FACULTY OF AEROSPACE ENGINEERING
DELFT UNIVERSITY OF TECHNOLOGY
Design and Production of Composite Structures

Thesis in partial fulfillment of masters degree
Final version

Development of permanent composite overwrap repairs for steel pipelines, incorporating Structural Health Monitoring.

In cooperation with:
The Cooperative Research Centre for Advanced Composite Structures Australia

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled 'Development of permanent composite overwrap repairs for steel pipelines, incorporating Structural Health Monitoring' by Raf Kempeneers in partial fulfilment of the requirements for the degree of Master of Science.

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Abstract

A good structural health monitoring system on a composite repair can improve the understanding of the life of such a repair. Currently, overwrap repairs are considered to be temporary in nature due to the unknown life expectancy. Using finite element modelling, a model was created of a pipe with a repaired defect and a composite overwrap. This model was then validated by testing pipe specimens that have the same defect and the same repair applied to it. In these models and test specimens an initial (100%) repaired damage is present which was increased to a 150% initial defect. A comparison between the 100% and 150% shows the ability of detecting the increase in both the model and the specimen for axial and hoop strain. Further damage is researched by implementing delaminations at the edges (ingress points for water/corrosion) and in between the edge and the initial repaired defect. The conducted tests revealed strain transfer problems on a (composite) surface containing voids/defects. The main issue however is that damage (and damage growth) is qualitatively detected in both the model and the test specimens.
Other tests included the comparison of adhesives that are used to apply the optical sensors to the pipe. This in order to rule out any errors in measurements between the surface of the composite repair and the fibre Bragg grating itself. The result was that there is no difference between adhesives in the conducted fatigue test. Also some material characterization was attempted but these results are not reliable due to the voided nature of the used cured composite.

The other aspects of a structural health monitoring system are of course the system used to detect strains. A close look at the available optical systems, such as Brillouin and Rayleigh scattering, shows that fibre Bragg gratings are the most suitable in this project. Deeper investigation into critical and less critical parameters shows that the design of such a sensor system is not trivial.
Consideration to coatings, temperature, fatigue limits, optical losses, cost etc. has to be given as these can influence the final resulting sensor system. The harsh environment the sensors operate in has to be researched in more depth in following reports since they are critical to the performance.

Acknowledgments

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List of Symbols

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μ	micro	(-)
E	Young's modulus	Pa
ν	Poisson's ratio	(-)
P	pressure	Pa
D	diameter	mm
t	thickness	m
ε_h	hoop strain	(-)
ε_a	axial strain	(-)
ε	strain	(-)
λ_B	Bragg wavelength	nm
n_0	refractive index	(-)
Λ	grating period	nm
$\Delta\lambda$	wavelength shift	nm
λ_0	base wavelength	nm
p	gauge factor	(-)
ΔT	temperature change	K
ε_m	mechanically induced strain	(-)
ε_T	temperature induced strain	(-)
α_{sp}	expansion coefficient per K temperature rise of specimen	K
dB	decibel	dB
κ	coupling constant	(-)
R	grating reflectivity as a function of both grating length and wavelength	(-)
β	fiber core propagation constant	(-)

Abbreviations

	List of Abbreviations
ASTM	American Society for Testing and Materials
TR	Technical Report
OGP	Oil, Gas and Petrochemical
FEM	Finite Element Method
FWHM	Full Width Half Maximum
FBG	Fibre Bragg Grating
FP	Fabry-Perot
IFPI	Intrinsic Fabry-P*é*rot interferometer
EFPI	Extrinsic P*é*rot interferometer
WDM	Wavelength Division Multiplexing
TDM	Time Division Multiplexing
OTDR	Optical Time-Domain Reflectometry
OFDM	Optical Frequency-Domain Reflectometry
SHM	Structural Health Monitoring
ACS	Advanced Composite Structures
CFRP	Carbon Fibre Reinforced Plastic
ASME	American Society of Mechanical Engineers
EMI	Electromagnetic interference
UD	Uni Directional
ORMOCER	ORganically MOdified CERamics
DTG	Draw Tower Grating
RSD	Relative Standard Deviation
RSG	Resistive Strain Gauge

List of Figures

List of Tables

Contents

Chapter 1

Introduction

When accidents happen in the Oil, Gas and Petrochemical (OGP) industry the consequences are most often quite severe. Leaking of chemicals into the environment has disastrous effects and implies some serious costs and revenue loss. Pipelines are used extensively in the OGP industry and their functioning is important. Maintenance of pipelines presents a major cost in the OGP industry as billions of dollars have to be invested each year [3, 27].

Composite overwrap repairs are already used for decades but they are only considered to be temporary. Deterioration of the original defect and deterioration of the composite pipe interface is contributing to this temporary aspect. Introducing a Structural Health Monitoring (SHM) system to constantly evaluate the performance of the defect in the pipe and to detect possible new and/or growing defects is the solution for this.
This thesis is part of a project that is aimed at introducing a damage sensing sensor system in order to asses the performance and the remaining life in the overwrap repair and as such the pipe. In this thesis there are two main theme's: one is aimed at the functioning of the SHM system in response to the occurence of different sorts of damage and damage growth. The other one is aimed at the practical aspects that are necessary for such a system to operate in the OGP industry.

The strain characteristics of the system are modelled with Finite Element Modelling (FEM) in order to define the response of the repaired pipe to different damage inputs. This is then compared with actual test data in order to validate the model. This validation is necessary if the model is going to be used in future modelling without having to constantly do real tests. Testing is done by varying the size of the initial repaired defect to see the changes that occur when it is growing. Also testing is done to see whether or not delaminated area's (which point to defects) in locations aside from the initial repaired defect can be sensed and if sensors can detect a growth in these area's. In order to achieve a better model also certain material characteristics (shear moduli) of the composite repair are determined while adhesive testing is conducted in order to rule out any problems in regards to the strain sensed by the sensors over a large number of cycles.

Practical considerations of a sensor system in the OGP industry are needed in order to clearly define the limitations of the system. Different methods of sensing exist that are suitable for such a system. Their possibilities and limitations have to be outlined in order to come to an understanding of a sensor system. Besides the way the SHM system functions consideration also has to be given to the operating environment and the resistance of the sensor system to such an environment. An optical sensor that dissolves in a certain chemical or stops functioning due to water ingress could be just a small part of such limitations.

Chapter 2

Pipeline repair

In the Oil, Gas and Petrochemical industry each year 2-3.3 billion dollar is lost due to repair of corroded or damaged piping. On top of that, a leaking or burst pipe can have major consequences for the environment as well.
Most of the traditional repairs involve replacing the section or welding and bolting new sections in place [3, 27].

A short overview of why pipelines are used is needed, together with the types of damages and the repair processes possible. In section 2.1 a short summary is given why pipelines are used in the industry. Section 2.2 contains an overview of the sort of damage encountered in the service life of a pipeline. When looking at repairing some forms of damage, there are three options available which are shown in section 2.3. To detect any damage in pipelines before they burst a range of parameters can be monitored, some of which are shown in section 2.4.

2.1 Pipelines in the Oil, Gas and Petrochemical industry

There are two main transportation methods in the Oil, Gas and Petrochemical (OGP) industry. There is batch transportation and pipeline transport. Batch transportation is done by using boats or trucks. The pipelines have a higher efficiency and are not weather dependent but the disadvantage is the high initial cost [28, 29]. Furthermore, for subsea drilling, pipelines are necessary to get the fluid or gas to the surface [30].

2.2 Types of damage in pipelines

There are several damage mechanisms in pipelines: [30]

- Event-based damage: landslides, earthquakes etc
- Condition-based damage: operating parameters change etc
- Time-based damage: corrosion, fatigue etc

An overview of these damage mechanisms are shown in figure 2.1. The focus in this project is corrosion, more specifically the repairing and detecting of corrosion. In more detail, this detection is covering the growth in the existing (repaired) corrosion damage, as well as the damage occuring outside this initial region. In an operational setup however all the other factors shown in figure 2.1 have an influence as well so they have to be included in the final monitoring system. Bending, fatigue and impact damage are just some of these factors.

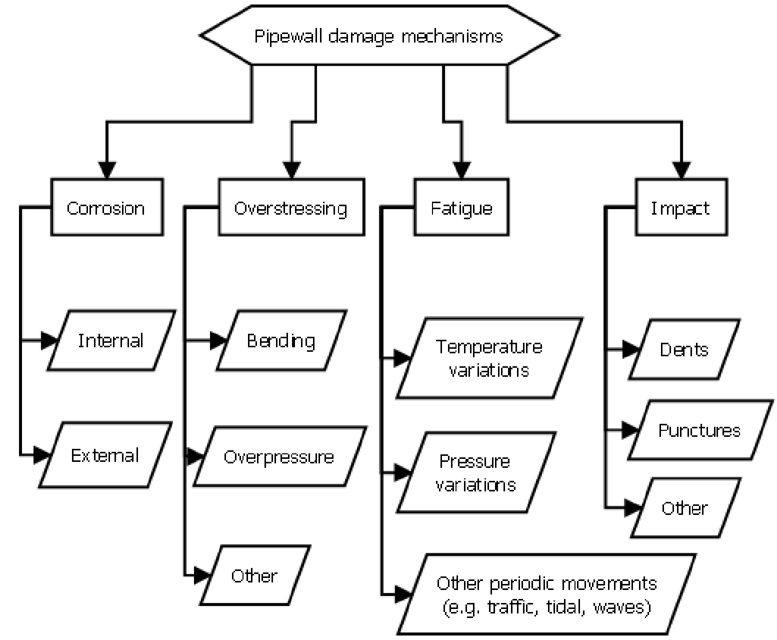

Figure 2.1: Overview of the possible damage mechanisms in pipelines

2.3 Repair processes used for pipelines

A pipeline can be repaired using a couple of methods. Welding and steel sleeves are used throughout the industry but they do have some distinct disadvantages. A composite repair offers some key advantages for repairing a pipeline in this case.

2.3.1 Welding

Welding is an extensively used method of repair but the explosion risk has to be managed by shutting down the pipe. The corrosive properties of the pipeline remain and the replacement panels/sheets have to be manufactured within reasonable tolerances to fit the curve of the pipeline. Underwater application is possible but posses quite some challenges for a quality repair.

2.3.2 Sleeves

Sleeves are used extensively when repairing pipelines but suffer from a couple of limitations. They need to be manufactured of-site for a certain pipe diameter and the corrosion resistance is not comparable with composite repairs. An example of a sleeve is shown in figure 2.2.

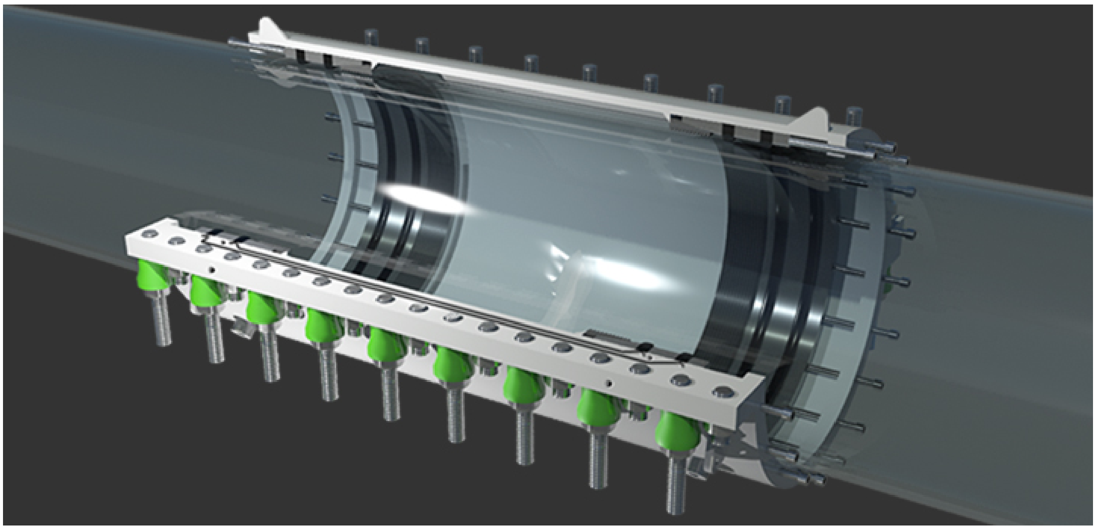

Figure 2.2: Example of a sleeve repair [1]

2.3.3 Composite overwrap repair

Composite materials have already been used for a decade by pipeline operators to repair their damaged pipelines.
Some *requirements* for composite repairs are: [2]

- Easy to install
- Reliable and permanent
- Economic advantages over conventional repair methods

The fibres of the systems can consist out of: [3]

- Glass fibre
- Aramid fibre
- Carbon fibre

Carbon Fibre Reinforced Plastic (CFRP) performs better than the others since it improves the ultimate internal pressure capacity, durability and corrosive properties [3]. Care should be taken however in using CFRP for the dangers of galvanic corrosion. The benefits of a fibre reinforced repair system are:

- Short repair time [27]
- Repairs can be done with the system online [3, 27]
- Explosion danger is non existent due to no welding or cutting [31], as far as the application process of the repair concerns
- 24 % cheaper than welding, 73% cheaper than replacing [3]
- FRP systems shield external corrosion growth [3]

Both the short and long term performance is important.
There is a program currently underway that tests the life of composite repairs but instead of using sensors, the Pipeline Research Council International has buried pipelines and is testing them over several

years [2]. This is done by burst-testing samples in intervals of a few years.

For the repair itself it is necessary that the application temperature is below the glass transition temperature in order to assure that the mechanical stiffness and creep resistance are good [31]. So the working temperatures should be kept in mind.

Currently, composite repairs are still regarded as temporary repairs, as mentioned in [2] and figure 2.3. By using a SHM/sensor system this could develop into a permanent solution.

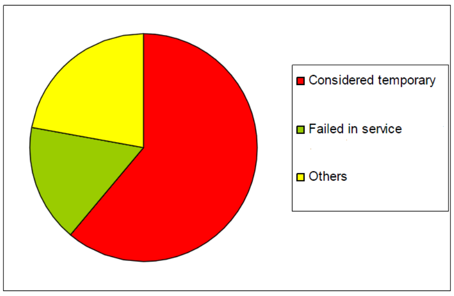

Figure 2.3: Reasons that composite repair materials were removed [2]

An example of a rupture pipe sample test can be seen in figure 2.4. A composite repair test on a machined pipe simulating corrosion is shown in figure 2.5.

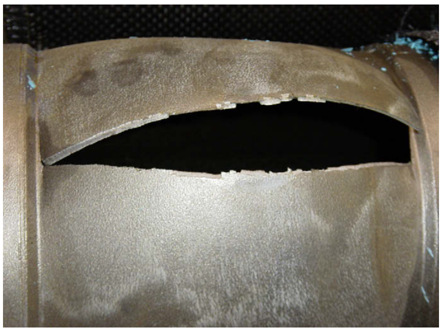

Figure 2.4: Example of a ruptured vessel with an axisymmetric defect [3]

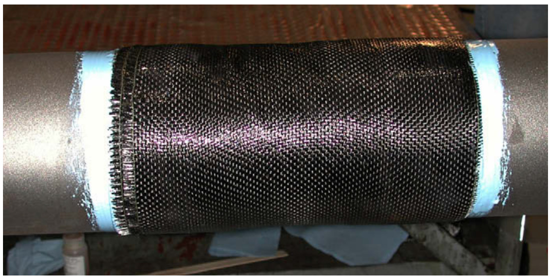

Figure 2.5: Repaired pipe test vessel [3]

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2.4 Damage detection system parameters for a SHM system

In order to perform the task of damage detection, a number of parameters need to be identified that are used for damage detection. Damage can be identified in a number of ways, for instance with a strain response or with acoustic sensors (fibre breakage). There is a classification between the main parameters (strain) which are mentioned in section 2.4.1 and the secondary parameters, mentioned in section 2.4.2. The main parameters satisfy the objective set-out for the project while the secondary parameters can give distinct advantages in supplementing the requirements for the project. This can range from temperature measurements, possibly indicating a leak, to shear strain measurements to gain insight in the general strain state.

In figure 2.6 the measurement specifications are visualized together with the justification of why that specific parameter should be monitored.

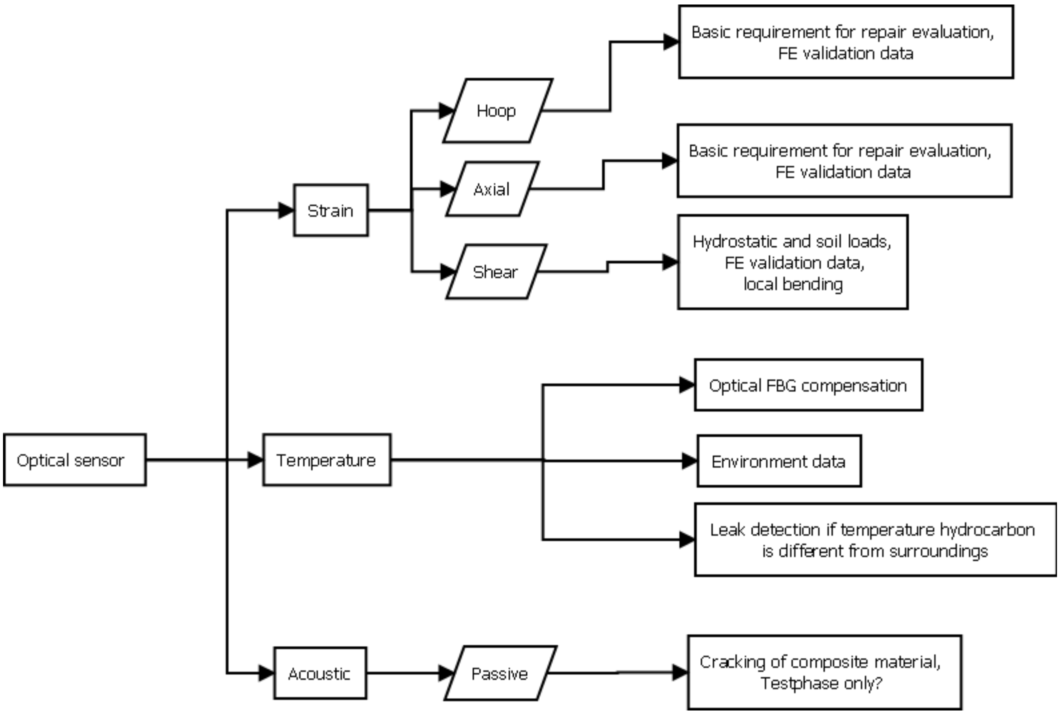


Figure 2.6: Relation of measured characteristics to specification [4]

2.4.1 Main parameters

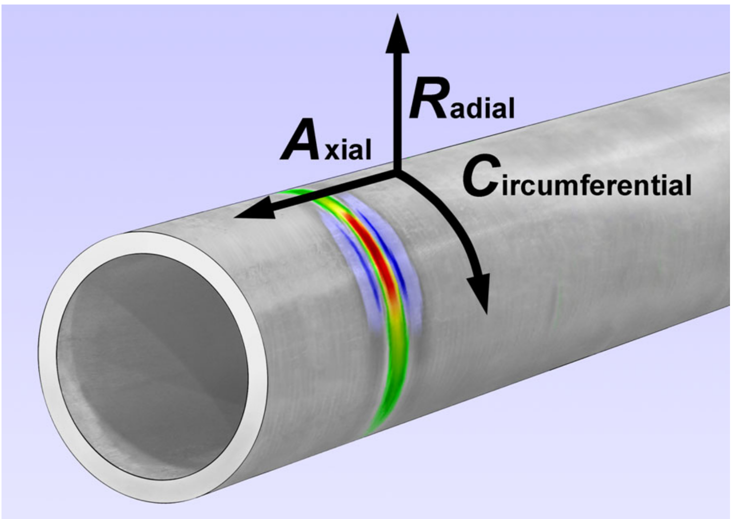


Figure 2.7: Radial, circumferential and axial directions [5]

Radial monitoring on an in service pipeline is not practical, as can be seen in figure 2.7.The goal of the project is to monitor the composite repair itself, radial monitoring would be out of plane.

Hoop- and axial strain are going to be measured. This is the basic requirement of damage detection for the project on the composite repair. The deterioration of the composite as such is related to changing strain. Delamination between the layers of the overwrap can lead to changes in strain. Fibre breakage can lead to changes in strain as well.
It is imperative to have an idea of the magnitude of strain that the sensors must measure.

2.4.2 Secondary parameters

Damage can also be detected by using temperature or acoustic sensing. Shear strain in itself can be used to determine a complete strain state.

2.4.2.1 Temperature

Leak detection using temperature sensors [32] is possible if the released liquid or gas differs in temperature from the surroundings so the temperature sensor will detect an anomaly.

Some sensors need temperature compensation when detecting strain, such as Fibre Bragg Gratings (FBG). Bonded FBG sensors are only dependant on strain.

2.4.2.2 Acoustic sensing

The acoustic sensing could include ultrasonic waves but further research is currently beyond the scope of the project. With this active or passive system a profile of the overwrap repair can be made. The choice for a strain sensing approach was made at the start of the project.

2.4.2.3 Shear strain

There are a number of advantages associated with measuring shear strain, in addition to axial and hoop strain. Measuring the full strain state at every sensor location allows correlation with the full strain state from FEM simulations. The sensor orientation is not critical and can be calibrated by increasing the pressure in the pipe. This pressurizing can be directly correlated to the principal strains. The relation of shear strain and damage detection could be a point of interest in further research.
Soil loads and tidal influences can also be monitored if the hoop strain and the spatial location of the sensors is known, or if the shear strain is known.

Packaging options are already available for a strain rosette [11] [26], however the project specifications are not met by the commercially available projects.

In figure 2.8 a simple rosette is shown created by using FBG's.

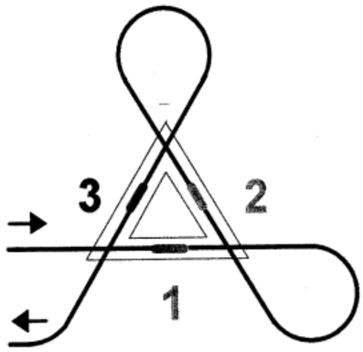


Figure 2.8: Fibre Optical Strain Rosette [6]

2.5 Conclusion

Pipelines are a much used and needed transport option in the Oil, Gas and Petrochemical industry. A significant problem is the deterioration of the pipe due to several types of damage such as landslides, earthquakes, corrosion, fatigue etc.

Deterioration due to corrosion can happen quickly depending on the operating environment of the pipe, even within five years of operation. Instead of having to replace the pipe there are three other possibilities: Welding, sleeving and applying a composite repair.
A composite repair offers distinct advantages such as reduced cost, no shut down of the pipe, no explosion danger and corrosion shielding of the pipe. The problem with this approach is the temporary aspect it is still considered to be. Implementing a monitoring system helps to gain insight into the deterioration of the repair and the pipe.

The designing of a system starts from identifying its main detection parameters, which are in this project hoop and axial strain. Secondary parameters such as temperature, shear strain and even acoustics have their uses as well but will not be considered at this time.

Chapter 3

Modelling of composite repairs on pipelines

In order to determine suitable sensor locations and also to get a feel of how the pipe and composite repair deform, some modelling is required. Analytical modelling and FEM modelling can be considered to address this goal.
In the confidential version this chapter contains the system specifications, the modelling and 3D strain plots that show how the repaired defects and delaminations behave

3.1 Analytical model of a pipeline

One of the options for an analytical model is from Murad [7]. In this PhD.-thesis a simple shell theory is introduced. The formulations are shown in equation 3.1 and 3.2. Delamination and damage at the pipeline are not incorporated. This is only useful for the steel pipe.
The equation for the hoop strain is:

$$\varepsilon_h = \frac{P \cdot D}{4 \cdot t \cdot E}(2 - \nu) \tag{3.1}$$

The equation for the axial strain is:

$$\varepsilon_a = \frac{P \cdot D}{4 \cdot t \cdot E}(1 - 2\nu) \tag{3.2}$$

In table 3.1 the variables are explained and some pipe characteristics that are going to be used are shown. These pipe characteristics are based on the pipespecimens that are used. Also the strain values that are acquired when filling in these variables are shown.

Table 3.1: Analytical vs. FEM vs. measurements at pipe surface, far field

P	Pressure (MPa)	2.8 Mpa
D	Outer diameter (mm)	84.15 mm
t	Wall thickness of pipe (mm)	6.45 mm
E	Young's modulus material (MPa)	200 GPa
v	Poisson ratio material (-)	0.3
ε_h	$155\mu\varepsilon$	
ε_a	$37\mu\varepsilon$	

3.2 An introduction to the theory of Patran/Nastran

Patran/Nastran is a Finite Element Model (FEM) package to develop models of structures. Patran is the pre- and postprocessor, which means that the model is created and the results are analysed in the same environment. Nastran is the processor, which takes the input and calculates the required output. In the case of this thesis a quarter model pipe with an overwrap repair is modelled using solid elements. The choice of using a 3D model is clear since the response of the strain on the surface of the repair has to be compared to damage effects on the surface of the pipe.

Patran enables the user to build a model using different groups and materials. Boundary conditions are used to simulate the conditions of the pipe and in the case of a quarter model boundary conditions are needed for the symmetry.

There exist different sorts of solid elements. As can be seen in figure 3.1 there are 4 main elements: hex, pyramid, tetrahedral and wedge elements. Tetrahedral elements are of constant strain, having no difference in strain across the element. Traditionally tetrahedral elements do not behave as well as hex elements, especially for non linear modelling [33]. The advantage is the robust meshing methods available for tetrahedral elements. In this project the model is build up using 8 node 'brick' hex elements. Brick elements are considered to be more reliable on non advanced elements. The geometry of the model is shown in figure **??**, this is based on previous work [34].
The thickness should consist of at least three elements in order to obtain decent results [33]. The delaminations are modelled by not equivalencing the nodes at those regions [35].

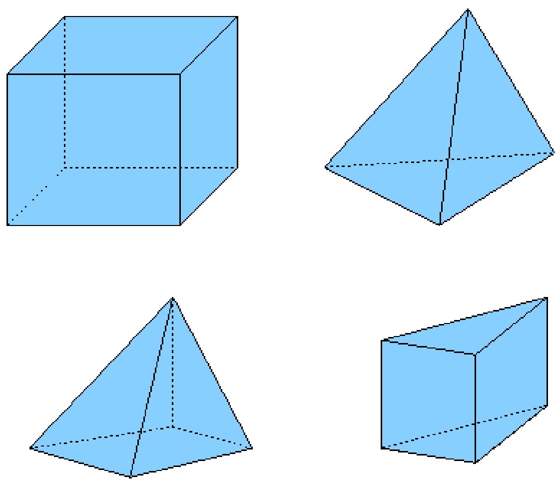


Figure 3.1: Hex, pyramid, tetrahedral and wedge element

3.3 Previous FEM modelling

The FEM model of Kessler et al [3] in figure 3.2 shows the modelling of the pipeline, the putty and the overwrap. The model itself is non-linear and there was a considerable amount of material testing done. However there were some errors.

- 10 node tetrahedral elements (which are not really good [33]) (marked by 1 in the picture)

- Straight corners (at the putty- pipeline interface) make the modelling easy but are not realistic, plus give local stress concentrations (marked by 2 in the picture)
- All layers are one element thick, which is not good for accurate modelling(marked by 3 in the picture) [33], each material should be at least 2-3 elements thick keeping in mind a decent aspect ratio so that the elements are not too much deformed
- No increase in mesh density at the area of interest

This is not considered to be a good approach.

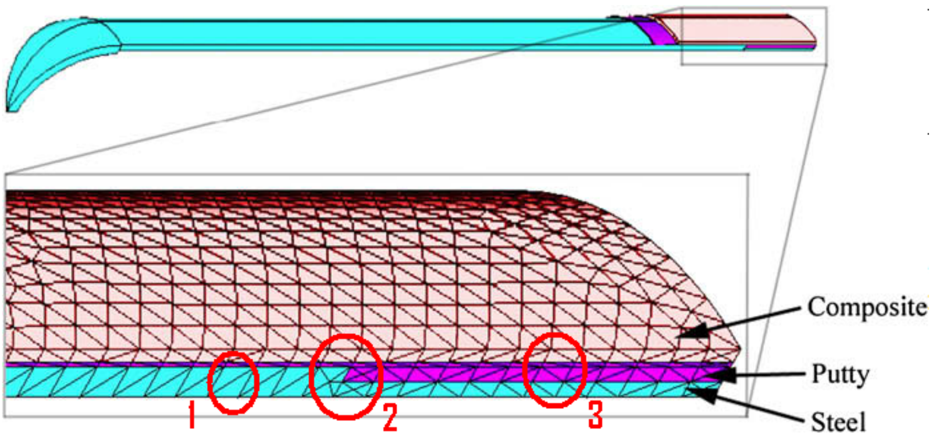


Figure 3.2: The full 3D Model used for the finite-element calculations and a zoomed in view showing the discretised finite-elements at the defect region (the elements are not shown in the full 3D model) [3]

The thesis of Murad [7] contains a nice background on composite repair FEM models.In the thesis of Murad some interesting things show up that are worth mentioning: [7]

- The model uses hex elements (although the choice is based on a completely irrelevant micro structure paper)
- It mentions deforming elements in some areas (which is normal)
- The model uses constraints between different elements, in order to tie elements together on different surfaces
- In the paper is stated that hex elements are better for producing good results while using reasonable computer time

In figure 3.3 the close-up of the elements in the repair is shown. A couple of remarks with this figure:

- The thickness direction of modelled steel, putty and overwrap should contain more elements (marked by 1 in the picture)
- The mesh should be refined at the defect (marked by 2 in the picture)
- The elements are deformed due to thickness change (marked by 3 in the picture)
- The aspect ratio of the elements in the hoop direction seems too large in figure 3.3 (marked by 4 in the picture)

- The elements through thickness do not match up (see earlier remark)

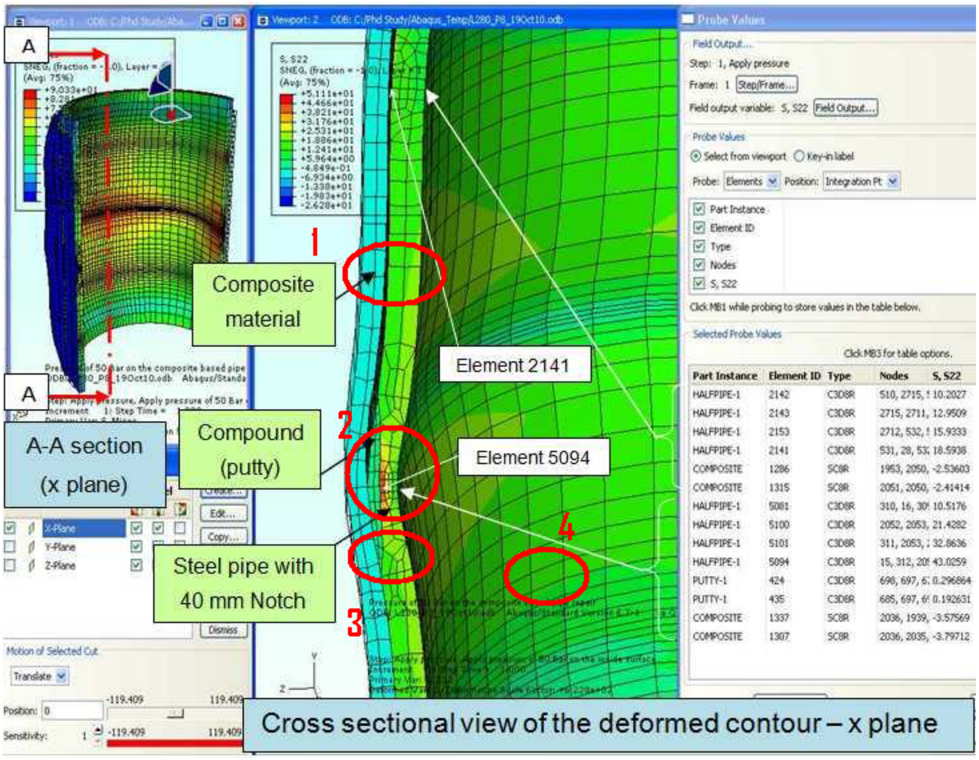


Figure 3.3: Finding the axial stress concentration value (${K_t}^a$) in the repaired steel pipeline (i.e. at elements 5094 and 2141) [7]

Both papers have no local increase in mesh density in the neighbourhood of the pipe defect. And both use too few elements through thickness and do not respect the aspect ratio for elements [33]. Both have got no defect modelling on the overwrap repair. Hex elements should be used for the best results [33].

Chapter 4

Strain monitoring system and considerations

As the pipeline itself has to be monitored, a way of sensing has to be chosen from existing techniques. This form of sensing has to be able to meet all the requirements of operating effectively in the environment of the pipe. There are a couple of approaches to (optical sensing), they are briefly explained in this chapter. Also the requirements of the system, operating in a subsea harsh environment, are compared to the characteristics and properties of optics.
In addition from the research into damage detection and damage growth using models, a scientific approach to all characteristics of the available sensing systems and all the variables to consider when using the system in the real world is important.

4.1 Optical sensing in strain monitoring systems

Since this report has a focus towards the OGP industry, there is a preference of using optical sensing technology instead of normal electrical strain gauges.

Optical sensors use a light pulse for data acquisition and sensing, so there is no need for supply of electrical power to the sensor, which makes them explosion proof and thus usable in highly volatile sensing areas. The interrogator, that is on a certain distance, is of course using electricity. There is also no effect on the sensor due to Electro Magnetic Interference (EMI). With an optical fibre, the possibility exists to incorporate multiple sensors in one optic cable, which reduces the cabling effort required [4, 13, 36].

Optical sensors inherit an aspect from the telecommunications industry giving most sensing techniques the ability to sense over tens of km [4, 13]. Optical cables can survive a high strain, high load cycle environments and are as such, suited for high frequency (in the range of Ghz) measurements or for a long lifetime operation [36]. Another advantage over electrical strain gauges is that optical fibre has excellent resistance to chemicals (even at elevated temperatures), corrosion and weathering effects. And finally, due to all the above properties, optical fibres are reliable when in service [13].

4.2 Optical sensing forms

There are three sorts of sensing: single point, quasi distributed or distributed sensing. Quasi distributed sensing uses a number of single point sensors in order to sense across a large surface.
A large number of methods can be used to interrogate a fibre, with a sensor embedded in the optical fibre or not. In the next section, a short summary is given of the general optical sensing technologies used

in the Oil, Gas and Petrochemical (OGP) industry or methods that could be applied in this industry. In figure 4.1 a visualization is shown of the different sensing lengths. The distributed sensor can show the entire movement of the specimen while the quasi distributed sensor can only sense at certain intervals. The single point sensor is sensing a signal but an approach like this will give errors if the actual strain pattern looks like the distributed one.

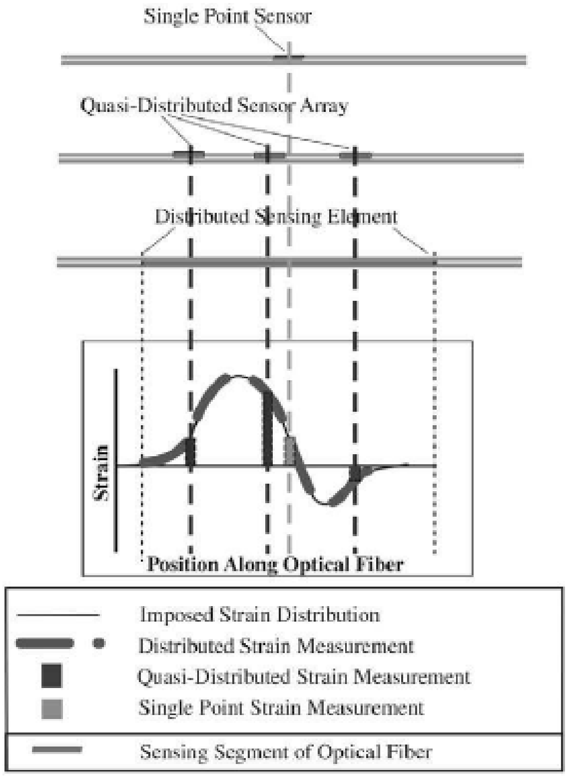


Figure 4.1: Differences in sensing [8]

In table 4.1 the two researched single point optic sensors are on top. The Fabry-Pérot and Fibre Bragg Grating sensors contain sensing elements in the fibre. The Rayleigh, Raman and Brillouin sensing principles are based on scattering of light in a normal optical fibre. Table 4.1 is adapted to reflect the current progress in optical sensing.
The coupling between different parameters denotes the fact that certain parameters are measured separately or that they are combined. For instance the Bragg grating sensors sense temperature and strain and when one parameter is to be sensed a compensation mechanism has to be incorporated.

Table 4.1: Comparison of Optical Sensing Technologies (distances approximate) [21] [23]

Technologies	Topology	Range	Temperature	Strain	Pressure	Vibration	Coupled
Fabry-Pérot	Multi-Point	< 10 km	Yes	Yes	Yes	Yes	Yes
Bragg grating	Multi-Point	< 50 km	Yes	Yes	Yes	Yes	Yes
Rayleigh	Distributed	< 70 m	Yes	Yes	No	No	Yes
Raman	Distributed	< 20 km	Yes	No	No	No	No
Brillouin	Distributed	< 50 km	Yes	Yes	No	No	Yes

4.2.1 Local sensing

This section includes the local sensing options currently available. To monitor a composite overwrap repair sensors have to be attached and connected locally.

4.2.1.1 Fabry-Pérot

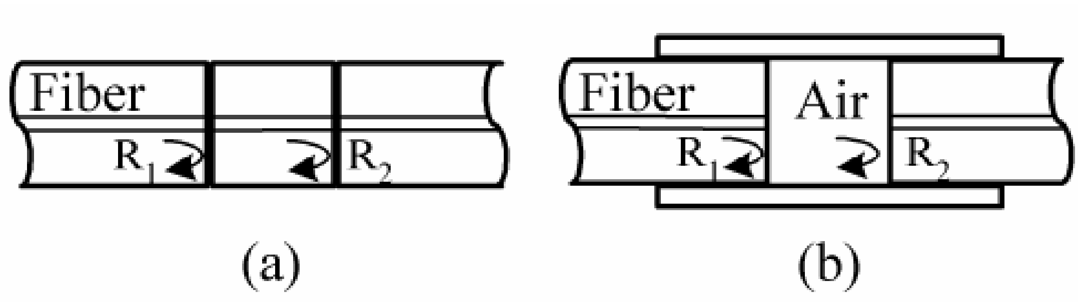


Figure 4.2: Intrinsic and extrinsic Fabry-Pérot sensor [9]

In a Fabry-Pérot sensor there are two mirrors at each end of the sensing section, as can be seen in figure 4.2. Light is partially reflected back and this interference between the multiple beams of light change when the distance between the mirrors changes. This spacing between the mirrors is dependent on physical phenomena [9,21], such as strain and temperature, which can be sensed with high accuracy [21].
There are two different Fabry-Pérot sensors as seen in figure 4.2, an Intrinsic and Extrinsic Fabry-Pérot Interferometer (IFPI and EFPI). An IFPI has a set of mirrors and fibre in between or it has splices engraved in the fibre while the EFPI has an airgap between the mirrors [9].
The third possibility in Fabry-Pérot sensors is an inline fabricated FP. This consists of a hollow core section between the mirrors, instead of the air gap in an EFPI.
The complete overview of different Fabry-Pérot sensors is shown in figure 4.3.

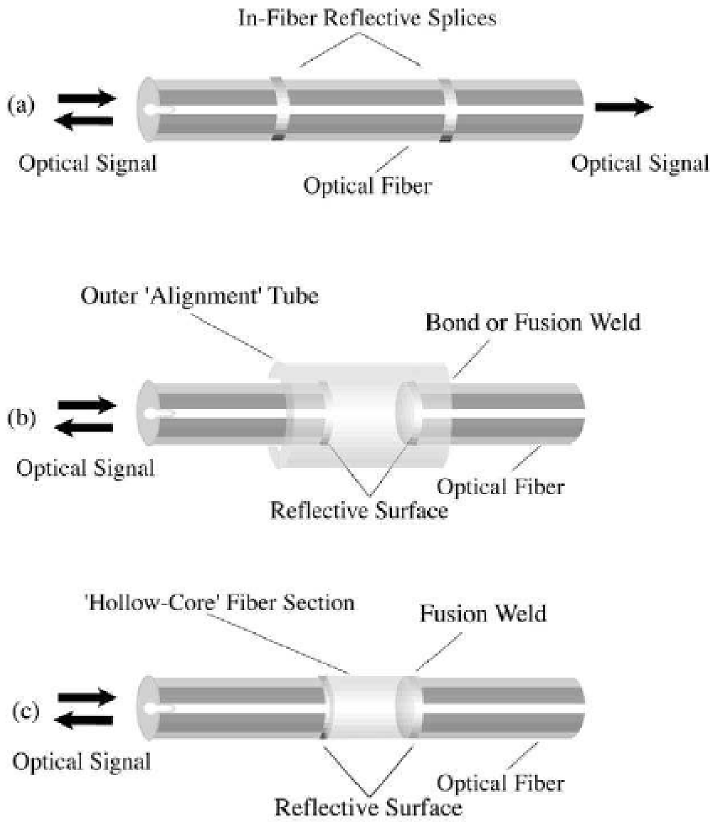


Figure 4.3: Intrinsic (a), extrinsic (b) and Inline (c) Fabry-Pérot [8]

4.2.1.2 Fibre Bragg Grating

Fibre Bragg Grating sensors are composed of periodic alterations of engravings in the fibre core. This can be seen as wavelength selective mirrors composed of thousands of fringes [6, 13, 37].
The most general FBG's are made up of constant period planes that have a perpendicular orientation to the longitudinal axis of the fibre [6].

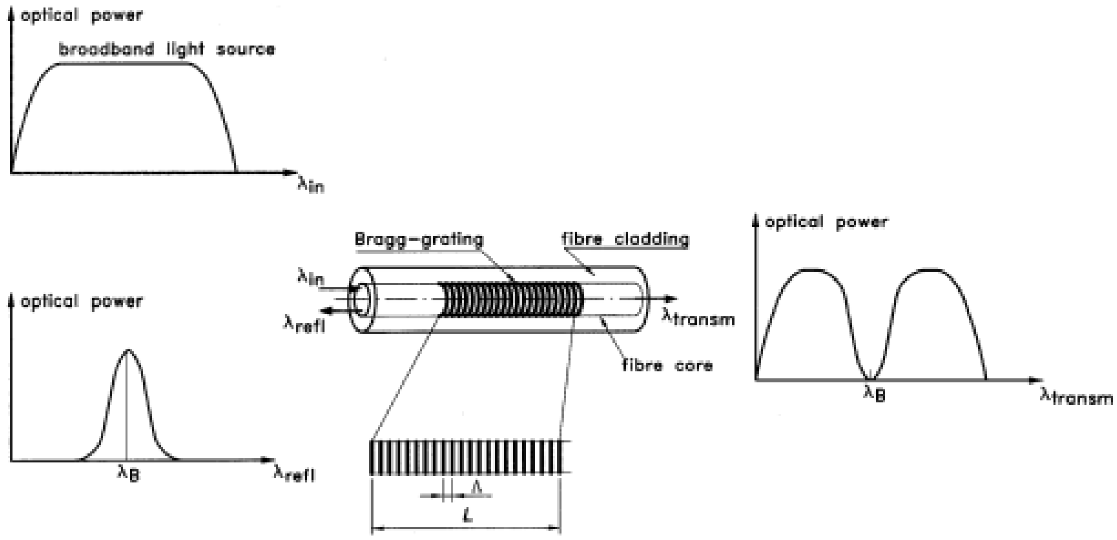


Figure 4.4: Fibre Bragg grating Wavelength reflection, λ_{in}= incoming light, λ_{refl} = reflected light, λ_{transm}=continuing light [6]

$$\lambda_B = 2n_0\Lambda \tag{4.1}$$

- λ_B = Bragg wavelength (nm)
- n_0 = refractive index (-)
- Λ = grating period (nm)

A visualization of the functioning of a FBG is shown in figure 4.4, with equation 4.1 relating the refractive index and the grating period to the Bragg wavelength. This equation shows that when the grating period changes the Bragg wavelength is affected and those changes can be quantified. This grating is stretched or compressed when subjected to strain or temperature resulting in a wavelength shift. This wavelength shift is linear [6, 8, 13, 37]. This shift can be observed in figure 4.5 for the behaviour of the FBG sensor.

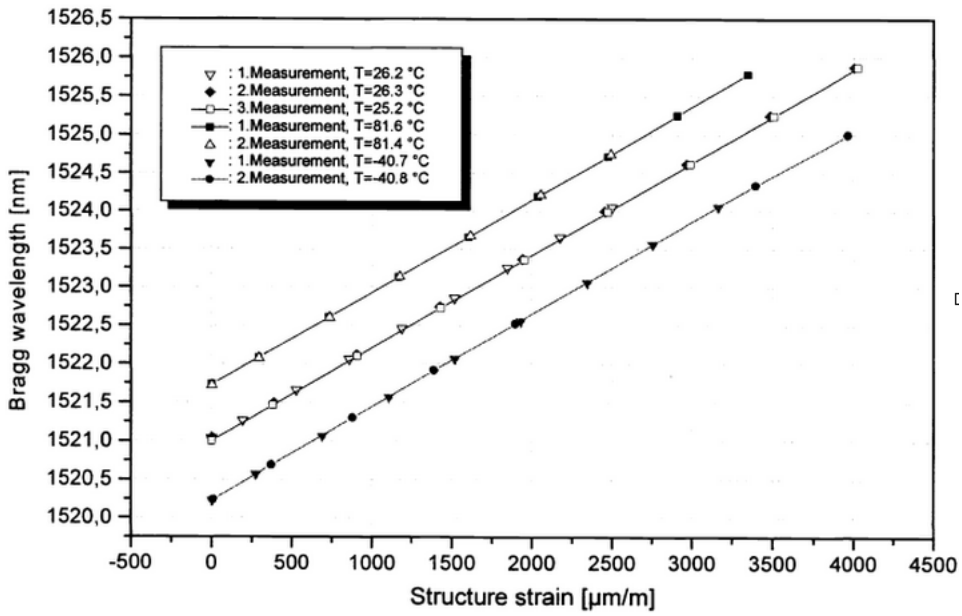


Figure 4.5: Fibre Bragg Grating: Temperature and strain response. [10]

Resolutions of 0.1^o C and $1\mu\varepsilon$ are possible dependent on the set-up of the system [13]. Using birefringence (see subsection 4.5.4) pressure can be determined as well [38].
Other remarkable advantages of FBG's are:

- Insensitivity to: [8]
  - Power fluctuation of the source
  - Variations in photodetector response
  - Losses in the connectors or macrobends of the fibre
- Very high strain capacity up to 5% [20, 37]
- A single fibre can contain many gratings [8, 13]
- Easy installation considering time, cabling and testing [37]
- Can be engraved during manufacture, up to 2000 FBG's an hour [8]

Disadvantages:

- Temperature dependence, there do exist temperature compensated FBG's [6, 8, 13, 37]
- Lateral forces lead to birefringence [8, 37]

The wavelength of a FBG changes with strain and temperature according to: [8]

$$\frac{\Delta\lambda}{\lambda_0} = k \cdot \varepsilon + \alpha_\delta \cdot \Delta T \tag{4.2}$$

- $\Delta\lambda$ = wavelength shift (nm)
- λ_0 = base wavelength (nm)

- k = 1 - p (-)
- p = gauge factor (-)
- ε = strain (-)
- Δ T = temperature change per unit (K)
- α_δ = temperature factor (1/K)

4.2.2 Quasi distributed sensing

A quasi distributed sensing system is based on point sensors at set locations to form one measurement system. This is mostly a multiplexed system. This is also the reason why the multiplexing techniques are mentioned here [9].
Different multiplexing options are highlighted in this chapter. With the broad range of available options, only the commonly used techniques are mentioned.

4.2.2.1 Topology

Multiplexing of sensors can be divided into three methods; the serial, parallel and hybrid multiplexing of sensors.
Parallel multiplexing uses different channels with a sensor. This can be seen in the bottom of Figure 4.6.
Serial multiplexing on the other hand consists of one fibre with the sensors spaced apart. This can be seen in the top of Figure 4.6.
Figure 4.7 and 4.8 show the Time Division Multiplexing (TDM) and Wavelength Division Multiplexing (WDM) system respectively. Hybrid multiplexing consists of a combination of the parallel and serial multiplexing. This setup is shown in Figure 4.9.

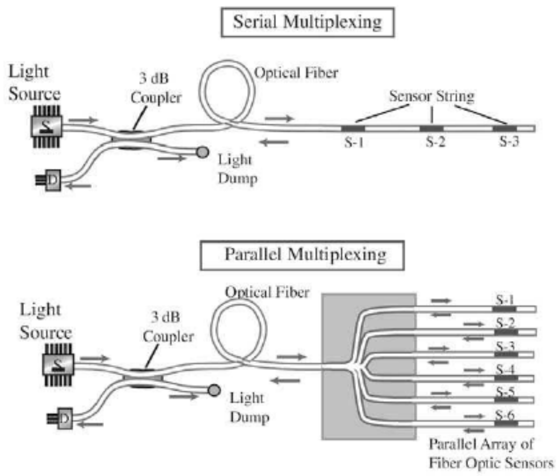


Figure 4.6: Simple Multiplexing Topology [8]

4.2.2.2 Time Division Multiplexing

Time Division Multiplexing (TDM) uses a lightpulse and measures the time of flight of the reflected light to determine the position of the sensor. The visualization can be seen in Figure 4.7.
With TDM hundreds of FBGs can be used because they all share the same bandwidth. Sharing the same bandwidth has some advantages such as having the entire bandwidth to use and being fully interchangeable. This means that replacing a sensor is straightforward since all engravings are the same.
The big disadvantage is that due to the time of flight interrogation the spacing between the sensors is between 1-2 m. New systems are however available that counteract this disadvantage and have a spacing of 1 cm [39]. Also the low reflectivity of the FBG's and as such the power required for multiple FBG's can be a problem.

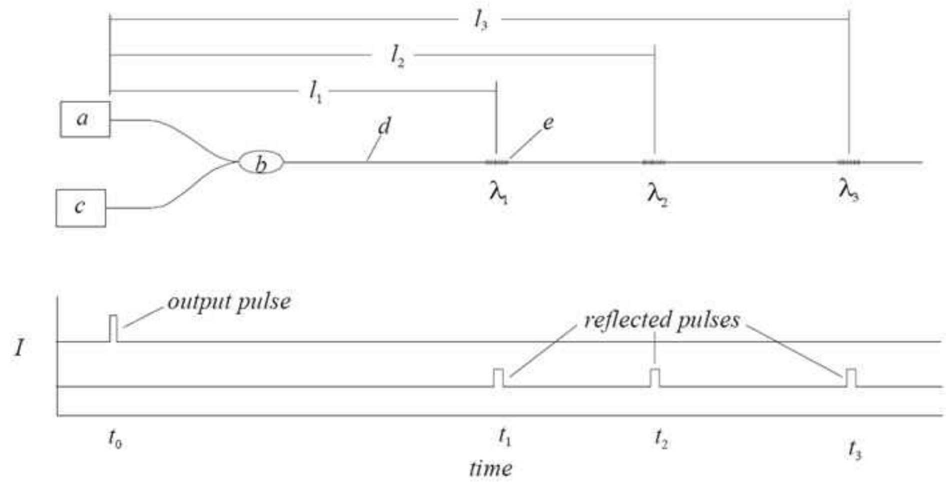


Figure 4.7: TDM schematic [11]

4.2.2.3 Wavelength Division Multiplexing

In Wavelength Division Multiplexing (WDM) every sensor has a unique specified wavelength written into the fibre. As such, each fibre contains sensors at different wavelengths [6, 8, 37].
When the interrogator is using a broadband light source only a small part of the energy is related to the FBG, which uses only a fraction of the bandwidth.
In contrary to the TDM technique, due to the unique wavelength of each FBG the spacing of the sensors is in the order of several mm.
Another advantage is that the grating is unique and as such the sensor can be clearly identified and matched to a location in the fibre and thus on the structure.

With interrogators using a tuneable laser the spectrum can be swept. Because of the high energy associated with tuned lasers the energy can be split into many small spectra without loss of signal quality [37]. The WDM setup can be seen in Figure 4.8.

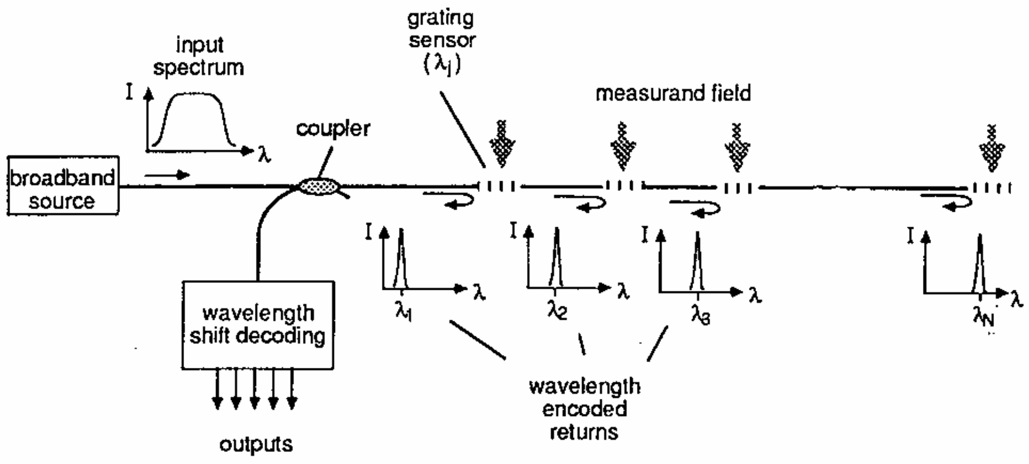


Figure 4.8: Tuneable Laser in a multiplexing setup [12]

4.2.2.4 WDM/TDM Hybrid

A hybrid system WDM/TDM system can be a great solution. In this way a channel can contain around 800 sensors depending on configuration. In figure 4.9 this setup is shown. In a deep sea environment this can be applied in such a way that a single fibre is able contain 800 sensors [40]. The spatial constraint using TDM is circumvented by using a group of sensors having a different wavelength on a repair patch and repeating this wavelength group at every repair location. The drawbacks can be a low interrogation frequency, which is not necessary for deterioration monitoring, and low reflectivity.The advantages are the use of one interrogator for up to 50 repair zones, containing 16-32 FBG's per zone. If breakage would occur this can be traced quickly using the TDM sensor output that will be missing.
This is only in an experimental stage yet.New repair spots can be just inserted into the existing line.

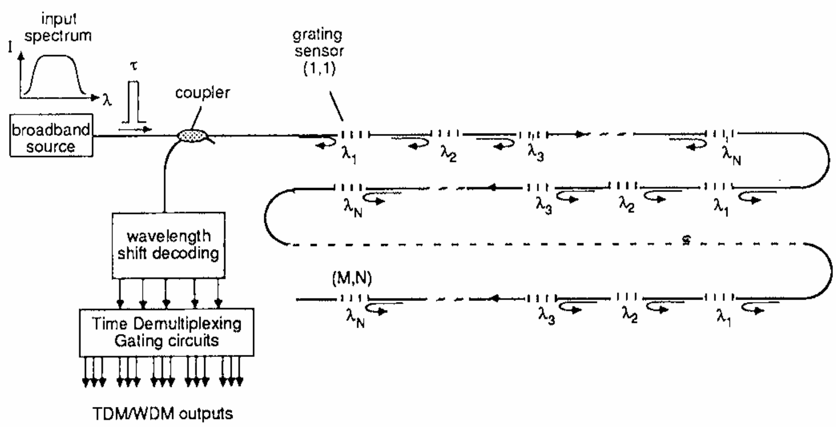


Figure 4.9: Hybrid WDM/TDM system [12]

4.2.2.5 Multiplexing Summary

In table 4.2 the summary of the interrogator systems is shown.
The TDM system is used extensively these days in distributed sensing in the OGP industry but this project requires sensors to be spaced closely together and the number of sensors will not be that large.
As far as topology goes, a multichannel system with sensors in a serial array in each channel is the preferred way to go. This system can be visualized in figure 4.8.
Hybrid WDM/TDM systems are not commercial yet, but they can be interesting in coming research.

A preliminary approach will consist of a WDM system for testing. This system also gives the oppurtunity to accuratly determine the position of each sensor, relating it to its wavelength.

Table 4.2: WDM and TDM comparison [8, 9, 24, 25]

WDM	TDM
(+) No restrictions on physical FBG spacing	(+)Large number of FBG's (+100) on a single optical fibre (+) Fully interchangeable sensors
(-) Bandwidth separation restricts number of FBG's (-) FBG's are not interchangeable (-) More expensive sensors	(-) Spacing between sensors around 1-2m for cheap systems

4.2.3 Distributed sensing

Distributed sensing is as the name suggests a way to sense a general distribution of strain and temperature. Distributed sensing relies on the scattering of the light in the fibre optic cable. Different scattering processes are the basis for the different measuring techniques available. These techniques can sense strain and/or temperature. Measurements can be done within a certain spatial resolution, but this can go down to mm level [41]. Recent breakthroughs using Rayleigh scattering are promising since good accuracy together with a high spatial resolution (sub-mm) is obtained [23].

All three of the distributed sensing techniques are used for static measurement of parameters, however large differences exist in spatial resolution, accuracy and sampling rate.
Sampling rates can hover between $0.3\cdot 10^{-4}$ to 5 Hz depending on the technique and the state of the art of the system. In Brillouin and Raman Scattering improving spatial resolution will see the use of even lower sample rates and signal processing [21, 23].

The next subsections contain a short overview of the techniques. A visualization can be seen in figure 4.10.

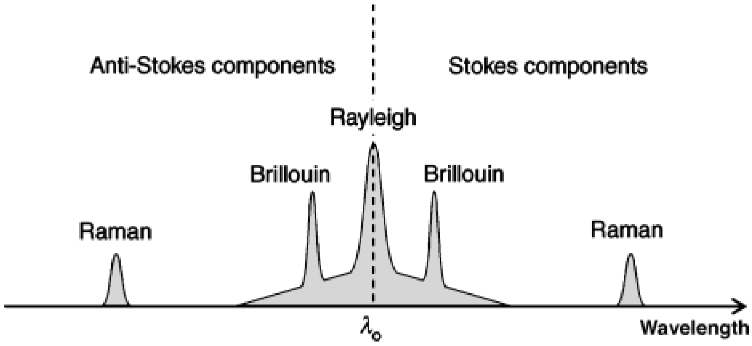


Figure 4.10: Distributed sensing: scattering of light [13]

4.2.3.1 Rayleigh

Instead of having components around the wavelength of the input light Rayleigh scattering has the same wavelength as the input light [9,41]. It is the most dominant type in scattering [21].
Rayleigh scattering works due to the inhomogeneities created during the manufacturing of the optical fibre. The density and composition fluctuations of the fibre form an unique key for identification [21,41].

With a narrow pulse the variation in Rayleigh backscatter can determine an approximate spatial location [21].
It is used for fault location, loss measurement and distributed sensing [9]. Distributed sensing includes temperature and strain [9,21,23]. Pressure, magnetic field and an electric field are also parameters that can be sensed [9].
Rayleigh scattering is only able to sense over a maximum length of 70 m [21,23].

The literature states limited accuracy due to fluctuation of the light source, optical connectors and fibre bending [9].
However a recent innovation [23] gives a high spatial resolution of 0.04 mm. It takes 5 seconds for the measurement and the associated calculations, with a 20 mm gauge length and 500 sample points.

4.2.3.2 Brillouin

Brillouin scattering arises due to acoustic wave interaction with light. There are inhomogeneities created by these sound waves. So acoustic vibrations are stimulated by the incident light [8,41].The temperature measurement using Brillouin scattering can be done by an ordinary fibre optic telecommunications cable since they are shielded against strain [13].

To satisfy the energy requirement of energy conservation, the frequency shift between original light pulse frequency and Brillouin scattering wave is measured. It consists of two components around this original pulse, the Stokes and Anti-stokes component. This frequency shift is sensitive to strain and temperature [13,41].
In Brillouin scattering, the sensing is distributed throughout the length of the fibre [9,13,21,41]. The spontaneous scattering efficiency is weaker then Rayleigh scattering but stimulated Brillouin scattering gives stronger signals than Rayleigh [8]. The sensing distance goes up to 50 km, with range extenders extending this to 150 km [13].

The strain resolution is 2 microstrain while the temperature resolution is 0.1^o C [42].

Stimulated Brillouin Scattering (SBS) is Brillouin scattering using a high power input which gives a high reflectivity, the downside is that if the optical fibre is used for data transfer there is a high noise factor in that data [43, 44].

4.2.3.3 Raman

Raman scattering is also a non linear process [9]. Raman scattering arises due to interactions (their vibrations and rotations) with molecules that are present in the optical fibre.Just as in Brillouin scattering there are two components, A Stokes and an anti-Stokes component [8, 13].The main drawback with Raman scattering is the fact that it can only give an absolute temperature indication [9, 13, 21]. The temperature at every point is measured by the intensity ratio of the two components. The spatial resolution is around 1 m and the temperature resolution around 0.2^o C [13]. This technique is popular in temperature profile determination of oil wells [21]. The typical lengths are around a maximum of 20 km sensing length [21]. There is a low signal to noise ratio, which can make interrogation challenging [9].

The low Raman scattering coefficient gives rise to high input powers and as added disadvantage there are long signal averaging times [8, 9].

4.2.4 Optical Sensing summary

Local sensing techniques exist in the form of Fabry-Pérot and fibre Bragg gratings. These allow high accuracy point measurements depending on the set-up used. Quasi distributed sensing using Fabry-Pérot and fibre Bragg gratings can be done using WDM, TDM or a WDM-TDM hybrid structure.
The problem with the Fabry-Pérot sensor is the fact that it is more difficult to manufacture. The density can also be a problem.
Fibre Bragg Gratings are easy to manufacture and can be densely packed. Furthermore each sensor can be easily identified (WDM) or can contain many sensors with a larger spacing (above 1 cm) (TDM). Since the project requires a dense packing and clear identification of location the WDM multiplexing system with the FBG is a good candidate.

Fully distributed sensing techniques consist of Rayleigh, Brillouin and Raman scattering. They each have their own unique properties sensing a different property of the backscattered light. Raman is a temperature only system which is an advantage and disadvantage at the same time.

The distributed systems cannot deliver the exact specifications set out for this project as far as Brillouin and Raman scattering goes. However recent improvements in the field of Rayleigh scattering can have potential for further investigation. The most important disadvantage is however the fact that it only can sense up to 70 m, and the connectors are a question mark since it is really sensitive to noise [23].

4.3 System Operating Environment

When a pipeline is repaired the durability of the system has to be considered. One of the factors that contribute to this durability is the operating environment in which the repair is going to be applied.
Since the repair is designed to be applied in the splash zone and subsea, the sensor system itself also has to be able to function in the same environment. Salt water, corrosive elements (chemicals) and temperature fluctuations are just some of the variables to consider. In section 4.5 and 4.4 these limitations are researched in more depth.

4.4 Optical sensing considerations

In this section the general considerations relating to optical sensing are mentioned. This ranges from optical fibre coatings to degradation sources and ageing.

4.4.1 Coating

The coating of optical fibres (and as such optical sensors) is of high importance. There are many specialist coatings available and this section deals with the most common and promising ones. Optical fibre is coated to protect it from water and hydrogen, which causes crack growth and reduces mechanical stability [37]. Weak optical fibre coating materials, weak optical fibre/coating or coating/host interfaces can lead to formation of cracks at low stresses, which compromises the function of the fibre [8, 45]. The strain transfer depends on the type of coating and the thickness of the coating. A thin layer provides greater shear strain transfer when the shear modulus of the coating is less than the host matrix.
The coating choice strongly influences the performance of the sensing system by reducing obtrusivity or by enhancing the sensing performance [8]. The following points summarise the influences of the main optical fibre coatings:

- No coating: maximum strain transfer [8] but weak [37]
- Acrylate: too soft [37], cannot precisely transfer strain from specimen to fibre (particularly at high temperatures) [37], use up to 100^o C [8], low thermal stability compared with polyimide and ORMOCER [46]
- Polyimide: stiff [37], better strain transfer (thin coating) [8,37], use up to 300^oC [8], bond between polyimide and glass breaks when highly strained [16], generally bonds well with various adhesives such as polyesters and epoxies [16], highest thermal stability [46]
- ORMOCER: relatively high Young's modulus, excellent corrosion properties [37], UV curable, improved adhesion to silica optical fibre, lower rigidity and brittleness, reduced water vapour permeability [46], use up to 200^oC [47]

4.4.2 Degradation sources

There are many sources of degradation present in the oil and gas production environment. It is a highly corrosive environment, particularly the splash zone owing to the presence of oxygen and salt water. Optical fibre and sensors require protection from chemicals and the environment. Sources of damage include, but are not limited to, sea water, utility fluids, hydrocarbon liquid, gas and mechanical damage. An example of mechanical damage to an optical fibre caused by abrasion can be seen in figure 4.11.

Figure 4.11: Abrasive damage [14]

Ageing is a problem concerning optical fibre and several coatings have been investigated in the literature. In figure 4.12 an example ageing behaviour of acrylate fibre is shown. Salt water has a small influence and temperature strongly affects the remaining strength of an acrylic coated optical fibre.

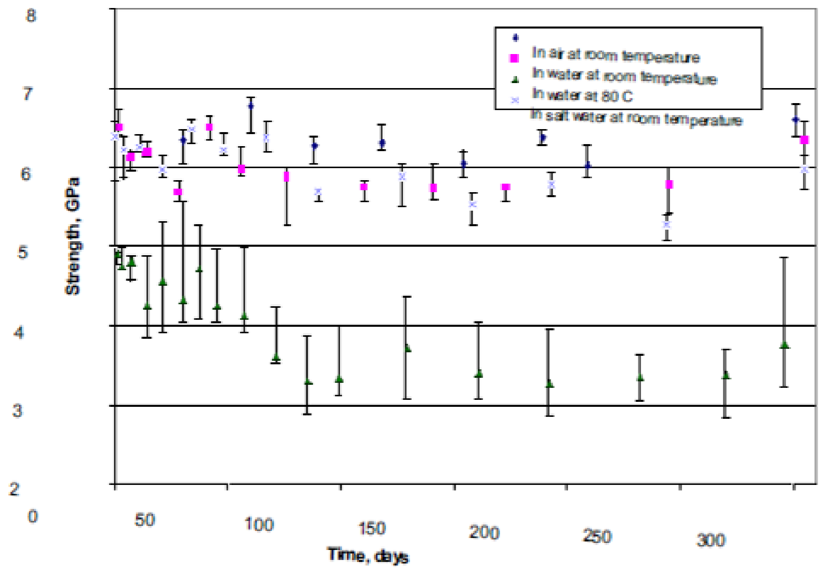


Figure 4.12: Acrylate fibre ageing behaviour [15]

Applications in harsh environments are a considerable risk owing to harmful chemicals, water and hydrogen, particularly when under high pressure and temperature or when the fibres are under high stress [45]. Degradation of the coating and also fracture can occur due to interaction with water. Reduced transmission can occur due to hydrogen diffusion [45].

Surface flaws or cracks, induced either mechanically or chemically, act as local stress concentrations, reducing the tensile strength of the optical fibre. Moisture ingress can cause fracture or affect the fatigue behaviour of the fibre [45].

For successful application in harsh environments it is imperative to retain the characteristics of the optical fibre, primarily mechanical strength and waveguide properties [45]. The optical fibres are dependent on the coating for their survivability and reliability. A carbon barrier layer can be incorporated to improve the optical fibre's resistance against fatigue and hydrogen induced loss but little information on strain transfer is available [45].

4.4.3 Optical Losses

The issues concerning optical losses due to wavelength and bending are discussed in this section. An example power budget is used to illustrate the potential losses in a sensing system.

4.4.3.1 Attenuation Loss

The attenuation losses that occur in an optical fibre are dependent on the wavelength that is interrogated. An overview of loss as a function of wavelength is given in figure 4.13. Lower wavelengths have more attenuation with some peaks at the light absorbing wavelengths.
For long range applications, the attenuation loss should be minimized and higher wavelengths should be used. Most optical telecommunication fibres use the 1300 nm and 1550 nm wavelengths, in order to minimise losses. The application considered in this project requires remote sensing over several km so using standard wavelengths is suitable.

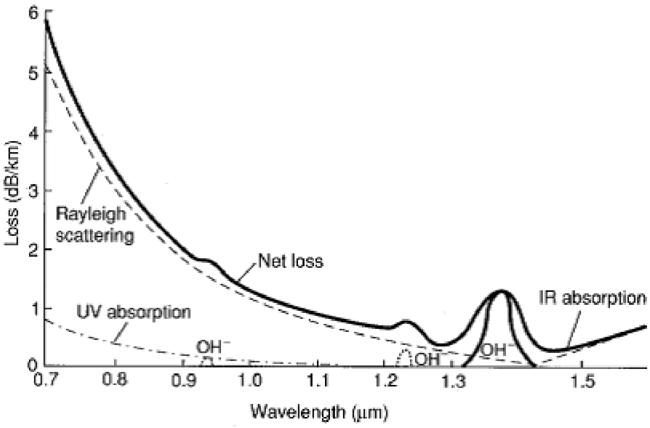


Figure 4.13: Attenuation loss versus wavelength [6]

4.4.3.2 Bending

Bending of fibre optics in general is an issue owing to the resulting losses and must be kept in mind when designing a system with FBGs so that bending induced losses are minimised. These losses become significant at radii below 25 mm. The minimum bending radii should be well above the allowable bending radii of the optical fibre [8]. The bending losses caused by bending of an optical fibre are illustrated in figure 4.14.

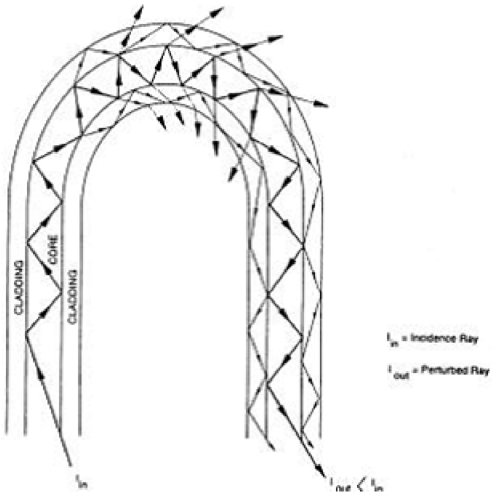


Figure 4.14: Bending loss in an optical fibre [16]

4.4.3.3 Power Budget

A power budget can be used to compare the available power to the accumulated losses occurring in a sensing system. A simple power loss overview of a send and receive system (not including gratings) is given in figure 4.15 [17], which shows that the power degrades by distance and also every time a connector or splice is passed. With FBG systems, the light travels to the grating and is partially reflected, so the losses are doubled since the light has to travel back to the interrogator. For the last sensor on the optical cable, the reflected light sensed at the source will be weak or non-existent if the losses are too high.

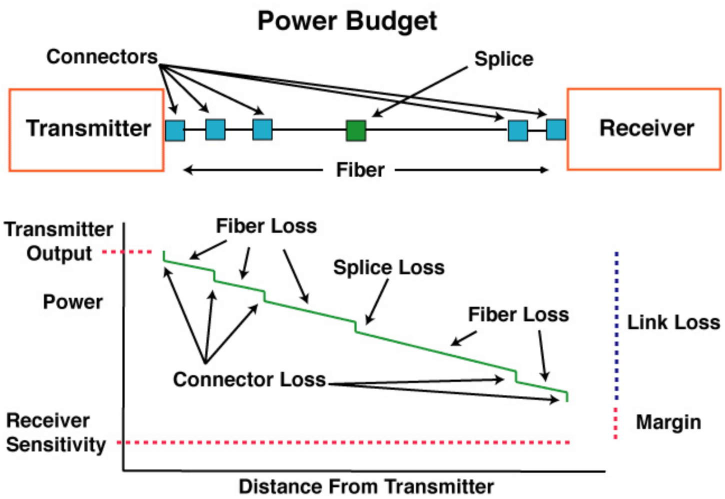


Figure 4.15: Optical losses occurring in cabling [17]

Typical values of losses occurring in an optical cable [17]:

- Splice: 0.02-0.05 dB/splice (using a fusion splicer,preferably in a controlled environment)
- Distance: 0.2-0.3 dB/km on 1550 nm (see figure 4.13)
- Connector: 0.1-1 dB/connector (prepared in the factory and using the fusion splicer: 0.1-0.2 dB/connector; in the field: 0.5-1.0 dB/connector)

- Bending losses: depend on the type of fibre

An example power budget, given in Table 4.3, provides a quick calculation for a typical sensor setup, with the expected losses for a best, worst and normal case. The distance to the repair is estimated as 25 km while the bending losses are overestimated as 1 to 3 dB. The dynamic range of an interrogator indicates the power available. A typical dynamic range of an interrogator is between 20-30 dB. All losses should incorporate a safety factor.

Table 4.3: Power budget

WDM system	Loss [dB]	No.	loss worst case	loss best case	normal
/fusion splice	0.02-0.05	33	1.65	0.66	0.99
/km	0.2-0.3	25	7.5	5	5
/connector	0.1-1	3	3	0.3	0.6
bending	1 to 3		3	1	2
loss			15.15	6.96	8.59
back and forth			30.3	13.92	17.18

4.4.4 System installation

Installing optical fibres is not trivial and must be performed with care to obtain the required properties. A good surface preparation is just the start of things. An understanding of the entire system (such as fibre directions and adhesive used) is imperative in order to obtain good results.

4.4.4.1 Surface Preparation

Surface preparation is a key element in bonding optical fibres, whether or not the sensors are pre-packaged. An in-depth investigation into the adhesion of sensors to the composite overwrap repair (applied pre- and post-cure) is necessary.
For application of a bare optical fibre to the surface of a repair, a method is developed to adhere the optical fibre to the composite. This involves:

- Coarse cleaning
- Smoothing
- Cleaning
- Roughening perpendicular to sensing direction
- Marking/template adherence
- Final cleaning

4.4.4.2 Resin Pockets

An issue relevant to embedded sensors is caused by resin flowing around the optical fibre causing a resin "eye" in the laminate, when the alignment of the optical fibre is not parallel to the reinforcing fibre [8,16]. In figure 4.16 the creation of the resin eye is visualized with different directions of the optical fibre. This effect is dependent on the angle mismatch of the optical fibre in relation to the reinforcing fibres. The effect is largest at a 90-degree angle.

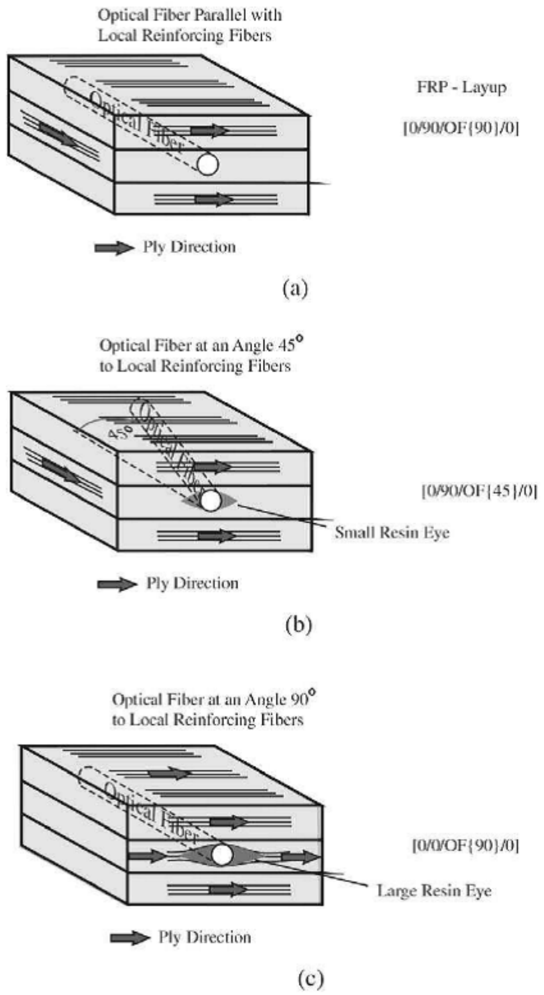


Figure 4.16: Resin eye vs. alignment [8]

This resin eye gives an error in strain transfer, a local weak spot and an initiation point for fatigue [8,16]. A resin eye is shown in figure 4.17 embedded in a composite.

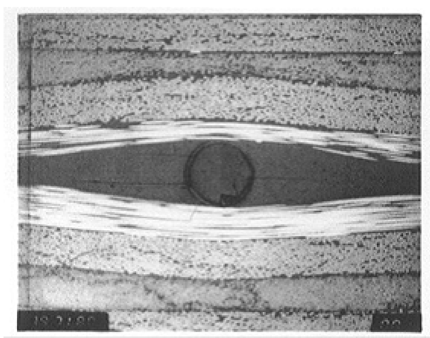


Figure 4.17: Resin eye [13]

4.4.4.3 Strain Transfer

Strain transfer is a key aspect when fibre optic sensors are used on structures and should be carefully considered. It could be assumed that the strain sensed in the optical fibre is equal to the strain in the host. However this is rarely the case since the optical fibre gives rise to stress concentrations which can cause

differences in the local and far field strain. To account for this, the micro-mechanical interaction between the optical fibre and the host has to be taken into consideration [8, 48]. FEM modelling and testing can help to define the interaction.
The strains sensed by optical fibre may be 10% different to the undisturbed laminate under axial loading of the fibre axis [6], owing to the micro-mechanical interaction. Analytical models have been used to calculate the shear lag characteristics of surface mounted optical fibres, however, there are limitations to this approach. Finite element modelling has also been used to investigate the behaviour [49].
The performance of surface mounted optical fibres is dominated by the adhesive thickness between the bottom of the fibre and the substrate, and the bond length of the fibre [48, 49]. In figure 4.18 the strain distribution is shown over the length of a surface mounded sensor for different adhesive thickness's. This shows the importance of having close contact between the fibre and the substrate. As the core of the optical fibre moves further away from the surface, only the middle of the fibre senses the correct strain.

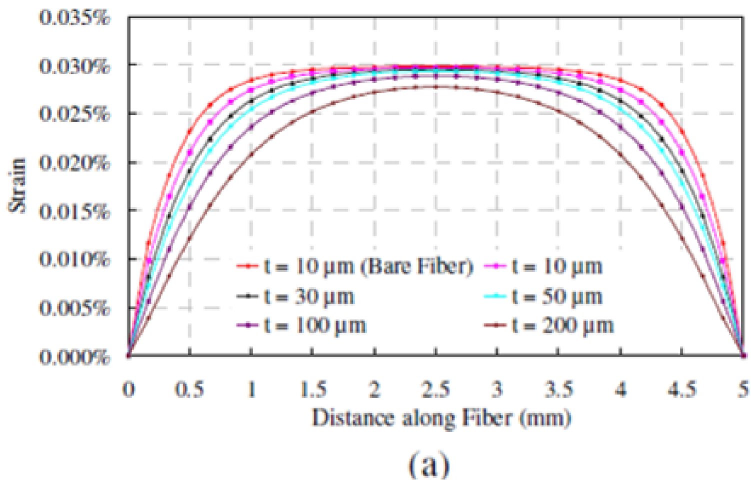


Figure 4.18: FE strain distribution along fibre core, t is the distance between the optical fibre core and the surface [18]

In figure 4.19 the strain transfer is shown for different coating thicknesses and coatings with different stiffnesses, furthermore there are different adhesive stiffnesses as wel. Note the considerable variation in distance over which strain is transferred. Stiffness of the coating is of importance in strain transfer.

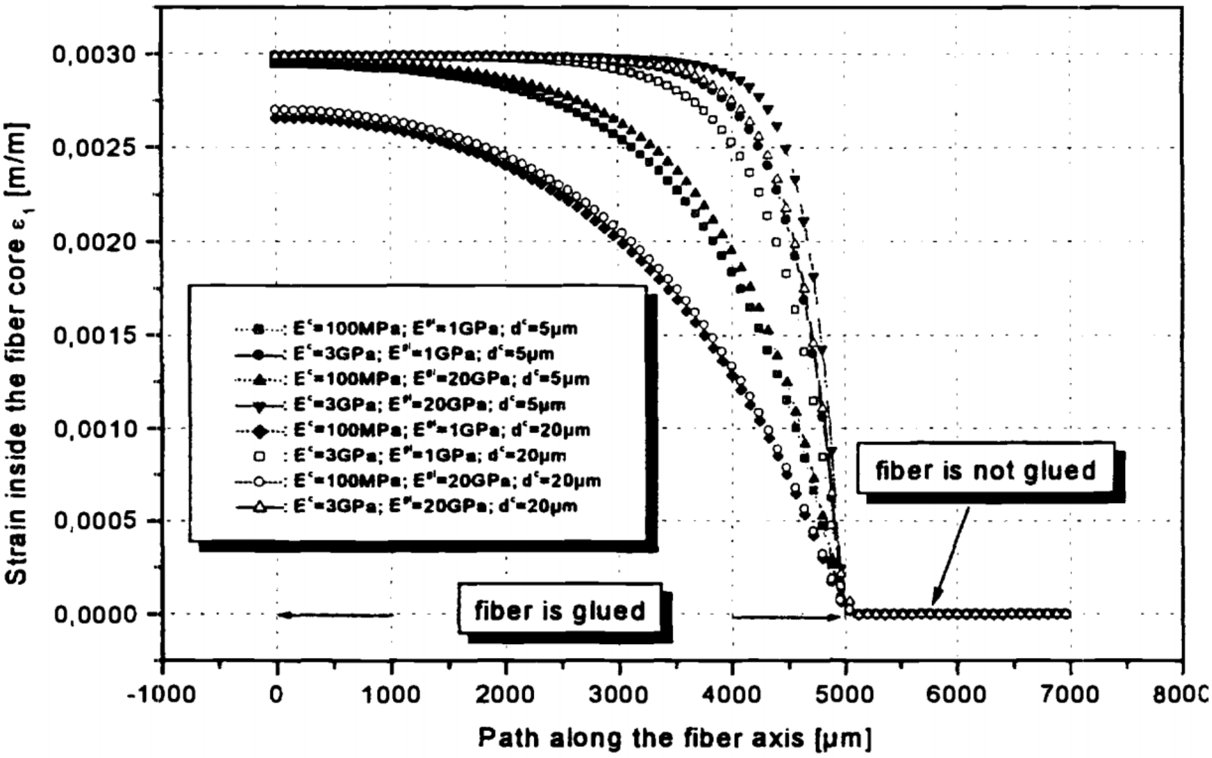


Figure 4.19: Axial strain progression in the fibre care. E^c= Young's modulus coating, E^{gl}=Young's modulus glue, d^c=thickness of the coating. The axial structure strain is 0.3 %. [10]

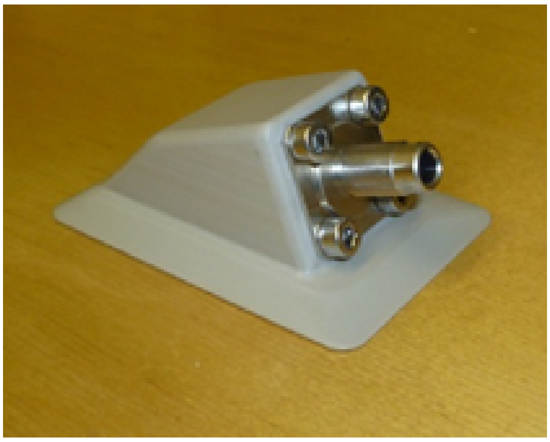
4.4.4.4 Obtrusivity

Embedding of optical sensors or pre-packaging in fibre reinforced materials can result in problems where the optical fibre disturbs the loading of the reinforcing fibres. Ideally, an optical fibre embedded in a laminate should not significantly affect the laminate. However the 52 μm to 125 μm optical fibre is around 10 times larger in diameter than the reinforcing fibres (glass: 5-20 μm, carbon: 5-10 μm). This mismatch in diameter can disturb the distribution of the reinforcing fibres [16, 48] and can cause perturbations in the strain field of the composite.

This obtrusivity effect may influence the measured strain values and strength of the laminate.

4.4.4.5 Connectors

Connections to optical fibres containing the gratings is not a trivial matter, the connectors must be robust and be able to operate in a subsea environment. However, there is an abundance of connector types available and selection of a suitable connector should be considered as part of a system design. The robust connector from Epsilonoptics is shown in figure 4.20a and the connector from seaconworldonline is shown in figure 4.20b. An ingress/egress point is shown in figure 4.21.



(a) Epsilonoptics connector [50]

(b) Commercial subsea fibre optic connector (seaconworldonline) [51]

Figure 4.20: Fibre optic connectors

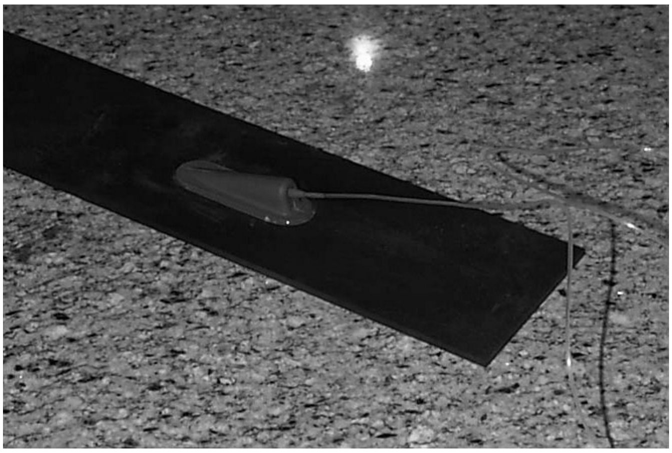


Figure 4.21: Strain relief protection jacket [19]

4.5 Fibre Bragg grating considerations

The optical system that is going to be used for sensing is the Fibre Bragg Grating (FBG) system. It is able to clearly distinguish between sensors, which makes the datahandling easy, and the equipment is available for this project. In this section an overview of production processes, installation characteristics and cost is shown.

4.5.1 Production Process

In addition to the coating, the production process also affects strength and fatigue resistance. There are two processes for inscribing FBG's into optical fibre, the standard process and the Draw Tower Grating (DTG) process. The standard process involves striping the coating from the optical fibre, inscribing the grating and reapplying the coating, depending on the type of coating. This gives discrepancies in the coating and is thus prone to failure. Surface flaws created by stripping and recoating weaken the fibre and create a path for water and chemical ingress [45]. The drawing tower process inscribes the grating during manufacture of the optical fibre, prior to coating, which produces a strong continuous coating without any discrepancies [37,52]. However, DTG's still have some challenges which limit the reflectivity, gauge length and sensor density [53].

The relative breaking probability of DTG's and classical recoated FBG's are shown in figure 4.22. This figure originates from a manufacturer of DTG's but the general consensus is that the DTG coatings are superior in performance.

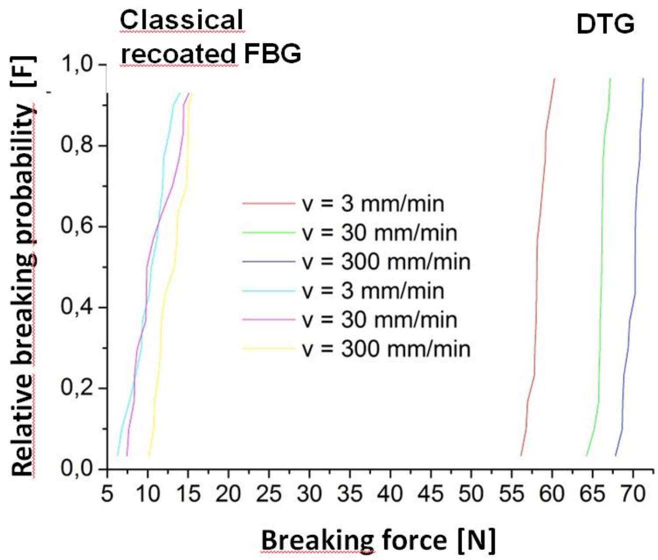


Figure 4.22: Draw tower gratings compared with classical recoated FBG's [20]

4.5.2 Temperature Compensation

FBG's are sensitive to strain and temperature. The wavelength measurements must be separated into a strain and temperature component. A temperature compensated FBG or a strain isolated temperature FBG is required [36].

4.5.3 Fatigue

In general, the best resistive strain gauges attain a non reversible change in zero of around 10 $\mu\varepsilon$. After 10^7 cycles, no changes in measurement characteristics can be detected with FBG's using the DTG process and ORMOCOR coating. Fatigue tests performed on DTG's show virtually no influence at around 2000 $\mu\varepsilon$ [36]. Fatigue tests on embedded acrylate coated FBG's revealed a continuously increasing ageing effect of 150 $\mu\varepsilon$ after 1.6x10^6 cycles.

4.5.4 Birefringence

Birefringence problems can occur when using sandwich packaging methods. Birefringence arises from transverse forces on the optical fibre. This transverse force causes a splitting of the spectrum or an elliptical profile. Birefringence can be helpful for measuring transverse strain or compensating for it. However it is preferred to have no splitting of spectrum in normal operating conditions [8]. In figure 4.23 the splitting of the spectrum is plotted with increasing transverse load applied to the optical fibre.

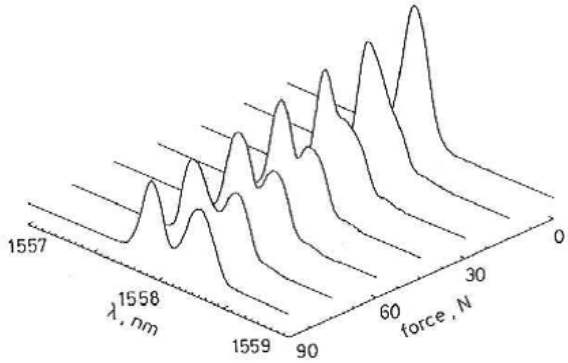
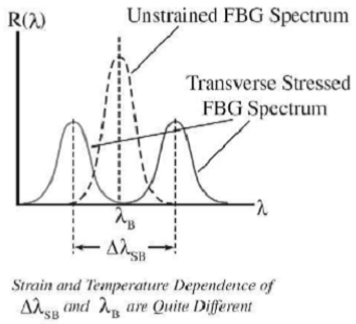


Figure 4.23: The arising of birefringence under transverse load [8]

Distortion of the reflected spectrum after curing of a FBG (uniform, specifically distorted or highly randomly distorted) is caused by residual strains and depends on the composite morphology in which the FBG is embedded and the coating of the FBG. These residual strains are created due to a mismatch in material properties (reinforcement fibres and resin, microscopic level) and ply anisotropy (non balanced/ non symmetric, macroscopic level). In figure 4.24 the embedding of a sensor can be visualized.



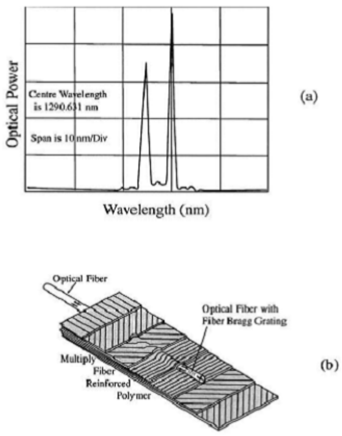


Figure 4.24: Birefringence detailed (left) and embedment of optical fibre (right) [8]

4.5.5 Wavelength Spacing

When a Wavelength Division Multiplexing (WDM) system is used, the interrogator's bandwidth and the spacing in wavelength determines the number of sensors that can be applied in one fibre. However, possible interference of spectra must be considered. An interrogator normally has a specific range of 60-100 nm [12, 54].

An example of a closely spaced system with a spacing of 1 nm and an interrogator bandwidth of 80 nm (1510-1590 nm) is given in figure 4.25.

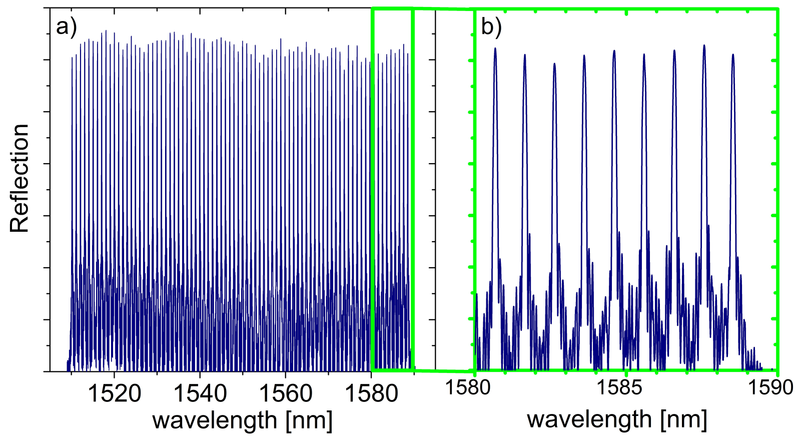


Figure 4.25: 80 FBG's in one fibre [20], a) general overview of all FBG's in the 1510 nm to 1590 nm range, b) detail between 1580 nm and 1590 nm

The array of sensors should be designed in such a way that there is no overlap in spectra. For strain measurements there is often a 5 nm spacing and for temperature a 1 nm spacing, because they are less sensitive.
An example of spectra shifts is shown figure 4.26. Issues occur when two adjacent spectra shift towards each other and begin to interfere, for example, if there is a large temperature and strain shift in opposite directions. If the wavelength spacing is too low, large pressure fluctuations or serious deterioration of the repair will make the spectra interfere with each other.

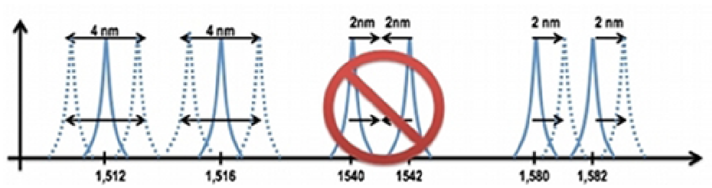


Figure 4.26: Fibre Bragg Gratings cooperation and interference [21]

4.5.6 System installation

Issues that can occur during the application of fibre optic sensors include lack of pre-straining (for compression measurements), misalignment of the fibre in relation to the intended orientation, placement of the sensor in the incorrect position and handling of the fibre optics. A good pre-packaging solution is required that protects the fibre, makes application of a sensor system in a sub-sea environment as straightforward as possible, avoids misalignment and is unambiguous to use.

4.5.6.1 Pre-straining of sensors

Pre-straining sensors is an important detail that should not be overlooked when designing a sensor system. If a pipe is at operating pressure when the sensing system is applied, any reduction in pressure (even a few millibar) could have an adverse effect on the ability of the system to accurately detect strain. The FBG would be compressed and could buckle. This would render measurements useless. The FBG should therefore be pre-strained in the packaging material to avoid this problem. The amount of pre-straining depends on the operational use. Small pressure operations could only require 100 microstrain of prestraining while other applications can require 1000's of microstrain.

4.5.6.2 Sensor Location relative to the repair

A practical problem to be considered is accurate placement of sensors in the positions intended and whether the correct wavelength is associated with the intended position. A measured change in wavelength (and thus strain) is meaningless without knowing the precise sensor position. Application in a subsea environment will be particularly challenging and if possible the sensor system should be designed to minimise the potential for measurement information to be compromised because of errors positioning sensors. Ideally, the SHM system should not consist of many separate sensors but a complete pre-packaged sensor patch.

4.5.6.3 Sensor Orientation relative to the repair

During installation of an SHM system, sensors will be applied to the repair in predetermined positions. All of the acquired readings will be dependent on the correct orientation of the FBG sensors. An offset in angle can strongly affect the values sensed. In figure 4.27 a uniaxial strain field is shown with its sensitivity to misalignment. Furthermore in figure 4.28 a bi-axial strain field is shown, showing an order of magnitude plot. Misaligning can have considerable consequences when considering the strain.

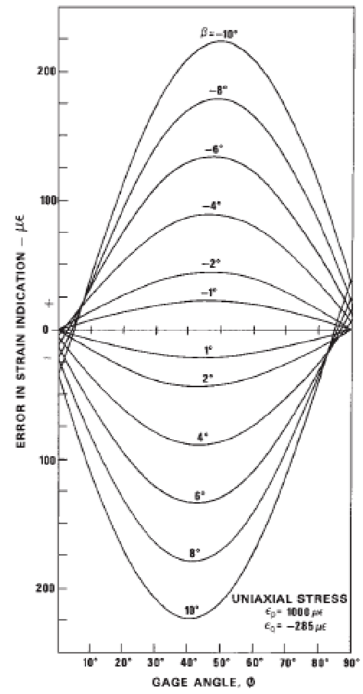


Figure 4.27: Error in strain due to gauge misalignment by an angle β for a uniaxial stress field [22]

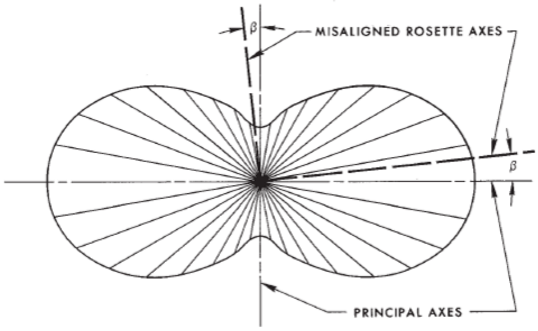


Figure 4.28: Bi-axial strain field with axes misaligned by an angle β from the principal axes [22]

4.5.7 Fibre Breakage

The potential for fibre breakage must be minimised, since all of the sensors beyond the break will be lost. With the correct precautions, such as good pre-packaging and a suitable cable protection system, fibre breakage should not occur.

4.5.8 Sensing system cost

Optical sensing using FBG's is relatively costly. As with all sensing equipment a 'box' is required to interrogate the sensors. In general terms, the FBG interrogator contains a light source which emits the light and when the reflected lights travels back it is recorded by a receiver (spectrometer, interferometer or polychromator). The cost of equipment varies considerably. The sensor cost itself depends on the manufacturing method, the coating and whether or not there is a form of pre-packaging around the sensor. In table 4.4 a general overview of optical fibre sensing equipment cost is given. Note that the cost of pre-packaged optical sensors is relatively high and the cost of large sensor arrays may be considerable.

Table 4.4: Cost overview of equipment [11,12,26]

Optical equipment	USD
Interrogators	
HBM (4ch.)	43000
Smartfibres STD (4ch.)	15000
Smartfibres 2 (4ch.)	20000
Smartfibres rugged (4ch.)	26000
Micronoptics (4ch.)	24000
Optical switches	
Micronoptics (4 - 16)	12000
HBM (4 - 16)	18000
Sensors	
Budget UD bare fibre	45
HBM UD pre-packaged	562
HBM rosette pre-packaged	815
HBM temp. pre-packaged	441
10 FBG UD chain bare fibre	750
Smartfibre rosette pre-packaged	900

Chapter 5

Experimental validation of strain sensing

Through validation a sense of realism can be obtained in relation to the modelling and the theory of a system. Material characteristics and behaviour are also difficult to predict without doing some testing as there are more influences than just an ideal environment. Within this chapter there are three main testing sections:

- The application and testing of optical sensors on a composite repair pipe specimen
- An Iosipescu V-notch test for characterization of the shear moduli of the composite repair
- An adhesive bonding test for ascertaining correct strain transfer characteristics

The results of the measurements on the composite repaired pipe specimen are shown in section 5.1. This section also includes the possible errors during testing which are valuable in determining if the sensors are measuring correctly. In section 5.2 the adhesive testing results are shown. And finally in section **??** the details of the V-notch testing are shown, which is done in order to ascertain the shear moduli of the composite repair.

5.1 Pipe repair testing

The objectives of testing the strain in the composite overwrap are closely related to the objective of this thesis. The modelling of composite overwrap on the pipe specimen is being validated and real life measurements help to establish a reliable model that can serve as a design tool.

5.2 Adhesive testing

Adhesives do have a substantial influence in strain measurement. The viscosity and shear strain are factors that are important when dealing with fibre optics. Adherent and adhesive interact and as such they have to be compatible in order for a correct bonding of the optical fibre (and sensor) to the surface.

Optical fibres are adhered to a surface for strain measurements, more specifically in this case the area of the FBG plus some overlap is adhered to the surface. Since a discussion about the use of certain adhesives in comparison with the glass of the striped fibre could be meaningful this test is undertaken to rule out any influences of adhesive used.
Strain transfer in itself is already discussed in subsection 4.4.4.3. This test's solely purpose is to rule out any adhesive/optical fibre creep or strain transfer.

5.2.1 Measuring set-up

As can be seen in figure 5.1 the measuring set-up consists of several distinguishable parts. The broadband laser source sends the light through the 123 circulator (from 1 to 2) towards the splitter. At the splitter the power is split between the optical switch and the reference gratings. This is done because of the losses when sending the signal through the reference gratings.
The main signal is send through the optical switch, this switch is controlled by Labview in order to determine its switching state. After the optical switch the two channels with the FBG's are present.
The reflected light is being guided through the 123 circulator (2 to 3) through the Fabry-Pérot filter. This filter is controlled by the Micronoptics ffp-c, the interferometer that detects the incoming light. A small piezo element drives a mirror which only allows a certain wavelength of light to pass through. If the electrical driving signal moves up and down the wavelength that passes through varies as such.In the ffp-c the optical signal is converted to an electrical voltage which is then send to the amplifier in order to improve the signal. This electrical signal is then fed to the oscilloscope which in its turn is connected to a computer with Labview.
In this set-up quite a substantial amount of losses was noticed. As stated previously every part induces losses, some which are substantial. Bending of fibre in the channels proved to be quite an influence when actual testing was taking place. Also the connectors that are made in the lab are a source of loss. There was however no substantial loss and the test results were satisfying.

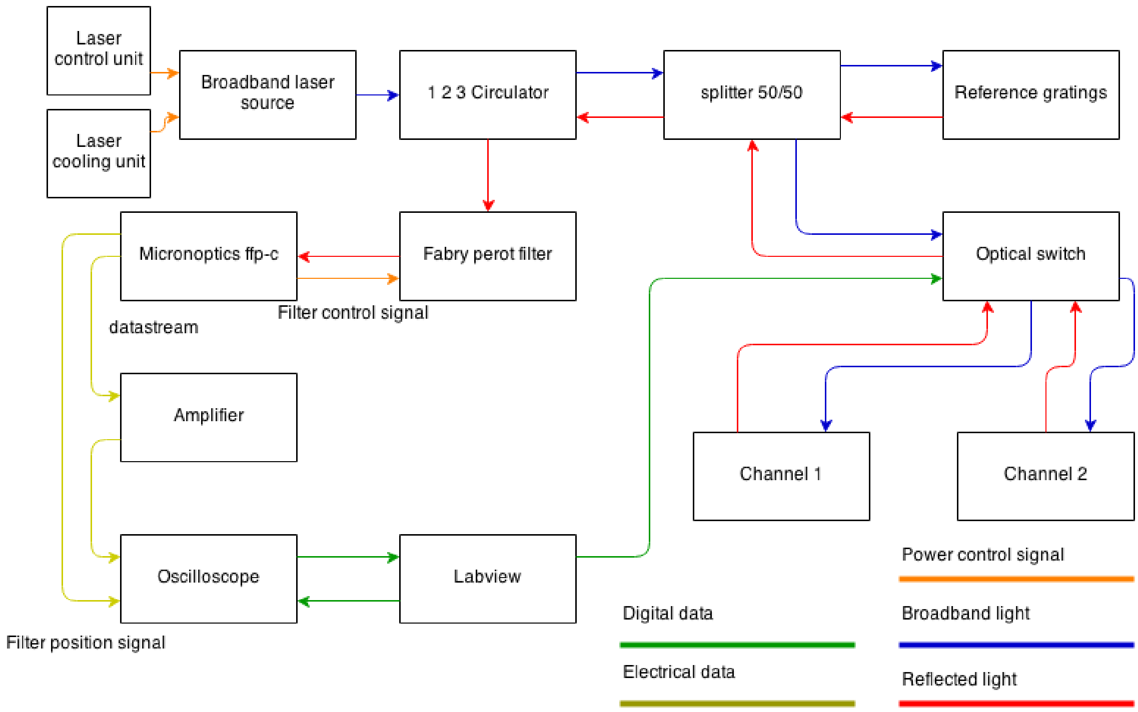


Figure 5.1: Schematic of test set-up.

5.2.2 Measurement software

A Labview program has been developed in order to acquire the data from the oscilloscope in relations to it switchstate and the time. A program in Matlab has been written in order to analyse the data which consists out of distinguishing the sensor peaks in relation to switch state.

At the end of the 5.5hr monitoring over 150Gb of data had to be analysed. In figure 5.2 an example of one dataset is shown. The peaks are not trackable in this state.

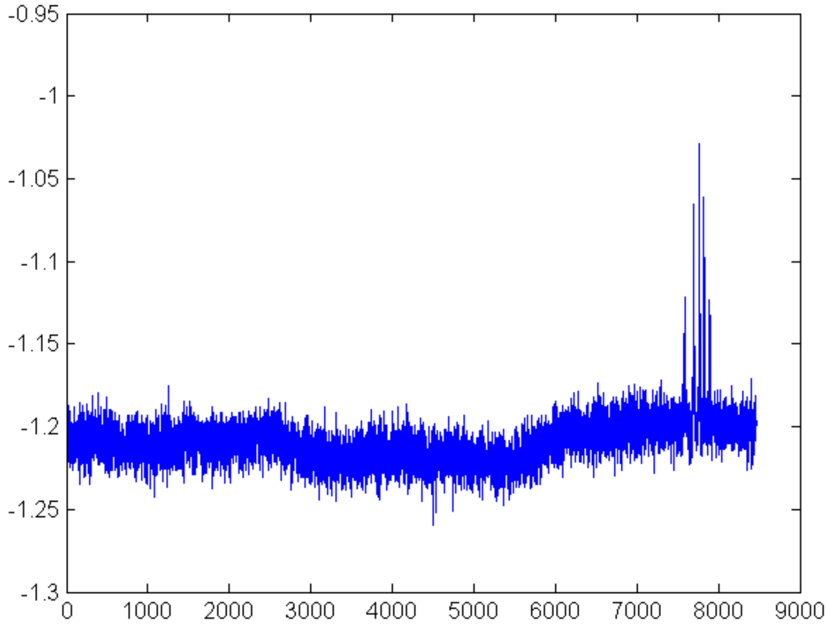


Figure 5.2: Example of a dataset, Peaks of FBG's

In figure 5.3 the dataset is reduced to only the shown width. This makes it convenient to introduce a threshold and peak detection algorithm. The peak detection is used to track the different peaks, not to calculate its position relative to its wavelength.

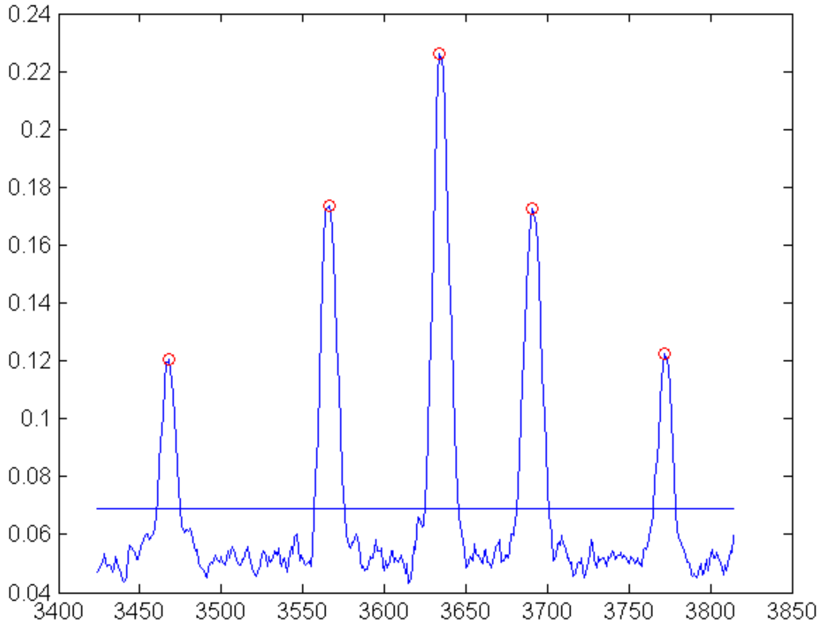


Figure 5.3: Narrowing the dataset together with threshold and peak detection

In figure 5.4 the surface area calculation under the peak can be seen. The position of the peaks is determined using a Full Width Half Maximum (FWHM) approach. The FWHM serves as the basis to get the position of the middle of the width of the peak.
The left and right peak are set wavelengths used to calculate the wavelengths of the other (sensor) peaks.

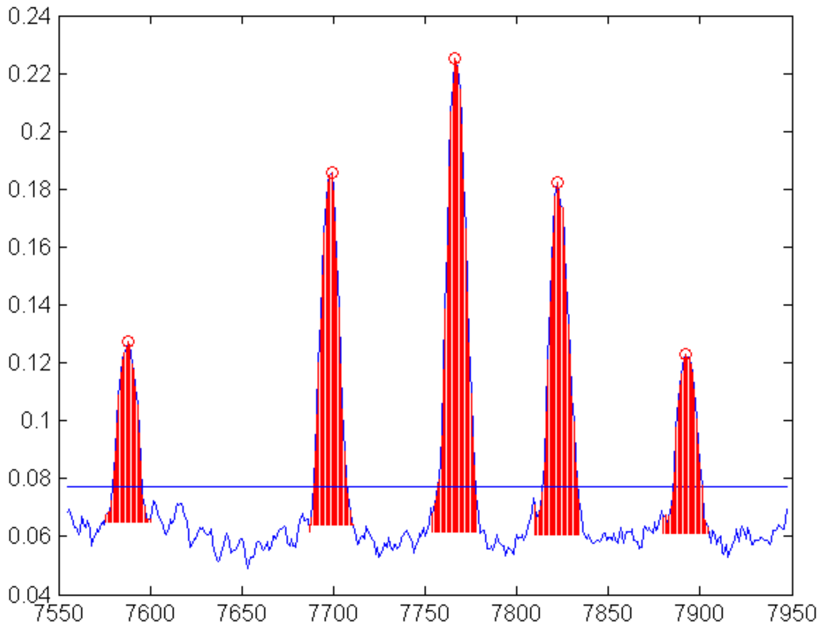


Figure 5.4: Area calculation together with FWHM, in order to get the relative wavelength

5.2.3 Results

In order to make sure that adhesive properties in relation with the fibre optic (glass) sensor were no problem, a test was conducted. A total of six sensors were applied onto an aluminium plate specimen. They were adhered on both sides of the specimen to exclude any bending effects should that be a problem. The sensors were adhered in pairs, with each one of the pair on the opposite side of the specimen. An overview of the switching state, wavelength and adherent used is given in table 5.1.

Table 5.1: Switching state and wavelengths related adhesives.

Switch 1 (T)	Adhesive	Switch 2 (B)	Adhesive
1548	Quartel BW - Cyanoacrylate	1548	HBM X120
1550	Hysol 9320NA	1550	Quartel BW - Cyanoacrylate
1552	HBM X120	1552	Hysol 9320NA

The final testing setup is shown in figure 5.5.

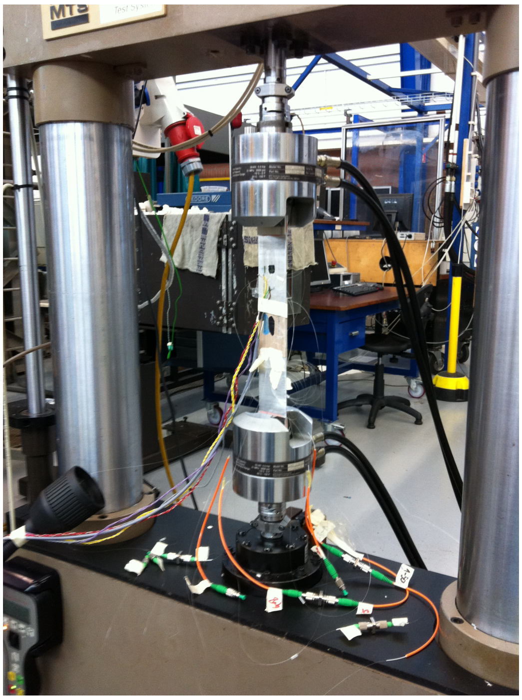


Figure 5.5: View of the test specimen in the fatigue bench

There are two runs, one with a cycling load of 0-2000N and one with a cycling load of 0-3000N. The run with the 2000N load gathered data for 5.5 hours while the 0-3000N test was run afterwards for one hour. This second test was to see if with more load a substantial difference could be seen. These load settings were applied based on a strain basis, meaning that the FBG sensor displacement was looked at relative to the reference gratings in order to avoid a wavelength overlap. As can be seen in figure 5.6 to 5.9 there is no noticeable decline in wavelength (and with that no decline in strain). The switch is shown in figure 5.1, as there is a switch between 2 channels in order to accommodate all the sensors.

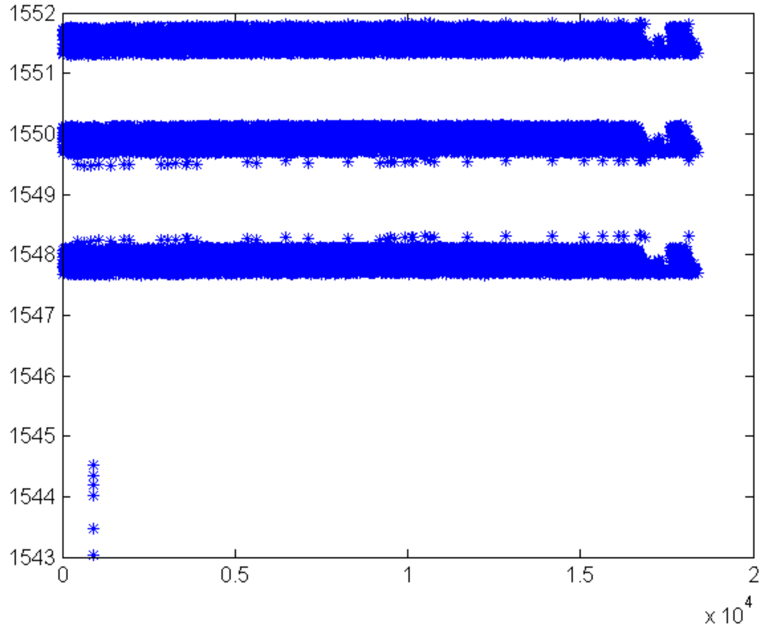


Figure 5.6: Switch 1 signals on 2000N fatigue bench.

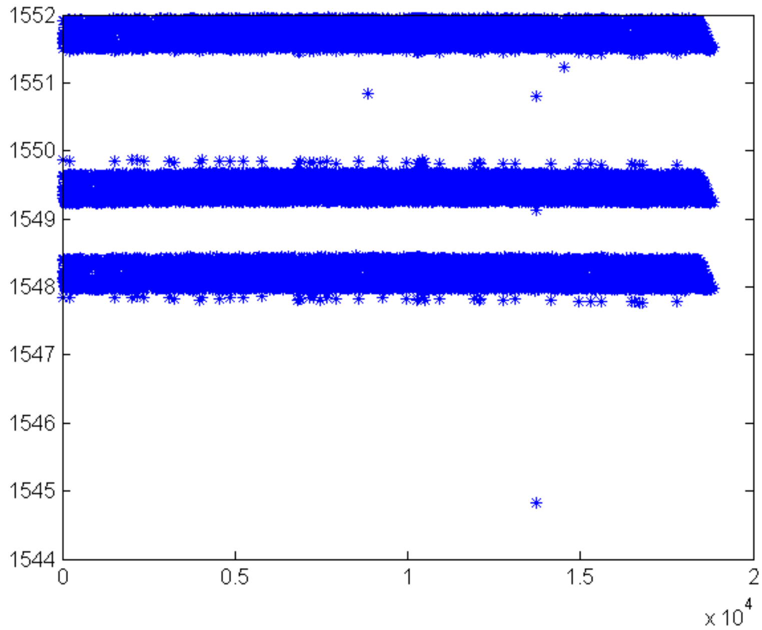


Figure 5.7: Switch 2 signals on 2000N fatigue bench.

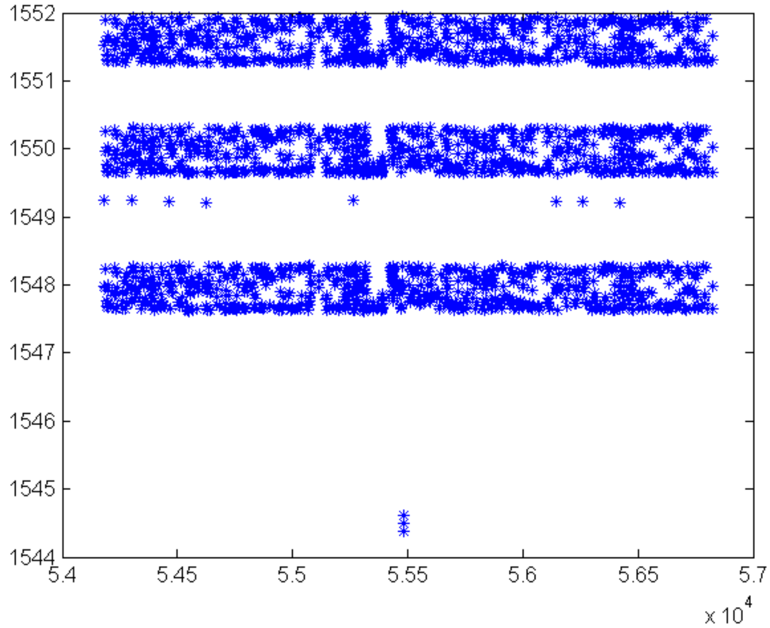


Figure 5.8: Switch 1 signals on 3000N fatigue bench.

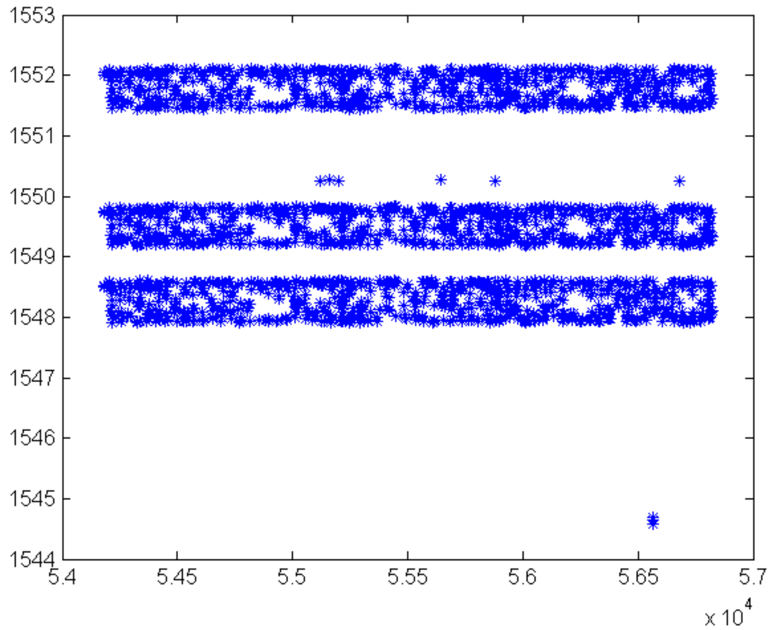


Figure 5.9: Switch 2 signals on 3000N fatigue bench.

Chapter 6

Discussion of results

The discussion part is confidential. It discusses the results from the comparison between FEM and the tests.

Chapter 7

Conclusions

The conclusions of the thesis are situated in a couple of research area's. A short recapitulation of the use of pipes and their problems, as well as a need for a monitoring system is given first. The sensing system used for SHM is second, giving a quick overview of the problems associated with optical sensing using Fibre Bragg Gratings. Lastly the test results are related back to the initial requirements.

7.1 Pipelines and repair

Pipelines are a much used and needed transport option in the Oil, Gas and Petrochemical industry. A significant problem is the deterioration of the pipe due to several types of damage such as landslides, earthquakes, corrosion, fatigue etc.

Deterioration due to corrosion can happen quickly depending on the operating environment of the pipe, even within five years of operation. Instead of having to replace the pipe there are three other possibilities: Welding, sleeving and applying of a composite repair.
A composite repair offers distinct advantages such as reduced cost, no shut down of the pipe, no explosion danger and corrosion shielding of the pipe. The problem with this approach is the temporary aspect it is still considered to be. Implementing a monitoring system helps to gain insight into the deterioration of the repair and the pipe.

The designing of a system starts from identifying its main detection parameters, which are in this project the hoop and axial strain. Secondary parameters such as temperature, shear strain and even acoustics have their uses as well but will not be considered here.

7.2 Optical sensing

There are different ways of sensing characteristics of structures. The first thing to consider is the environment of the pipeline and its composite overwrap that is monitored. Since the environment has an explosive nature, electricity based sensors are not wanted. Optical sensing is as such a logical replacement. They operate in highly volatile area's without a problem. The signal in an optical cable is able to travel over a distance up to tens of km. The optical cables can survive high strain and fatigue prone environments.
There are different forms of sensing, but the project requires a point sensor for which the Fibre Bragg Grating is an ideal solution. The FBG is easy to multiplex (in different or in the same optical cable), has a high insensitivity to disturbances and is easily mass produced.

Of course, due to the environment the optical fibre will have to operate in, the problems and considerations of optical fibre and FBG's are researched.

The coating of the optical fibre is of importance for protection against corrosion, but it affects strain transfer. There are numerous coatings available, each with specific characteristics. Acrylate is too soft and not resistant against temperatures above 100^{o}C, polyimide is better and has a thinner layer of coating but ORMOCER is the better one as it has excellent corrosion properties and good strain transfer.
Possible degradation sources are chemicals, sea water and mechanical damage. A good sensor packaging option has to protect the optical fibre from these influences. Harsh environments and ageing have to be minimized as much as possible.
Optical losses are important as well. The attenuation loss is dependent on the wavelength that is used for the interrogation of the sensor. 1300nm and 1550nm are the points where losses are at a minimum. Bending of optical fibres should also be minimized, radii below 10 cm should be avoided.
Another thing to consider is the number of sensors needed. The number of sensors can be determined from the range of the interrogator and the spacing of each sensor. This is normally 5nm for strain and 1nm for temperature.
Strain transfer is a key aspect when using sensors and as such is very important. Careful sensor installation, adhesive selection and surface preparation is needed in order to minimize losses.
FBG's are made by inscribing gratings in the core of the optical fibre. There are two standard production processes available when inscribing gratings, standard and drawing tower. The drawing tower is better for reliability since no recoating is needed.
Correct alignment of the FBG's in relation to the principal axis is important in order to sense the correct strain.

7.3 FEM modelling versus test results

The objectives of testing the strain in the composite overwrap are closely related to the objective of this thesis. The modelling of composite overwrap on the pipe specimen is validated using real life measurements which helps to establish a reliable model that can serve as a design tool.

An analytical model of a pipe is not able to give a reasonable insight into the strain state around the defect. A look at previous FEM models, irrespective of the results even, reveals that there are serious shortcomings in these models. They have some problems regarding element aspect ratio's, the number of elements through thickness used and they do not have a local increase in elements in the area of interest. A new FEM model is made that incorporates these elements but the new model is also based on a repair system designed by the CRC-ACS. This is necessary for the validation in the test phase. The repair system that is used has been developed using a machined out pipe, simulating a defect, a putty like material to fill the void and a composite overwrap to take up some load from the pipe and protect the defect from the elements.

There are three main FEM models in this thesis. They serve to research damage growth in the main repaired defect and to research delamination occurrence and growth at the edges and in the middle of the composite overwrap. The 100% damage model is based on the mentioned previous developed repair system, with a 150% damage model simulating the growth in the main defect area. A third model is based on edge delaminations and a delamination in between the edge and the repaired defect. These defects are researched in order to get a clue for the damage that occurs due to edge delaminations and the corresponding growth.

A series of measurements using data points are collected in the testing. FBG's are used to detect axial and hoop strains at predetermined positions. For the 100% and 150% repaired defect these are situated

around the repaired defect zone in order to detect the strains around this zone.
For the simulated delamination the sensors are applied across the delaminations in both axial and hoop direction.

7.3.1 Adhesive comparison

Adhesives can have a substantial influence on strain measurements. The viscosity and shear strain are factors that are important when dealing with fibre optics. The adherents and adhesive interact and have to have a good compatibility in order for the correct bonding of the optical fibre (and sensor) to the surface. In order to rule out any influence of adhesive, three different adhesives are tested against each other: A cyanoacrylate as used in the testing, a specifically designed optical fibre adhesive (HBM X120) and an aerospace grade adhesive (Hysol EA 9320NA). After a 5.5 hour fatigue test with a 2000 N load and a one hour fatigue test with a 3000 N load there was no difference in strain sensed by the FBG's. This rules out that the differing results in sensor application are dependent on the adhesive used.

7.3.2 Shear modulus

For a model to be able to properly represent the actual system, the correct material properties have to be obtained from the materials that are used. Shear moduli were missing as a material characteristic in the FEM model. After production of the specimens for the V-notch test according to ASTM D5379, a close look under the microscope revealed that the specimens were full of voids and cracks due to the low curing temperature of the specimens. This production process is based on a real application process, but for materials testing it is not ideal. The results of the V-notch test are as such not conclusive and no results can be drawn from them. The material characteristics used in the model are still based on literature.

Chapter 8

Future work

The modelling can be extended to include more types of damage in order to correctly assess certain types of damage such as bending and impact. This can then be implemented in a SHM system that is monitoring a finite number of sensors.
Adhesive testing should also include harsh environment testing, in order to avoid a possible loss of strain transfer when the adhesive gets affected.

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