 1,78 g/gm^3$) and the thickness from the microscopy (0,6mm).

$$C_{pe,x} = \sqrt{\frac{A_{xx}}{\rho h}} = \sqrt{\frac{18,23}{1,87 * 0,6}} = 4031 m/s \tag{4.6}$$

$$C_{pe,y} = \sqrt{\frac{A_{yy}}{\rho h}} = \sqrt{\frac{31,99}{1,87 * 0,6}} = 5340 m/s \tag{4.7}$$

For the flexural wave velocity:

$$C_{pf,x} = \sqrt[4]{\frac{D_{xx}}{\rho h}} \sqrt{\omega} = 1,18 * \sqrt{\omega} \ \ m/s \tag{4.8}$$

$$C_{pf,y} = \sqrt[4]{\frac{D_{yy}}{\rho h}} \sqrt{\omega} = 1,36 * \sqrt{\omega} \ \ m/s \tag{4.9}$$

These velocities have implications for the impact detection using piezo elements and will be tested further and discussion in chapter 6 and 7

4.3 Quasi-Static vs Dynamic Indentation

Due to the high number of experiments needed in this thesis it would be beneficial to find the most time-efficient way to simulate an impact. Quasi-static indentation as a substitute for dynamic drop weights would allow more control and more accurate measurements due to lower required sampling rates. Thus an experiment was set up to test the hypothesis that a quasi-static indentation is a satisfactory substitute for a drop weight test. Two glass fibre composite pipe sections were fitted with a strain gauge on the inside of the pipe directly underneath the impact point. One pipe section was impacted using the test setup from section 3.2 with the 2,9kg impactor from 1,5 meters. The other was indented in a hydraulic press with the impactor fitted into the press. To test the hypothesis we first measured the maximum strain in the drop weight impacted pipe and recorded the visible damage such as delamination and fibre failure. For the second pipe, the indenter was driven into the pipe with a slow strain rate to avoid dynamic effects until the strain was equal to the maximum recorded strain in the impacted pipe. From figure 4.4 one can see the difference in damage pattern at the same strain level. Delamination is visible as a change in refractive index in the composite whereas fibre failure in combination with matrix cracking is visible as loss of translucency. Figure 4.4 demonstrates the difference between the two visible failures. Interestingly, at the same strain-level the impacted pipe showed no signs of fiber failure, with a large delaminated area. The quasi static indented pipe showed very limited delamination yet visible fibre failure (fiber buckling) with a crack length of 8mm. Based on the discrepancy between the two tests it was concluded that equal strain in static and dynamic testing did not yield similar damage patterns. The indentation was therefore continued until the visible delamination damage was approximately equal to that of the impacted pipe (figure 4.5). From the images one can see that significant local fibre buckling was present in the static indentation and not visible in the dynamic test. This fibre buckling greatly reduces the local strength of the composite pipe whereas delamination is not a significant contributor to strength reduction. Therefore it was concluded that equal delamination area for static vs. dynamic testing is not a suitable approach and ultimately, static testing is most likely not a suitable substitute for dynamic testing.

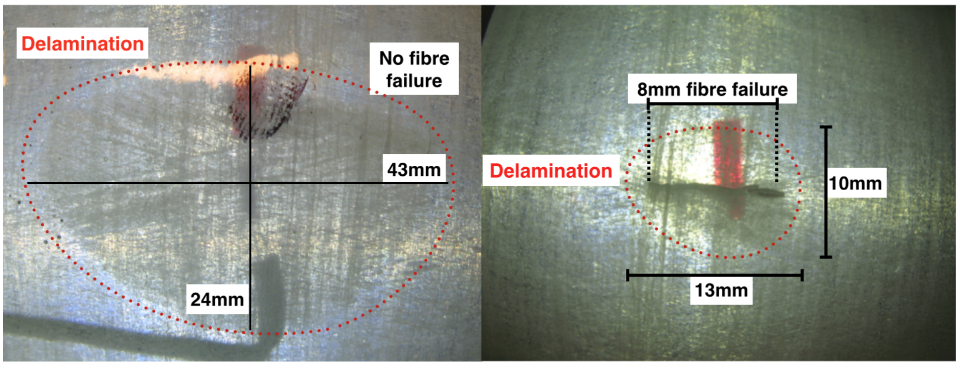


Figure 4.4: Static vs. dynamic at same strain-level

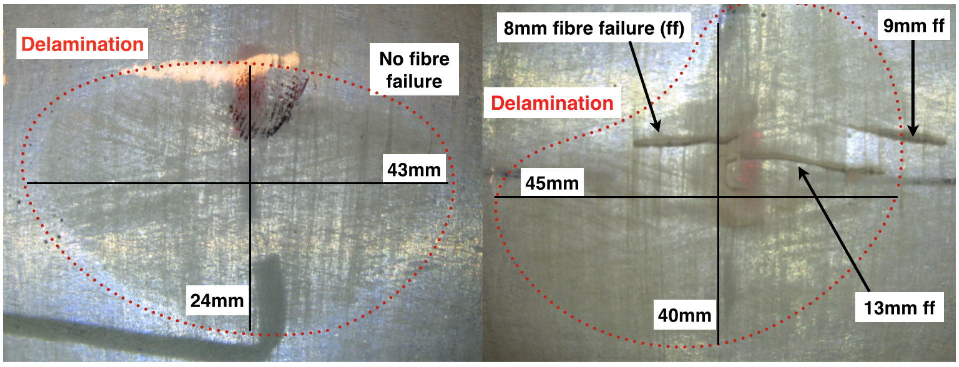


Figure 4.5: Static vs. dynamic at same delamination size

4.4 OBR Response under Impact Loading

4.4.1 Residual strain after impact hypothesis

Due to the high impact wave propagation velocity in composites combined with the low sample rate of OBR measurements, it will not be possible to directly record an impact in a composite pipe using OBR. However our hypothesis is that the residual strains in the impacted area will be measurable with a high resolution technology like OBR. To test this hypothesis; a grid of optical fibers were glued to a composite pipe section and impacted from the drop height determined in section 3.4.1 (1500mm). The optical fibre grid is shown in figure 4.6. The point of impact is at the centre of the inner square.

The results from this test were promising. From figure 4.7 the 8 different measurement lengths are plotted and numbered. The 1-4 longitudinal measurement refers to the horizontal fibers in figure 4.6 whereas the 1-4 hoop direction refers to the vertical fibers in figure 4.6. The residual strain in the optical fiber after impact was registered as high as 4000μ strain with an average of 500 μ strain. The background noise or the natural fluctuation of strain for the OBR measurement was measured to be approximately 20 μ strain. Therefore it most likely that the residual strain after an impact can be detected by an OBR measurement and the hypothesis is strengthened.

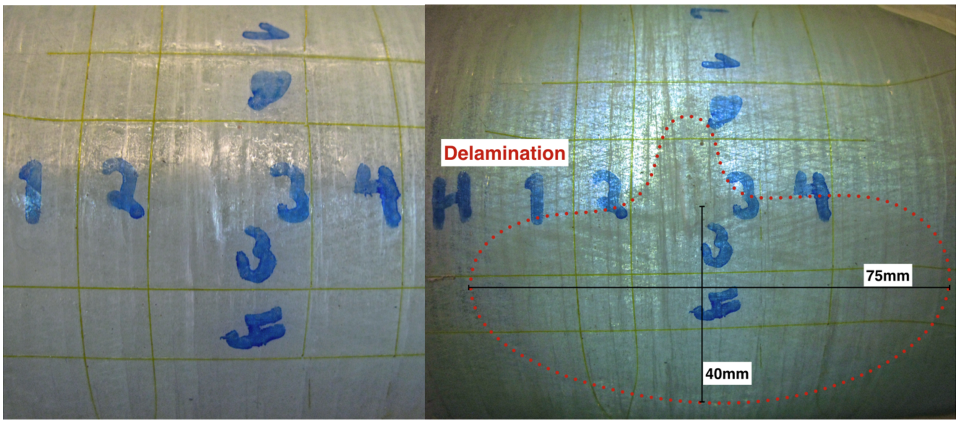


Figure 4.6: Optical fibers in a grid, before and after impact

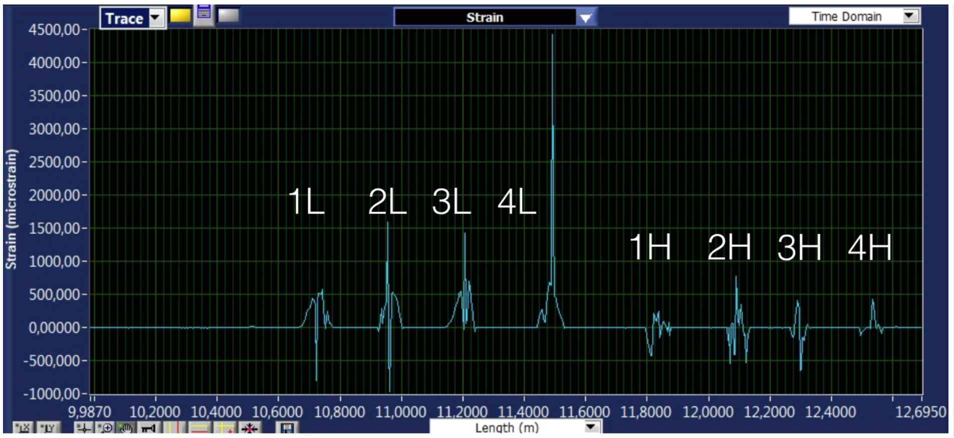


Figure 4.7: The corresponding residual strain reading

4.4.2 OBR Impact Detection under Protective Layer

The next step in the investigation of OBR fibre measurements in an impact protection system is to ensure that OBR measurements can be performed under a protective layer. If a protective layer is placed between the impactor and the composite pipe, the damage pattern and therefore the residual strains will most likely be affected. Therefore tests were performed to ensure that a residual strain measurement could be performed when the pipe is subjected to impact through a protective layer.

The chosen impact protection material X-PVC was cut into cylindrical shapes with a thickness of 10mm at the point of impact. From section 3.4.2 it was shown that a protective layer thickness of 10mm would yield visible damage, however the impact damage was significantly reduced. Thus a layer thickness of 10mm was chosen to ensure that damage would be created simultaneously as the effect of a protective layer would change the force distribution during the impact. A composite pipe section was fitted with a grid of optical fibres (as shown in figure 4.8)and connected to the OBR 4600. Using the test rig described in section 3.2 the composite was impacted with a drop height of 1500mm.

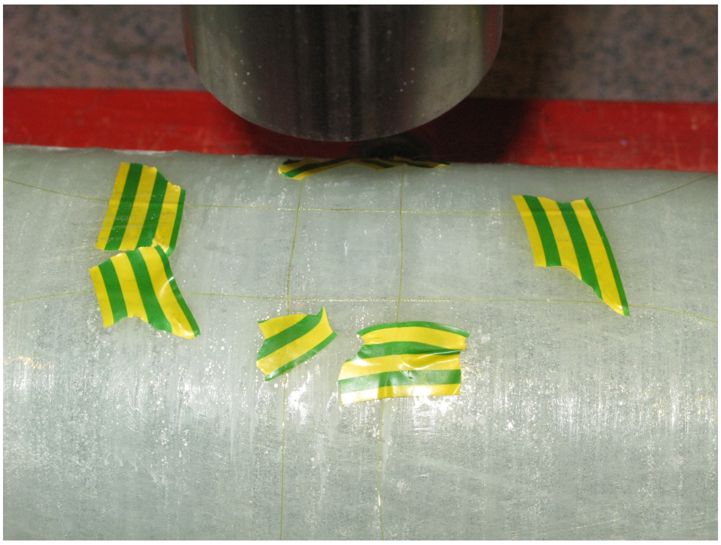


Figure 4.8: Optical fibers in a grid to detect residual strain after impact, ready for impact in the rig. (Yellow and green tape only used to fasten fibers while gluing)

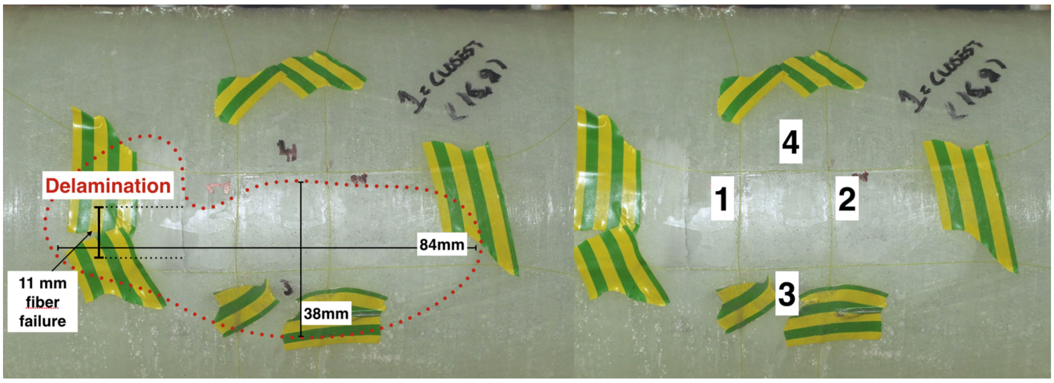


Figure 4.9: After impact with a protective layer

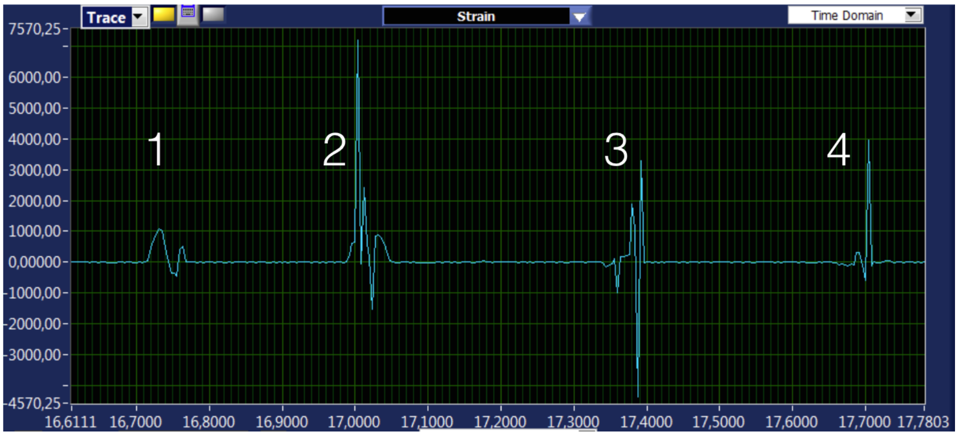


Figure 4.10: The residual strain OBR reading

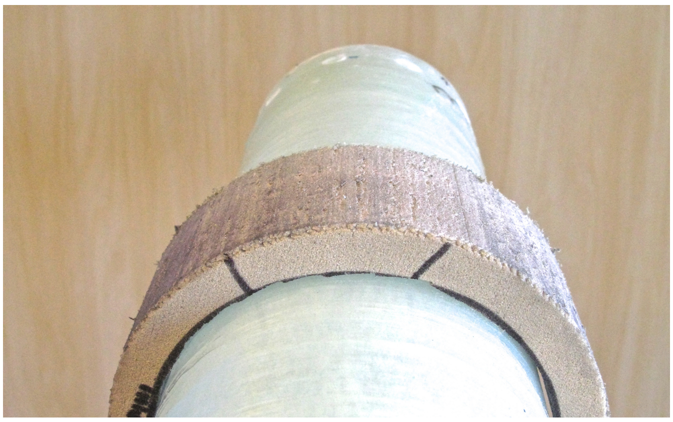


Figure 4.11: The cut-out protective layer before impact

Figure 4.9 shows there is extensive visible damage after the impact and an elevated residual strain reading should be expected. Figure 4.10 shows the OBR residual strain reading from the grid. Residual strains were as expected, elevated and readable. No significant difference in the OBR reading between the protected and un-protected sample was identified. It was decided that since the damage on the protected pipe was considerable, it could not be concluded that residual strain readings under a protective layer were detectable. What this test did show however was that the damage pattern for a protected pipe was very similar to that of a un-protected one, which supports the possibility of residual readings under a protective layer. Based on this test it was decided that a new test had to be conducted to fully conclude that fibre measurements under a protective layer are possible.

A new test was conducted with the exact same parameters as in the test described above. However to limit the damage on the composite pipe the drop height was reduced to 1000mm. The recorded strain (figure 4.13) was significantly reduced, but maintained at a high enough level to be detectable (+-500μstrain). The damage pattern in the composite pipe was evaluated to be only delamination, no fibre failure. This test further supports the hypothesis that residual strains after impact can be detected through a protective layer.

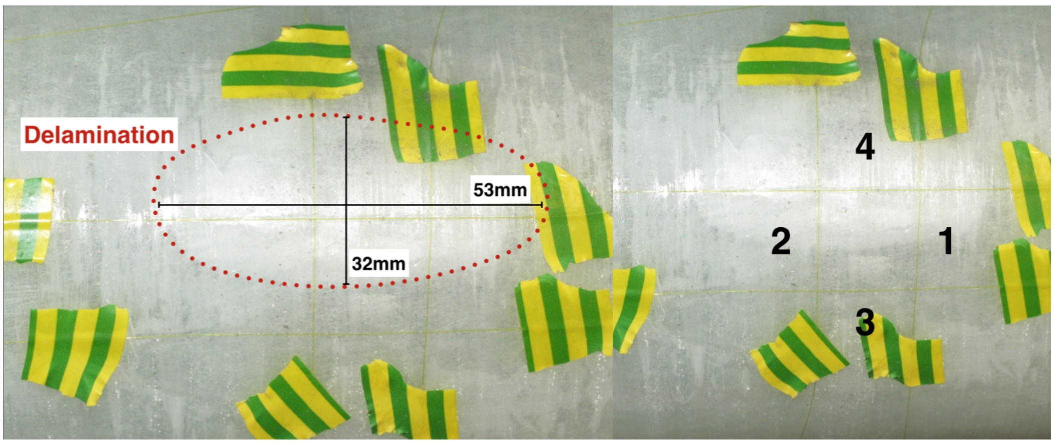


Figure 4.12: Impact pattern from 1000mm impact test

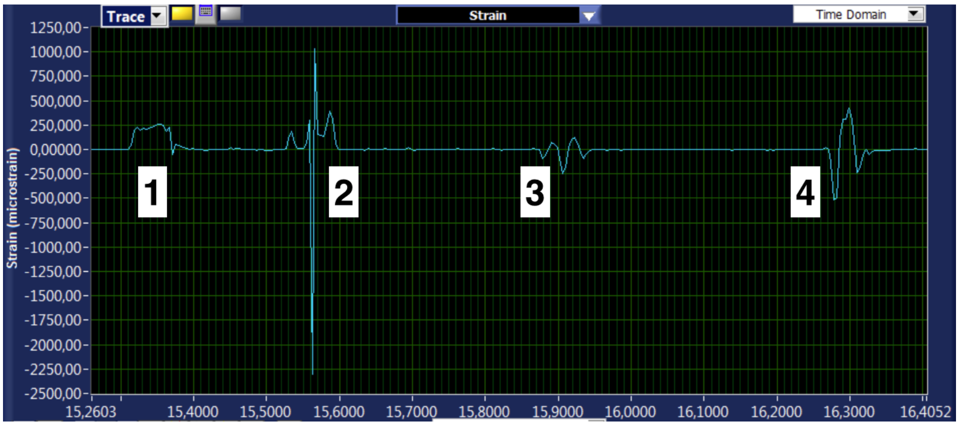


Figure 4.13: OBR reading from 1000mm impact test

4.4.3 Prediction of damage extent from OBR

As stated in section 4.1.1 the hypothesis was that impact severity or the residual strength of composite pressure vessel could be determined from the level of residual strain measured. From the literature review in chapter 2 several technologies have been able to predict, at some degree, the extent of damage after an impact in composite pressure vessels. However the main challenge remains, namely predicting the residual strength or the maximum safe operational pressure for the vessel.

Chapter 5 outlines the attempts of testing the residual strength in the composite pipes to provide reference for correlation between residual strain and residual strength. However as described in chapter 5 the pressure tests were unsuccessful, hence a comparison of the residual strength (burst pressure) and the residual strain from the OBR readings was not possible. On the contrary, it was observed that the residual strain in the composite pipes varied with visible damage. In drop tests where only delamination was visible, the level of residual strain was comparably low; around 200-800 μ strain [D.5]. For drop tests where fibre failure was visible residual strains were observed to be in the range of 1000-6000 μ strain [D.3]. This is a clear indication that the recorded residual strain is proportional to the imposed damage where the initiation of fiber failure seems to cause a substantial increase. However, the residual strain for different impact energies varies substantially and with a small sample size no mathematical relationship could be determined for the relationship between residual strain and imposed damage. A comparison of damage pattern and residual strain can be found in appendix D. This will be investigated further in developing the prototype. It is believed that with further investigation and development OBR measurements have the potential to give predictions for the level of damage.

4.5 Strain Gauge Response under Impact Loading

As described in section 4.1.2 conventional strain gauges have a high sampling rate. A test was set up to investigate whether an impact cycle could be detected by such a strain gauge. The strain gauge was attached on the inside of the pipe directly beneath the impact point, this was to ensure that the strain could accurately be read and the strain gauge would survive the impact. Figure 4.14 shows the strain gauge setup. The pipe was impacted from a height of 1500mm using the impact rig (section 3.2) Figure 4.15 shows the impact strain history. A clear impact signature with a peak strain of approximately 22500 μstrain and an impact duration of 0,01 seconds is shown. This test proves that conventional strain gauges, if placed in the correct position, can be very effective in detecting an impact.

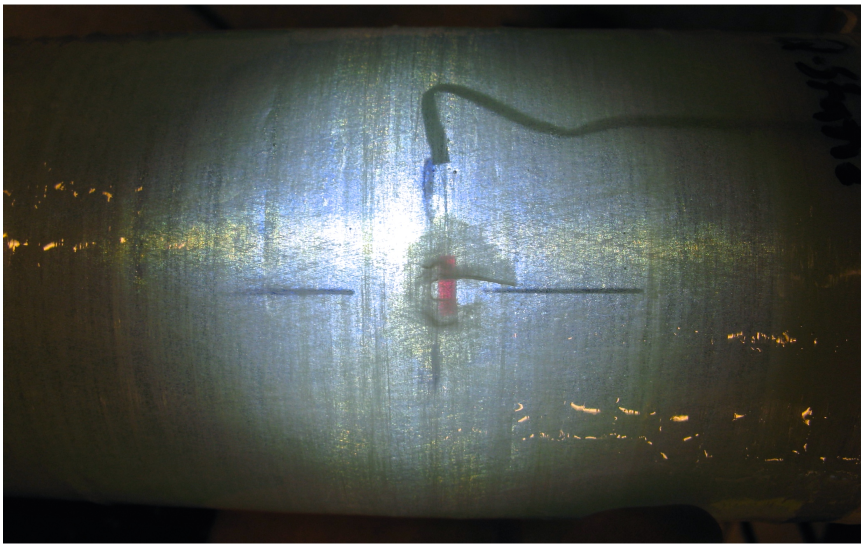


Figure 4.14: The strain gauge glued inside the pipe

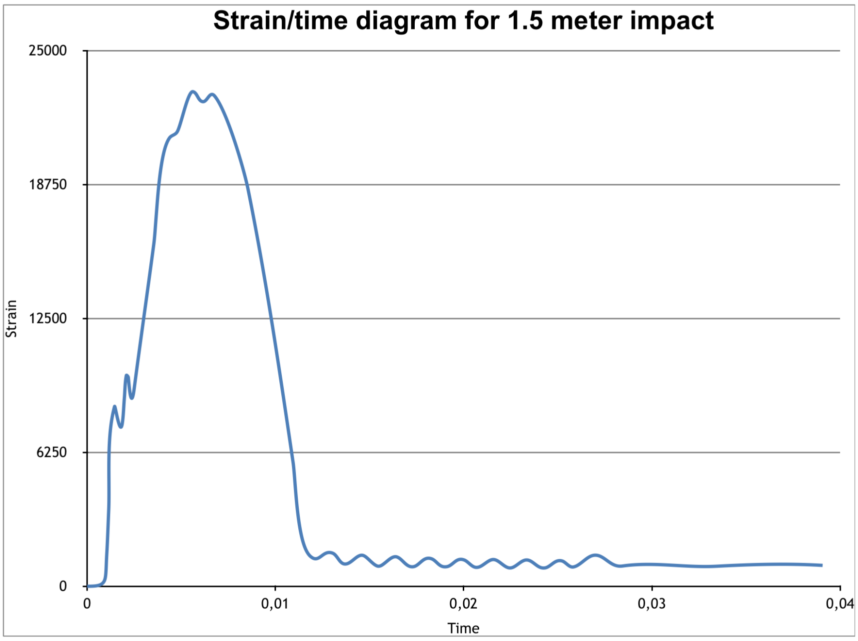


Figure 4.15: The strain gauge response, time in seconds, strain in μstrain

4.6 Low cost Piezo Electric Impact Detection

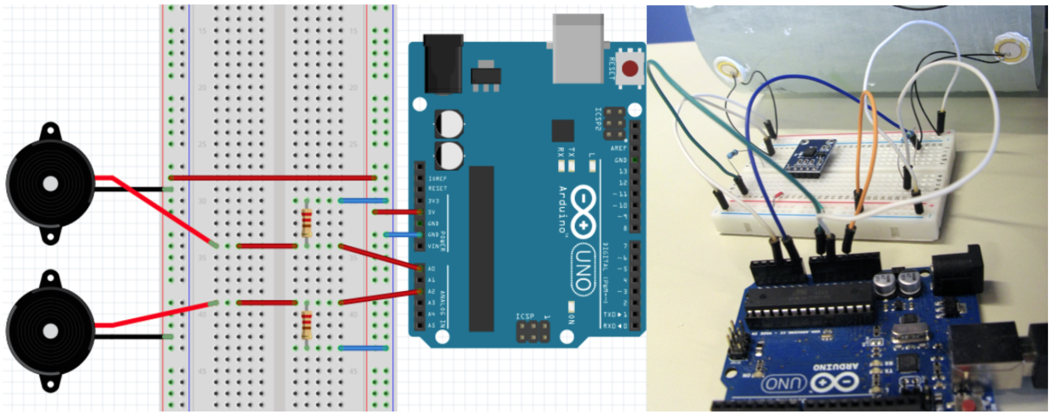


Figure 4.16: Wiring setup of the the piezo electric sensors

This thesis aims to investigate and develop low cost solutions for impact detection in composite pressure vessels. From the literature review in section 2.2.2 several research papers have been successful in measuring impacts with piezo elements attached to a composite pressure vessel [15]. In these papers, piezo elements record vibrations in the composite structure with both location and magnitude of the impact being estimated. These systems have utilized complex and expensive piezo elements in addition to sophisticated high sample rate recording equipment, which has allowed estimation of impact location and magnitude. For simple impact detection however, it is believed that a simple array of low cost piezo elements can detect an impact on the composite structure. To test this theory, a preliminary setup was constructed using a pipe section of a glass fiber composite tube with piezo elements attached. Figure 4.16 shows the preliminary setup to test the piezo element's ability to detect impact vibrations through a composite tube. A pair of piezo elements attached to each end of the pipe are wired to analogue read-ports (A0 and A2) of the Arduino and to the 5V power supply. The reading ports are also grounded through a 1Mohm resistor to protect the Arduino board and ensure a stable read-signal. The Arduino board is connected to the PC through USB. Matlab was then used to record the output from the Arduino. (See appendix E for Matlab-code)

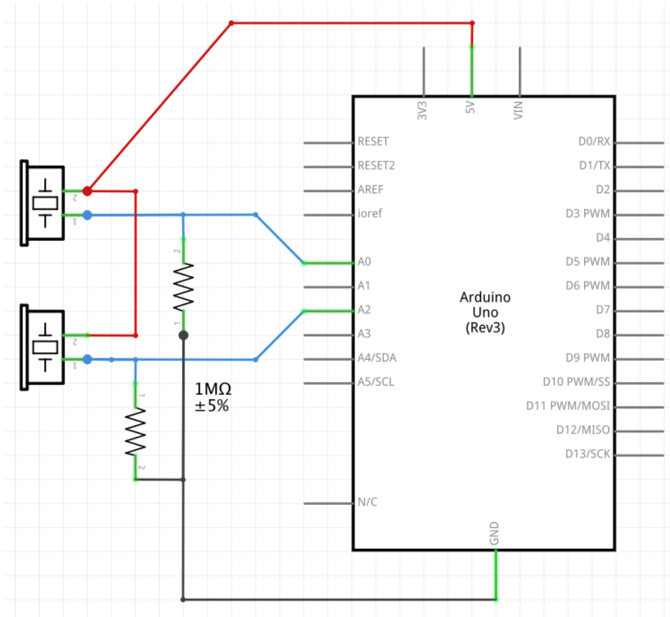


Figure 4.17: Schematic of the wiring setup for the piezo electric sensors

The first parameter that was investigated was the coupling or attachment method to attach piezo elements to the tube. As discovered during the literature review, the coupling method in a piezo setup has major implication for the efficiency of the elements in regards to damping and sensor requirements. Acrylic glue was used to attach the first set of test-piezos. They were attached directly on the circumference of the pipe thus following the pipe curvature. To test the piezo sensors the recording was started and the composite pipe was repeatedly impacted by a blunt object at low impact energies (in this case my coffee cup). From the reading (figure 4.18) one can observe the voltage from each piezo sensor. The readings showed voltage-jumps when the pipe was impacted, however voltage did not decrease after impact. Some of the voltage jumps were not linked to an impact and were considered to be noise. After several tests and a thorough inspection it was evident that the piezo elements were damaged by the bending moment as a result of following the curvature of the pipe-section. This issue would be mitigated with larger pressure vessels (smaller curvature) however it would be beneficial to find a universal solution.

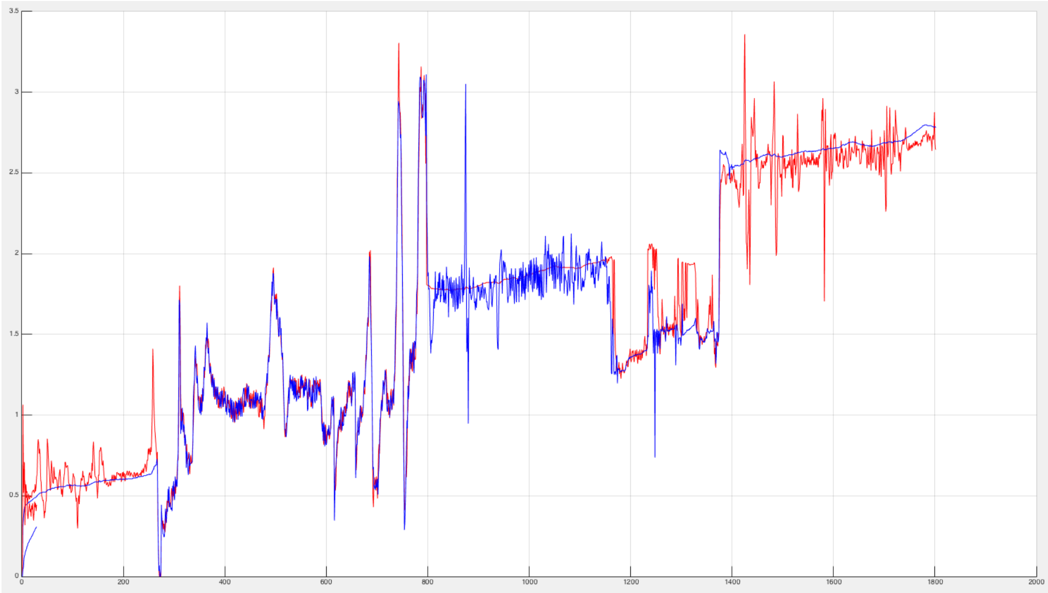


Figure 4.18: Reading from piezo elements, each piezo in different color, x-axis: time, y-axis: piezo output voltage

Therefore for the following tests, high viscosity epoxy was used to glue piezo sensors on without inducing a curvature. The test was repeated with the same setup and method as previously. The readings seen in figure 4.19 show that a stable low voltage was achieved during an idle condition and a clear noticeable voltage-spike was registered during an impact. Another important factor that was expected; with higher impact forces the registered voltage increased, thus a correlation between impact force and voltage was observed.

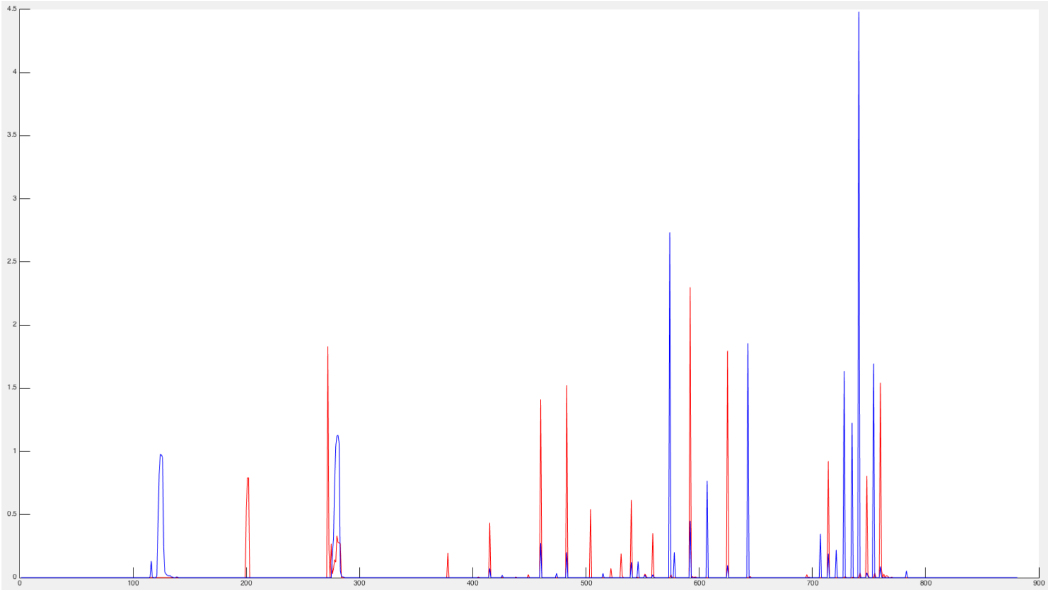


Figure 4.19: Reading from piezo elements, each piezo in different color, x-axis: time, y-axis: piezo output voltage

The choice of grounding resistor proved important. From the schematic in figure 4.17 one can see that 1MΩ resistors were used. Before using 1MΩ, several other resistors were attempted; 220 kΩ as well as 500 kΩ. These proved to ground the piezo sensors too well and so the output signal could not be picked up by the Arduino. By coupling several 1MΩ resistors together in series, higher resistance was tested. This provided an oversensitivity of the piezo sensors thus the analogue readings reached saturation very quickly. Therefore 1MΩ was chosen as a middle ground. It should also be noted that different piezo sensors that were nominally equal displayed different signal amplitudes with the same resistors thus resistor tuning might be implemented.

The tests above show that impact detection is possible in composite pipes with low cost sensors. Further it shows that even comparably small impacts can be detected. By ensuring that the low cost piezo elements are attached without a curvature, they are then able to detect impacts in composite structures. To further test whether this low cost solution is applicable for larger pipe sections in combination with a protective layer, a prototype was developed (section 6)

Chapter 5

Residual strength testing

As mentioned in section 4.4.3 this thesis attempted to find correlation between measured residual strain after impact in a composite pipe and the residual strength in the pipe. The ultimate test of the residual strength of the composite pipe is a pressure test where the burst-pressure is recorded and compared to an un-impacted composite pipe. Therefore a large number of pressure tests were performed on both impacted and un-impacted composite pipes. Unfortunately none of these tests were able to achieve a burst-pressure in the composite pipe. This is believed to be mainly due to leaks in the liner (the water-tight inner layer). All conducted experiments are presented in detail in appendix C. It describes the pressure tests conducted, different sealing methods attempted, the results and suggestions for improvement. These pressure tests have not contributed towards the overall goal for this thesis, however they are included to provide guidance for future pressure testing and residual strength testing. This is also in accordance with the latest urge in the scientific community to publish negative results, in order to prevent others from conducting the same experiments.

Chapter 6

Prototype

This chapter will describe the development of a prototype that will incorporate the technologies tested in chapter 4. The prototype was tested under impact loading to verify its ability to detect impacts and assess damage. The prototype consists of piezo elements, an accelerometer, fiber optic strain measurement (OBR) and a protective layer (X-PVC foam). The piezo sensors register vibration in the composite pipe, thus enabling impact detection. The accelerometer will measure acceleration of the whole system thus enabling distinction between direct impact and global movements (movement of the whole assembly). OBR sensors will register local residual strain in the composite pipe after impact to indicate the extent of damage.

6.1 Prototype assembly

6.1.1 Piezo and accelerometer with Arduino

The low cost solution consisting of piezo elements and an accelerometer were attached to one of the test specimen composite pipes. The piezos were glued directly onto the composite using epoxy (section 4.6). The accelerometer was attached to the composite pipe via a small planar surface and with tape, thus making it detachable. The wiring to the Arduino was done via a breadboard, as shown in figure 6.2. This allowed a flexible layout that could be changed quickly to accommodate troubleshooting of the setup. The wiring is shown schematically in figure 6.1. Figure 6.3 shows the piezo layout where each piezo is assigned a color. The same colors will be used for recordings of impacts through Matlab and allows identification of each sensor.

The total price of the prototype low cost solution is shown in table 6.1. 200NOK is considered low cost compared to most measurement equipment. (As a reference, NTNU acquired the OBR system for 1.000.000,- NOK)

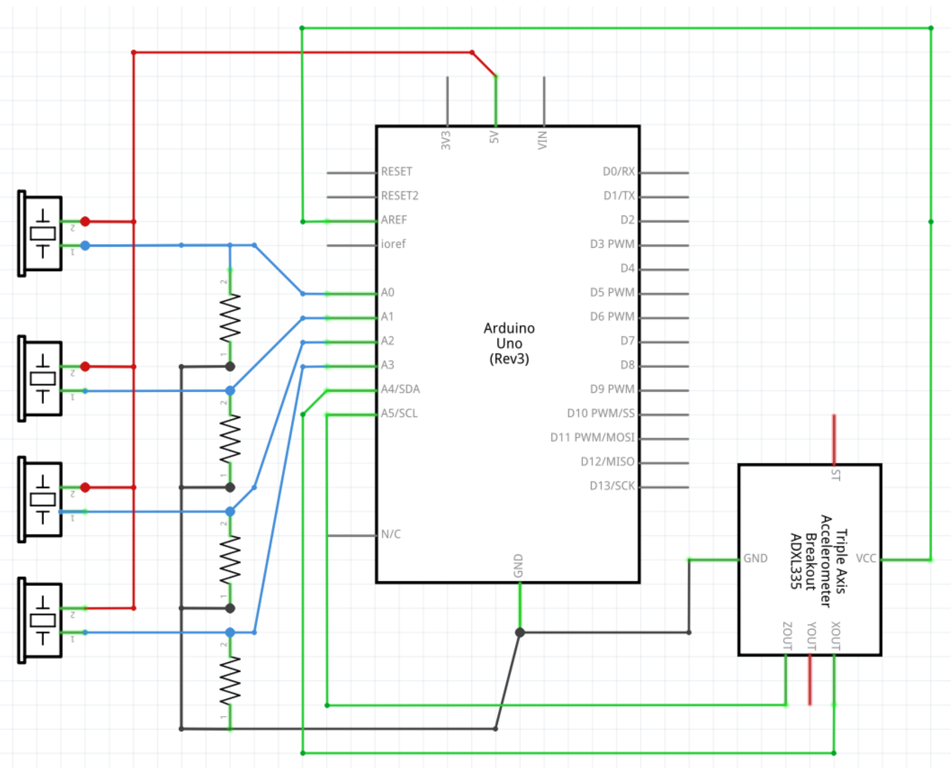


Figure 6.1: Schematic of prototype wiring

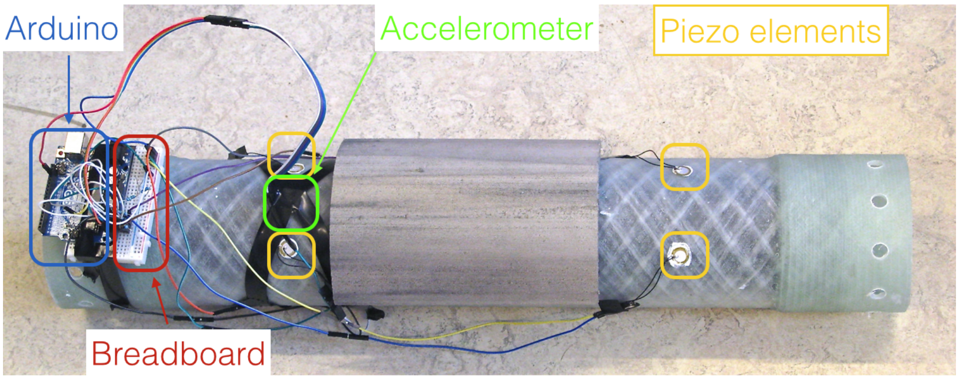


Figure 6.2: Picture of the prototype with all components

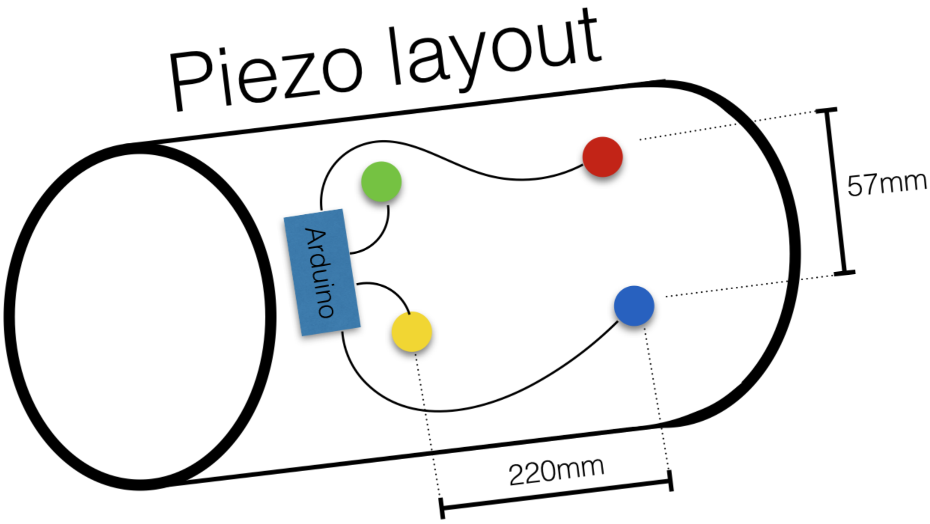


Figure 6.3: Layout of piezo elements, with colors corresponding to Matlab-plots

Unit	Price
Arduino	175 NOK
Piezo 20pc	10 NOK
Accellerometer	15 NOK
Wiring	2 NOK
SUM	202 NOK

Table 6.1: Total price for the low-cost solution

6.1.2 OBR measurement

The OBR fibers were glued in a grid using the same procedure as described in section 4.1.1. The grid layout is shown in figure 6.4. In order to simulate a full scale OBR measurement system, the fibre-grid was extended to cover a larger area in comparison with previous experiments.

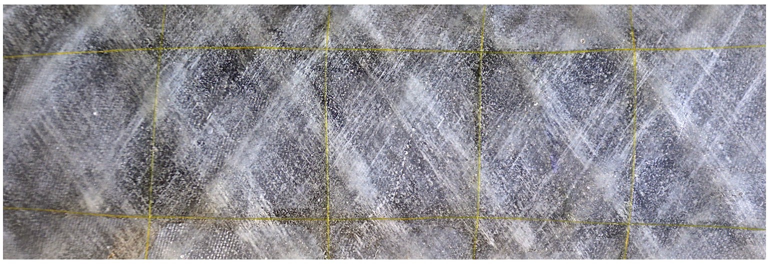


Figure 6.4: Layout of OBR fibers on prototype

6.1.3 Protective Structure

The protective structure for the prototype was cut from a X-PVC plate to fit the curvature of the pipe. The protective thickness was 10mm; in accordance with previous tests (section 3.4.2). The plate was cut to size to cover all OBR fibers.

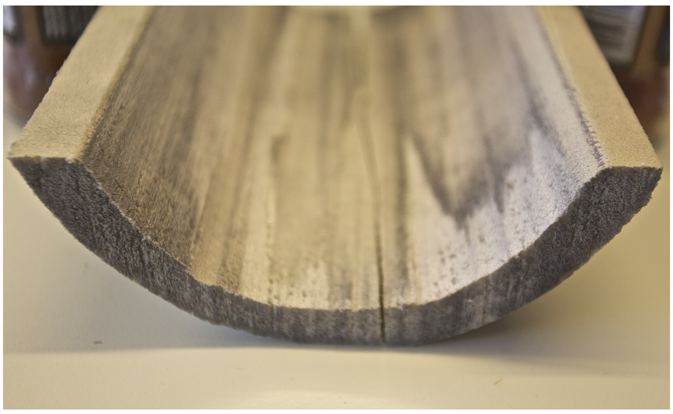


Figure 6.5: The 10mm protective layer cut out for the prototype

6.2 Test Setup

To test that all systems were able to function together, the prototype was tested in the drop test impact rig. Figure 6.6 shows the prototype connected to all systems ready for the impact.

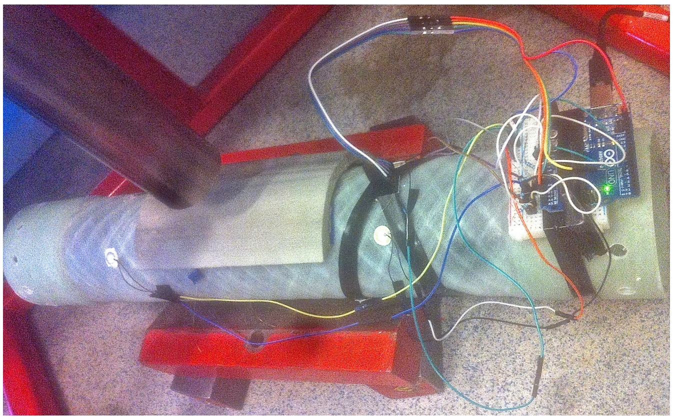


Figure 6.6: Full prototype assembly

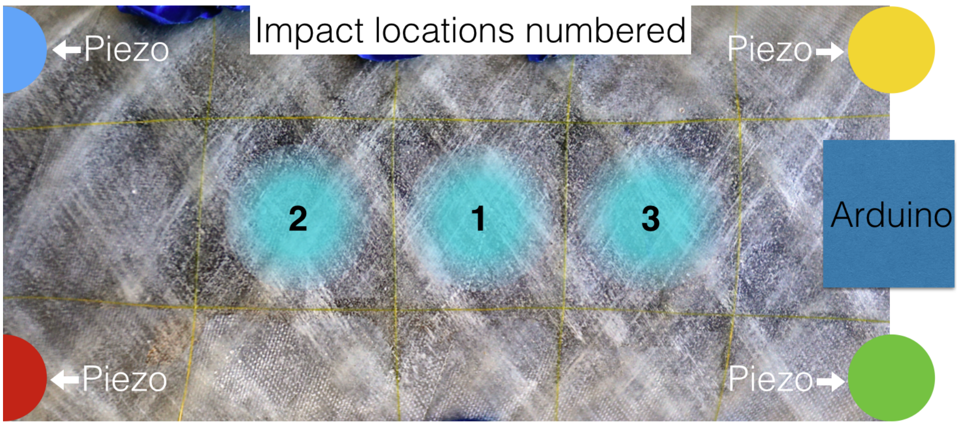


Figure 6.7: Impact locations for the three drop tests

Three impact tests were conducted to ensure correct readings. The drop height was 1000mm to ensure that the system was able to detect impacts in the low energy regime. Impact location was moved for each test, one impact in each OBR-quadrant (figure 6.4)

A simple assembly drop-test was also set up. By dropping the whole assembly one can simulate a global system movement to test the system's ability to distinguish between global movements and local impacts. In this test the whole assembly was dropped from a height of 0.4 meters. The accelerometer and piezo values were recorded with the same running code as in the previous impact experiment.

6.3 Results

In summary, the impact test yielded promising results. The piezo sensors showed a clear reading at the time of impact, the accelerometer registered small global movements and the OBR measurements showed residual strain. Figure 6.8 shows the piezo reading from the last impact which is chosen to exemplify all three measurements. All three impact readings had approximately the same response (all readings can be found in appendix G). The piezo plot showed a rapid voltage spike that occurred over one sampling cycle for three out of the four sensors (red sensors seems to have lost contact during impact). Additionally one can see that two piezo sensors one the closes side of the impact (yellow and green) have registered the impact one time increment earlier than the piezo sensor on the far-side (blue). The sampling rate was measured using the Matlab built-in timer and was found to be approximately 100Hz. Each analogue port had a reading time of 1.3 ms, thus with 6 ports (4 x piezo + 2 x accelerometer) the full loop cycle time was 10ms.

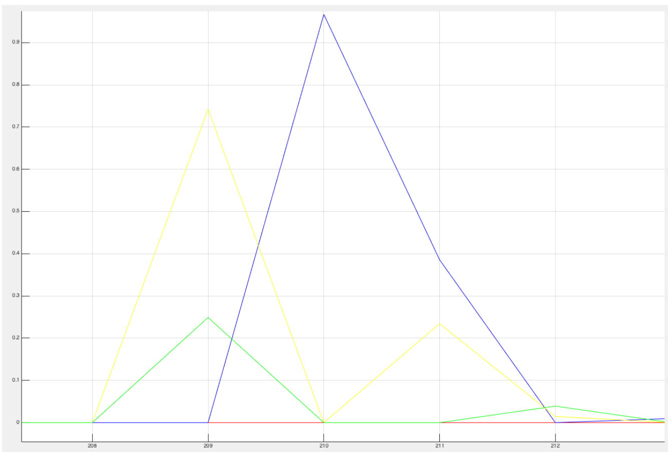


Figure 6.8: Piezo signal reading for each piezo sensor during impact, 1000mm drop, 10mm protection

The OBR measurements showed elevated residual strains at the location of impact. The residual strain in the third impact test reached a value of approximately 4500 μ strain, which is a comparably larger when compared to background strain. The OBR measurements also provided an indication as to the location of the strain. Figure 6.9 shows the residual strain after impact along the fibers. The figure is a visualization of actual measurements (shown in figure G.12). The dashed line that lies on top of the fiber signifies zero strain. Arrows denote the direction of positive strain. Color denotes which direction the fiber measures; red: hoop direction, green: longitudinal direction and the light blue circle denotes actual impact location. It shows that residual strain at the location of impact is significantly higher than the other recorded strains. This could allow for impact location detection using OBR fiber measurements.

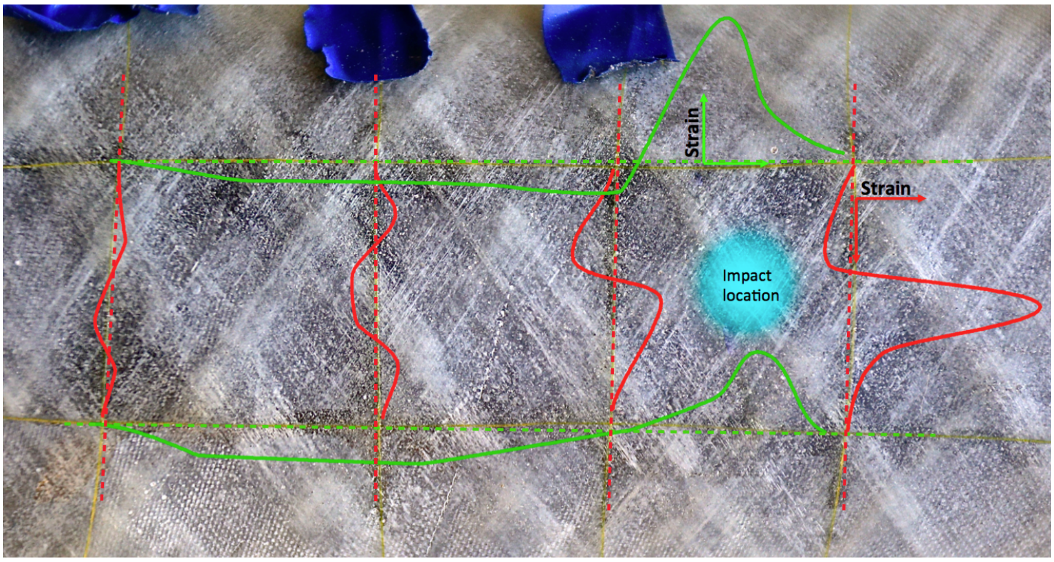


Figure 6.9: OBR residual strain along the optical fibers, 1000mm drop, 10mm protection

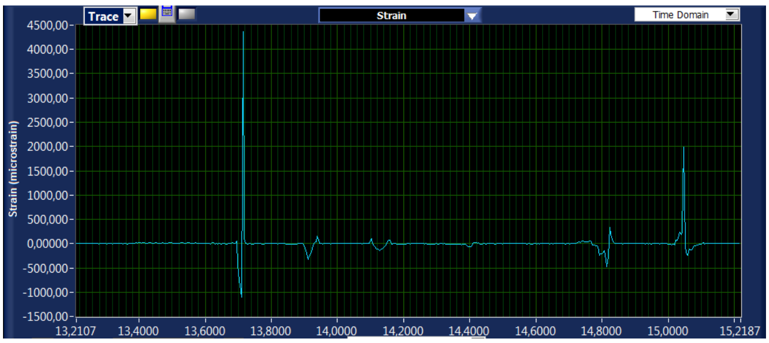


Figure 6.10: Corresponding OBR measurement, 1000mm drop, 10mm protection

The assembly drop test yielded readings that were used as a comparison with the impact test. Figure 6.11 (left) shows the piezo sensor reading combined with the accelerometer reading (red and blue) for the assembly drop test. Figure 6.11 (right) shows one of the impact tests. When comparing the two, one can see that the piezo reading magnitude is at the same level, however the accelerometer registered prolonged changes in imposed acceleration. In the accelerometer readings, impacts were recorded as short spikes in acceleration that returned to a constant value within 2-3 time increments (10-15 ms). For the assembly drop test however, the change in acceleration took place over a period of 20-25 time increments (100-125 ms). To distinguish the two readings one could simply use the duration of the deviant readings from the accelerometer. A more accurate approach would be to record the integral of the accelerometer reading in order to calculate the total absolute value of impulse per weight (specific impulse). This will indicate the specific amount of force over time which is applied on the system. Table 6.2 shows the specific impulse for all tests (Appendix E for Matlab-code).

	Impact test 1	Impact test 2	Impact test 3	Assembly drop test
Ax	2.41 Ns/kg	2.00 Ns/kg	1.80 Ns/kg	10.45 Ns/kg
Az	2.14 Ns/kg	2.22 Ns/kg	1.81 Ns/kg	7.52 Ns/kg

Table 6.2: Specific impulse comparison for all prototype tests

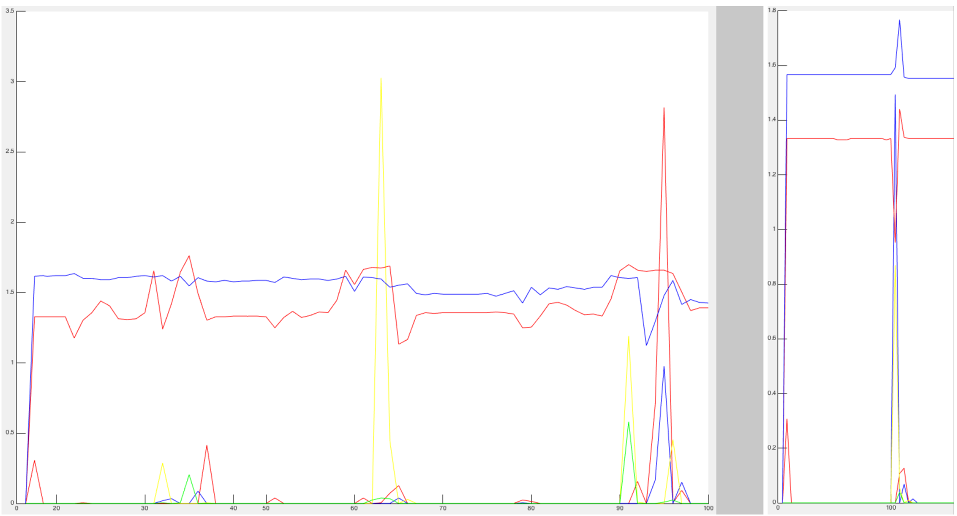


Figure 6.11: Piezo and accelerometer. Left; assembly drop test, Right; impact test

Some noise was created by the accelerometer which had to be filtered. As seen from figure 6.12 the idle noise was in the magnitude of 0.016 G. If not taken into account this would have increased the accumulated specific impulse readings. Therefore all changes smaller than 0.02 G were filtered from the impulse calculation. (See appendix E for Matlab-script).

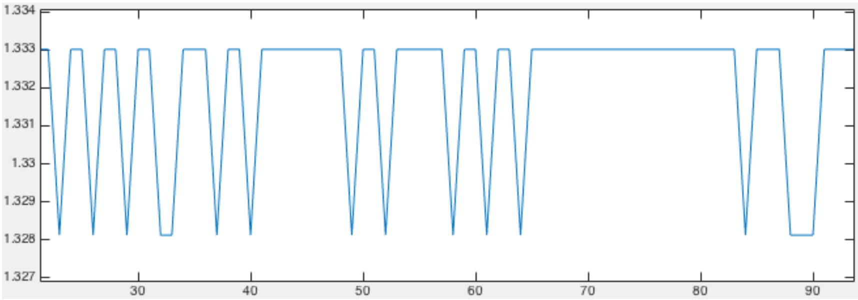


Figure 6.12: Accelerometer background noise without imposed acceleration

Lastly, to also mention the protective structure, it successfully dampened the impacts without suffering complete structural failure of the X-PVC foam. The indented surface showed clear signs of impact and the impact location could easily be determined at the foam surface. The underlying composite structure showed no visible damage (Figure 6.13).

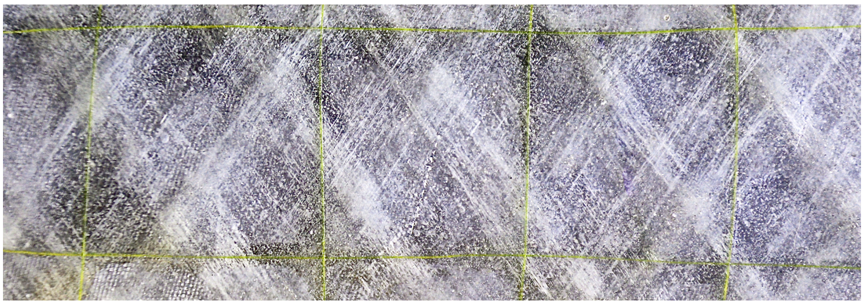


Figure 6.13: Impacted area shows no visible damage on the composite

Chapter 7

Discussion

This chapter will evaluate and discuss all experimental results obtained through this thesis and compare them to known theory. Further different potentials for improvement and suggestions for future tests are outlined.

7.1 Protective material

The protective structure for the prototype was cut to simulate a full coverage of the composite pipe. Performance of the protective structure should be compared to the design criteria listed in section 3.3. From the separate material testing one can conclude that X-PVC is the most applicable material among those examined. The prototype test further underlines the material's suitability. During the testing it was not fully penetrated, no visible damage was imposed on the underlying composite and the impact location was clearly visible from the indentation. One could conclude that X-PVC is very suitable for the application of protection composite pressure vessels. However a factor requiring further investigation is the material's suitability for large scale production. For the applications in this thesis the protective structures were cut from a moulded plate. For large pressure vessels, the material should be malleable or moldable to be applicable for commercial production. Since cross-linked polymers normally require heating or pressurization to form the cross linking bonds, the production is expected to be more complex than for example thermoplastics. More research is needed to conclude which material is most suitable for the application in an impact protection system.

7.2 Low cost system

The low cost impact detection system showed promising results during both impact testing and assembly drop testing. Firstly the drop weight impact event was recorded with clear voltage spikes from the piezo sensors, an unambiguous indication of an impact event. In all three impact tests the piezo sensors successfully recorded the impact with an increase in voltage between 1 and 4 volts which is easily measurable. The system's ability to measure the voltage spike greatly depends on the properties of the piezo sensor and the calibration. Each low cost sensor has a different sensitivity in regards to signal strength and needs to be tuned by changing resistance in the grounding resistor (figure 6.1). In this experiment constant resistors were used, however with variable resistors (potentiometers) and a newton-meter all piezo sensors could be calibrated, thus most likely increasing the accuracy of every sensor. Additionally, by calibrating each sensor one could investigate the signal strength for each sensor in an attempt to estimate impact magnitude. As from the preliminary testing (figure 4.19) a correlation between impact force and voltage spike was observed. This could potentially be used to estimate both impact magnitude but also impact location using the assumption that the distance from impact location is directly proportional with the recorded voltage. The grounding of the piezo sensor also proved important to low noise levels. It was noticed during experiments that poor grounding of the piezo sensor increased the noise level to the extent where impacts were hard to distinguish from the background noise. The prototype test shows that it is possible to achieve a low level of noise by choosing the appropriate grounding resistance.

Another possibility that was highlighted by the prototype experiment was determination of impact location using the piezo signal. As seen from figure 6.8 the piezo sensors closest to the impact location registered the impact one time increment before the sensors furthest away from the impact location. This indicates that it would be possible to determine the approximate location of the impact using low cost sensors. Due to the low sampling rate achieved with the Arduino it was not possible to further evaluate this possibility. However, micro controllers with higher sampling rates and faster processing would most likely be able to pick up this difference. In theory the Arduino should be able to achieve a sampling frequency of 10kHz, however due to the need for communication with Matlab, non-local data storage and the fact that all analogue ports were used, the sampling rate achieved was limited to 100Hz. It is believed that a significantly higher sampling rate on the Arduino could be achieved with local data processing and storage. Unfortunately, the time scope of this thesis did not allow for the testing of this setup. In summary, the author strongly believes that with a higher sampling rate it would be possible to approximate the impact location with a low cost system.

In regards to the piezo reading from the prototype, lamb wave propagation from the theory in section 4.2 can be used to describe the measured values. As shown in the equations for flexural lamb wave velocity (equation 4.8) they are dependent on excited frequency. Since impacts generate a large variety of frequencies, one can assume that that an impact will generate low frequency flexural waves. Based on this assumption the time difference in registered by piezos on opposite sides of the impact in the prototype test is most likely due to these low frequency waves.

With an increased sampling rate however, the micro controller would be able to record the different flexural wave frequencies and velocities. There are two approaches to piezo detection with a higher sampling rate. By calibrating the piezo sensors the different wave patterns could be detected and impact location could be determined. By accurately detecting the wave pattern, meaning what frequencies are detected at a certain time, the distance to the impact location can be calculated based on time of flight. This could be achieved by time-gating and amplitude gating. By filtering out only the high amplitude, low velocity waves one can focus the time of flight calculation on the low frequency flexural waves. This could somewhat reduce the need for high sampling rates. However these solutions require sophisticated calibration equipment and potentially hi-fidelity piezo sensors which are expensive. The second approach relies on a dense piezo array. Rather than few, high quality piezo sensors, several low quality sensors in a close grid could determine location. Because time of flight from the impact to the first piezo sensor will be short with a dense grid, the flexural wave will not have time to significantly disperse thus amplitude sensitivity is not as important. This allows the use of cost-effective piezo sensors and micro controller without the need of extensive calibration. Therefore it is suggested that future tests incorporate a higher sampling frequency, but still use low-cost piezo sensors in a dense array.

The purpose of the assembly drop test was to test the system's ability to distinguish between a local impact event and a global movement. The calculated specific impulse was recorded 4-5 times higher for the global movement. The system's ability to detect the difference in accumulated acceleration greatly depends on the accuracy, resolution and noise from the accelerometer. In this experiment the accuracy and resolution was to a large extent constrained by the Arduino micro controller. Since every analogue reading-port has a maximum resolution of 1024 values, the resolution and therefore the accuracy might be reduced. The prototype test however indicates that the level of resolution achieved most likely is sufficient to distinguish between impacts and global movements. In regards to noise the accelerometer readings show that noise was limited to one measurement increment and could be omitted by implementing a signal level filter in the Arduino running code. An increased number of accelerometers placed in alternative locations could also increase the accuracy of the system. By measuring the acceleration of the supporting structure in addition to the composite itself one could compare the two signals to determine whether movement is due to impact or global movement. With all these factors taken into account, one can most likely distinguish between a local impact and global movements using accelerometers.

The prototype has demonstrated that a low cost system consisting of piezo elements and an accelerometer is capable of detecting impacts though a protective layer and prevent false positive impact readings. Further it has highlighted several potentials for improvement that should be investigated further.

7.3 Optical fiber residual strain measurements

For both the preliminary tests and the prototype, the OBR measurements showed elevated residual strains post impact. Thus they could potentially be used for impact detection. More interestingly, they show elevated residual strains in the location of the impact. For the preliminary tests, the fiber layout was centered around a predetermined impact location hence the readings did not highlight this effect. For the prototype test the fibre distribution was extended, thus the difference in strain became measurable. From figure 6.9 one can clearly see that the strains surrounding the impact location are elevated. It is a proof of concept for OBR strain measurement as impact assessment.

It should be emphasized that all residual strain tests during this thesis have been conducted on hollow (air filled) pipe sections. This implies that residual strains after impact would be detectable when the instrumented pressure vessel is empty. When pressurized, it is likely that the elevated general stress in the composite vessel would amplify the residual strain after an impact event. One can therefore argue that the tests conducted in this thesis could be considered to be worst case scenario in terms of residual strain measurements. This further supports the theory that OBR strain measurement is a feasible impact evaluation technique.

For the application of detecting impact magnitude or damage assessment, the results are inconclusive. The measured residual strain was not consistent with impact energy. The author was unable to find a clear correlation between impact energy and the level of residual strain. Measurements from impacts with same drop height display dissimilar levels of strain. The three impacts on the prototype were all conducted from 1000mm, the maximum and minimum residual strain however for the three impacts were respectively (-800,200), (-600,600) and (-1000,4500). Several factors could contribute to this discrepancy and it is believed that the complex intrinsic properties of composite pipes in addition to variable boundary conditions play a major role.

One important aspect regarding the OBR measurements is the cause of residual strain. Although the scope of this thesis does not allow thorough investigation of this aspect, it should be discussed and considered for future work. Observations based on a limited amount of impact tests indicate that residual strain correlates with impact energy. However the level of residual strain is not fully proportional with visible damage. It was observed that the measured residual strain was significantly higher with fiber failure than with only delamination as visible damage (appendix D). Additionally the size of the delamination area seems to have some correlation with residual strain although no clear correlation could be identified. The source of residual strain could also be due to loss of cohesion between the pipe and the optical fiber. Fibers closer to the impact will more likely experience decohesion. Therefore the increased strain at impact location might be a result of cohesion failure. However in all cases the sample size is too small to conclude. Based on the OBR residual strain tests during this thesis, one can conclude that more work should be conducted to understand the residual strains after impact, for this method to be effective in evaluating the damage in composite structures after an impact event.

Chapter 8

Summary and Recommendations for Further Work

This thesis has examined the possibilities of impact protection, detection and assessment combined for composite pressure vessels. A new low-cost solution for impact detection has been developed and tested. By first testing each protection and detection technology and method separately, one was able to identify strengths and limitations with each technology in order to later combine them into a final prototype.

8.1 Summary and Conclusions

The first part of the thesis focused on current research on the field of impact protection and detection for composite pressure vessels. Major effort has been put into the development of impact detection and assessment methods and technologies. The majority of studies have successfully detected impacts, however damage assessment has proved to be uncertain. Additionally, the technologies used are complex and expensive. Thus the need for a simple and low-cost solution for impact detection became apparent. Another aspect which also was highlighted through the literature review, was the investigation of a protective structure in combination with impact detection and assessment.

Therefore this became a focus of the thesis in addition to the low-cost solution with the goal of the development of a fully functional prototype.The development of the prototype was separated into separate functions; impact protection, impact detection and impact assessment with the corresponding technologies; energy absorbing material, low-cost sensor technology and OBR technology respectively.

For the protective structure a comprehensive materials search was conducted where the most promising materials were impact tested. By recording the material's impact response in terms of energy absorption per weight, failure modes etc. The final choice became cross-linked PVC which proved its effectiveness through several impact tests. X-PVC satisfies the chosen selection criteria for impact protection materials on all aspects. However, the material has not been tested in full scale production in cylindrical shapes, thus further testing is needed to fully verify the material's applicability.

For the purpose of a low cost solution, cheap elements were obtained to test their ability to detect impacts. A low cost accelerometer was also implemented to ensure accurate impact readings and mitigate false positives. These sensors were connected to a low cost micro controller (Arduino), attached to a composite pipe and tested. During impact testing the low cost solution proved to be very effective in detecting impacts and mitigating false positives. Additionally the testing showed potential for impact location detection which should be further investigated. In summary the low-cost solution shows great potential and should be considered for further development. This could enable impact detection for a wide range of composite pressure vessels where impact detection is too costly today.

Fiber optic measurements have been researched as means of impact detection and assessment. For this thesis, the goal was to implement fibre optic strain measurements to assess damage after an impact and indicating the residual strength of the pressure vessel. Initial tests with the OBR strain measurement showed significant residual strains after impact both with and without a protective layer during impact. Unfortunately the author was unable to fully seal the composite tubes to obtain reference burst pressures to correlate with residual strains after impact, thus a connection between residual strains and residual strength could not be determined. The author therefore relied on residual strain to evaluate the extent of damage. Despite a limited sample size, it was observed that residual strain increased with visual damage. With increased delamination damage the residual strain seemed to increase. When fiber failure occurred, the residual strains seemed to reach significantly higher values than for delamination only. Additionally, the OBR measurements showed elevated strains in the impacted regions thus enabling determination of impact location. Conclusively, OBR measurements have the potential for impact damage detection and assessment. Although this thesis has proven the OBRs potential, more work is required to validate its performance.

In summary, this thesis has achieved the following objectives:

1. Found an effective impact protection material through experimental testing
2. Successfully developed a low cost solution for impact detection
3. Found a promising method for impact assessment

8.2 Recommendations for Further Work

There are several areas of interest highlighted by this thesis that could be investigated in future work. The different recommendations for extension of this thesis have been listed by time span.

In the short term the developed low cost solution could be upgraded with a faster micro controller and local data collection and storage to maximize sampling rate. This could enable impact location determination with the low cost peizo sensors. Recommendations for new micro controllers are; Raspberry Pi or CHIP which have significantly more computing power and higher sampling rates than the Arduino used in this thesis. Using the same wiring setup as in this thesis, but running all signal processing on the micro controller itself with a higher clock frequency, it is believed that impact location could be determined.

As a short term goal for the OBR measurements one could investigate repeated impacts on a structure with an OBR-fiber grid. Although it has been argued in this thesis that repeated impacts are not likely due to the detection of the first impact, it is still important to validate whether the system can register repeated impacts. Thus a simple test could be conducted using the same testing equipment as used in this thesis.

The last recommendation for in the short term is to impact OBR-fibers directly. Throughout this thesis, great care has been taken to not impact the fibers directly to prevent fiber breakage and loss of signal. However, during the service life of the vessel one should expect impact directly onto the OBR-fibers. Thus an impact test should be conducted to test whether the OBR measurements can be conducted with an impacted fiber, though a protective layer, and directly onto the fiber itself.

As a recommendation for the long term, several aspects could be further investigated. Firstly the correlation between residual strength in a pressure vessel (or composite pipe) and the residual strain after impact could be researched. The results of this thesis show the residual strain in the composite structure after impact does indicate the magnitude of the impact. The ultimate goal for an impact assessment system is to provide the user of the pressure vessel with information of the residual strength of the vessel after an impact event. The author believes that using OBR strain measurements, one could predict (within a reasonable degree of accuracy) the residual strength in the composite using residual strain. Therefore the suggestion for future work is to fully pressure test a large number of impacted and un-impacted specimens to determine whether there exists a correlation between residual strain and residual strength.

Secondly, several tests are needed to further verify the effectiveness of the low cost impact detection system. Specifically, testing different impact energies to find sensing-limits, testing optimal sensor distribution across the vessel for optimal sensing and increase the amount of accelerometers to further increase the accuracy of local vs. global movements. The author would also suggest to implement an array of transistors coupled to the piezo sensors to enable a dynamic sensing range. This would increase the resolution and the sensitivity of the low cost solution without a significant increase in price.

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Appendix A

Acronyms

FE Finite Element

FEA Finite element analysis

FEM Finite Element Method

CES Cambridge Engineering Selector

EPP Expanded polypropylene

PUR Expanded polypropylene

EPS Expanded polystyrene

EPS Expanded polystyrene

EPS Expanded polystyrene

FRP Fiber reinforced plastic

PVC Polyvinyl chloride

X-PVC Cross-linked Polyvinyl chloride

PET Polyethylene terephtalate

LDPE Low density Polyethylene

AE Acoustic Emission

OFDR Optical Frequency Domain Reflectometery

OBR Optical Backscatter Reflectometry

Appendix B

Complementary Information to the literature review

The literature review in section 2 used several different studies. The articles used are summarized and referenced separately in this section.

B.1 Summarized articles; impact protection

The first paper in the list is "Material behavior of polymers under impact loading" by Du Bois et. al. [1] The paper is a comparative review of different materials models for polymers where special attention is giver to the crashworthiness of the materials. Specifically elastomeres, foams and thermoplastics were investigated. Most of the paper focuses on how to accurately model these material for FEA (Finite element analysis). It concludes that accurate models for FEA analysis of crushable foams is achievable with satisfactory accuracy. Failure modes like brittle fracture and lateral bulging are not taken into account which poses a challenge for modeling of foams with higher densities. The paper concludes that an impact FE-analysis of compressible foams is fully achievable.

"Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram" by M. Avalle et. al. [2] aims to experimentally evaluate the energy absorption characteristics of three polymeric foams under static and dynamic load conditions. It explaines and utilizes two different material characterization diagrams (energy-absorption and efficiency) to determine the impact absorption properties of expanded poly propylene (EPP), Rigid Polyurethane (PUR) and Polystyrene/ Polyamide foams. All materials were tested for different densities to ensure a thorough design basis. The paper concludes that all the cellular structural foams are suitable for impact protection. Due to their very low weight, low cost and high workability they are a suitable for a large variety of applications. Further the paper concludes that the PUR and PE/PA foams have a higher efficiency than the EPP foam in general. It also concludes that PE/PA foams can withstand multiple impacts where as the PUR foam looses most of its integrity after one impact.

"Thin-walled structures as impact energy absorbers" by W. Abramowicz [3] investigates thin walled component behavior under impact loading with a focus on transportation vehicle energy absorbers. To a large extent this paper attempts to find suitable analytical deformation models that can describe the load cycle under impact loading in crushable profiles. It also provides describes optimum design for both profile shapes and profile orientation for maximum energy absorption. In general this paper provides an overview of the basic concepts of profiles design. The paper concludes that support structure design in combination profile design is essential for the effectiveness of impact energy absorbers.

"Collapsible impact energy absorbers: an overview" by Alghamdi [4] outlines different profile shapes used as impact absorbers and the common modes of deformation. circular and square tubes, frusta struts honeycombs and sandwich plates are all investigated. The paper does not compare the different shapes and their effectiveness. It does however provide an overview of all available shapes and their properties for further investigation.

"Mechanical models of cellular solids: Parameters identification from experimental tests" by Avalle et. al. [5] attempts to find the most feasible models to use in materials selection for engineering purposes. They used experimental tests and compared them to existing models to test which models are most effective. Further the study highlights different important aspect that need to be taken into consideration during material selection. Finally the study correlates density to design criteria which results in a tool to identify the optimum density. In essence the paper provides a tool to identify the optimum density for the chosen application and loads. It concludes that the new material model is a combination and simplification of existing models to provide an easy to use paradigm for cellular foam selection.

"Impact mechanics and High-energy absorbing materials: review" by Qiao et. al. [6] is a review of current computational methods in regards to impacts as well as a review of current design concepts for impact absorption. The computational models covered are rigid body dynamics, stress wave propagation and nonlocal models as well as finite element and finite difference methods. In regards to this thesis the important part of this papers is the high energy absorbing materials and structures. Both collapsible metal structures and composite sandwich structures are investigated for high energy impact purposes. Other principles like ceramic armor, magnetorheological fluids and memory alloys are also investigated as possible energy absorbers. The paper concludes that impact absorbing design is difficult because of the many mechanisms that are acting concurrently during impact. However there are many feasible solutions available today that can withstand high energy impacts.

B.2 Summarized articles; impact protection

"Application of composite materials in high pressure technology" by H. Torab and M. Aggarwal [7] wrote in 2014 a paper that summarizes application of composites for high pressure purposes. The study outlines the different manufacturing technique available today and what typical application each is used for. The study also looks at structural health monitoring for composites both current technologies but also new technologies that are expected to emerge. They paper concludes that the use of pressurized composite structures has increased in the last decade and that it will rise significantly in the next due to its versatility and estimated unused potential.

"Low velocity impact and residual burst pressure analysis of cylindrical composite pressure vessels" by E. Kim, I. Lee and T.K. Hwang. [8] This paper contains an impact analysis and a residual burst-pressure analysis of a cylindrical composite pressure vessel. Advanced modeling and analysis criteria were used to obtain a FEM (Finite element method) analysis using ABAQUS and VUMAT. Experimental tests were compared to values obtained through the FEA. Specifically impact behavior, impact damage and residual strength/burst pressure was compare with the FEA values. The authors conclude that the with the advanced modeling techniques used (weibull distribution, Hashin criteria etc.) are able to predict the experimental values in a satisfactory manner. Fiber failure was predicted with great accuracy where as delamination was the least accurately predicted failure mode. Further the authors observed that the residual strength of the pressure vessels in terms of burst pressure was to a large extent dominated by fiber failure and that delamination did not significantly contribute to the loss of burst strength.

"Delamination prediction of composite filament wound vessel with metal liner under low velocity impact" by Z. Changilang et. al. [9] investigates the mechanical impact behavior of a composite pressure vessel with a metal liner both with and without internal pressure. The authors use a modified Hertzian contact law on combination with a direct integral Newmark-scheme method (in the time domain) to model the material and impact behavior. The study concludes that the difference in impact damage in pressurized versus non-pressurized vessels is significant. Pressurized vessels are predicted to experience significantly more damage than un-pressurized vessels under impact loading. There are however some weaknesses with this paper. No experimental tests are conducted to verify the predicted values, and the calculation does only cover delamination. Therefore these calculation alone cannot predict the strength of a composite pressure vessel. It does however show that internal pressure is an important factor to consider for impact damage assessment.

"The effects of repeated transverse impact load on the burst pressure of composite pressure vessel" by I. Demir et. al. [10] This paper investigates the effect of repeated impact loads on composite pipes, both pressurized and un-pressurized. Impact energies of 10,15,20,25 and 30 Joules were tested at both at room temperature and at elevated (70 degrees C) temperatures. The specimens were impacted, then pressure-tested to find the burst pressure. The study found that burst pressure decreases with elevated impact energies and elevated temperatures. The study also found that the burst pressure was higher for specimens impacted while un-pressurized than for the ones impacted while pressurized. Finally the study concludes that an impact load on a pressurized composite vessel will severely decrease it's strength and should therefore be protected against impacts.

"Distibuted sensing of composite over-wrapped pressure vessel using fiber Bragg gratings at ambient cryogenic temperatures" by J. Grant [11] is a proceeding conducted by NASA to investigate the potential of fiber Bragg grating sensing in pressurized composite vessels. A carbon fibre vessel was pressurized up to 2800 psi (193 bar) and the strains in the pressure vessel was monitored by the fibers sensors. The authors conclude that fibre measurements are promising for damage evaluation in composite pressure vessels, however more work is needed to fully validate the effectiveness of such measurements.

"Damage evaluation and analysis of composite pressure vessels using fiber bragg gratings to determine structural health" by M. Kunzler et. al. [12] This study investigates an array of fibres wounded into a composite vessel which is then impacted and damage location is estimated with the strain readings. By using a specially designed software that interprets the strain signals from each individual strain fibre it is able to determine impact location and magnitude. The proceeding concludes that that the location and magnitude of the impact can be estimated with a fair degree of confidence and thus fibre optical strain imaging may be a viable non-destructive method to monitor damage in composite pressure vessels.

"Monitoring of fibre reinforced composites with embedded optical fibre Bragg sensors, with application to filament wound pressure vessels" by J. Degrieck et. al. [13] is a study of fibre Bragg sensors to test the sensors ability to measure strain accurately measure strains when embedded into composite structures. This is done by investigating the linearity of strain measurements compared to the applied force. Several experiments were conducted by pressurizing the vessel and measuring the output strain both during pressurization and over a long period of static internal pressure. The study concludes that embedded optical fibres shows excellent performance and could be used as a health monitoring system.

"Use of acoustic emission to evaluate residual strength in FRP pipes after impact damage" by G. Ramirez. [14] This article investigates the use of acoustic emission (AE) to predict the level of damage in composite pipes after impact. Glass fibre reinforce pipes were impact tested then later measured with AE to determine the level of damage. Then the pipes were pressure-tested to measure the residual strength and correlate the data with the predicted strength from the AE readings. The authors conclude that AE can be used as impact detection and with careful calibration it can also predict the level of residual strength in the composite pipes after impact.

"Arrays of conformable ultrasonic Lamb wave transducers for structural health monitoring with real-time electronics" by L. Caprineri et. al. [15] is a research paper investigating the use of piezo electric sensor arrays to monitor composite pressure vessels. The authors have developed custom software that interprets the piezo signals and shows that such monitoring is possible. However this study does not include extensive testing thus the study can only prove the potential of Lamb wave monitoring.

A real-time electronic system for automated impact detection on aircraft structures using piezo electric transducers". by L. Caprineri. [16] This study is a complementary study to the one previous listed. The same setup has now been tested experimentally and the software for location detection has been implemented. The study has presented a real-time detection system for impact detection and location determination. The accuracy was measured to be approximately 20mm.

"Impact damage monitoring of FRP pressure vessels based on impact force identification" by S. Atobe. [17] This paper investigates distributed strain measurement networks and their ability to estimate the location and extent of impact damage. Using transformation matrixes calibrated for the experiments the authors successfully determined the impact location regardless of damage formation. Further in regards to damage severity the authors were only successful in determining damage initiation. Due to degradetion of structural stiffness they were unable to determine the estimated true peak force. Estimating damage size from the impact duration however showed promising results and was recommended for further study by the authors.

"Numerical/experimental impact events on filament wound composite pressure vessel" by G. Perillo et. al. [18] is a study where impacts on pressurized composite pressure vessels were experimentally and numerically investigated. The study used an advanced FEM analysis using Puck and Hashin criteria for matrix cracking and fiber failure and cohesive zone theory to estimate delamintaion. Further a composite pressure vessel was impacted at low velocity and impact energy was recorded. The experimental impacts were then compared to the FEA to validate the model. The paper concludes that the FEA was successfully able to predict the impact events for low velocity impacts with less than 5% error.

"A smart polymer composite for repeatedly self-healing impact damage in fiber reinforced polymer (FRP) vessels" by Jones Nji. [19] Composite panels with a self healing matrix (resin) was repeatedly impacted with a impact energy of 42 joules. The same panel manufactured with conventional matrix was then also subjected to the same loads and the number of impacts before failure was registered. The paper concludes that the self healing resin increases the impact tolerance of the composite by 20%. The paper suggests that a lot of work still remains for the resin to be commercially applicable but that these preliminary tests show that self-healing composites could be used for service life extension.

"Manufacturing and testing composite over wrapped pressure vessel with embedded sensors" by C. Frias and H. Faria. [20] This study investigates two leading techniques for non destructive testing of composites; piezo electric sensors and optical fibre sensing. The aim for both sensors is to detect critical events during the service life of the composite pressure vessel. The applicability of the piezo sensor and the optical fibre sensor was evaluated in terms of embedebility, accuracy, sampling rate etc. The study concludes that piezo electric sensors proves to be the superior in terms of accuracy and ease of handelig. On the other hand optical fibres prove to be a promising technology that should be investigated further to uncover its ultimate potential.

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Appendix C

Burst pressure testing

A large number of pressure tests were performed on both impacted and un-impacted composite pipes. Unfortunately none of these tests were able to burst the composite pipe. This is believed to be due to a combination of leaks in the liner (inner sealing layer) and the liner/end-fitting interface. This chapter will describe the pressure tests conducted, different sealing methods attempted, the results and suggestions for improvement. These pressure tests have not contributed towards the overall goal for this thesis, however they are included to provide guidance for future pressure testing and residual strength testing. This is also in accordance with the latest urge in the scientific community to publish negative results to prevent others from conducting the same experiments.

The sealing problem

When subjecting the pipes to internal pressure, two main causes for leakage are present:

- Leakage between pipe and end-fitting
- Leakage through pipe matrix

The leakage between pipe and end-fitting is countered by a tight fit and an o-ring sealing the interface. However, the end-fitting used was originally designed to leak before burst[16]. The o-ring seal is broken by the bolt-holes in the pipe when the internal pressure and therefore the strain is sufficiently high [REF]. This limits the test-pressure for this setup.

The pipe itself is not completely water-tight, as tiny cracks in the epoxy matrix appear at low stresses. These cracks allow water to seep through at a low rate hence the need for a liner.

One of the challenges when sealing the pipe is that the interior is not accessible after attaching the last end-fitting. This makes the sealing more difficult, as the method used needs to be performed before attaching the last end fitting.

Test setup

The pressurization tests were conducted by sealing each end of the composite pipe using metal end fittings produced by Anders Fossa in 2014. Various solutions were used to reduce leakage through the pipe. The pipe was then pressurized internally by a high pressure inlet in one of the end fittings, using a high pressure pump with 1000 Bar capacity. The pressure was logged using a digital manometer.

Liner methods attempted

No liner

Since the pump is able to supply a relatively large flow of water, the pressure is able to build up a considerable amount even with leakage through the matrix. With no sealing apart from the o-rings sealing the pipe/end-fitting interface, the pressure was able to build to 110Bar. At this pressure the pump was unable to supply enough flow to overcome the leakage. The leakage at this point was mainly through the end-fitting interface, where the longitudinal forces pulled the bolt-holes of the pipe onto the o-ring. The pipe used was roughly 3mm thick, with an additional $\pm 45°$ layer reinforcing the

Figure C.1: A composite tube with end-fittings attached ready for pressure testing

Figure C.2: Composite tube inside metal shield during testing

ends.

Rubber Balloon

An attempt was made to seal the pipe by using a balloon as an internal liner, attached to a machined pressure nipple at the interior of end fitting. Unfortunately the balloon burst before reaching high pressures, rendering the method useless. It is still thought to be one of the more promising solutions, as it can be easily assembled before attaching the end-fittings. However, a very robust balloon needs to be used, as there is considerable movement between the pipe and the end-fitting during pressurization. A suggestion is to use a weather-balloon or similar.

Plastic foil

Thick plastic foil attached to the interior of the pipe with sticky-tape was attempted both to seal through matrix leakage, and to alleviate some of the leakage through the pipe/end-fitting interface. The method proved effective when it was used to stop the locally large leakage at points of impacts, where it was able to form a tight seal and

Figure C.3: Burst rubber balloon after pressure test

Figure C.4: Plastic liner method before assembly

stopping the local leakage. When sealing the interface between the pipe and end-fitting, it was not as effective. The end which was accessible from the outside before attaching the last end-fitting was able to provide an adequate seal. The last end-fitting interface was not accessible from the outside, therefore it could not be visually inspected and aligned, thus a good seal was not achieved.

PET pipe

Using a PET pipe as a liner provided a robust seal preventing leakage from the pipe through the matrix. It also enabled additional sealing of the pipe/end-fitting interface by sealing the interface between the PET-pipe and the end-fitting with sticky-tape, prior to attaching the end-fittings. However, the same problem with leakage through the end fitting interface presented itself. As the pressure increases a gap between the PET-pipe and the end fitting emerges and grows. This breaks the seal of the liner, and leakage occurs.

End-fitting interface

To prevent the excessive leakage through the end-fitting interfaces, sealing them with sticky tape before attaching the pipes to the end fittings was attempted. This did, to some extent, prevent leakage, however at elevated pressures this method failed to pr ovide an adequate seal.

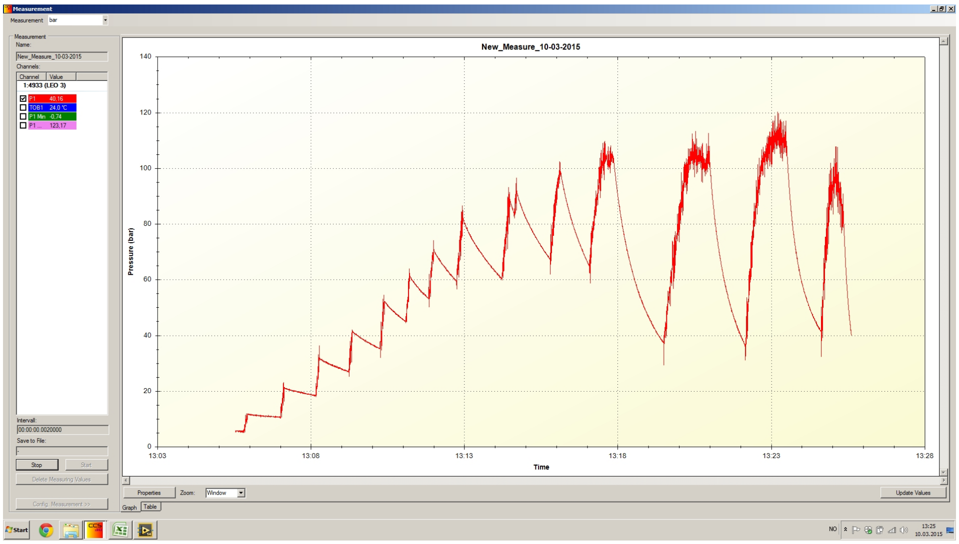

Figure C.5: Pressure readings throughout a pressure test

Discussion of results

The tests conducted showed that even with no liner or extra sealing the pressure is able to reach 110Bar before the rate of leakage exceeds the pumps capacity. At this pressure the limiting factor is the pull-out of the end fittings. By having thicker reinforcements of the pipe at the ends, this pressure can likely be increased somewhat. However, the geometry of the end fitting makes it so that it can only be reinforced to a thickness of 5mm. Therefore it is unlikely pressures far exceeding 110Bar is achievable without a good sealing method.

None of the attempts to seal the pipe were able to overcome both the problem with leakage through the matrix and the leakage through the pipe/end-fitting interface. Eventually the large strains rendered all the sealing techniques ineffective. The most promising approach is thought to be the balloon approach, but using a much thicker and flexible balloon than what we attempted. Due to the large movements of the parts supporting the flexible balloon the liner must also be flexible.

Recommendation for future work

For future attempts to reach burst pressure the following recommendations are made:

- Use a new end fitting not designed to leak before burst.
- Use end-dome with pressure inlet to wind a tank which can be directly pressurised.

A new end fitting is currently being developed by Vadim Khentalov (Current master thesis at NTNU). This end fitting is not designed to leak before failure, hence the movement of the end fitting is not as critical. Additionally it supports thicker pipes, meaning the pipe ends can be reinforced further, making the tear out of bolt-holes less prominent.

Alternatively, omitting the end-fittings altogether, and instead winding onto domes with a pressure inlet and a liner allows for a very promising seal. The disadvantage being that only one specimen can be wound at a time.

Appendix D

Impact damage and OBR measurements

This appendix includes all pictures with corresponding OBR measurements from drop weight impact tests. The residual strain measurements are correlated with delamination area and drop height (Impact energy).

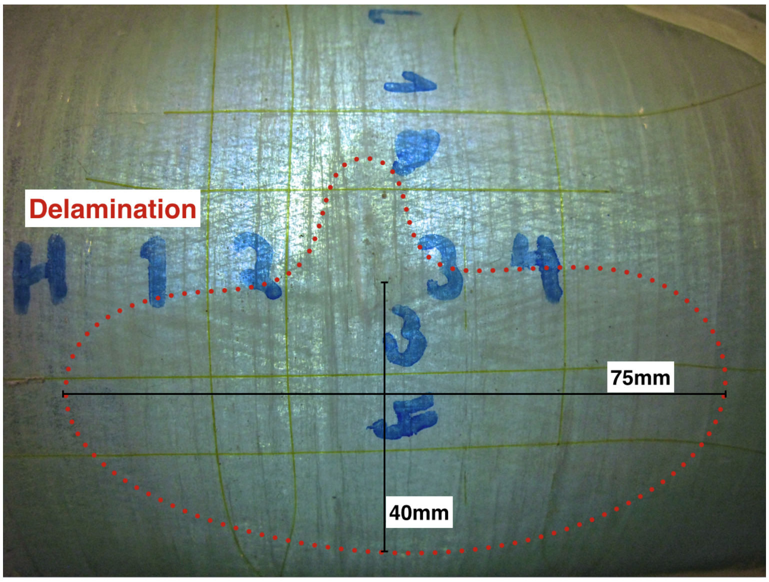

Figure D.1: Fiber grid for OBR residual strain; without impact protection, 1500mm

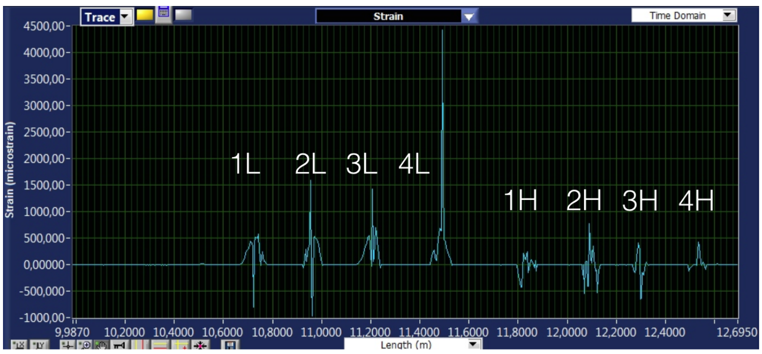

Figure D.2: OBR measurement for impact without impact protection, 1500mm

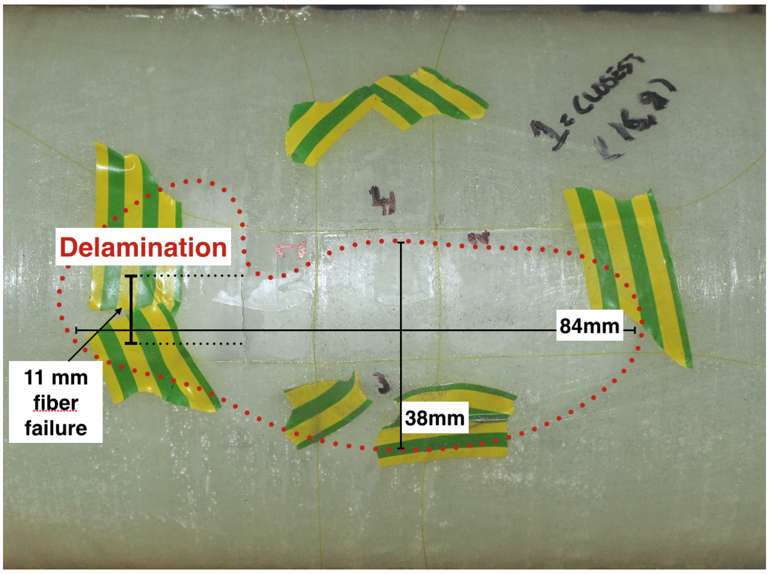

Figure D.3: Fiber grid for OBR residual strain; with impact protection, 1500mm

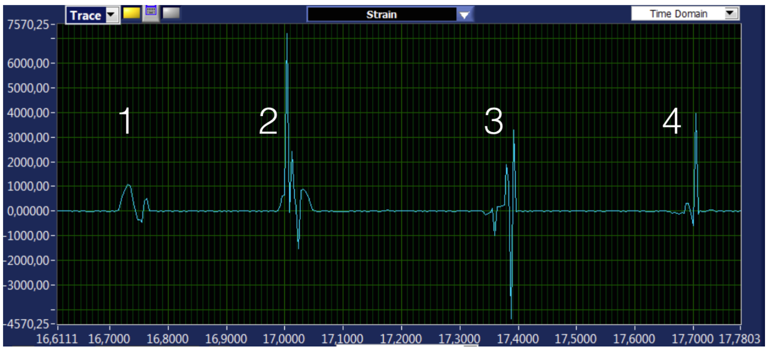

Figure D.4: OBR measurement for impact with impact protection, 1500mm

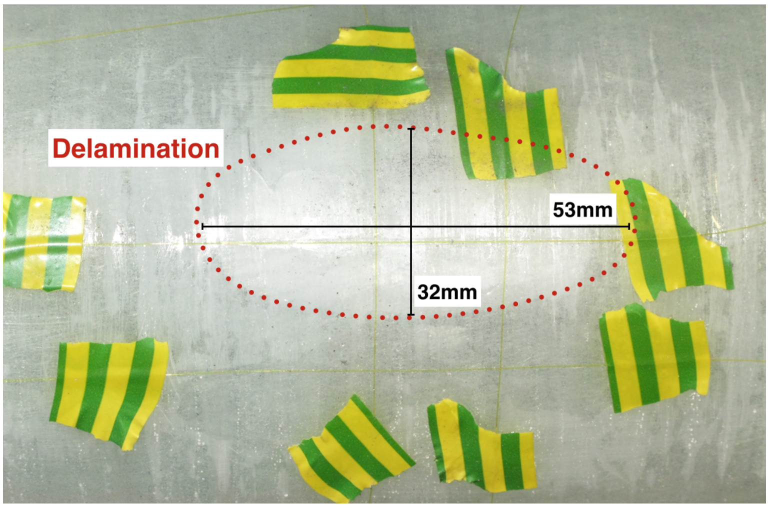

Figure D.5: Fiber grid for OBR residual strain; with impact protection, 1000mm

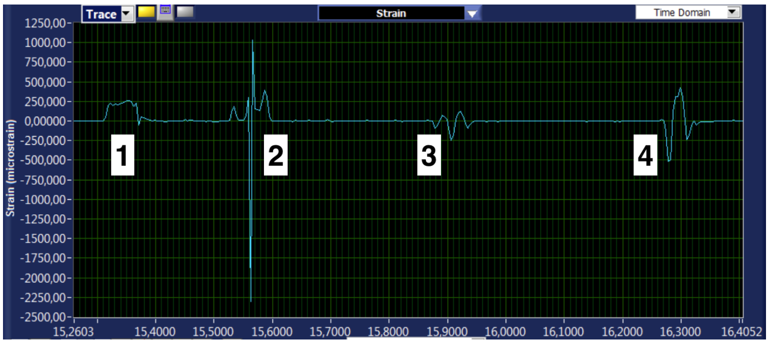

Figure D.6: OBR measurement for impact with impact protection, 1000mm

The measurements are summarised in table D.1 were delamination area is correlated with drop height (Impact energy) and measured residual strain.

Table D.1: Table summarizing drop test results

Drop height	Protection	Delamination area	Avg. Residual strain
1500mm	0mm	9425 mm^2	500 μ strain
1500mm	10mm	9910 mm^2	2000 μ strain
1000mm	10mm	5330 mm^2	400 μ strain

Appendix E

Matlab code

This appendix contains the Matlab running code for the low cost solution. The running code used for the prototype study was a further development of the running code for the preliminary study. Therefore only the running code for the prototype is included.

E.1 Prototype Running Code

The code below is he running code which communicates and stores values from the piezo sensors and the accelerometer during impact tests and the assembly drop test.

```
a = arduino('/dev/tty.usbmodem1451'); % routes the Arduino connection to USB
interv = 200; %How long the code runs
passo = 1; %Time increment

t=1; %Initiate time value
x=0; %Initiate x reading value
y=0; %Initiate y reading value
```

```
z=0; %Initiate y reading value
q=0; %Initiate y reading value
bo=0; %B old value
co=0; %C old value
do=0; %D old value
eo=0; %E old value
ax=0; %accellerometer x axis
az=0; %accellerometer z axis

while(t<interv)
b=readVoltage(a,0); %Reads analog port 0 in arduino
c=readVoltage(a,1); %Reads analog port 1 in arduino
d=readVoltage(a,2); %Reads analog port 2 in arduino
e=readVoltage(a,3); %Reads analog port 3 in arduino
axr=readVoltage(a,4); %Reads analog port 5 in arduino
azr=readVoltage(a,5); %Reads analog port 6 in arduino

x=[x,b]; %Writes analog voltage values from port 0 to x
y=[y,c]; %Writes analog voltage values from port 1 to y
z=[z,d]; %Writes analog voltage values from port 2 to z
q=[q,e]; %Writes analog voltage values from port 3 to q
ax=[ax,axr]; %Writes analog voltage values from port 5 to ax
az=[az,azr]; %Writes analog voltage values from port 6 to az

hold on
plot(x,'r');
plot(y,'b');
plot(z,'y');
plot(q,'g');
axis auto;
grid
```

```
bo=b %Store new value for next loop
co=c %Store new value for next loop
do=d %Store new value for next loop
eo=e %Store new value for next loop

t=t+passo; %Increase time counter
end

figure;
plot(ax,'r');
plot(az,'b');

fid = fopen('myfile-x.txt', 'wt'); % Open for writing
for i=1:size(x,2)
fprintf(fid, '%d ', x(i));
fprintf(fid, '\n');
end
fclose(fid);

fid = fopen('myfile-y.txt', 'wt'); % Open for writing
for i=1:size(y,2)
fprintf(fid, '%d ', y(i));
fprintf(fid, '\n');
end
fclose(fid);

fid = fopen('myfile-z.txt', 'wt'); % Open for writing
for i=1:size(z,2)
fprintf(fid, '%d ', z(i));
```

```
fprintf(fid, '\n');
end
fclose(fid);

fid = fopen('myfile-q.txt', 'wt'); % Open for writing
for i=1:size(q,2)
fprintf(fid, '%d ', q(i));
fprintf(fid, '\n');
end
fclose(fid);

fid = fopen('myfile-ax.txt', 'wt'); % Open for writing
for i=1:size(ax,2)
fprintf(fid, '%d ', ax(i));
fprintf(fid, '\n');
end
fclose(fid);

fid = fopen('myfile-az.txt', 'wt'); % Open for writing
for i=1:size(az,2)
fprintf(fid, '%d ', az(i));
fprintf(fid, '\n');
end
fclose(fid);
```

E.2 Impulse calculation Code

This section contains the code used to calculate the specific impulse for the accelerometer.

```
sum-ax=0; % initiates value
sum-az=0; % initiates value
avgx=mean(ax); % stores average of accelerometer readings in variable
avgz=mean(az); % stores average of accelerometer readings in variable
for i=1:size(ax,2) % loop at length of accelerometer reading array
if abs(avgx-ax(i))>0.02 % filters out changes smaller than 0.02 G
sum-ax=sum-ax+abs(avgx-ax(i)); % if G exceeds filter limit, add value to cumulative variable
end if abs(avgz-az(i))>0.02 % filters out changes smaller than 0.02 G
sum-az=sum-az+abs(avgz-az(i)); % if G exceeds filter limit, add value to cumulative variable
end
end
sum-ax % Displays out cumulative acceleration values for the X-axis
sum-az % Displays out cumulative acceleration values for the Z-axis
```

Appendix F

Winding procedure

F.1 Preparations

Before starting the winding procedure, the mandrel was thorougly cleaned with acetone, before it was coated in 2 layers of **FlexZ Z3.0** Slipcoat system and one final layer off **RENLEASE QV5110** slip wax. It proved important to apply a thick layer of wax onto the parts of the domes that were inserted into the mandrel(figure F.1). If not properly sealed in this fashion, epoxy will get into the interface between the parts, and extracting them will be difficult.

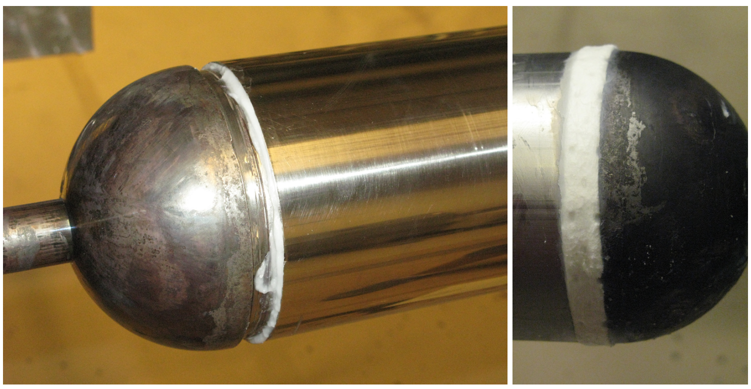

Figure F.1: Wax applied between end dome and mandrel, breather soaked in wax is then wound into groove.

To get a smooth surface over the grooves in the end domes and to further improve the seal, breather fabric was cut to the correct size, soaked in wax and wound into the groove.

The pipe was mounted in the machine, and the length from each of the two grooves were measured from a fixed reference point (this is important since after winding, finding the grooves into which you want to cut can be difficult). The distance between the chuck and the top of the first dome also needs to be measured, as this offset needs to be specified in the programs, in order for the machine to know where to start winding. This is important to get right, as errors here can cause the machine to collide into itself.

The winding process was started by pulling the fibre through until the wetted part reached the mandrel, winding it a few rounds by hand, and then taping it to the central axle of the mandrel (figure F.2).

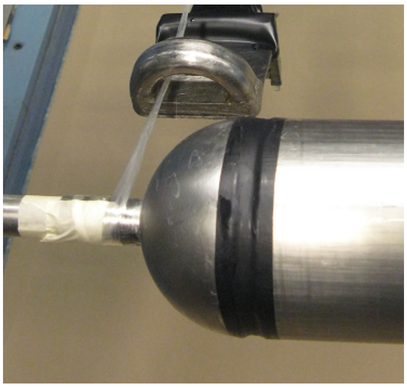

Figure F.2: Fibre attached before winding.

F.2 The Winding process

Our pipe was wound with both helical and hoop layers. This gives us transitions in the winding process where steps need to be taken to make sure the fibre orientates itself correctly.

The first transition is at the very beginning, when the fibre that is wound around the axle needs to reach the top of the dome where the hoop program begins. Since the dome is very steep, and the fibre very slippery, it won't easily follow the movements of the machine.

The solution for this was to manually traverse the eye to the starting position, applying a few rounds of rotations while guiding the fibre to the top of the dome. After the fibre had been wound on top of itself a few times, there was enough friction to hold the fibre in place. The hoop program could then be started.

When going from helical to hoop layers, the transition is especially troublesome. The fibre will immediately start on the low angle helical winding after finishing the hoop. This means that the fibre will go from an angle of 90° to an angle of ≈15°. There is not enough friction to support this, and because of that the fibre from the hoop layer will get pulled along by the helical winding (figure F.3).

When winding a layup with a constant angle the transition becomes more smooth. However during the first few winding cycles one may need to hold the fibers in place so they do not slip off the dome end. In the case for the second pipe winded a constant angle of 55° was used. During the first 6 cycles the fibers was held in place when turning at the dome-end.

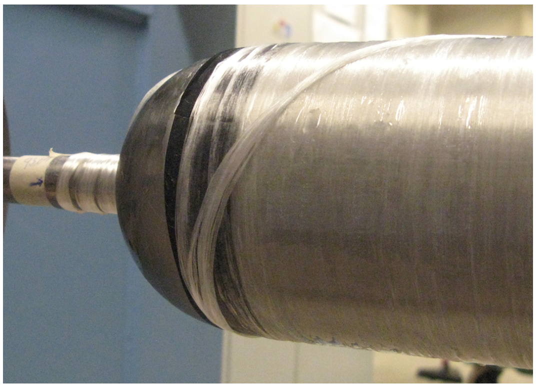

Figure F.3: Fibre pulled downward by helical layer transition.

To counteract this effect, a similar approach as for the start was taken. During the transition, the speed of the machine was turned low, and the fibre was held in place at the edge of the dome by hand. This needed to be held tightly for a few rotations, until the fibre was held in place by the fibres wound on top of it. The path of the fibre where held in place deviated by a small amount, but it quickly assumed its correct path. This method was quick and easy, albeit a bit messy.

For the last transition, when going from helical to hoop, the problem is the same as when starting the winding process. The fibre needs to traverse the dome, and place itself neatly onto the mandrel. This was solved in the same manner as for the first hoop layer (figure F.4).

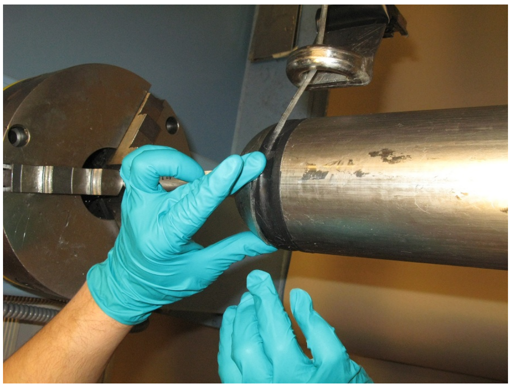

Figure F.4: Fibre manually held in place so it doesn't slip off dome.

The CNC winding commander software has an option where you can insert transition layers. These are however only good for transitioning between one helical layer to another. It is simply a layer with very low coverage, where the fibre angle is changed gradually. Angles high enough to enable hoop winding without slipping are not available however.

An alternative method to the transitions could be cutting the fibre and manually winding the start of each layer. This was not done however, as simply holding the fibre in place provided adequate results.

F.3 After winding

After winding, the mandrel needs to rotate for 24 hours, to ensure even distribution of epoxy as it cures. This is also a good opportunity to remove excess epoxy manually. It was not done for our pipes, and as a result, a thin layer of excess epoxy remained on the outside of both pipes.

It is also important to remember to clean the machine before the epoxy hardens.

After the 24 hours of curing in room temperature, the mandrel and pipe was placed in an oven at 80°C for 8 hours.

F.4 Pipe extraction

When the pipe was done curing, it was mounted back into the machine, and the grooves located by using the measurements taken earlier. A fein saw was used to cut the pipe at the grooves. This was attempted both by hand and by attaching it to the machine. Doing it by hand while rotating the mandrel in the machine proved to be the quickest and easiest solution.

The first end dome was removed by threading a thick metal cylinder onto the axle, and attaching a simple end fixture at the end by using the M8 threads. The metal cylinder is then knocked against the end fixture to remove the dome.

The remaining dome is removed by inserting a steel rod and knocking it out from the inside.

To remove the pipe from the mandrel, the mandrel was pushed and pulled out using the jig in figure F.5.

Figure F.5: Jig for separating pipe from mandrel.

The first few centimetres are pushed through by using a jack. This requires a great deal of force to overcome the static friction, and to break apart the wax connecting the pipe to the mandrel. After initially pushing the mandrel, a heavy strap is thread through the pipe, and the mandrel is then pulled through by using a heavy duty lifting jack. The strap is fixed to the pipe by using a metal end plate that only covers the mandrel (figure F.6).

Figure F.6: Strap is secured to the plate, then pulled through.

To protect the polished mandrel, tape was applied to the hole in the jig. This was not sufficient, as the pipe quickly rips multiple layers of tape apart. A better solution proved to be using both tape, and some rags to keep the steel mandrel away from the jig.

The glass fibre was removed from the end domes by burn-off at 500°C for 5 hours.

F.5 Quality control of produced pipe

To control the quality of the produced pipe, a burn-off test, microscopy analysis and void fraction. Small sections of the pipe was cut to display both longitudinal and hoop direction of the pipe. The section were moulded into epoxy then polished to prepare for microscopy.

F.5.1 Microscopy

The goal of microscopy is to inspect the quality of the produced composite. Firstly one looks at the density of fibres. Are the fibers evenly distributed? Is there a thick layer of epoxy on the outside of the pipe? Are there any impurities and voids? These questions should be answered and documented. Further one can measure the thicknesses of each layer which can the be used as input for a FEM analyses.

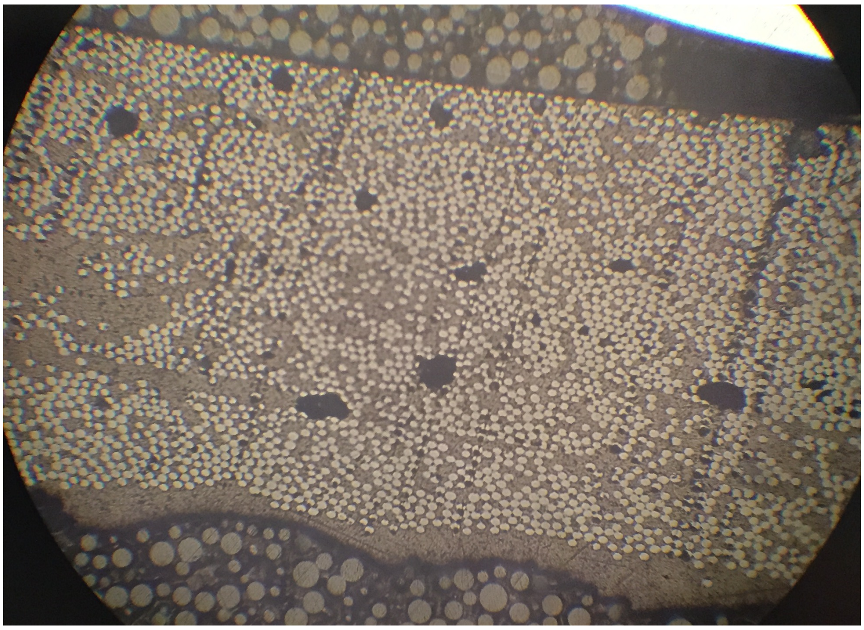

Figure F.7: Hoop view of +-55° wounded pipe

One can see that there is a small layer of epoxy on the outside (bottom) of the pipe, this is insignificant for the strength of the pipe, however one must take this thickness into account when building an FEM model. Further the fiber distribution looks satisfactory, with some patches on only epoxy. These patches could be mitigated by higher fiber-tension during winding. Lastly the void fraction can be calculated. The black ares on the image are voids, thus one can use pixel-counting to approximate void fraction (this is shown in the image below). the calculated void fraction of 1.9% is considered to be a normal void percentage.

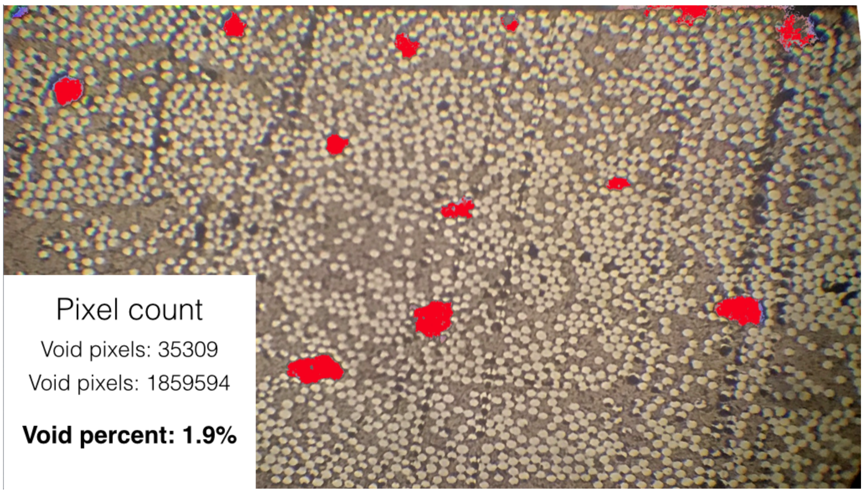

Figure F.8: Voids marked in red

F.5.2 Burn-off test

The burn off test is done to calculate the volume fraction of epoxy vs fibers in the composites. This will indicate the quality and strength of the composite, and is a crucial parameter to enable accurate FEM analysis of the composite. Samples are heated to a temperature of 500 degrees Celsius to burn off the epoxy. By weighing the samples before and after the burn-off combined with the material density of the two components, the volume fraction can be determined by the following formula:

$$X_f = \frac{V_f}{V_{total}} = \frac{V_f}{V_m + V_f} = \frac{m_f/\rho_f}{m_m/\rho_m + m_f/\rho_f} = \frac{\frac{m_{total}-m_m}{\rho_f}}{\frac{m_m}{\rho_m} + \frac{m_{total}-m_m}{\rho_f}} \tag{F.1}$$

Appendix G

Prototype impact measurements

This appendix contains all prototype measurements, both piezo readings and OBR residual strain measurements.

G.1 Impact One

The first impact on the prototype was done in the center of the OBR grid (figure G.3).

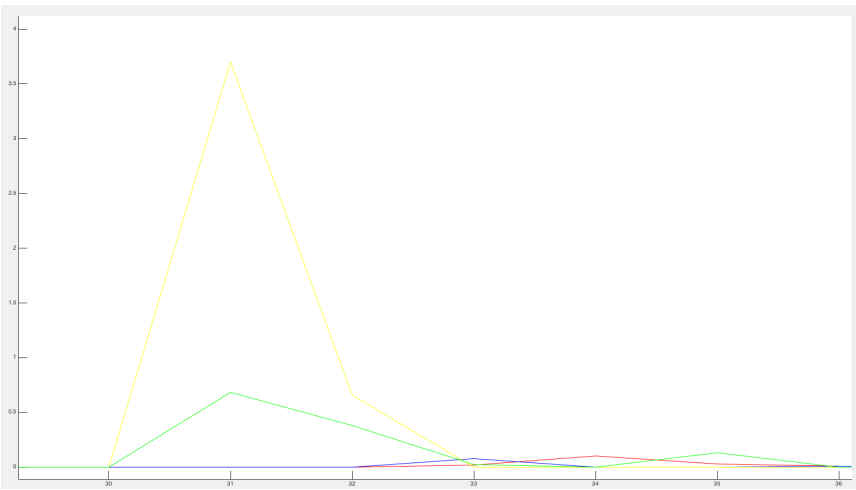

Figure G.1: The piezo response (1000mm, 10mm protection)

The piezo response from the piezo elements closest to the Arduino seem not to have registered the first impact wave and have a very low response compared to the piezo elements on the far side of the Arduino (See figure 6.3).

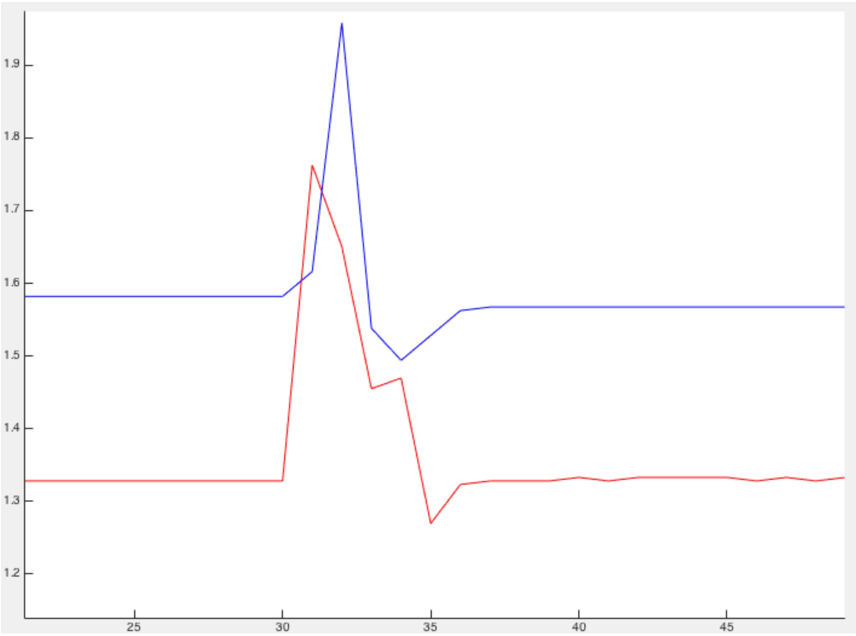

Figure G.2: The accelerometer response (1000mm, 10mm protection)

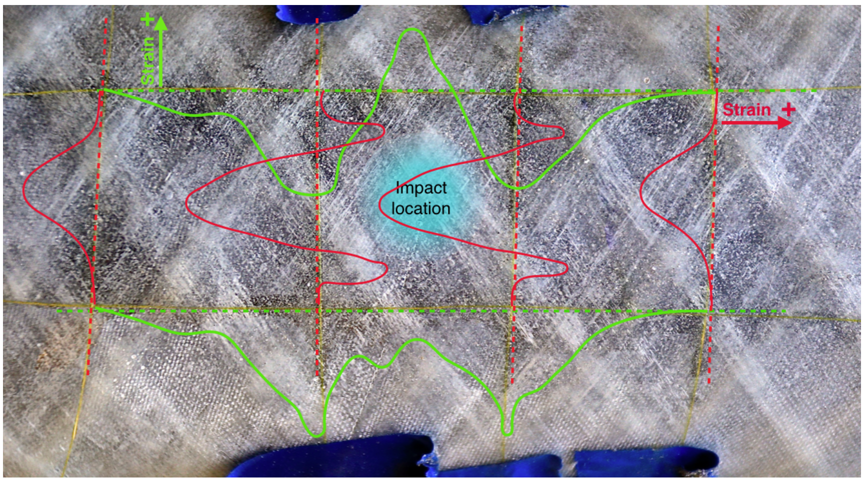

Figure G.3: The OBR residual strain (1000mm, 10mm protection)

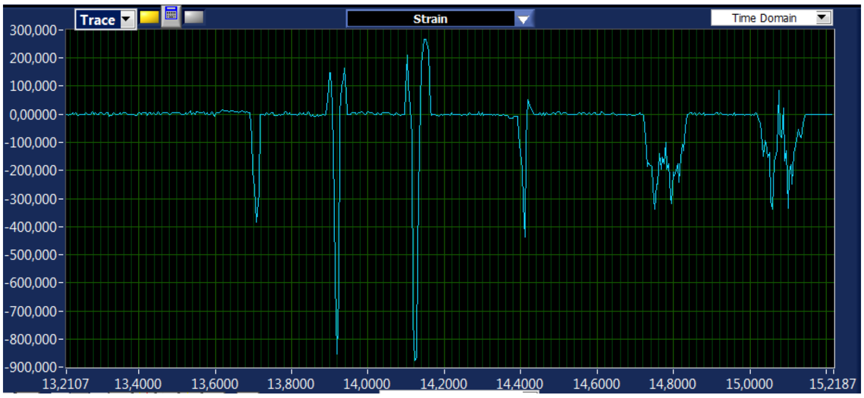

Figure G.4: Corresponding OBR measurement

G.2 Impact Two

The first impact on the prototype was done in the center of the OBR grid (figure G.7).

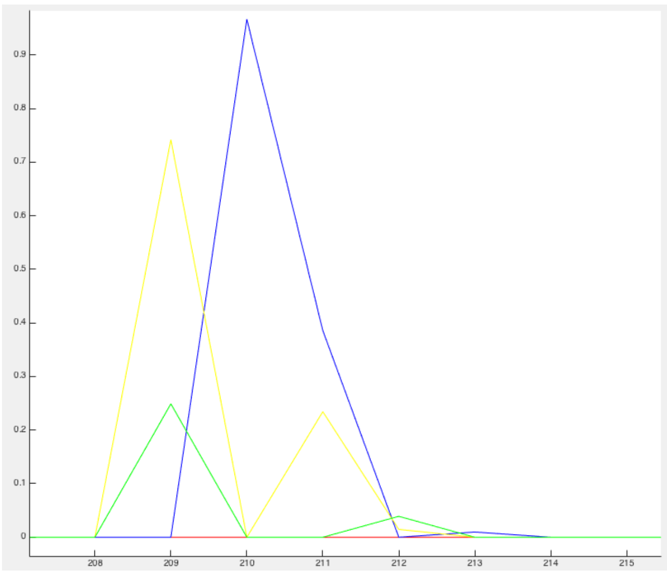

Figure G.5: The piezo response (1000mm, 10mm protection)

The piezo reading for the second impact, the one presented in the thesis, shows a clear indication of the wave propagation where the piezo elements closest to the impact register the impact wave before the elements on the far side of the impact.

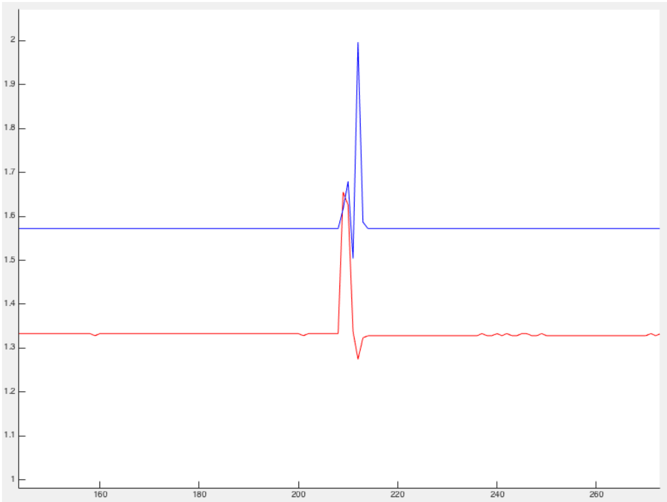

Figure G.6: The accelerometer response (1000mm, 10mm protection)

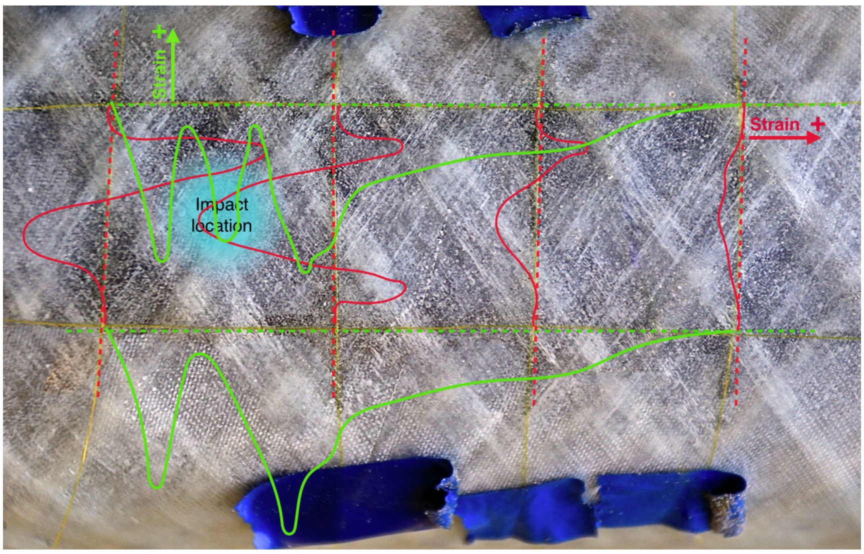

Figure G.7: The OBR residual strain (1000mm, 10mm protection)

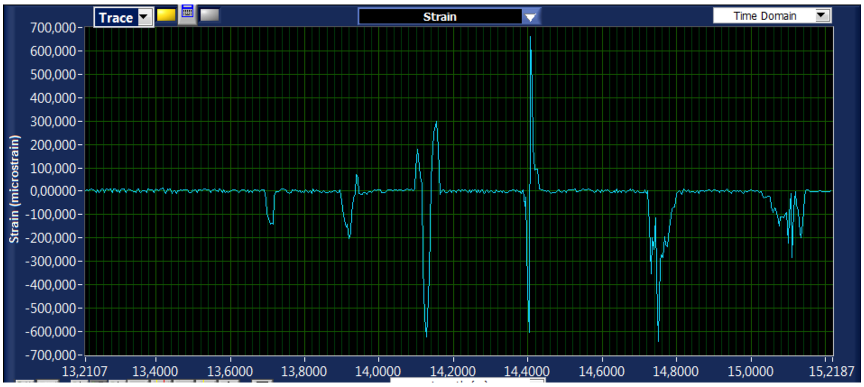

Figure G.8: Corresponding OBR measurement

G.3 Impact Three

The first impact on the prototype was done in the center of the OBR grid (figure G.11).

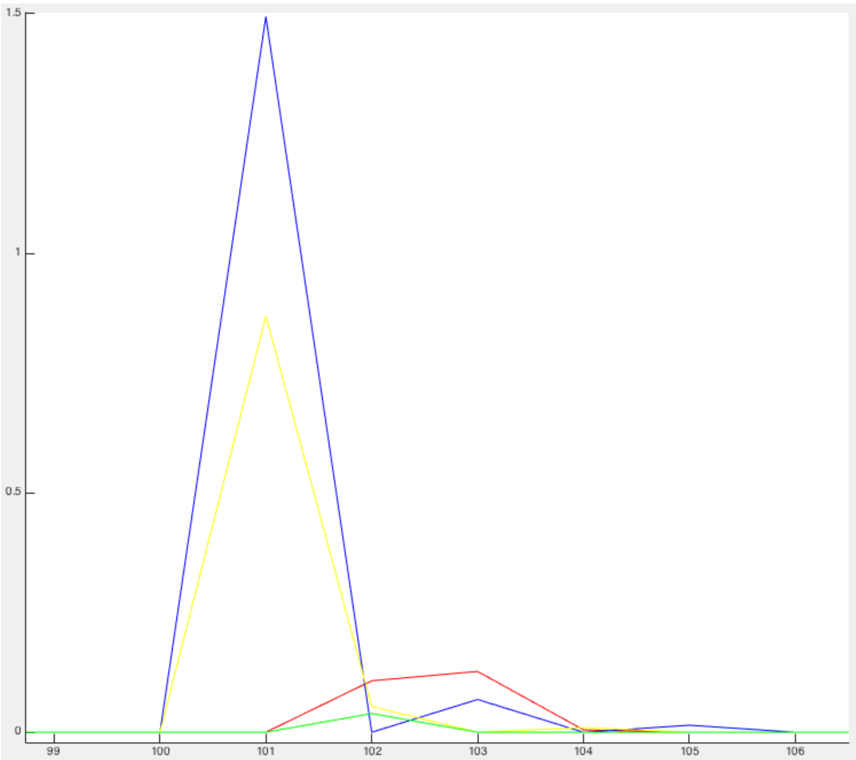

Figure G.9: The piezo response (1000mm, 10mm protection)

The piezo reading for the third impact might indicate that the impact wave has propagated faster than in the previous test, as piezo elements on each side of the impact registered the wave simultaneously (within one measurement cycle).

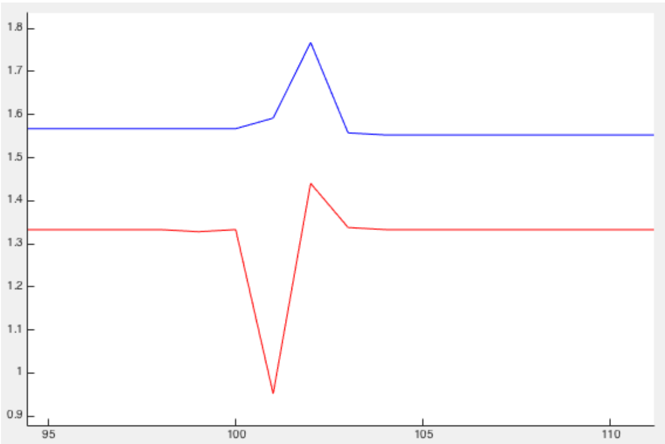

Figure G.10: The accelerometer response (1000mm, 10mm protection)

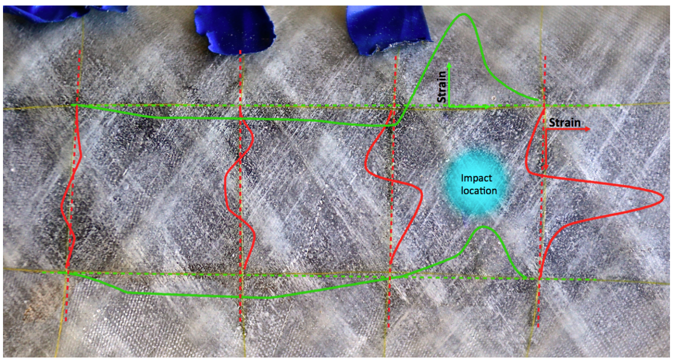

Figure G.11: The OBR residual strain (1000mm, 10mm protection)

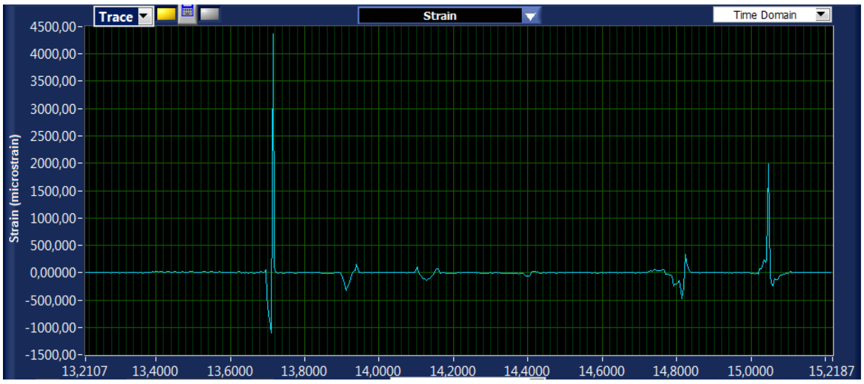

Figure G.12: Corresponding OBR measurement

From these three impacts one can see that for the low cost piezo solution the impact showed clear voltage spikes that indicate an impact event. The OBR residual strain measurements show elevated strain in the area of the impact. Further it is believed that the impact location can be estimated by analyzing the strain shape curve.

THE NORWEGIAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENGINEERING DESIGN
AND MATERIALS

MASTER THESIS SPRING 2015
FOR
STUD.TECHN. PAUL A. KOPPERUD

Innovative Impact Protection and Monitoring System for Composite Pressure Vessels

Composite pressure vessels are becoming widely used for transporting gas and lately also hydrogen. In order to enable extensive use of the pressure vessels, it is of primary importance to ensure their societal acceptance and thus safety under transportation must be secured. In particular, the knowledge on composite overwrapped pressure vessels' (COPV) behavior when submitted to mechanical impacts is limited and existing standards are not well-appropriate to composite materials.

The main objective of this master thesis is to explore and develop an innovative impact protection solution combined with a system for detection of possible damage to the pressure vessel. A simplified prototype of the proposed system shall be built and tested experimentally.

Formal requirements:

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the master's thesis is submitted.

Risk assessment of experimental activities shall always be performed. Experimental work defined in the problem description shall be planed and risk assessed up-front and within 3 weeks after receiving the problem text. Any specific experimental activities which are not properly covered by the general risk assessment shall be particularly assessed before performing the experimental work. Risk assessments should be signed by the supervisor and copies shall be included in the appendix of the thesis.

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

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

Torgeir Welo
Head of Division

Andreas Echtermeyer
Professor/Supervisor

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for produktutvikling og materialer

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

Enhet: **Dato: 24.02.2015**

Linjeleder: Andreas Echetermeyer

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

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave: Paul A. Kopperud.
Tittel på oppgaven: Innovative Impact Prtoection and Monitoring System for Composite Pressure Vessels

Signaturer: *Ansvarlig veileder:* *Student:*

ID nr	Aktivitet fra kartleggings-skjemaet	Mulig uønsket hendelse/ belastning	Vurdering av sannsyn-lighet (1-5)	Vurdering av konsekvens: Menneske (A-E)	Ytre miljø (A-E)	Øk/ materiell (A-E)	Om-dømme (A-E)	Risiko-Verdi (menn-eske)	Kommentarer/status Forslag til tiltak
1	FEM analyser på PC	PC-Fatigue	1	B				1B	Teoretisk
2	Oppgaveskriving	PC-Fatigue	1	B				1B	Teoretisk
3A	Vikling av rør med "Fillament Winding"	Klemmskader og andre skader i maskin	1	D				1C	Verneutsyr, sensorer, bruk i henhold til opplæring/manual
3B		Søl av kjemikalier på hud	3	B				3B	Verneutstyr, orden på laben
3C		Søl av kjemikalier på øyne	1	D				1D	Vernebriller, orden på laben
3D		Søl av kjemikalier på klær	3	A		A		3A	Verneutstyr, orden på laben
3E		Søl av kjemikalier på utstyr og gulv	3			C		3C	Tildekking av utstyr og gulv, orden på laben
3F		Mekanisk skade på utstyr	2			C		2C	
4A	Trykktesting	Splint skade og vannjett-skade	2	C				3C	Verneutsyr
4B		Øyeskader fra splinter	1	D				1D	Vernebriller
4C		Mekanisk skade på utstyr	2			C		2C	Bruk i henhold til opplæring/manual
5A	Impact testing	Klemskade under impact	1	D				1D	Verneutstyr og hensyn til klemsoner
5B		Øyeskader fra splinter	1	D		A		1D	Vernebriller

Enhet: **Dato: 24.02.2015**

Linjeleder: Andreas Echetermeyer

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

Kort beskrivelse av hovedaktivitet/hovedprosess: Masteroppgave: Paul A. Kopperud.
Tittel på oppgaven: Innovative Impact Prtoection and Monitoring System for Composite Pressure Vessels

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

Signaturer: *Ansvarlig veileder:* [signature] *Student:* Paul A. Kopperud [signature]

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	FEM analyser på PC	Paul Kopperud				Teoretisk
2	Oppgaveskriving	Paul Kopperud				Teoretisk
3	Vikling av rør med "Fillament Winding" maskinen	Paul Kopperud	"Filament Winding" kurs, brukermanual	Obligatorisk opplæring, HMS kurs, verneutsyr, sensorer for nødstopp		
4	Trykktesting av rør	Paul Kopperud		Obligatorisk opplæring, HMS kurs, verneutstyr		
5	Impact testing	Paul Kopperud		Opplæring, verneutstyr		