CHALMERS
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FIBER REINFORCED POLYMERS FOR REHABILITATION OF PIPELINES

Action Research and Case Study

Master's thesis in the Master's Program
Structural Engineering and Building Technology

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Department of Civil and Environmental Engineering
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Gothenburg, Sweden 2016

Master's Thesis BOMX02-16-118

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Examensarbete BOMX02-16-118/ Instutionen för bygg- och miljöteknik

Chalmers tekniska högskola 2016

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ABSTRACT

The pipeline networks in several Swedish industries, such as water, sewage, district heating and petrochemistry are subjected to extensive maintenance challenges ahead. The situation demands implementation of efficient and reliable repair methods. Wrapping with fiber reinforced polymers (FRP) is a repair method that have gained international appreciation during the last decades. Recently, the interest has grown also in Sweden. The method allows for quick installation processes on pipes in service which eliminates downtime costs. High strength and corrosion resistance provide additional advantages. Despite these appealing properties, the use of FRP wraps has been limited in Sweden. The purpose of this thesis was to explore the potential use of FRP wraps as a pipe repair method. Firstly, an action research was conducted in collaboration with industry representatives in the Gothenburg area. The objective was to examine the underlying reasons for the limited usage and clarify what is needed for a reliable implementation. The action research concluded several hindrances within the technical-, jurisdictional- and social areas. The thesis presents these areas and suggests solutions as well as recommendations of further research. The most significant hindrances in each category respectively were considered to be the undeveloped inspectability, limitations in regulation *AFS 2016:1* and conflicting viewpoint on responsibility. In order to examine the current design procedure for pipe repair with FRP wraps, a case study was conducted. The case was a distribution pipe in a water tower. The repair design was based on the Swedish standard *SS-EN ISO 24817:2015*. A glass fiber wrap was used in the final design which satisfactory comply with the governing requirements. Finally, cost estimations were made to compare this repair with a conventional pipe replacement. The comparison proved that FRP wraps would be a less expensive alternative for this case.

Keywords: FRP-wraps, Pipeline Repair, SS-EN ISO 24817:2015, Pipe Rehabilitation, Fiber reinforced polymers, wet layup, wrapping

FIBERARMERADE POLYMERER FÖR REPARATION AV RÖR

Aktionsforskning och Fallstudie

Examensarbete inom mastersprogrammet Konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

Rörledningsnäten inom flera svenska industribranscher, såsom vatten och avlopp, fjärrvärme och petrokemi, kommer inom de närmaste åren att ha ett stort underhållsbehov. Situationen kräver framtagning av effektiva och hållbara reparationsmetoder. Förstärkningslindning med fiberarmerade polymerkompositer (FRP wrap) är en reparationsmetod som erhållit internationell uppskattning under decennier. Sedan ett antal år har intresset för metoden vuxit även i Sverige. Metoden möjliggör för korta installationstider på driftsatta ledningar vilket ofta är gynnsamt ur kostnadssynpunkt. Dess höga hållfasthet och korrosionsbeständighet är ytterligare exempel på fördelar. Trots metodens goda egenskaper har implementeringsgraden hittills varit låg i Sverige. Syftet med denna studie var att undersöka potentialen för rörreparationer med FRP wraps i Sverige. Till att börja med genomfördes aktionsforskning i samarbete med branschrepresentanter i Göteborgsregionen. Målet vara att tillsammans lokalisera anledningarna till det begränsade användandet samt klargöra vad som skulle behövas för ett lyckat införande. Slutsatsen av aktionsforskningen vittande om att flertalet hinder finns inom det tekniska-, juridiska- och social planet. Rapporten formulerar tydligt dessa problemområden och ger lösningsförslag samt rekommendationer för vidare forskning. De mest tongivande hindren inom respektive kategori bedömdes vara inspektionsbarhet, begränsningar i förordningen *AFS 2016:1* samt meningsskiljaktigheter kring ansvarsfördelning. För att studera det nuvarande tillvägagångssättet för reparationer av rör med FRP wraps genomfördes en fallstudie. I fallstudien konstruerades en reparation av en matarledning i ett vattentorn. Reparationen designades baserat på den svenska konstruktionsstandarden *SS-EN ISO 24817:2015*. Resultatet blev en linda av glasfiberväv som med lätthet möter hållfasthetskraven. Slutligen jämfördes prisbilden för denna reparation med den konventionella metoden där hela röret byts ut. Resultatet av denna kostnadsanalys visar på de ekonomiska fördelarna med FRP wraps.

Nyckelord: FRP-wraps, Pipeline Repair, SS-EN ISO 24817:2015, Pipe Rehabilitation, Fiber reinforced polymers, wet layup, wrapping

CONTENTS

PREFACE

This Master of Science thesis was conducted at the Department of Civil and Environmental Engineering, division of Structural Engineering, at Chalmers University of Technology during the summer of 2016.

We would like to extend our gratitude to our supervisor Reza Haghani for his constructive feedback and guidance throughout the project.

We would also like to thank, one and all, the industry representatives that have participated in this study. Their contributions have been essential for progression of the work and vital for the eventual research findings.

Gothenburg August 2016

Arvid Melander

Johan Österberg

1 INTRODUCTION

1.1 Background

Between the 1950's and 1980's, the Swedish water and waste water pipes were built out extensively (Malm, et al., 2011). The maintenance of these networks has in some cases been neglected leaving companies and municipalities with challenges to maintain serviceability of the pipes. A considerable part of the existing pipe systems used for water supply, sewage and public heating and cooling in Sweden has an increasing need of maintenance within a near future (Malm & Svensson, 2011). Several other industries using pipelines in production, such as petro-chemical industry, experience similar maintenance problems.

In the last two decades, fiber-reinforced polymers (FRP) have increasingly been used to repair water and wastewater pipes in the United States (Pridmore & Ojdrovic, 2015). The material was introduced in the 1950's by the vehicle industry and with improved manufacturing technics during the 1960's, the applications grew. In the 1990's the need for rehabilitation of infrastructure increased due to aging infrastructure. In combination with decreasing cost of FRP materials, FRP was increasingly used to repair ageing structures (Yang & Kalabuchova, 2014). The first method for using FRP materials in pipeline repairs was developed by Southwest Research Institute and Battelle over two decades ago (Pridmore & Ojdrovic, 2015). Considering the unique challenges that pipes are subjected to, such as bi-axial stress fields, the FRP material have shown applicable. The material's most beneficial properties are considered to be its high strength characteristics, corrosion resistance and possibility to influence the direction of the fibers (Bedoya, Alexander, & Precht, 2010). One of the main reasons for using FRP materials is to minimize time when the pipes are off-service (Pridmore & Ojdrovic, 2015).

In the 2000's, the interest of using FRP in U.S.A. grew as a result of an increased demand of rehabilitation. Since then, the methods using FRP for pipe repairs have gradually improved (Pridmore & Ojdrovic, 2015). Recently the methods of using FRP wraps to repair pipes has grown increasingly in Europe. In countries such as France, Germany and United Kingdom the methods are today widespread and considered as a competitive alternative to conventional repair methods (Essvik, 2016). With growing need of pipe repairs in Sweden, companies interested in using FRP wraps have become more and more common on the market.

Judging on this background, the technique seems to have great potential and no obvious reason that contradict an increased implementation unfolds. Despite the growing interest from multiple companies in Sweden willing to use FRP wraps, there are few rehabilitations made with the method today. Evidently, an investigation of this matter of could be of high value for the Swedish industry.

1.2 Aim and Research Questions

The purpose of this thesis is to explore the potential use of FRP wraps as a pipe repair method in Sweden. The thesis aims to contribute with an objective investigation in a field where insufficient research has been conducted. It therefore hopes to provide knowledge to guide the industries' future approach towards the repair method.

Two research questions has been formulated to satisfy the objective:

1. What are the underlying reasons for today's limited use of FRP wraps as a pipe repair method in Sweden?

2. What would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?

1.3 Method

According to Yin (2003) the objective of the report governs the choice of research strategy. Taking the duality of the research question into consideration, the methodology of this research has been divided into three parts. To answer the research questions, an *Action Research* was conducted. To examine the applicability of the method, and thereby verifying the second question, a reasonable case study was developed in collaboration with the industry. However, in order to give the thesis legitimacy within a designated context, a technical framework was established in Part I.

Part 1 *Technical Framework*

- Pipe systems in Sweden and typically the Gothenburg area.
- FRP's material properties.
- Introduction to FRP wraps for pipe repair.

Part 2 *Action Research*

- Various forms of collaboration with industry representatives.
- Compilation of the current situation.
- Predictions and suggestions on future development.

Part 3 *Case Study*

- Hand calculations based on SS-EN ISO 24817:2015.
- Cost analysis.

1.4 Limitations

The nature of the method does not allow for too strict limitations. However, to establish a proper research framework and optimize the usefulness of the results, some restriction must be drawn.

- The research primarily focuses on pipeline networks adjacent to Gothenburg. The collaboration within the action research was made with local actors out of convenience. It is possible that others could have furthered assisted the cause. In hindsight, it is for example understood that the Swedish authority *Arbetsmiljöverket* could have provided helpful insight. However, unfortunately, their participation is absent in this study due to time limitations and miscommunication.

- There exist a variety of FRP wrap products on the market but no evaluation of their performance are given in this study.

- The case study is conducted on an existing pipe with a semi-fictive, yet reasonable defect. The assessment made as a desk study including neither lab- nor field tests.

- During the process, the researchers disregarded the initial intentions of a Finite Element analysis (FEA) as part of the Case Study. A FEA were not considered to contribute to the objective of this research.

PART I – TECHNICAL FRAMEWORK

2 PIPE SYSTEMS IN SWEDEN AND GOTHENBURG

There are a variety of pipe systems in the Gothenburg urban area and in the rest of Sweden. This report focuses on some of the areas of the industry where FRP wraps could become a potential repair method for pipes. In order to understand the technical side of the industry, this chapter examines how the different pipe network function. Such basic knowledge is essential for the work within the "Action research" conducted as Part 2 of this study. It also serves as an explanatory background to the industries increased demand of new solutions for pipe repairs. Below, district heating and cooling-, water and sewage management- and petrochemical and process industries are introduced. The FRP wraps examined in this report could also be used at nuclear power plants, water power plants etc. but due to that the principles are similar within different pipe systems they are not further discussed here.

2.1 Pipe users in Gothenburg

The district heating and cooling in Gothenburg is operated by *Göteborg Energi*, a group of companies in Gothenburg that handles energy, including electricity, biogas, district heating and cooling etc. The part of *Göteborg Energi* that handles district heating is roughly divided into two parts, one that produces the heating and cooling, one that distribute it to the customers (Syrjänen, 2016).

The unit at Gothenburg municipality responsible for drinking water distribution and sewage management names *Göteborgs kretslopp och vatten*. They are responsible for the whole process from raw water, to purification and distribution to customers. When the water is used it is transported back to a sewage plant run by the Gothenburg municipality owned company *Gryaab*, which cleans and emit the water back to a water-course (Gryaab AB, 2016).

In the Gothenburg area with surroundings there are numerous companies working in the petrochemical- and process industry. The different companies all have different needs and prerequisites depending on what media handled and products they produce. Their common divider are their use of pipeline networks.

2.2 District heating and cooling

District heating and cooling is a way to produce heating and cooling at a plant centrally and thereafter distribute it within a geographical area around the plant. The energy is distributed in pipelines with tempered water to residential buildings, larger offices and industries.

For district cooling water is cooled down, at an energy plant, to 6-10°C depending on outdoor temperature (Håkansson, o.a., 2009). The water is then pressurized and distributed to costumers through insulated pipes buried in the ground. At the costumer's facility the water passage a heat exchanger that chill air locally (Svensk Fjärrvärme AB, 2005). The water then returns in pipes back to the plant with a temperature of about 16-20° C (Håkansson, o.a., 2009). The same principle applies to district heating. Water is heated at the central heating plant, then delivered, in pipes to the customers, at a temperature of 70-120°. The water is then returned to the heating plant at a lower temperature than delivered depending on outdoor temperature etc., see Figure 1 (Svensk Fjärrvärme AB, 2005). For both systems the design pressure for the pipes is 1.6 MPa (Svensk Fjärrvärme AB, 2005), (Håkansson, o.a., 2009).

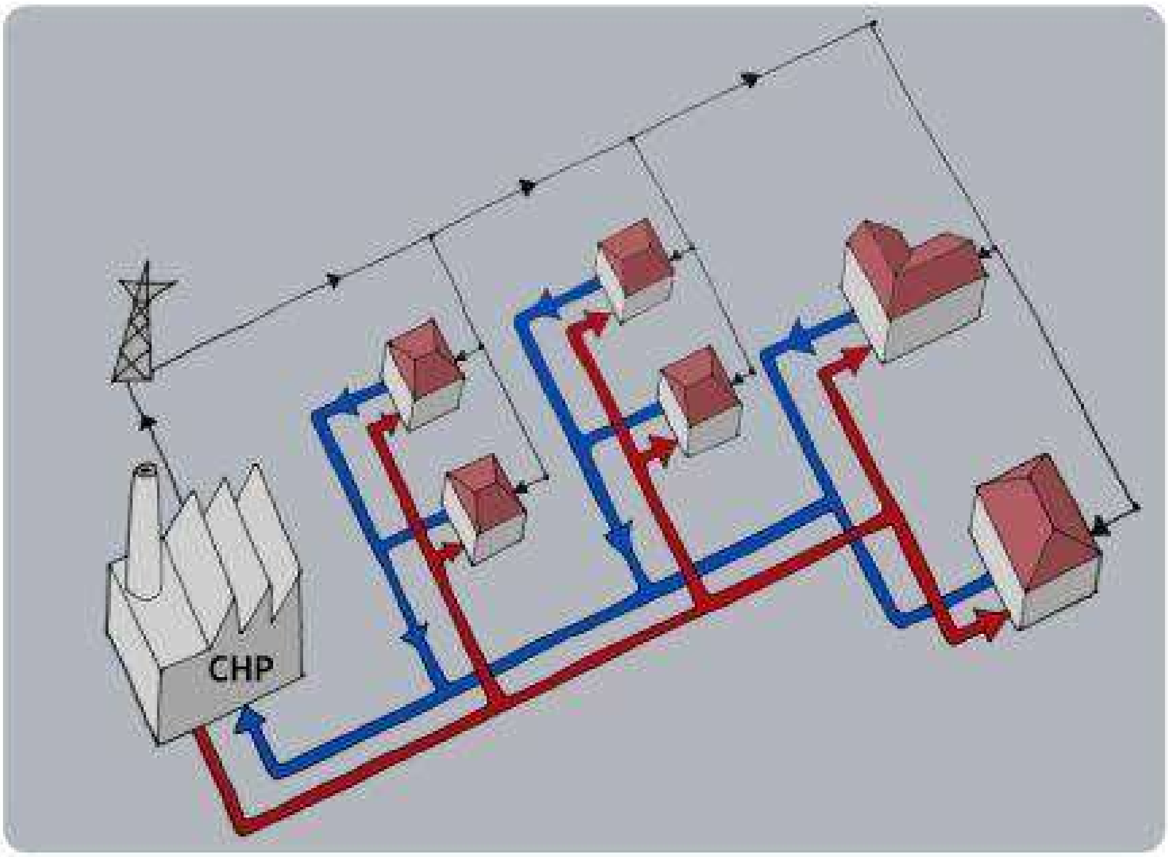


Figure 1 Schematic illustration of a district heating network (Nordic Folkecenter for Renewable Energy, 2010)

The pipes for district energy usually consist of welded or seamless steel pipes. The steel pipes can be coated with 3-layer polyethylene or thermosetting plastic, both to protect against corrosion. There are also pre-isolated pipes used in the ground for distribution. These pipes do not require further protection against corrosion due to the insulation. Other recurrent pipes include copper pipes, PEX-pipes, PE-pipes, pipes of stainless steel and pipes made of two pipes inside each other with insulation in the void (Svensk Fjärrvärme AB, 2008).

Depending on what type of pipes that are used, there are different ways of joining the pipe sections. For steel pipes and pre-insulated steel pipes the common way to do this is by welding the end sections together or by using flanges with bolts. For the other type of pipes the joints are made of nodular cast iron and pressurized couplings, as well as different type of welds for plastic materials (Svensk Fjärrvärme AB, 2008).

At energy plants the most occurring pipe problem is external corrosion due to moisture trapped between the pipe and the insulation. It is also common with extensive corrosion at flanges connecting pipe sections.

Within the distribution branch the same problems with external corrosion often are present. Other common problems occur when settlements crack the pipes or excavators accidentally hit pipes causing damage.

2.3 Drinking water

The production and distribution of drinking water in Sweden can briefly be described as follows. Firstly, the water is collected from a raw water source. From the inlet the water is led in pipes to a water plant where the water is purified. Thereafter the water is pressurized and transported to reservoirs, such as water towers, and then delivered to customers by pipes. The maximum temperature is 20°C, but normally the water is about 10°C (Göteborgs Stad - Kretslopp och Vatten, 2015).

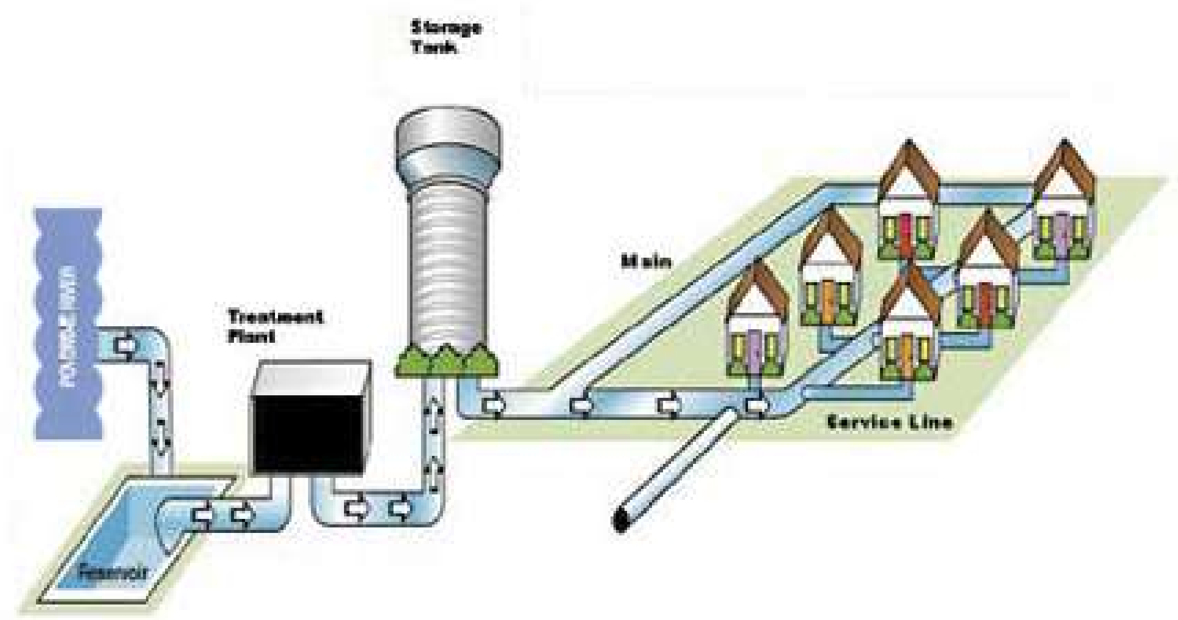


Figure 2 Illustration of drinking water distribution (Hawkins, 2016)

The water is distributed through buried pipes to the end costumer. The most common pipe materials in Sweden are cast iron, nodular cast iron, steel pipes, PVC-pipes (pipes made of Polyvinyl chloride) and now a days plastic pipes (PE-Pipes, Polyethylene) (Johansson F. , 2016).

For steel and iron pipes, the most recurring problem is corrosion that leads to crack failure. For PE and concrete pipes, a common cause of failure is settlement causing the joints between pipe segments to crack. The failures occur more occasionally during winter and spring when the pipes, due to weather changes, are subjected to temperature differences and freeze-thaw cycles in the ground (Johansson F. , 2016).

2.4 Waste water

Water collected from sewage from buildings and drainage is lead to a sewage plant where it is purified by various chemical reactions and sedimentation. The sewage water is transported to and from the plant in pipes buried in the ground. For sewage transportation the most common pipe materials in Gothenburg include concrete, PVC and PE.

Similar to drinking water distribution discussed in the previous chapter, problems with the pipes mainly occur from corrosion and settlement cracking the pipes. However, media transported in sewage pipes is more corrosive than pure water, thus making internal corrosion a more prevailing problem. Media transported in sewage pipes is normally not pressurized but transported by gravity. This means that the pressure in the pipes is quite low compared with pipes for drinking water and district heating and cooling.

2.5 Other industries

In addition to the applications mentioned above, there is a variety of other industries that use pipes in the Gothenburg area. The great variance makes it an extensive task to give information about specific pipe usage for each industry. Pipes can be used to transport practically any kind of media. In Gothenburg for example, oil refineries and chemistry industries using pipes. In most cases the pipes have quite high working pressure. Later in this report the European and national regulations are described and discussed. The European pressure equipment directive (PED) regulates pressure equipment with working pressure over 0.5 MPa. Discussed in chapter 7.6.1 – *"Governing regulations for FRP wrap repairs",* this directive affect when FRP can be used why petro and process industry in not further explained here.

3 FIBER REINFORCED POLYMERS

In this chapter the material characteristics of fiber reinforced polymers are introduced. Proper and complete descriptions of a material must be comprehensive in order to cover its complex nature and extensive variation of properties. In the scope of this research, however, each and every material aspect will not be covered. Yet, the most relevant properties of fiber reinforced polymers, in the context of this study, will be presented.

3.1 Composition

Composites consist of two or more constituents combined into one material aiming to achieve more aspirational properties that of each individual component alone (Fagerström, 2016). Fiber reinforced polymers are built of fibers embedded into a polymer matrix also called resin. Simply explained, the task of the fiber is to carry loads while the resin mainly distributes and holds the fibers together (Sjögren, 2010).

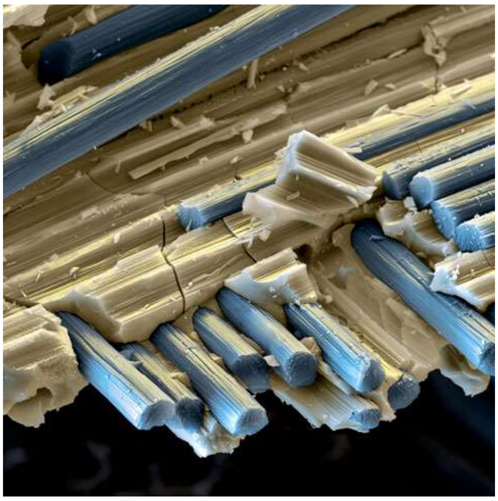


Figure 3 Scanning electron microscope image of a composite composed of fibers (in blue) and matrix (in brown) (Eye of Science/Photo Researchers Inc.)

Lee & Estrada (2015) made an attempt to list which parameters that influence the mechanical, thermal, and hydrothermal properties of FRP. They herein formulate the properties as functions of the selected constituents as well as the volume fractions among them. Holloway (2001) further expanded the list by including the orientation of the fiber as a parameter. These mentioned parameters are dealt with below.

3.2 Fibers

Fibers are stiff and strong intended to carry most of the load applied on the composite (Fagerström, 2016). Naturally, the appropriate choice of fiber depends on the desired properties in its application. As for FRP reinforcement, it means that the selection is governed by characteristics such as tensile strength, failure strain, corrosion resistance, fatigue resistance and dimensional stability (Matthys, 2000). In this chapter, the most interesting fibers for civil engineering applications are presented, namely aramid, carbon and glass (Saeed N. , 2015).

Generally, FRP fibers offer tensile strengths greater than that of steel. They commonly behave linear elastically up to the tensile ultimate failure. One should be cognizant of the fact that the physical and mechanical properties vary considerably; especially between different fibers types, but to a certain extent within a specific type of fiber as well (Matthys, 2000). Hence, designers must carefully attain proper data from manufacturers. Some measures of the most essential properties are presented in Figure 4.

Fibre type	Tensile strength [N/mm²]	Modulus of elasticity [kN/mm²]	Ultimate strain [%]	Density [kg/m³]	Fibre diameter [μm]
Aramid – IM	2700-4500	60-80	4.0-4.8	1400-1450	12-15
Aramid – HM	2700-4500	115-130	2.5-3.5	1400-1450	12-15
Carbon – Pitch HM	3000-3500	400-800	0.4-1.5	1900-2100	9-18
Carbon – PAN HM	2500-4000	350-700	0.4-0.8	1800-2000	5-8
Carbon – PAN HT	3500-5000	200-260	1.2-1.8	1700-1800	5-8
E-glass(1)	1800-2700	70-75	3.0-4.5	2550-2600	5-25
S-glass	3400-4800	85-100	4.5-5.5	2550-2600	5-25

IM: intermediate modulus, HM: high modulus, HT: high tensile strength

Figure 4 Properties of fibers (Matthys, 2000)

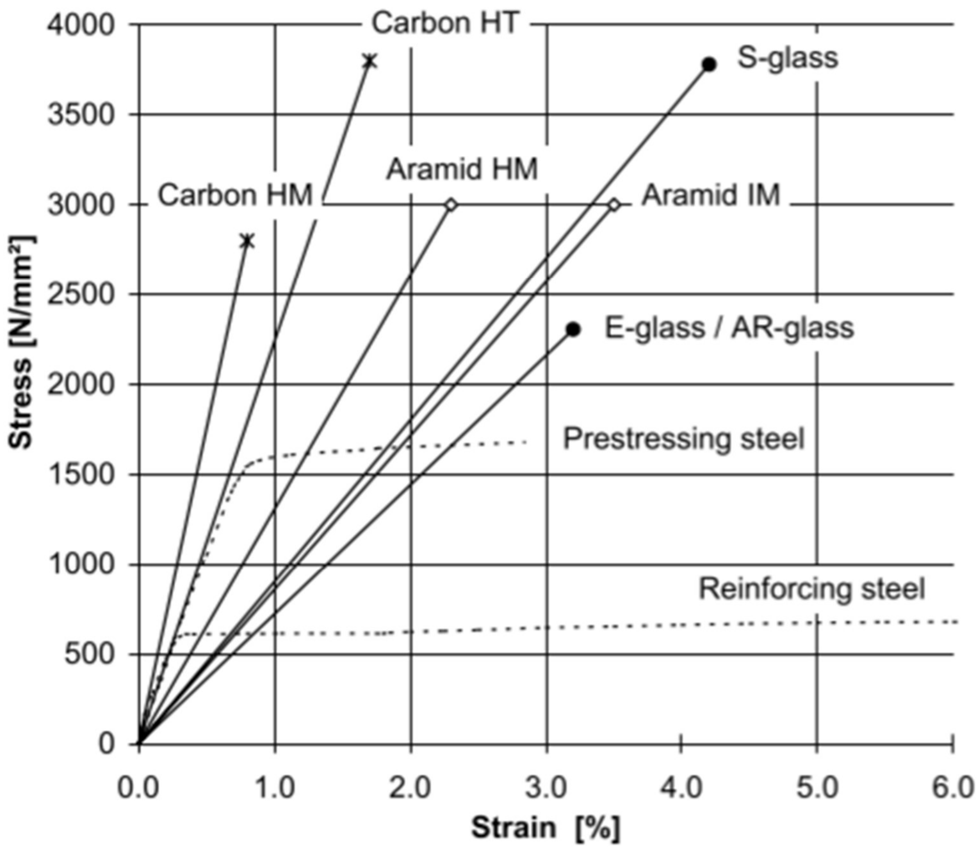


Figure 5 Tensile stress-strain behavior for fibers (Matthys, 2000)

Aramid fibers

Aramid fiber is the generic name for the organic aromatic polyamide fibers which consist of carbon, hydrogen, oxygen, and nitrogen (Lam, 2015). After producing a liquid crystal polymer with these ingredients, the fiber is created by spinning the dissolved polymer to form a solid fiber (Rosato & Rosato, 2004). The chain of molecules is oriented along the fiber axis which allows the strength of the bonds to be exploited (Gorse, Johnston, & Pritchard, 2012). The commercial product it is often referred to as Kevlar (Sjögren, 2010). The fiber's most advantageous properties are its tensile strength, high modulus of elasticity and toughness (Lam,

2015) (Sjögren, 2010) (Fagerström, 2016). Rosato and Rosato (2004) also included the abrasion resistance, creep-rupture characteristics and chemical as well as mechanical stability over a wide temperature range in their description. On the downside its low compressive properties are found, together with high moisture absorption, low melting temperature and susceptibility to degradation in sunlight (Lam, 2015) (Sjögren, 2010) (Fagerström, 2016). Saeed (2015) claimed that the combination of these disadvantages, yet to a relatively high price, has made the fiber less attractive for use in structural engineering applications. However, if the benefits would still outweigh, the designer should take special consideration to the difference between the tensile and compressive strength in fiber direction (Sjögren, 2010).

Figure 6 Bundle of aramid fibers (User:Cjp24, 2009)

Carbon fiber

Carbon fiber is a graphite material which is produced by heat treated and stretched eithpolyacylonitrile (PAN), rayon or mesophase/isotropic pitches (Sjögren, 2010) (Lam, 2015). Lam (2015) claimed that carbon fibers have the most desired properties from a civil engineering applications viewpoint. These properties are primarily; high tensile and compressive strength, high stiffness and corrosion resistance (Fagerström, 2016). On the contrary, the material possess some disadvantages. Its benefits must be justified in comparison to its high cost; it has a low failure strain which means it is brittle; its anisotropic composition gives some insecurity in behavior prediction (Fagerström, 2016). Although the high material cost, a low weight of repairs as well as the shortage of installation lead time can reduce the total life cycle cost (Chan, Tshai, & Johnson, 2015). Despite this fact, Johansson (Johansson F. , 2016) believed that the high cost normally has made the use of carbon fiber applications unjustified in Swedish water and sewage networks. Yet another complication in civil engineering is the fact that the fibers has the potential for electrical conductivity. Therefore, when placed in direct contact with steel galvanic corrosion is initiated (Pridmore & Ojdrovic, 2015). The presence of an electrolyte, such as saltwater, will even further accelerate this process (Tavakkolizadeh and Saadatmanesh, 2001). The resin in the composite should indeed cover all the fibers but is not considered to sufficiently provide a long-term contact prevention (Ehsani, 2015). However, if proper measures are taken this issue can be avoided. Examples of these measures are a nonconductive layer of fabric or an isolating epoxy film between the carbon fibers and the steel surface. (Chan, Tshai, & Johnson, 2015) According to Ehsani (2015) the most widely accepted practice in the pipe industry is to apply glass fiber as the nonconductive layer.

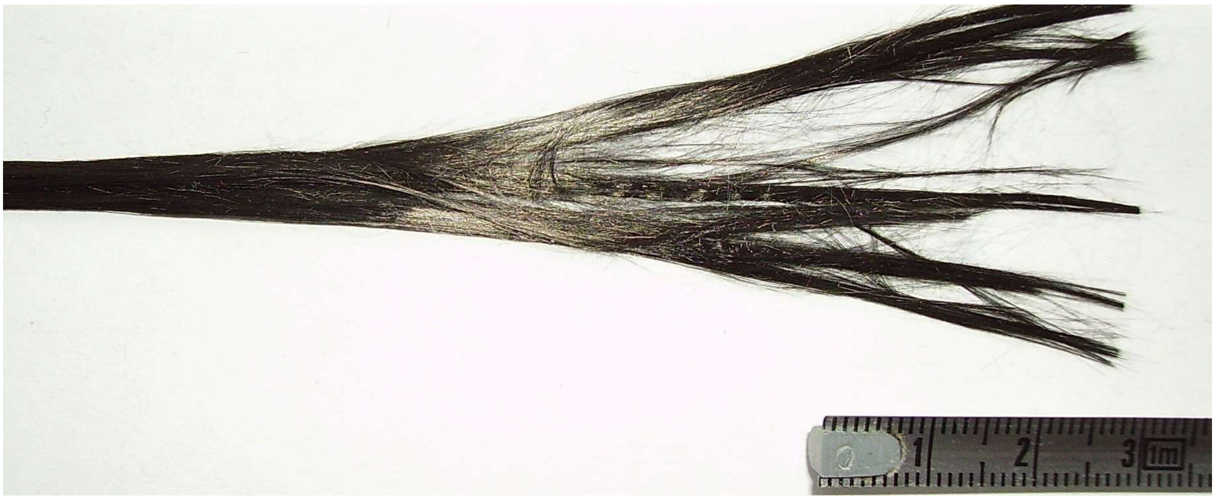


Figure 7 Roving of carbon fibers (User:Cjp24, 2009)

Glass fiber

Glass fibers, which mainly consist of silica, are produced by first melting the raw material followed by pulling the mold through nozzles generating long strings. Depending on the composition of the raw material several types of glass fibers with different properties can be made. The most commonly used is electro glass (E-Glass) which has a pleasant performance-cost ratio and desirable corrosion resistance (Sjögren, 2010). However, fiber glass's disadvantageous properties include a relatively low stiffness, sensitivity to moisture and an abrasive behavior (Fagerström, 2016). Their poor durability in alkaline cementitious environments have caused further concern (Lam, 2015). Glass fiber pipes have previously seldom been used in Swedish water and sewage pipe networks due to their low impact strength which causes complications to field installations (Johansson F. , 2016). In order to improve the performance, i.e. reduce thickness and therefore weight on fiber glass sections, Chan, et al. (2015) suggested pretensioning of the fibers. They believed that this technique would raise the demand in structural repairs.

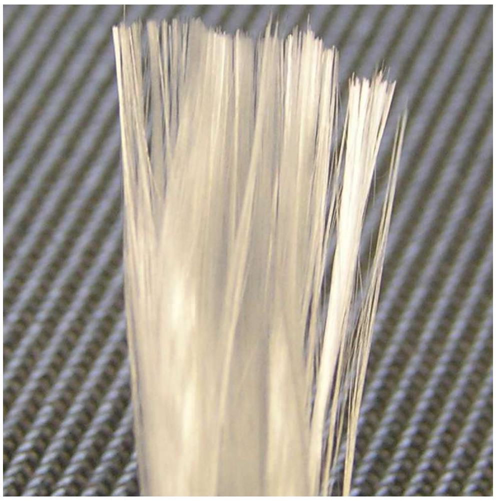


Figure 8 Glass fiber roving (in white) (User:Isthmus, 2005)

3.3 Resins

The resin is the matrix of the composite which transfers and distributes the load between fibers, stabilizes and binds the fibers together as well as protects them from environmental attacks and impact. The specific properties of the resin influence the composites' mechanical performance such as transverse stiffness and strength together with shear and compressive properties (Fagerström, 2016). Above mentioned mechanical properties, but also elongation and thermal expansion, depend on whether the resin is post cured or non-post cured (Deaton, 2015).
Understandably Deaton (2015) emphasized the importance of clearly identified resin choice. In extreme civil engineering environments, such as underwater applications, adhesion and curing are limited and specially formulated resins are therefore required (Djukic, Sum, Leong, & Gibson, 2015). There are primary two resin options available, namely thermoplastic polyurethane and thermosetting epoxies (Deaton, 2015).

Thermoplastic polymers

Thermoplastic polymers consist of linear or branched polymers connected with weak intermolecular bonds. Upon heating thermoplastics soften or melt without breaking the chemical structure and therefore enables a reversible chemical process (Fagerström, 2016). Their physical characteristics naturally make them temperature dependent. This property, combined with a stress induced creep behavior has made them generally less used in construction. However, the most common thermoplastic polymer, polyurethane, possess some attractive features for certain pipe repair applications. Deaton (2015) claimed that polyurethane generally is easier to work with, compared with epoxy, and have a compelling advantage for sub water pipe wrapping. The sub water advantage unfolds when utilizing polyurethane's ability to cure under ambient temperatures via water activation. On the downside, however, is its tendency to hydrolyze in water (Djukic, Sum, Leong, & Gibson, 2015). For land use, similar proactive curing initiations enable certain FRP repairs to be pre impregnated at the factory ensuring a maintained fiber- to-resin ratio (Deaton, 2015).

Thermosetting polymers

Thermosetting polymers consist of molecules cross-linked in a three dimensional structure. Upon curing, these strong bonds form a fixed network, which, unlike thermoplastic polymers, does not debond during heating (Fagerström, 2016). This means that the material do not melt and that recycling is limited in practice (Sjögren, 2010).

In the inexpensive price range thermosetting polymers offer lower temperature dependency, higher chemical resistance and better mechanical properties than thermoplastic polymers. Therefore, they have become popular in the field of civil engineering applications (Deaton, 2015) (Sjögren, 2010). Most commonly used among the thermosetting polymers are epoxy. Especially novalac-based epoxies have a high resistance to a wide range of chemicals and offer great strength. Due to its composition, epoxy generally has a higher temperature rating and moisture stability compared to its thermoplastic rival, polyurethane. On the contrary, the ease of use is generally allocated to polyurethanes (Deaton, 2015). Sjögren (2010) and Deaton (2015) both described how epoxies have a tendency to better bind directly to steel and may not even require the use of a primer layer in reparation applications. Djukic, et al. (2015) on the other hand, stated that epoxy should only be applied on dry surfaces and can be negatively affected by contaminants and surface moisture. Epoxies are, because of their strength, commonly used for FRP pipe repairs in high pressure systems (Deaton, 2015). However, the use of epoxy introduce some concerns that should be taken into consideration. Working with epoxies may cause allergies and proper protection must therefore be used (Sjögren, 2010). According to health hazard policies in Gothenburg it is decided that epoxies should not come in contact with drinking water (Johansson F. , 2016). For environmental reasons, the use of epoxies should be questioned because of their limited recyclability. Consideration should also be taken to the time dependent durability concerns.

Table 1 Properties of resins (Matthys, 2000)

Resin type	**Tensile strength** [N/mm^2]	**Modulus of elasticity** [kN/mm^2]	**Density** [kg/m^3]	**Cure shrinkage** [%]
Polyester	35-104	2.1-3.5	1100-1400	5-12
Vinyl ester	73-81	3.0-3.5	1100-1300	5-10
Epoxy	55-130	2.8-4.1	1200-1300	1-5

3.4 Additives

Full composite action between two materials can be achieved with a competitive adhesive. In the case of FRP wrapping for pipe repair, the adhesive is used to glue the FRP wrap onto the pipe surface. When wrapping is made with the so called "wet-layup"-method described in chapter 5.1 – *"Repair procedure"*, the adhesive can also be seen as a part of the composite in which it acts as the resin. Adhesives face challenges to provide sufficient bond over a long time due to the harsh environments pipes are exposed to (Matthys, 2000). Heshmati, et al (2015) explained how adhesive bonding causes an inevitable yet crucial disadvantage by creating a link between materials which often become the weakest with respect to failure. Due to this, this chapter expands on the requirements which adhesives must fulfill.

Major factors for the quality of the adhesive are directly related to when it is applied. Working characteristics such as mixing, application and curing must allow for sufficient joint quality, adequate adhesion, gap-filling properties etc. The workability and eventual bond quality must not be too sensitive to the level of surface preparation under varying environmental conditions. Moreover, proper workmanship is crucial for the overall result and in practice this means that quality control is needed (Matthys, 2000). When speaking of long term durability, the chosen adhesive must exhibit moisture-, chemical- and attrition resistance as well as present low creep behavior and thermal stability. Its glass transition temperature, explained in chapter 3.5 – *"Glass transition temperature*", should be considerable compared to the service temperature. On mechanical characteristics, consideration should be taken to the range in which the flexural (bending) modulus fall. In the advised range, the lower limit restricts of creep whereas the upper aims to minimize concentrations of stress. Moreover, the moisture absorption should be as low as possible (Matthys, 2000).

Epoxies are the most widely used and accepted adhesive in civil engineering applications (Matthys, 2000). This is because epoxies relatively well fulfills the above described requirements. In addition, their working characteristics enable some desirable abilities: bonding on a relatively large areas using only contact pressure can accommodate irregular or thick bond layers to a certain extent (Matthys, 2000).

3.5 Composite properties

In this chapter the composite material characteristics will be described, i.e. the combined properties of the above introduced constituents.

Fiber-Matrix bonding

As previously stated, the matrix holds the composite together and transfers load to the fibers. Because of this interaction, the bonding between the resin and the fibers are of the upmost importance for the composite's properties (Sjögren, 2010) (Clarke, 1996). Often, a high strength bond assuring a composite with high stiffness and strength, is desirable.

However, for some applications a relatively weak bond can better meet requirements on ductility (Sjögren, 2010). Thus, when a strong bond fails, it causes a high concentration of stress which may induce sudden fiber failure – a brittle failure undesirable in a civil engineering viewpoint. The bond strength depends on how well the resin penetrates and wets the fiber and hence gives possibility for chemical binding, mechanical interlocking, electrostatic attraction and molecular entanglements (Sjögren, 2010). Therefore, the bond between fiber and resin are dependent on the interactive compatibility between the materials. This compatibility depends on the combination of materials rather than individual choices of components. For example may aramid fibers bond inadequately with certain polymer matrices due to the unpolar fiber structure, unless consideration is taken to their interaction (Pridmore & Ojdrovic, 2015).

Fiber direction

In addition to the bond, loading direction and angle between fibers govern the mechanical properties of the bond (Holloway, 2001). The fiber direction for FRP composite is controlled in the manufacturing process giving one of the key advantages of the material. By alternating the fiber direction, the inner load path within the material can be adjusted. In repair of pipelines, where internal pressure creates primarily hoop stresses, the designer can chose to arrange a larger portion of the fibers in this the hoop direction (Ehsani, 2015).

Fiber fabrics

Normally, FRP wraps for pipe repair utilizes a fabric of fibers which are either uni- or bidirectional. A wide spectrum of different commercial reinforcing fabrics are available on the market. Pridmore and Ojdrovic (2015) claimed that for repair of pipelines, the best practice includes only the use of unidirectional carbon fiber fabric. On the contrary, Ehsani (2015) suggested using a combination of unidirectional and biaxial fabrics, to provide strength in both longitudinal and transverse directions. Such a bidirectional carbon fiber fabric can be seen in Figure 9. Ehsani exemplified how one layer of unidirectional carbon fabric along the length of the pipe and two layers of unidirectional carbon fabric in the hoop direction will best meet the strength requirements for a steel pipe. However, to prevent galvanic corrosion, Ehsani further suggests the application of a layer of glass fabric as a dielectric barrier. Although the authors referred to above present valid motivations, the use of carbon fibers can be questioned due to its high cost.

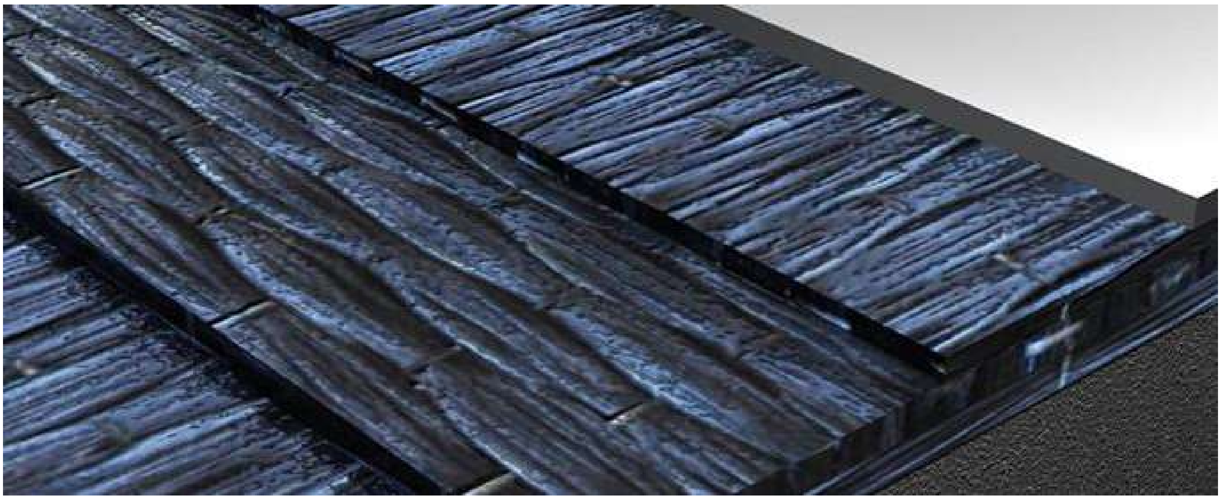


Figure 9 Carbon fiber fabrics in dual direction (Structural Group, Inc., 2016)

An increasing number of manufactures offer products for FRP wrapping of pipes. In the scope of this study, the different products will not be evaluated based on their choice of fiber type and fabric composition. Summarized, each solution have their own advantages and the suitability is highly dependent site specific conditions. Hence, no product can be chosen as the universal winner.

Fiber volume ratio
In addition to the above described, the mechanical properties of the final composite will be dependent upon the *fiber volume ratio* i.e. the relative proportions of the polymer and fiber, denoted V_f (Holloway, 2001).

$$V_f = \frac{Volume\ of\ fiber}{Volume\ of\ composite}$$

Glass transition temperature
When using polymer materials as structural components subjected to higher temperatures, knowledge about the glass transition temperature T_g is of particular importance. At T_g, the amorphous regions of polymers transform from hard to viscous (Matthys, 2000). The change of molecular mobility of polymer materials and elevated temperatures can significantly influence the mechanical properties. The matrix has lower a lower T_g than the fibers, thus governing the FRP composites at elevated temperatures. According to Matthys (2000) research, the matrix general has a T_g between of 130 to 140 °C for pre-fabricated FRP elements.

Failure mechanics
The failure mode for composites designed with continuous fibers in one direction starts with failure of the weakest fiber. The procedure continues with failure of the second weakest and progress in the same manner until the stress in the remaining fibers become too high for the material to restrain and the material collapses. The main factors that influence this failure mode are the amount of fibers, the fiber properties and the polymer properties. The collapse differs due to the bonding between the fibers and polymers. With strong bonding the collapse occurs from the fibers collapsing. With weaker bonding the fibers will loosen from the polymer and a pull-out phenomenon occurs. In practical use of FRP materials uniform loading in one direction is quite unusual and materials are often designed to be able to restrain stresses in multiple directions.

4 CONVENTIONAL PIPE REPAIR METHODS

In order to put FRP wraps in perspective, other potential pipe repair solutions will now be briefly evaluated. This objective approach is believed to facilitate greater understanding of the benefits with FRP wraps.

According to contractors in the Gothenburg area the traditional repair procedure includes, a shutdown of operation, cutting out the damaged part of the pipe and replacement with a whole new section. The new pipe is normally welded to the old one. This method is time consuming and because the pipe has to be off service during the repair the procedure decrease productivity. If the pipe is crucial for large part of the facility, the downtime during the repair may cause major expenditures.

Facilities with pipes that requires authorized inspection, further explained in chapter 7.6.1 – *"Governing regulations for FRP wrap repairs"*, must regularly shut down the plant letting inspection bodies certify that the pipes are in adequate condition. This leaves pipe owners with the possibility to temporarily repair the pipes between each inspection, while the plant is in service. However, such a measure impose increased responsibilities upon the pipe owner to account for the performance and safety of the repair. When next scheduled inspection takes place, the temporary repair must be cut out and refitted with a new pipe as described above.

There is a variety of ways to rehabilitate pipes today. Which method that suits each case best depends on a mixture of parameters including, pipe material, load exposure, kind of damage and what the pipe is used for. Discussed later in this report, long term repairs on high pressure pipes are limited due to safety hazards, instead whole pipe sections have to be replaced.

4.1 Compound box

A method that has become increasingly popular during the last years is using a specially designed box that capsules the damaged part and is filled with compound sealing the repair. The repair needs to be designed and produced specifically for each repair making the repair expensive. Since the repair needs to be produced for each single application the manufacturing time is long. At delivery from the producer the box is attached on the damage. Thereafter the epoxy compound is injected in valves located around the box. The valves also let air trapped in the box escape and the compound to cure. The repair method is seen as a safe way to repair a pipe temporarily. Since it is designed specifically for each case the repair method has very good compatibility with the pipe it is applied on. The manufacturing of the boxes can be optimized to design requirements which allows for an efficient material usage.

Figure 10 Shows a repair for a flange joining two pipe sections. The valves on the box let the injected compound to cure (SMC Swede, 2016)

4.2 Clamps

Another way to repair a pipe temporarily is to use a clamp. There are different clamps on the market used to repair pipes. The clamps are made of either plastic or metallic materials or fabrics. An advantage with this method is the quick procedure of applying it to the damaged pipe. The fabric clamps are normally used for emergence leak stop while the metal and plastic clamps are more used for long term repairs. Some products can be combined enabling long term repair for pipes with wall through defects streaming media. Due to their low temperature and pressure working ranges, these repair clamps can in many cases not be used.

Figure 11 Shows a clamp made of fabric. The method is used for temporary repairs and can be combined with a compound box to increase lifetime (3XEngineering, 2016).

4.3 Slip lining

Some pipes can be repaired with tubes injected within the pipe. This can be seen as a permanent repair method but can only be done in low pressure pipes. This method is especially lissome on buried pipes since it does not require excavation. However, it does not allow pipes to be repaired while in service. The installation procedure can simplistically be described as follows: Between the two wells where the damage is located, a tube made of polyester is injected. Examples of installation procedures are by turning the tube inside out and with pressurized water push it through the pipe or by bursting the old pipe and in the same time relining with a new pipe.

When the tube has reached the second well the tube is fixated and opened up to the original pipe. A disadvantage with this method is that it requires the whole pipe section to be repaired, even though just a part of it damaged, and is therefore expensive.

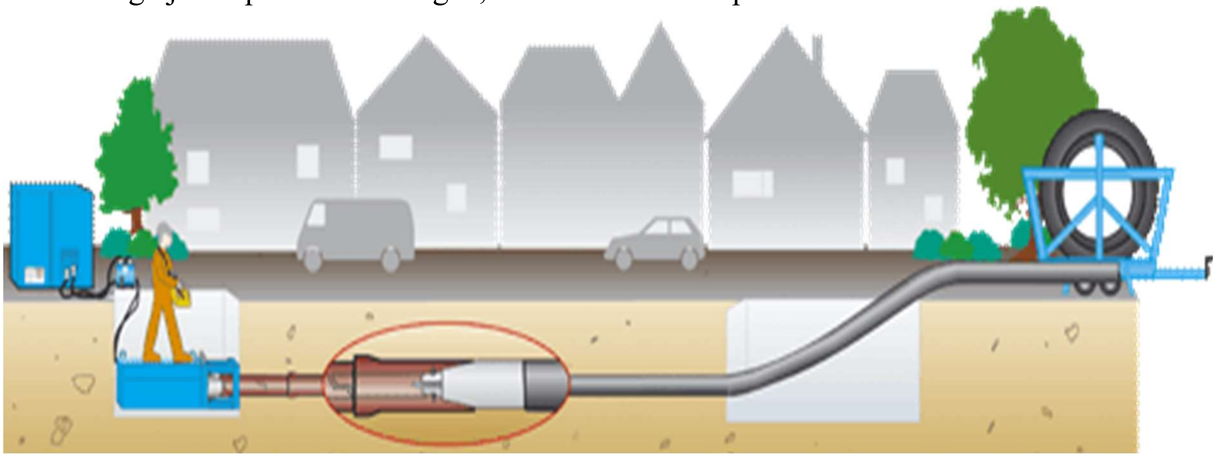


Figure 12 Illustrates how an old pipe is bursted in the same time as a new pipe is injected. (JVAB, 2016)

4.4 Steel sleeves

Repairing pipes with so called steel sleeves are popular in USA. This method forms an additional steel layer around the damaged area and attached to the existing pipe. This is a quite quick and reliable method but is preferably installed on steel pipes since it commonly requires the sleeve to be attached by welding. Another disadvantage with this method is that the original pipe is affected by the weld. This might build up stress concentrations in the regions where the sleeve is attached enabling long term effects such as fatigue damages. Welding may also result in hydrogen embrittlement that may cause brittle cracking in the original pipe.

Figure 13 Shows a steel sleeve used for long lasting repairs (Romac Industries, 2016)

5 FIBRE REINFORCED POLYMERS AS WRAP REPAIR

In chapter 3 – "*Fiber Reinforced Polymers"* a fairly general introduction of the materials FRP was given. With this knowledge in mind, the use of FRP wraps for pipe repair will now be introduced. FRP wrapping is a method of rehabilitating pipes by winding a fiber fabric around the defected area in sufficient axial extent and number of layers. In this study, the so called "wet-layup"-method is employed which refers to the fact that the composite is built in-situ. Adhesives are applied to the pipe both before and during the wrapping of the fiber fabrics. Thereafter, the components cure upon the formation of the composite (FRP) take place in which the adhesive act as resin.

Figure 14 Example of repair with FRP wrapping (Power wrap, 2013)

5.1 Repair procedure

Most FRP-wraps manufacturers have their own education for personnel applying FRP repairs on pipe. Some manufacturers educate contractors to use their products while other restrict the use for the products to their own employees, mediating a solution from design to finished repair. The educations aim to certify workers performing repairs to ensure national standards concerning pipe repairs and quality are followed. The products and repair procedure have in most cases been certified by external certification bodies.

In the following section the application process of FRP wraps is described. The way the wraps is applied differs marginally between the different fabrications but here a general procedure presented by Essvik (2016) is described. If the damage is of type B "through wall" the leak can be sealed with an epoxy compound. This is a formable quick hardened paste that can be used to seal smaller holes in a pipe. During hardening, the compound is attached to the pipe with a strap to stop the flow. If the damages is of Type-A (not through wall) the step above is disregarded.

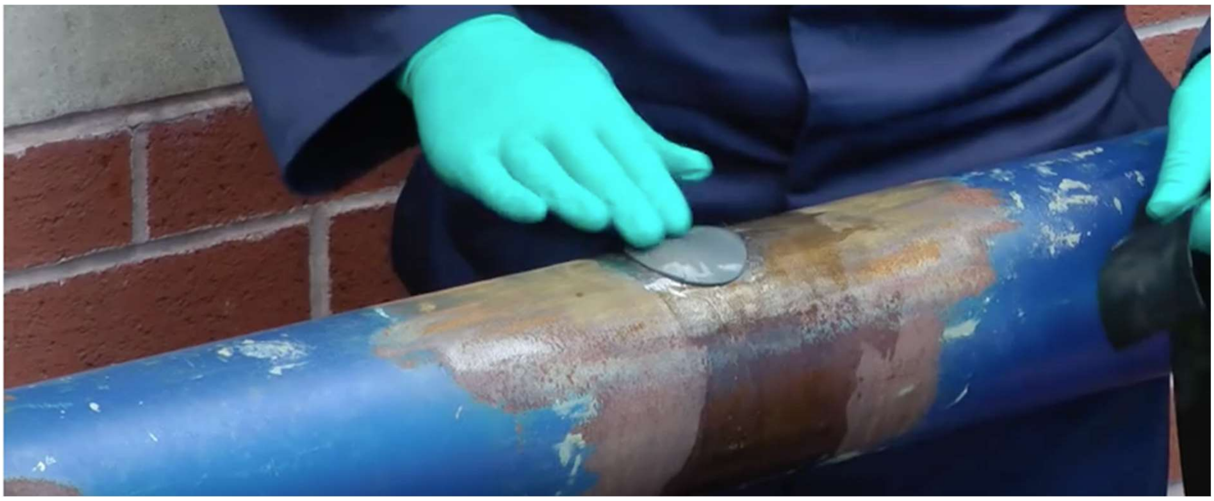


Figure 15 The leak is temporarily sealed with a epoxy compound. (Belzona Channel, 2011)

When the leak is sealed and the compound has hardened, the next step is to either blast or grind the damaged pipe. The surface preparation has to be done carefully to ensure that the wrap sticks to the pipe even during high pressure. Many manufactures prescribe that the surface should be treated until the quality level white metal (ISO SA3) is obtained, see Figure 16.

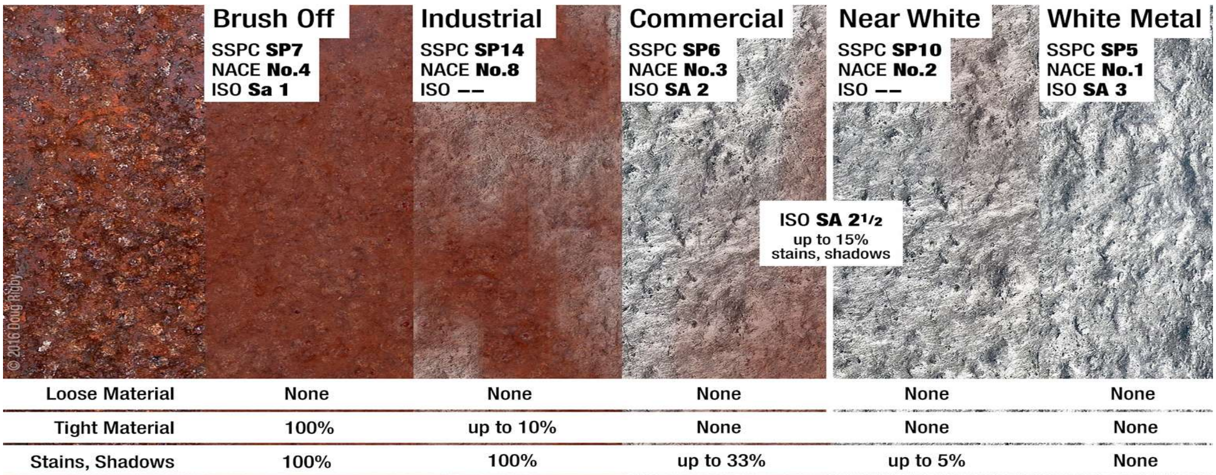


Figure 16 Quality of the surface preparation. White metal is necessary to obtain optimal bonding between the FRP wrap and the pipe. (Blast Journal, 2016)

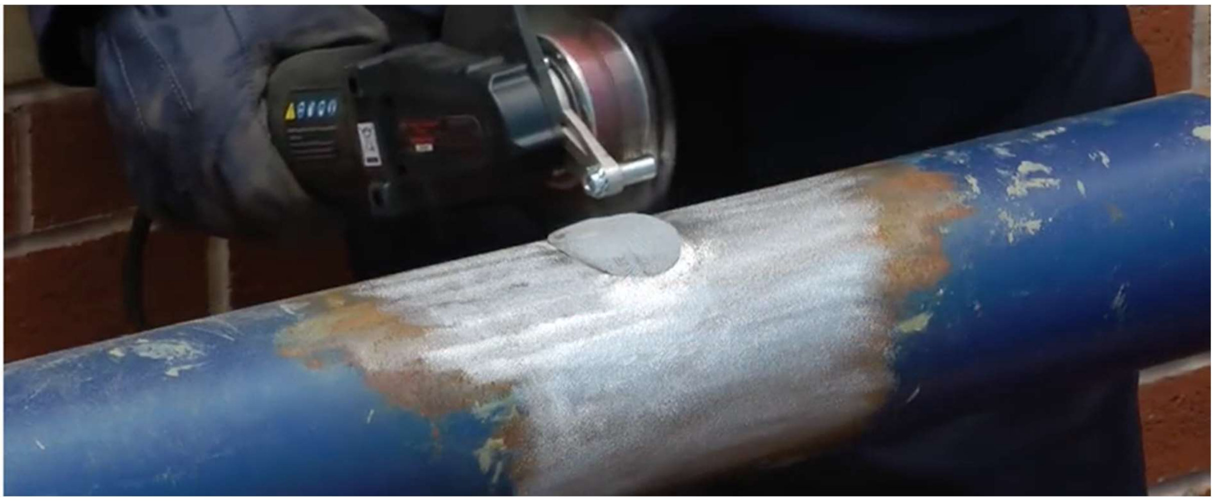


Figure 17 The pipe surface is prepared for wrapping by grinding the pipe material until white metal occur (Belzona Channel, 2011)

When the surface is blasted some manufactures recommend to use a primer on the damaged surface to prevent from further oxidation of the pipe material. The primer is usually a liquid substance that further enables adequate bonding between the pipe and wrap.

Figure 18 A distance on each side of the damage is marked out to show where the FRP should be applied. The pipe has been prepared with a primer to prevent further oxidation of the pipe(Youtube Woronko premium partner Loctite partner channel, 2014).

When the primer has dried out an epoxy compound is applied and formed to restore the pipe's original geometry. This is an important step to ensure that no air bubbles are trapped between the pipe and the wrap. It also creates a support for the wrap and enables stresses in the pipe to spread symmetrical in the wrap.

Figure 19 An epoxy is applied to build up the pipes original geometry (Youtube Woronko premium partner Loctite partner channel, 2014)

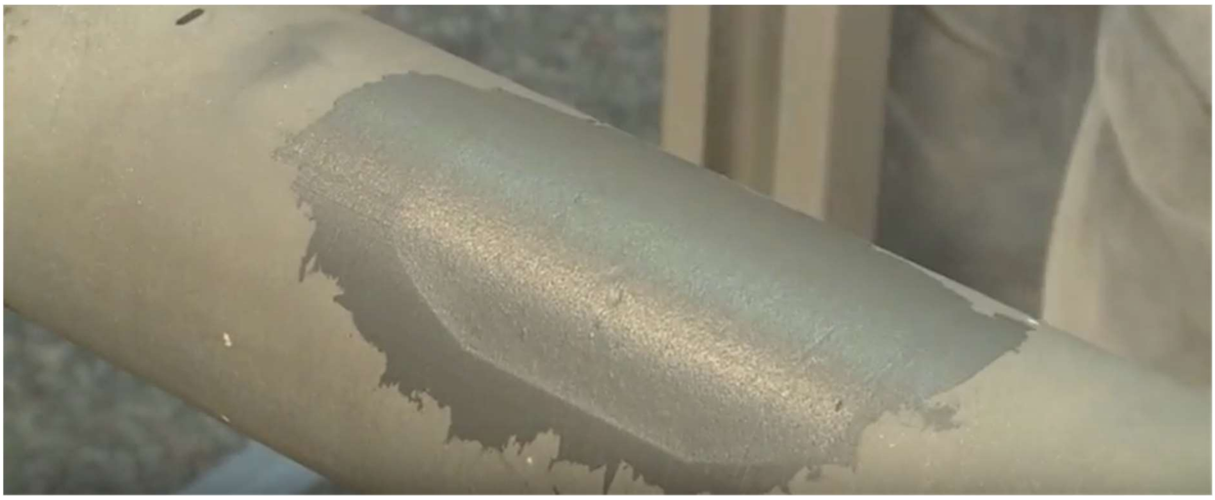


Figure 20 The epoxy is flattened to restore the original pipe geometry (Youtube Woronko premium partner Loctite partner channel, 2014)

When the epoxy base has hardened an adhesive is applied around the pipe on the damaged part. The adhesive acts as a both glue and matrix for the wrap. The wrap is also drained in the adhesive to ensure maximum bonding and impregnation of the wrap. When this is done the wrap is wound round the marked out area on the pipe. Care is taken to prevent air entrapment between the wrap and the pipe. An overlap on each wrap, of half the width of the wrap is normally used to ensure strength and sealant.

Figure 21 After the epoxy has hardened an adhesive is added (Youtube Woronko premium partner Loctite partner channel, 2014).

Figure 22 The wrap is wound around the pipe (Youtube Woronko premium partner Loctite partner channel, 2014).

Figure 23 The adhesive attaches the FRP-wrap to the pipe (Youtube Woronko premium partner Loctite partner channel, 2014).

When the adhesive and wrap has dried out some manufactures recommend to paint the pipe with a protective paint to restore the original look and protect the wrap from exterior damages.

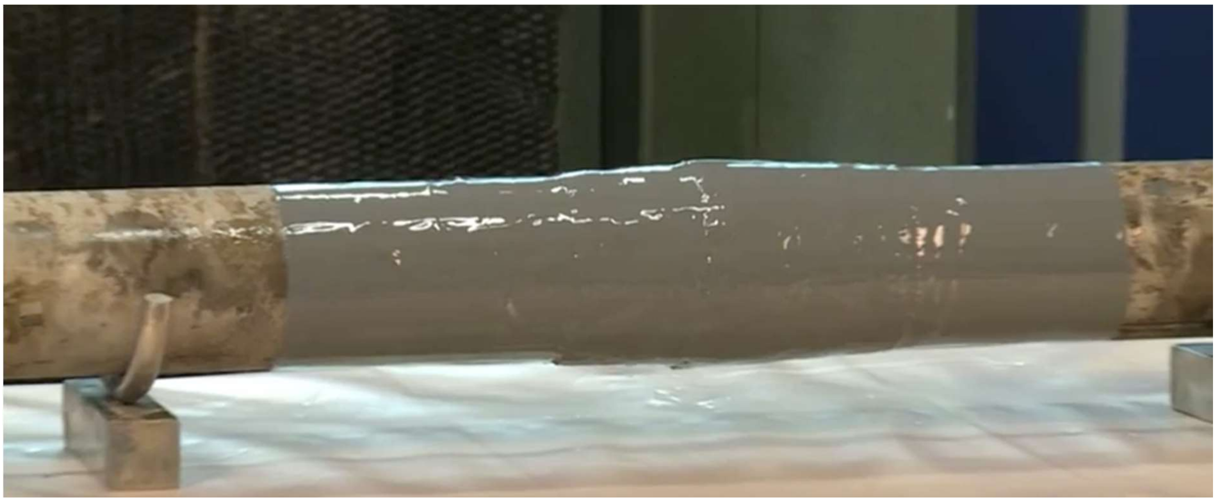


Figure 24 The pipe is finally painted with a protective paint (Youtube Woronko premium partner Loctite partner channel, 2014).

Within a few hours, the curing process has finished and the whole repair procedure is at its end. If the above described installation is conducted properly, the repair remains reliable over the indented life time, provided that other aspects of the design is fulfilled. The quality of the workmanship is a crucial factor and its significant importance is further discussed in the next chapter.

5.2 Literature review

As part of the introduction of FRP wraps for pipe repair, a brief summary of the literature on the subject will now be given. Some of the studied literature are written with indications of being bias. When reading this introduction, bear in mind that these authors may have slightly exaggerated the benefits of FRP wraps.

5.2.1 Mechanical properties

Many authors highlighted the physical properties of FRP wraps. Ehsani (2015), Lee & Estrada (2015), Deaton (2015) Chan, et al. (2015) and Sirimanna, et al. (2015) all claimed that the high specific stiffness, high tensile strength as well as high strength-to-weight ratio are attributes especially viable for pipe repairs.

Lam (2015) further showed how the ultimate bending strength and flexural stiffness of tubular steel members can be increased with FRP wrapping. Lam referred to a test where the ultimate strength, relative to the bare steel member, was increased by 27% and the corresponding flexural stiffness was increased by 18%.

Djukic, et al (2015) conducted a study where composite repairs proved to sustain pressures beyond that of the original pipe strength in the region containing the defect. On this basis they emphasized the effectiveness of overwrap repairs for restoring the original pressure rating of damaged pipelines.

On the contrary, Bruce (2015) wrote a thesis in which the feasibility of FRP wraps were questioned. Compared to conventional steel sleeves he argued that FRP wraps are less effective because of their elastic modulus not being equivalent to that of the steel pipe. Due to this fact, he stated that the FRP composites in general must withstand much higher strains than steel before equivalent loads can be carried. When FRP are wrapped over the steel pipe, the wrap's elongation is constrained by the steel and it is not until the steel begins to yield that the repair carries notable shares of the load. A behavior which is confirmed in a study by Saeed and Ronagh (2015).

In the previous chapter, the risk of failure that adhesive bonding introduces to the repair system was elaborated. Chan, et al. (2015), Ehsani (2015) and Djukic, et al. (2015) all stressed this fact and described the importance of an effective load transfer between the pipe and FRP wrap. They also pointed that the bond must prevent any ingress of fluids between the FRP and the host pipe. Related to the adhesive bond is FRP wrap's susceptibility for brittle failures. Chan, et al. (2015) showed how de-bonding at the steel-composite interface may propagate rapidly. Lam (2015) further underlined the materials brittleness.

5.2.2 Fatigue properties

Combined with the advantageous physical properties described above many researchers also accentuated the possibility of increase fatigue life of the repaired pipe (Saeed & Ronagh, 2015), (Ehsani, 2015) (Lam, 2015). Saeed & Ronagh (2015) referred to experimental test on FRP-reinforced pipes under cyclic fatigue pressure testing which, according to them, revealed results of a considerable increase in the service life. Lam (2015) made another attempt to examine the fatigue life of a wrapped pipe. With a FRP wrap covering the crack tip, Lam argued that both the stress intensity factor can be reduced significantly and further opening of the crack restrained, thus extending the fatigue life.

However, the above described susceptibility for brittle behavior is present also under cyclic loading. According to Deaton (2015), there are three possible mechanisms of failure for FRP wraps subjected to cyclic loading; cyclic de-bonding of the adhesive, inter-laminar failure, and adherent failure. In the study, Deaton stated that if a composite endures cyclic loading and a crack does develop, the FRP is near failure and only a few more cycles may be required before a crucial crack propagation begins.

Yet again Bruce (2015) made some remarks on the considerably lower stiffness of composite materials compared to steel and hence criticized their use on pipelines being subjected to cyclic pressure fluctuations. Chan, et al (2015) claimed that there are no definite studies on the fatigue strength between steel and FRP wraps subjected to combined loadings. Deaton (2015) further emphasized the lack of available research on fatigue failures on FRP reinforced pipes but claimed that some of the general concepts discussed in the airline and wind turbine industry could possibly be applied.

5.2.3 Durability and long term behavior

One of the most accentuated advantages with FRP wraps seems to be their durability and resistance to chemical attacks (Sirimanna, et al., 2015) (Deaton, 2015).
Heshmati, et al (2015), Pridmore & Ojdrovic (2015), Ehsani (2015) Chan, et al. (2015) Djukic, et al (2015) (Lam, 2015) (Saeed & Ronagh, 2015) all specifically noted the enhancehed corrosion resistance.

Saeed & Ronagh (2015) argued that FRP wraps can be considered as a lifetime repair, due to their ability to retard the growth of external corrosion by isolating the external defect from corrosive environments.

Fatigue life and durability issues, together with the material selection and quality of fabrication are factors governing the long-term performance of FRP-wrapped structural components. To be able to estimate this time-dependent performance in the presence of reasonable uncertainties, lay at the core of infrastructure management (Lee & Estrada, 2015).

Pridmore & Ojdrovic (2015) could via a durability study show positive results for FRP wraps and hence drew confident conclusions on their potential to perform well as a long-term solution for pipeline rehabilitation. However, Bruce (2015), once again enhanced the appealing properties of steel compared to composites, this time concerning long-term qualities. He claimed that, unlike steel, FRP materials' mechanical properties degrade over time. While corrosion of the steel pipe often is the reason for rehabilitation, this statement must be questioned. On the other hand, Bruce is correct when points out that the performance of FRP wraps on pipelines in the ground has not been investigated beyond 20-25 years. Despite the fact that composite materials are used widely in the aerospace and automotive industries, there exist few or no standardized tests for accelerated aging as well as reliable life estimations of the materials (Chan, Tshai, & Johnson, 2015). Lee & Estrada (2015) acknowledged this issue but informed that some adequate investigations have just recently begun. Though, as Djukic, et al. (2015) claimed, the necessary assessment through accelerated testing can both be unreliable and expensive unless it is accompanied with proper field experience.

The long term durability is heavily dependent on the surrounding environment. Heshmati, et. al. (2015) specifically identified moisture and temperature to be the most critical environmental factors for FRP composites. The presence of moisture reduces the elastic modulus and strength of resins and adhesives. For FRP composites in general, it should be noted that it is specifically the properties related to the resin, such as interlaminar shear strength, that are susceptible to moisture-induced degradation. On the contrary, fiber-dominated properties, such as tensile strength, are less sensitive to moisture (Heshmati, Haghani, & Al-Emrani, 2015). However, for FRP wraps in particular some additional moisture sensibility apply since the composite act in conjunction with the pipe material. When exposed to moisture, the stability of interfacial adhesion between wrap and pipe is the most important factor for the long term durability. Based on this fact, Heshmati, et. al. (2015), recommended further research on the effects on adhesive joints subjected to cyclic moisture exposure.

In their study Heshmati, et. al. (2015) also elaborated on the second critical environmental factor, namely temperature. They claimed that certain conditions such as temperature variations and cycles, freezing, freeze-thaw periods as well as elevated temperatures reduce the performance of FRP composites. However, the wide range of adhesives used, together with the vast number of possible fiber-matrix combinations make it extremely difficult to draw any generalized conclusions on temperature dependency.

The combined effect of moisture and temperature, so called hygrothermal ageing, introduce an exposure conditions susceptibly even more damaging than each individual condition alone. Similarly as other researchers, Heshmati, et. al. (2015) argued that until now, the uncertainty related to long term performance and environmental durability have been critical barriers to the wide use of FRP composites in civil engineering applications.

5.2.4 Aspects of construction

One of the main reasons for the development of FRP wraps for pipe repairs was the challenges conventional solutions met in construction. Lesmana (2015) exemplified scenarios were complicated work permits are required to face safety hazards and inaccessible locations that require scaffolding etc. which made maintenance with traditional methods an arduous and expensive task.

Several authors agreed that the absence of hot work, i.e. that welding is not required, provides a decisive safety advantage in fire sensitive applications found in the process industry (Chan, et al., 2015) (Lesmana, 2015) (Saeed & Ronagh, 2015) (Djukic, et al., 2015). Because welding is avoided, the repair can be made with reduced interruption on production. When avoiding heavy welding equipment as well as utilizing the lightweight of the FRP wrap itself, limited scaffolding may be needed (Djukic, et al., 2015) (Lesmana, 2015). These simplified and straightforward installation procedures with low down times have proven to be a cost-effective repair alternative which also allows pipeline operators to quickly respond to disturbances (Lee & Estrada, 2015) (Saeed & Ronagh, 2015).

Bruce (2015) confronted the above stated advantages and claimed that the installation of steel sleeves not necessarily are more complicated. He argued that the installation procedure, for the type of steel sleeve that FRP wrap's aims to replaced, has recently become just as simple. However, what that statement actually implied, is not well defined.

When repairing steel pipes with FRP wraps it is of importance that the steel is blasted and cleaned until white metal. In cases with pipes working under high pressure and with hot media, its hazardous to blast the pipes due to the risk of cracking. This means that it can be difficult to ensure that the metal surface fulfills the requirements that the manufacturer of the wraps specify. Another question that has been addressed is how FRP wraps withstand fire and heat. FRP materials have during the last years been improved and tests now show that plastic materials sometimes have better resistance towards fire and heat than metallic materials. Despite positive test results, not all concerned instances have been convinced that FRP wraps is suitable for pipe repair (Dekra, 2016).

5.2.5 Comments on cost

Addressing the aspect of cost, Ehsani (2015) assumed that many engineers falsely believe that FRP wrap repairs are more expensive. Sirimanna et al. (2015) described how, when compared to some of the conventional repair systems, composite solutions may be more reliable and cost-effective. Promoters for FRP wraps often argue that when all attributes of the chain are considered, the option will be quite attractive. Although Bruce (2015) acknowledged that the mobilization cost for composite repair installations may sometimes be less, by stressing the importance of a low raw material costs, he argued for the competitive properties of steel sleeves.

In order to make a proper cost comparison, it is appropriate to make a life cycle cost analysis (LCC) (Lee & Estrada, 2015). Chan, et al. (2015) referred to such an analysis conducted for the US Department of Transportation (Farrag, 2013). Their study presented that, when using FRP wraps instead of welded pipe sleeves, the overall costs can be reduced by 24%. Compared to replacing the whole pipe section, the cost reduction can be up to 73%. Koch et al., (2001) found similar results in their comparative study.

5.2.6 Quality assurance

Concerns on how to assure proper quality of the FRP wrap repairs have frequently arisen. According to Djukic, et. al. (2015) the relatively juvenile technic currently lack satisfactory quality control procedures and inspection techniques. They claimed that most composite repair contractors today propose toughness measurement as well as visual inspection. However, further measures are required, including more reliable and less skill-dependent application techniques. Other researchers shared the concern for quality sensitivity related to the skill of the bonder (Lee & Estrada, 2015) (Pridmore & Ojdrovic, 2015). Based on the above mentioned research and the findings made in this thesis, the following can be concluded: due to an often rather conservative design, the skepticism towards quality is primarily not focused on whether the FRP wraps meet the *minimum* requirements or not. It is rather related to an uncertainty in how to more precisely determine the quality of the repair with more consistent insurance. Many manufactures and contractors can today present rather extensive quality control programs and the progress continues. However, as (Holmgen & Nylander, 2016) well outlined, when competing with the rigorous and well established quality control programs that steel repairs currently offer, there are still much work ahead.

6 DESIGN OF FRP WRAPS IN PIPE REPAIRS

One of the main purposes of this report, formulated in the second research question, is to examine *what would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?* In order to do so, a case study is later presented in this report. To understand how the FRP wrap was designed in this case study, this chapter reviews the design standard used. Furthermore, this chapter gives insight in some of the technical considerations associated with FRP wrap design.

There are a variety of standards concerning pipe repairs with FRP-wraps. The three most renowned are ISO 24817, ASME-PCC-2 and CSA-Z662. The ASME-PCC-2 is the American standard, CSA-Z662 the Canadian and ISO 24817 the international. All three of the codes handles the design by calculating the required thickness of the repair. Swedish Standard Institute have adopted the European standard EN-ISO 24817:2015, which in Sweden is called SS-EN ISO 24817:2015. This standard is the one explained in this chapter and used in the case study later in this report. Today, most FRP wraps manufacturers have their own calculation software, based on the standards mentioned above, that enable quick and easy design assessment.

6.1 Design procedure

This chapter only attempts to explain the main design procedures in the standard *SS-EN ISO 24817:2015*. All figures and tables referred to in this chapter originates here from. There are numerous of choices in the standard not described here, these include how fatigue is handled, different type of pipe geometry etc. The design procedure mainly aims to calculate the number of laminate layers used to build up the repair. Depending on what input data that is available and if the defect is through wall or not the design procedure differs. In the diagram below the procedure is shown. The standard includes design procedures for rehabilitation of pipes exposed to: external corrosion, external damages, internal corrosion, crack defects or just strengthening.

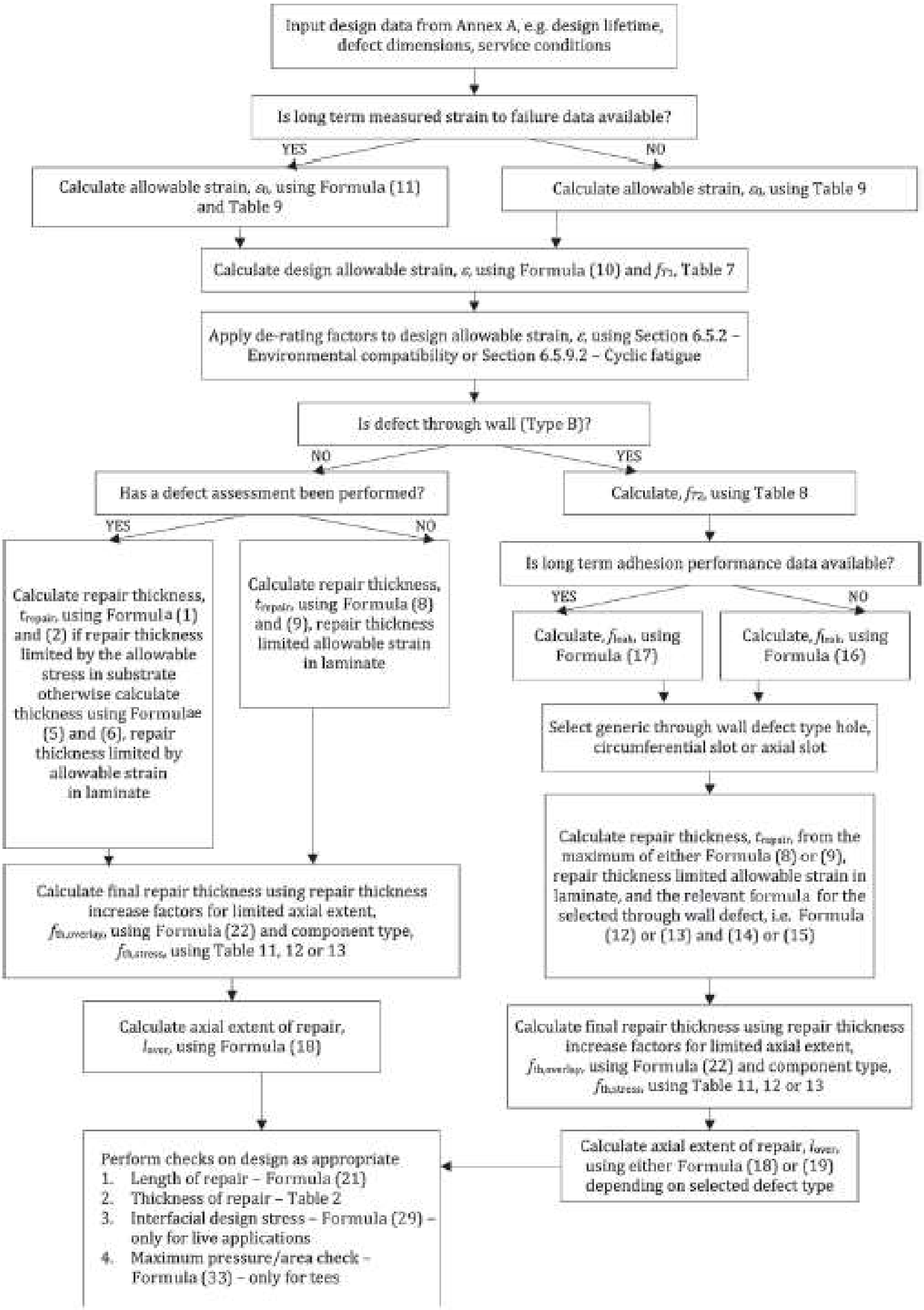


Figure 25 Shows the design procedure for ISO EN-SS 24817:2015

The first part of the design procedure classifies the repair. The design code categorizes repairs in three classes; *Class 1* for pipes with design pressure < 2MPa and design temperature <40°C, *Class 2* for pipes with design pressure < 2MPa and design temperature <100°C, *Class 3* - "limited to repairs design in compliance with this International Standard and of thickness equivalent to <D/1"2 and temperature "defined in 7.5.3" in the code.

Table 2 Describes how repair class is chosen

Table 2 — Repair class

Repair class	Typical service	Design pressure	Design temperature
Class 1	Low specification duties, e.g. static head, drains, cooling medium, sea (service) water.	<2 MPa	<40 °C
Class 2	Fire water/deluge systems	<2 MPa	<100 °C
Class 3	Produced water and hydrocarbons, flammable fluids, gas systems. Class 3 also covers operating conditions more onerous than described above.	Limited to repairs designed in compliance with this International Standard and of a thickness equivalent to < D/12	Defined in 7.5.3

The defect type, dimensions, design temperature and repair lifetime all influence the maximum pressure, thus accounted for by a factor calculated in Annex D for defects through wall and otherwise Annex C. The next part of the design procedure is to collect data about the damaged pipe. Required data include material properties, working pressure and loads, working temperatures, defect type and geometries. The needed data can be seen in Table 3 below.

Table 3 The table shows input data that is required to perform the calculations. The required data may vary depending of the characteristic of the repair

Geometry	
External pipe diameter	mm
Original wall thickness	mm
Defect geometry	
Defect diameter	mm
Remaining substrate thickness	mm
Through wall type defect	Yes/No
Pipe Material Properties	
Tensile yield strength	MPa
E-modulus	GPa
Linear temperature expansion coefficient	
Loads	
Axial load	N
Shear load	N
Working pressure (max and min)	MPa
Torsional moment	Nm
Bending moment	Nm
Other loads	N
Repair laminate properties	
E-modulus - circumferential	GPa
E-modules - axial	GPa
Poisson's Ratio	
Thermal expansion coefficient - circumferential	
Thermal expansion coefficient - axial	
Glass transition temperature	°C
Heat deflection temperature	°C
Lap shear strength	MPa
Other data	
Repair design lifetime	years
Design temperature	°C
Temperature when the repair is applied	°C
Number of loading cycles	-
Type of component to be repaired (tee, bend, etc.)	

If the pipe is buried in ground the following data, presented in Table 4, is also needed.

Table 4 Additional data needed for buried pipes.

Burial depth	mm
External pressure of the pipe	MPa
Soil pressure	MPa
Weight of the soil	MPa/mm

When the data above is collected and the class and lifetime for the repair are determined, the maximum allowable strain ε_{a0} and ε_{c0} can be calculated. This is done either by using equation 11 and table 9 or just table 9 depending on if "long term measured strain to failure data" is available.

Table 5 Gives the equations to calculate allowable strain in axial and circumferential direction. The lifetime is expressed in years, and represent the designed repair lifetime.

Modulus	Allowable strain Class 1	Allowable strain Class 2	Allowable strain Class 3
For $E_a > 0,5\ E_c$			
— Continue-1 ε_{c0}	$0,004\ 214*10^{-0,011\ 35\ t_{lifetime}}$	$0,003\ 634*10^{-0,008\ 13\ t_{lifetime}}$	$0,003\ 061*10^{-0,004\ 4\ t_{lifetime}}$
— ε_{a0}	$0,004\ 214*10^{-0,011\ 35\ t_{lifetime}}$	$0,003\ 634*10^{-0,008\ 13\ t_{lifetime}}$	$0,003\ 061*10^{-0,004\ 4\ t_{lifetime}}$
For $E_a < 0,5\ E_c$			
— ε_{c0}	$0,004\ 214*10^{-0,011\ 35\ t_{lifetime}}$	$0,003\ 634*10^{-0,008\ 13\ t_{lifetime}}$	$0,003\ 061*10^{-0,004\ 4\ t_{lifetime}}$
— ε_{a0}	$0,002\ 768*10^{-0,022\ 1\ t_{lifetime}}$	0,001	0,001

$$\varepsilon_c = f_{perf} f_{T2} \varepsilon_{lt} \qquad (equation\ 11)$$

where;

ε_{lt} is the lower confidence limit of the long-term strain,
f_{T2} is the service de-rating factor,
f_{perf} is the temperature de-rating factor.

If long term strain to failure data is available, ε_{c0} does not need to be calculated from table 9. Instead ε_c is calculated.

The next step in the code is to calculate the temperature de-rating factor f_{T1}. This is done in accordance to table 7.

Table 6 Gives the equation to calculate temperature de-rating factor.

Temperature factor; f_{T1}	$0,000\ 062\ 5(T_m - T_d)^2 + 0,001\ 25(T_m - T_d) + 0,7$

With this factor in combination with thermal expansion coefficients and allowable strain measures the allowable repair laminate thermal strains can be calculated according to equation 10.

$$\varepsilon_c = f_{T1} \cdot \varepsilon_{c0} - |\Delta T(\alpha_s - \alpha_c)| \qquad (equation\ 10)$$

$$\varepsilon_a = f_{T1} \cdot \varepsilon_{a0} - |\Delta T(\alpha_s - \alpha_a)| \qquad (equation\ 10)$$

where;

ΔT *is the temperature difference between design and installation,*
α_s *is the pipe material's thermal expansion coefficient,*
α_c *is the repair material's thermal expansion coefficient in circumferential direction,*
α_a *is the repair material's thermal expansion coefficient in axial direction.*

Depending on whether the defect is through wall (Type B) or not (Type A) the procedure now branches up. If a defect assessment for Type-A defects has not been made, the repair thickness must be calculated according to equation 8 and 9. This is done by calculating equivalent loads and pressures from the axial and torsional moment and loads. Using the equivalent loads and pressures, geometry of the pipe, allowable strain and E-modulus the minimum laminate thickness can be derived in both axial and circumferential direction. The maximum value of these two determines the design.

$$t_{min,c} = \frac{1}{\varepsilon_c}\left(\frac{p_{eq}D}{2} \cdot \frac{1}{E_c} + \frac{F_{eq}}{\pi D} \cdot \frac{\upsilon}{E_c}\right) \qquad \textit{(equation 8)}$$

$$t_{min,a} = \frac{1}{\varepsilon_a}\left(\frac{F_{eq}}{\pi D} \cdot \frac{1}{E_a} - \frac{p_{eq}D}{2} \cdot \frac{\upsilon}{E_c}\right) \qquad \textit{(equation 9)}$$

where;

$t_{min,c}$ *is the minimum repair thickness in the circumferential direction,*
$t_{min,a}$ *is the minimum repair thickness in the axial direction,*
D *is the external diameter of the pipe,*
E_a *is the axial modulus of the repair laminate,*
E_c *is the circumferential modulus of the repair laminate,*
υ *is the Poisson's ratio of the repair laminate,*
F_{eq} *is the equivalent axial load acting on the pipe,*
p_{eq} *is the equivalent internal pressure acting on the pipe.*

However, if a defect assessment has been performed and the maximum allowable working pressure is known i.e limited by allowable stress in the pipe the minimum thickness is calculated according to equation 1 and 2 or 5 and 6. The input variables are the geometry of the pipe, the E-modulus ratios between the substrate and the laminate, the allowable pressure and equivalent pressures and loads. In this case, the minimum thickness is chosen to the highest of the values calculated based on allowable strain respectively allowable stress.

If the stress is the limiting factor equation 1 and 2 are used to calculate minimum thickness.

$$t_{min,c} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(p_{eq} + \frac{2\upsilon F_{eq}}{\pi D^2} - p_s\right) \qquad \textit{(equation 1)}$$

$$t_{min,a} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_a}\right) \cdot \left(\frac{2F_{eq}}{\pi D^2} - \upsilon \frac{E_a}{E_c} p_{eq} - p_s\right) \qquad \textit{(equation 2)}$$

where;

E_s *is the substrate material modulus,*

s *is the allowable stress in the substrate,*

p_s *is the maximum allowable working pressure for the pipe.*

If the strain is the limiting factor equation 5 and 6 are used to calculate minimum thickness.

$$\varepsilon_c = \frac{1}{E_c t_{min,c}}\left(\frac{p_{eq}D}{2} + \upsilon\frac{F_{ax}}{\pi D}\right) - \frac{p_s D}{2E_c t_{min,c}} - \frac{p_{live}D}{2(E_c t_{min,c} + E_s t_s)}$$

$$t_{min,a} = \frac{1}{\varepsilon_a}\left(\frac{F_{eq}}{\pi D}\cdot\frac{1}{E_a} - \frac{p_{eqD}}{2}\cdot\frac{\upsilon}{E_c}\right)$$

where;

F_{ax} *is the applied axial load,*

t_s *is the minimum remaining substrate wall thickness,*

p_{live} *is the internal pressure during the repair.*

For Type-B defects the calculations branch up whether data depending on long term adhesion performance is available or not. The two branches respectively give a value f_{leak}, that represents the service de-rating factor, simply explained as the probability of pipe failure. This is done in accordance to equation 17 if the data is available and equation 16 if not.

When this is done the geometry of the defect has to be determined. Depending on what type of defect that is present equation 12, 13, 14 or 15 is used. These give the minimum repair thickness in combination with equation 8 and 9 described above.

The last equation used to calculate the thickness handles the number of layers that should be applied in the repair.

$$n = \frac{t_{design}}{t_{layer}} \qquad \textit{(equation 35)}$$

where;

t_{design} *is the minimum repair thickness,*

t_{layer} *is the thickness of each laminate layer and n is the number of layers.*

When the minimum thickness is calculated the axial extent of the repair is calculated in the same manner for both Type-A and Type-B defects. If the pipe defect to be repaired is located in a part of the pipe where stress concentrations occur, the laminate thickness is increased with a safety factor. This factor is determined based on the defect location, with alternatives such as tee, bend or flange etc. The thickness must be further increased if the defect is located near a support, end dome or in rigid attachment etc. due to the tables and equation below.

Table 7 Safety factors to increase repair thickness for pipe components in piping systems

Piping system component	Repair thickness increase factor $f_{\text{th,stress}}$
Bend	1,2
Tee	2
Flange	1,1
Reducer	1,1

Table 8 Safety factors to increase repair thickness for pipe components in cylindrical vessel components

Cylindrical vessel component	Repair thickness increase factor $f_{\text{th,stress}}$
End dome, main body connection	1,1
Supports, saddles, rigid attachments	1,5
Tees, nozzles	2

Table 9 Safety factors to increase repair thickness for pipe components in spherical vessel components

Spherical vessel component	Repair thickness increase factor $f_{\text{th,stress}}$
Supports, saddles, rigid attachments	1,5
Tees, nozzles	2

$t_{design,component} = t_{design,straight\ pipe} \cdot f_{th,stress}$ *(equation 32)*

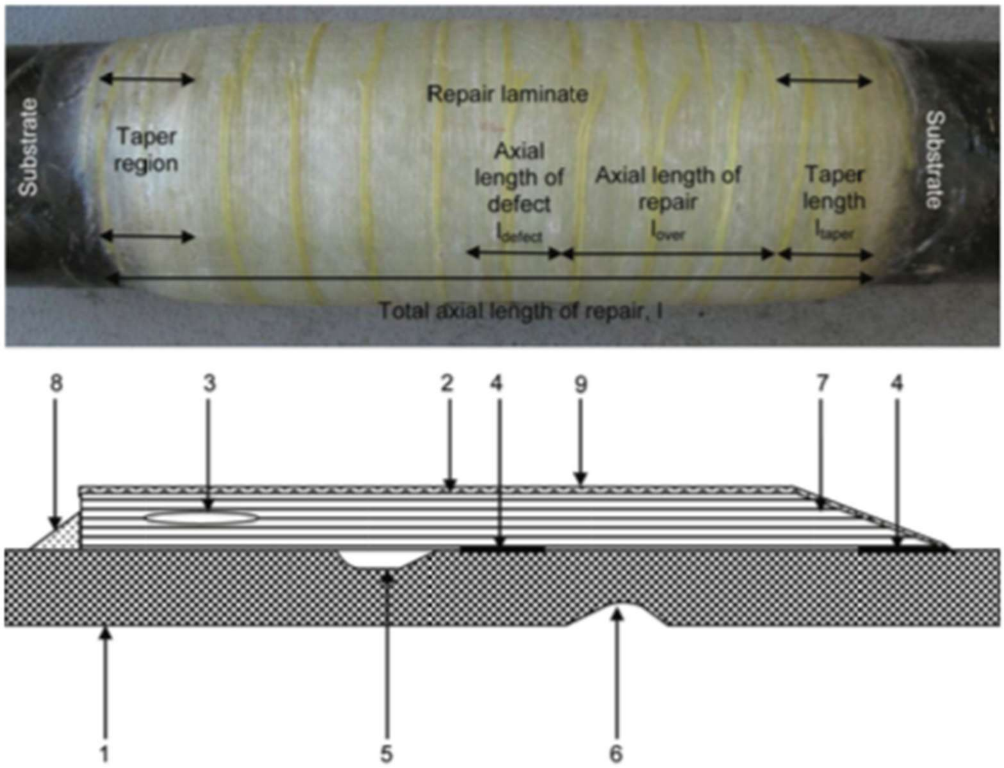
This axial extent is determined by a geometrical relationship between the pipe diameter and its original thickness. For circular defects the diameter of the defect also influences the length. The length must be checked with regard to applied axial force to ensure that the laminate can transfer the load sufficiently. Maximum strain, E-modulus in axial direction, lap shear strength and laminate thickness and the length of the repair are the input variables in this equation.

For slot type defects the following is used
$l_{over} = 2\sqrt{Dt}$ *(equation 18)*

For circular defect the corresponding equation is used
$l_{over} = 4d$ *(equation 19)*

The total repair length is calculated by:
$l = 2l_{over} + l_{defect} + 2l_{taper}$ *(equation 20)*

l_{taper} *is recommended to be 5:1 ratio of the total repair length.*



Key

1 substrate, pipe wall
2 repair laminate
3 internal laminate defect
4 interface delamination de-bond
5 external defect (with filler)
6 internal defect
7 taper of laminate (extends beyond overlay l_{over})
8 adhesive fillet
9 resin rich surface layer

Figure 26 shows the different lengths used to calculate the total length for the repair

The final part of assessment is to perform checks to verify the design. This includes checks on the overlay of the wrap and the pressure difference between when the repair is performed and when the pipe reaches the maximum allowable pressure. A last check only affects repairs in tees, and restricts the maximum allowable design pressure for the pipe.

PART II - ACTION RESEARCH

7 ACTION RESEARCH WITHIN THE PIPE INDUSTRY

Based on the knowledge gained from the technical framework presented above, the thesis now enters the second part. With a holistic approach, combining different procedures, this part aims to answer the research questions:
1: "*What are the underlying reasons for today's limited use of FRP wraps as a pipe repair method in Sweden?*"
2: *"What would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?"*

7.1 Scientific methodology

In this chapter, the theoretical framework for the chosen research method is derived and described. The selected method is an *Action research*, which briefly can be defined as a method in which the researchers collaborate with their clients to make the problem's diagnosis and together formulate an appropriate solution. Furthermore, the practical steps in this process are presented and motivated below.

Inductive
When approaching the first research question there was no use in initially assuming a theory later to be verified. The underlying reasons for the limited use of FRP wraps in Sweden could simply not be intuitively guessed. On the other hand, formulation of a declaratory theories would rather suit as the *outcome* of research. This order of linking data with theory is an inductive strategy and its process involves drawing generalizable conclusions out of observations (Bryman & Bell, 2003). An inductive strategy is typically performed within a *qualitative* research.

Qualitative research
Research design is commonly divided into quantitative and qualitative research. The distinction between these approaches is heavily debated but will not be dealt within the scope of this study. Roughly described quantitative researchers employ specified measurements and qualitative researchers do not. Instead of measured sampling, the qualitative research emphasizes the formulation of words in the collection and analysis of data (Bryman & Bell, 2003). In accordance with the inductive stance mentioned above, qualitative research entails an approach in which theory emerge out of researched data. In this context, the meaning of term *data* is rather vaguely defined since it includes all various forms of information collected within the framework of the qualitative research.

Gradual development
When considering the open-ended formulation of the of first research question it can be understood that addressing it must be made in an iterative fashion (Bryman & Bell, 2003). Initially, the optimal steps to answer the question is not known and the next move to take in the research will constantly be dependent on the result of the previous. Through the development of the research the problem formulation was gradually narrowed down.

Flexibility and limited structure
Within this action research several encounters with people occurred. According to Bryman and Bell (2003), a research structure that is not kept too strict, increases the possibility to genuinely discover the perspectives of the people within the study. They further believe that the research problems best can be resolved by seeing through the eyes of the people involved. In doing so,

the full picture of the situation may be uncovered. However, the studied business area is unfamiliar to the researchers. Therefore, adopting a flexible strategy that enables sampling of important aspects that initially may not have occurred to the researchers, unacquainted to the situation, is suitable. As a result, fairly general rather than specific questions were formulated in the initial stages. This allows the researchers to engage in social settings with a general focus in mind and thereafter gradually narrow down the research by constantly making as many observations of these settings as possible. With this approach, the direction of the investigation can change in order to optimize the result.

Quality of research

Bryman and Bell (2003) argued that the actual findings of a qualitative research are restricted. For instance, it is questionable how the findings can be generalized onto other business settings. This is due to the fact that the research is conducted within a limited sample range, i.e. in collaboration with a small group of people in a certain locality and on a certain market. However, the objective of the research is not to formulate a theory representative on other settings, but to simply understand the chosen one alone. On similar grounds the possibility to replicate the research is highly doubtful. This is because the flexible and unstructured strategy cannot follow standard procedures and is instead dependent on the researchers own unique ingenuity. In this qualitative research, the investigators themselves are the main instrument for data collection and analysis.

Qualitative researches have been criticized for their lack of transparency. They tend to neglect satisfactory explanations to what the researcher actually have done and how the study's conclusions were derived (Bryman & Bell, 2003). Hence, this methodology chapter requires a rather thorough review. Naturally, there are limits to which this process can be described. Throughout this text, reasonable, yet fairly comprehensive explanations will be given to decisions and judgements made in the research. The chosen procedure of action research is criticized on identical grounds for its lack of repeatability, ambiguous quality, and for focusing on action at the expense of research findings. However, it is believed that the involvement of concerned actors in issues relevant to them provides an insight unattainable elsewise.

Configuration of Action Research

There are several reasons to why an action research is an appropriate choice for this study. This decision is motivated by its convenient process but also based on its contribution of value to the industry itself.

Argyris, et al., (1985) gave a summarized definition of action of research:

- Performed experiments are made on existing problems within an organization and are developed to facilitate their solution.
- Project progression in an iterative process including problem identification, planning, action, and evaluation.
- Generates re-education, changed patterns of thinking as well as action within actors in the participating organizations

A major motivator in this study was the fact that the outputs in this chosen type of research become more relevant, readable, and interesting to both the industry representatives and the academic audience (Bryman & Bell, 2003).

7.2 Actors in the industry and their role

On beforehand, the researchers had limited awareness of the industry structure and its associated actors. In accordance with the above described theory, an iterative process have therefore successively defined relevant collaborators. In this chapter these actors will be introduced briefly. Their role will be further developed in succeeding chapters.

Operators

Initially, the targeted market actors were the network owners and operators. After all, they themselves are responsible for the maintenance of their pipes. Therefore contact was established with the local municipal operators for district heating and also water and sewage; *Göteborg Energi* and *Kretslopp & Vatten.* Further into the research it was found that the repair method was used, to a small extent, in the petrochemical industry. However, it was decided to continuously work in collaboration with the introduced actors.

Manufacturers

The implementation of new technics on the market commonly starts with manufactures promoting their products. As for the case with FRP wrapping for pipe repairs the technic is, as mentioned before, already widely used internationally. Therefore, a fairly complete package including tested products, existing design codes and certified installations could potentially be adopted by the Swedish industry. Despite this fact, the FRP wrappings struggle to find acceptance in Sweden. The objective of this research is to explain this situation and therefore the internationally renowned manufacturers' perspective were of substantial value.

Contractors

Despite the relatively low use of FRP wraps in Sweden it was found that there regionally are some entrepreneurs with this expertise. Accessing their practical knowledge became a major focus within the action research and the methodology in doing so is further described in the succeeding chapter.

Inspection bodies

To assure proper quality, pipe repairs subjected to certain exposure must undergo a verification process. Certain companies are entrusted to inspect compliance with governing regulations. These companies are believed to possess valuable technical expertise on the topic as well as knowledge of the regulating framework. The consulted inspection bodies during the research were *Dekra* and *Inspecta*.

Authorities

It was gradually acknowledged that a major implication for the implementation of FRP wrapping in Sweden was governed by national regulations established by authorities such as *Arbetsmiljöverket* and *Myndigheten för Samhällsskydd och Beredskap*. The published regulations were therefore to be scrutinized in order to grasp the jurisdictional framework. Another authority, *SWEDAC* - Swedish Board for Accreditation and Conformity Assessment, acts on behalf of the previously mentioned. This authority inspect the inspector, which means that they review and approve certification- and inspection bodies.

Associations
There are several different associations that centrally organize and support their members in collective matters. *Svensk fjärrvärme* is the Swedish district heating association; *SPBI* the Swedish petroleum and biofuel institute; *Svenskt Vatten* the Swedish water & wastewater association and *Swetic* the Swedish association for testing, inspection and certification. Via these associations information and contacts can be distributed.

Non-governmental organization
The design standard SS-EN ISO 24817: 2015 has previously been introduced and will be further dealt with later in the report. *SIS*, the Swedish Standards Institute, coordinates the standardization in Sweden and communicate with international organizations such as the European CEN and global ISO. SIS arranged the implementation of SS-EN ISO 24817: 2015 in late 2015.

7.3 Practical methodology

When considering the vast number of actors introduced in the previous chapter it may be understood that achieving and maintaining contact with these presents challenges and must be made efficiently. The contact strategies in the early stages differed from how the relation was kept further on. The approach varied depending on the utility of the responses and the actors' willingness to cooperate.

Initial moves
The first step in the action research was primarily based on the findings made in the literature study which had given a brief overview of the involved industry actors. A substantial amount of the studied literature was published in collaboration with manufactures and contractors and hence the researchers had mostly been exposed to a certain perspective. Based on this view, an e-mail was formulated that sought to quote: "coordinate with industry representatives to attain a relevant objective with useful application". The e-mail informed about the upcoming research, asked for feedback and introduced for the concept of collaboration. Other than this targeted focus, the e-mail also asked for help in finding other relevant contacts within the industry. This sampling approach, where initial contact was made with a limited group of people and then uses these to establish contacts with others is called *snowball sampling* and is discussed by Bryman and Bell (2003). They argue that the method can be useful in qualitative research especially when tracing the connections may give useful insight in the relationship between people in the industry; a motivation which is relevant in this case. The e-mail was sent to several recipients, primarily network operators but also a few manufacturers.

The first mailing generated various responses which therefore required individual strategies in the following approach. Some declared that they had limited knowledge or ability to further contribute. Some recommended other people in the industry that they believed would take interest in the work. Others themselves accepted the opportunity to establish a deeper collaboration. Summarized, the responses appeared as expected based on the snowball sampling theory. No major conclusion could be drawn from this step, rather did it facilitate the future work.

Depending on the respondents' answer and role, the preceding move was one of the following:

- E-mail which expanded on the topic
- Telephone conversation to further establish the relation
- Suggesting or accepting meeting invitation

Early engagement with industry representatives, especially via telephone conversations, showed to be a profitable way to understand the structure of the industry. Before engaging in new contacts, reflection upon the purpose of that particular interaction was made. Respectfulness and patience were virtue so that the client would feel comfortable.

The research included meetings of various forms with different actors. The format for most of the meetings were kept flexible and adjustments were made to meet special requests and scheduling matters. The meetings were often arranged on the client's premises, on their initiative, although meeting rooms were always offered by the researchers.

Meetings with operators
Within the first few weeks of the research, meetings were set up with *Göteborg Energi* and *Kretslopp & Vatten.* The purpose of these initial encounters were first and for most socially motivated i.e. rise interest and gain trust. The fact that the overall strategy for the thesis was not entirely developed gave these actors the possibility to themselves adjust the research into a form applicable within their organization. Rather than directly addressing the research question, more conceptual considerations were discussed: *If FRP wraps were to be used, under which conditions would it be most suitable?* Moreover, a major objective of these meetings was to grow knowledge of the current pipeline network and how they are repaired today. These considerations have provided basis for the chapter "Pipe systems in Sweden". Similarly, the general approach towards implementation of new technics was discussed.

Meetings with certification bodies
After the initial contact with operators, manufacturers and contractors it gradually became overwhelmingly obvious that the certification bodies did and would play major roles for the status of FRP wraps for pipe repairs. At this point, the researchers had gained a more comprehensive understanding on the technical and practical aspects. However, better jurisdictional knowledge was necessary for a meaningful discussion with the certification organs. There are a quite substantial collection of regulation governing the use of FRP wraps for pipe repairs and the researchers themselves have limited prior knowledge in this field. These regulations will be covered in chapter 7.6.1 - *Governing regulations for FRP wrap repairs*. Luckily, the certification organs themselves offered guidance in interpretation of the regulations. Emanating from this groundwork, meetings were set up with representatives with technical expertise from the certification bodies.

The framework for discussion in these meetings was automatically defined and hence a certain structure was already given. Therefore, it was decided that the format for the talks would be semi-structured. Instead of a preprinted questionnaire, three themes were formulated on beforehand. In the first theme the interviewee was given the opportunity to present their way of work and describe their role in this matter. In the second they were asked to judge the applicability and comment the feasibility of FRP wraps in pipe repairs. Finally, the current hindrances for the use of the method was debated and prediction for the future developments in this field was discussed.

In order to encourage independent speech and leave the answers to the participants the questions asked within the themes were initially open ended. Further into discussions, when the essence of the subject had been narrowed down, more closed and complex questions were formulated (Eriksson & Kovalainen, 2008).

Authoroties
It was believed the possibility to discuss the matter with the responsible authorities would be limited. Therefore, formulation of precise questions was required to receive rewarding and constructive responses. Due to this, the contact with authorities was scheduled in a later phase when sufficient knowledge would have been achieved.

7.4 Semi-structured qualitative interviews

According to Pierre Carpentier at *Svensk Standard*, initiatives to adjust existing standards are often driven by manufacturers and contractors. The urge to sell their products and services could motivate their incentive to expedite the development of compatible design codes and regulations (Carpentier, 2016). Other stakeholders, such as the pipe network owners, can naturally also be part of this process. However, this may require a sufficient budget for research and development. Actors in the public sector, such as *Kretslopp & Vatten* and *Göteborg Energi* may have limited such funds. With this in mind, an interview session addressing the active FRP wrap contractors intends to elaborate the first research question. A major objective of the interviews was to achieve better understanding of the current situation. They can be seen as a sub method in the research and does not cover the entire main objective.

Emanating from the theory presented in the chapter 7.1 - *"Scientific methodology"*, the interviews were conducted qualitatively. To allow for exploration of the interviewee's point of view, i.e. encourage the direction in which interviewees take the interview, a certain extend of flexibility was needed. On the other hand, in order to keep focus on the research interest and facilitate grounds for comparison of data in the analysis, some structure was necessary. The optimal compromise was found to be the semi-structured interview (Bryman & Bell, 2003). When conducting the semi-structured interviews, the researchers had prepared a set of questions on fairly specific themes to be discussed, referred to as an *interview guide*. However, the interviewees were given vast freedom in how to respond. Depending on the progression of the interviews, the schedule changed. For example, questions were asked in a different order than outlined and follow up questions were added to pick up on things said by interviewees. Also, the exact formulation of the questions were customized to each interview. The sessions often took the form of organized talks rather than predetermined interviews. One could argue that they simply could be titled as meetings instead because the interviewees themselves often had some questions addressed to the researchers. However, this outcome was appreciated by all participants and can easily be justified within the framework for the action research (Bryman & Bell, 2003).
The themes for these set of interviews were;

1. Background of the research + Introduction of the interviewee and their work with FRP wraps
2. General discussion about the industry and its attitude towards new technics
3. The current situation for FRP wraps in Sweden
4. Future developments

The full interview guide and a list of interviewees can be found in Appendix A.

Conducting Interviews
Brinkmann and Kvale (2015) suggested that the first minutes of an interview are decisive for the overall result. With some elementary behavioral manners such as showing interest, listening and respecting what the interviewees are saying, a better outcome can be obtained (Brinkmann & Kvale, 2015). In accordance with the methodology presented for qualitative semi structured interviews, the formulation of the questions in the interview guide were open ended. Further into discussions, when the essence of the subject had been narrowed down, more closed and complex questions were asked (Eriksson & Kovalainen, 2008). Throughout the talks, the interviewee was given there possibility to clarify, elaborate and expand on the interview questions or other related concerns (Brinkmann & Kvale, 2015). When asked if they were comfortable with the interview being recorded, some of the interviewees declined. Thus, careful notes were taken instead. All participants had Swedish as their native language and naturally the interviews were therefore held in Swedish. However, due to the participation of the researcher's supervisor, a part of one interview was held in English. The interviewee in this particular case was an experienced English speaker and the change of language did therefore not disturb the quality of the talks. The length of the interviews varied between thirty minutes and two hours depending on how talkative the interviewee was and which topics that arose.

7.5 Analysis

In this chapter the process of analyzing the substantial amount of data collected is described. Because qualitative data, derived from an action research, typically take the form of a large body of unstructured material consisting of different media, they are rather complex to analyze. In theory there are actually no well-defined rules about how qualitative data analysis should be carried out (Bryman & Bell, 2003). However, the researchers found appropriate steps that gave some structure to the process.

Firstly, verbal sources such as the interview sessions with the contractors, the meetings with certification bodies as well as phone calls were considered. Secondly, all e-mail correspondence was gathered and re-read. Finally, all the remaining data collected was overviewed. Remember that relevant data must not only be direct sources but all forms of information collected within the entire action research.

After the compilation of the different sets of sources, the process of linking the data to the research question begun. As mentioned in the chapter 7.1-*"Scientific methodology"* the research has an inductive stance i.e. the analysis of the data lay ground for declaratory theories to answer the first research question. The question, "*What are the underlying reasons for todays limited use of FRP wraps as a pipe repair method in Sweden?"* assumes that there are *underlying reasons*. The analysis aims to find means to specify which these reasons may be. In order to do so, the material somehow needed to be better organized. After some thorough consideration, a simple way of categorizing the data was recognized. Below, these four categories are explained.

1. Some of the data collected needed little or no interpretation. The input information was complete and trustworthy and did also directly address the research question. This information was mainly given by the certification bodies when commenting on how regulations affect the use of FRP wraps. Moreover, this information could simply be verified by confirming its validity in given regulations.

2. Other data did not either need much interpretation but was only considered as fully trustworthy when re-mentioned by several sources. Similarly, this information corresponded directly to the research question and had a certain accuracy. Under this category, some technical issues and criticism of material properties are found.

3. Even single hints or guesses from more or less trustworthy sources that in some way directed the question were interesting. However, this type of information often required further research. Here, the iterative approach in the action research became useful. Uncertain statements could simply be verified by consulting other collaborative partners in the research. Other uncertainties were sometimes cleared after examining technical data sheets or reviewing the technical framework in the report.

4. In previous categories, adoption of typical qualitative analysis methodology has not really been made i.e. little interpretation of the data has been needed as the answers have been rather straight forward. This last category covers social aspects of the problem. On the contrary, here the qualitative analysis methodology has indeed been needed. The researchers successively discovered patterns that could explain why the use of FRP wraps in Sweden have been limited. However, these indications were rather abstract and required a more thorough analysis. In order to do so some analyzes technics were employed:

   - Different perspectives were viewed in the light of the actors' own interests
   - Statements that stood out were identified and their origin reviewed
   - Certain attention was payed to *how* the actors uttered their opinion

   Finally, common sense and the researchers' own experiences were used to draw conclusions on how social discourses within the industry could affect the use of FRP wraps.

7.6 Results

The basis of this study is of technical character, however, during the research it became apparent that much focus must be directed on jurisdictional concerns in order to answer the research questions. This realization has redirected the way in which the results are presented. In order to give adequate background to the final conclusions, firstly, *the governing regulations for FRP wrap repairs* must be addressed. Thereafter, to further clarify the current situation, a chapter describing w*here FRP wraps cannot be used today and why* is followed by w*here FRP wraps can be used today and how.* Not until now, the research can be concluded and recommendations on further research given.

7.6.1 Governing regulations for FRP wrap repairs

At first, the question whether FRP wraps are allowed for pipe repairs or not may seem simple; it is either allowed or not. However, on a second look, after having discovered the governing regulations, the situation appears less simple. In this chapter, a brief review of the regulations controlling the use of FRP wraps for pipe repairs is given. However, this matter cannot be summarized briefly with full coverage. Instead, the concerned reader is advised to themselves review the regulations referred to.

The Swedish regulations concerning pipes and pressurized equipment consists of the following documents:

- *Pressure equipment directive 14/68/EC (PED) European Union Directive*
- AFS 2016:1 – *Arbetsmiljöverket* – Requirements on pressurized equipment and pipes, based on PED
- ASF 2002:1 – *Arbetsmiljöverket* – Regulations on how to use pressurized equipment and pipes
- ASF 2006:8 – *Arbetsmiljöverket* – Regulations on how testing of pressurized equipment and pipes should be performed
- ASF 2005:3 – *Arbetsmiljöverket* – Regulations on how inspection of pressurized equipment and pipes should be performed
- ASF 2005:2 – *Arbetsmiljöverket* – Regulations on how containers, pipes and facilities should be designed
- MSBFS 2009:7 – *Myndigheten för samhällsskydd och beredskap* – Regulations on how natural gas pipelines should be designed

In Sweden, the European Union directive ”*Pressure equipment directive 14/68/EC (PED)”* regulates how newly produced pipes should be designed. The criteria in this directive is mandatory to meet within the EU. *Arbetsmiljöverket (Swedish work environment authority*) has, based on the *PED*, made national regulations for new produced pipes described in *AFS 2016:1.* This regulation is adapted for pipes and pressurized equipment that has a maximum pressure higher than 0.5 bar. Yet it excludes pipelines used to transport media between facilities such as pipes for distribution of district heating. It also excludes pipes and equipment used for water power plants.

However, the *PED* and *AFS 2016:1* do not handle repair of pipes. For this concern the *PED* refers to national regulations (European Commision, 2015).
“*AFS 2005:3-Besiktning av trycksatta anordningar*” (*inspection of pressurized equipment*),”*Swedish work environment authority*”, defines how inspection on pipes should be performed. Some pipes carrying pressurized media are subjected to authorized inspection due to *AFS 2005:3 §12*. To determine whether a pipe is subjected to authorized inspection, the diagrams 6-9 in AFS 2016:1 categorize pipes into class A-C. For pipes in class C, no such inspection is required. These pipes fall under the general safety responsibility of the pipe owner. However, inspection of pipes in class A and B must be accomplished with respect to *AFS 2005:3 §29* and *§30*. *AFS 2005:3 §29* specifies how inspections should be performed when a pressurized system has undergone extensive repair. Stated in *AFS 2005:3 §30,* the inspection must prove that the repaired system fulfils the regulations described in *AFS 2016:1* with exception to *§3.3* and *§3.4*, and the regulations stated in *AFS 2005:2*. The inspection has to be done according to the rules set by a third party organ, i.e. inspection body, stated in Annex 1 in *AFS 2016:1* and *AFS 2005:2*.

This means that repaired pipework and pipelines, depending on classification, have to fulfil the regulations in either *AFS 2016:1* including Annex 1 or *AFS 2005:2*. *§3.1.2* in both *AFS 2016:1* and *AFS 2005:3* describes how permanent joints should be designed and tested. It states that

1. the joints should have the same or higher properties as the material that is joined or that the properties have been taken into account in design calculations.
2. the joint should be performed by personnel that has sufficient competence to perform the work.
3. the methods and personnel should be certified by a third part body that should be either a notified body or by a third party organization recognized by a member state.
4. the third party should ensure that above is fulfilled by relevant tests stated in harmonized standards or equal tests and investigations.

The definition of *permanent joints* is "*joints which cannot be disconnected except by destructive methods*". Discussion has arisen concerning the definition of permanent joints and whether FRP wraps should be considered as such or not. Inspection bodies have claimed they that FRP wraps should motivated by *Guideline F-05* to PED 2014/68/EU. Yet, some manufactures beg to differ. At the time of publication this issue had not been resolved.

In the fourth point above, the regulation refers to "harmonized standards". Previously, in chapter 6 - *"Design of FRP wraps for pipe repairs"* the *SS-EN ISO 24817:2015* was introduced as the appropriate standard for FRP wrap design. This standard is not written in accordance with the EU directive and can therefore not hold the status of harmonizing. A purpose for having a harmonized standard is that *manufacturers, other economic operators, or conformity assessment bodies can use harmonized standards to demonstrate that products, services, or processes comply with relevant EU legislation.* Consequently, these advantages do not automatically hold for the case with FRP wraps for pipe repairs if *SS-EN ISO 24817:2015* is employed. This fact have proved to complicate the quality assurance of the design procedure.

Even though the regulations take repair into consideration there are, as in most regulations, no specified methods on how repair should be performed or inspected. This means that the regulations allow for interpretation. Inspection bodies in Sweden have, in consultation of *Arbetsmiljöverket,* interpreted this as that repaired pipes have to fulfill the regulations in *AFS 2016:1*. This means that any repair of pipes in category A and B, other than pipe replacements, does not fulfill the regulations. As discussed in chapter 2.2 – *"Conventional methods for pipe repair",* pipe sections of category A and B, that requires repair have to be cut out and refitted with a new section welded or fixated with flanges to the old pipe. Only in doing so, the system can be considered to hold the same standard as when newly produced.

Dekra (2016) described that if a damaged pipe is repaired with FRP wraps the original system still contains a defect. The repair may solve the problem but does not restore the pipe identical to its original appearance. Thus, the regulations in *AFS 2016:1* are not fulfilled. Even if a FRP wrap product *itself* would to be certified and fulfill all regulations in *AFS 2016:1* and *AFS 2005:2,* it would still, due to what is said above, be uncertain if it could be used as a pipe repair in an existing system. The text above shows that for pipes of class A and B, it is complicated to implement FRP wraps repair with current regulations.

7.6.2 Where FRP wraps cannot be used today and why

As mentioned in the text above, there are obstacles in the implementation of FRP repair method governed by *PED*. This chapter attempt to briefly explain which pipes that are affected by *PED*. *AFS 2016:1* states that neither pipes used for natural gas and transportation of fluids between facilities, nor systems for waste water and fresh water distribution are affected by the regulation. *AFS 2016:1* also excludes products used at nuclear plants and systems designed to be used with pressures below 0.5 bar. Roughly concluded, this means that pipes used in petrochemical and process industries are affected by *PED* and must not be repaired with FRP wraps today. Natural gas is regulated in *MSBFS 2009:7*. This code states that the pipes used for transportation of natural gas are subject for inspection which may decrease the possibility to use FRP wraps as a repair method due to the fact that *AFS 2005:3* describing inspection procedure refers back to *PED*. For all kind of pipes mentioned in this chapter, the possibility to repair with FRP wraps today is limited. This is, as mentioned above, due to that repairs are not described or regulated in any of the regulations explained in the previous section. However, there are some cases where it could be possible to use it which is described in the next section.

7.6.3 Where FRP wraps can be used today and how

District heating and cooling distribution systems are excluded in *PED* but regulated in *AFS 2005:2*. Water and waste water pipes are also excluded in *PED*. Since there is no guide for how, when and where to use FRP wraps today, each case has to be checked so that it is ensured that wraps can be used. As a rule of thumb, pipes that are not subjected to inspection may be repaired with FRP wraps. Therefore FRP wraps could be an option if a water, district heating or waste water pipe is subject to a repair. Since district heating and cooling are regulated in *AFS 2005:2* it is especially important to check whether the repair could be done with FRP without violating any regulations. This could possibly be controlled with help of an inspection body which has good knowledge of how each regulations works and what pipes that are affected by these.

7.6.4 Conclusion & recommendations on further research

In this chapter the action research is concluded and attempts are made to answer the research questions. A thorough answer to the first research question "*What are the underlying reasons for today's limited use of FRP wraps as a pipe repair method in Sweden?"* is given. There are no simple single answer to the question but several factors that combined explain the situation. The second research question "*What would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?"* is addressed but not as thoroughly dealt with. Further progress is instead delegated to future research and to industry representatives themselves. The holistic approach taken in this action research has generated a broad spectrum of aspects. The output from the above described analysis is categorized under three main headlines namely: *Technical- Jurisdictional* and *Social aspects*.

Technical aspects

Lack of material knowledge among several actors

Judging from the phraseology used when people technically described FRP as a material, knowledge is missing. For example: when the word *strength* is used, it commonly falsely intends to include both *stiff* and *though*. Several similar misunderstandings give appearance of unprofessionalism and leads to restricted reliability and effectiveness. Hopefully, as the material become more used, the common knowledge will increase.

Technical obstacles with FRP wraps for pipe repair
Although FRP wraps introduce several advantages, naturally the technique meet some challenges. Below the most crucial issues that have become apparent in the research will be presented.

Quality assurance (Inspectability) of repair
When compared to conventional repair methods, such as welding, improvements are necessary. The current installation procedure is considered to give fluctuating quality levels with somewhat unreliable inspection measures. This matter is further addressed in chapter 4.6 “Quality assurance”

Preparation of pipe surface – Blasting to required grade of fineness
In order to ensure proper bond between the pipe and composite repair the surface should optimally be blasted to fineness level “white metal”. This basting procedure is described in chapter 5.1 “Repair procedure”. The hazards related to blasting on high pressure pipes transporting hot media is described in chapter 5.2.4 - "Aspects of construction". On severely damaged pipes and where repairs are difficult to access, obtaining this level of fineness have proved to be complicated.

Mechanical erosion
Some media in the industry contain particles that through erosion attack the interior of the pipe material. A concern expressed by operators and inspection bodies is how well FRP wraps would withstand such wear. Due to the limited research on this matter the stakeholders have remained reserved to the product.

Chemical resistance
One of the claimed advantages with FRP wraps are their chemical resistance. Therefore, listing it as an issue may seem confusing. However, throughout the research this matter has been frequently addressed. The industry are uncertain of the technics performance on chemical resistance. The resistance towards chemical attacks varies between FRP wraps and conventional pipe material such as steel. Therefore, despite the fact that FRP wraps generally have comprehensive resistance, the dissimilarity to conventional materials is seen as a weakness. A more comprehensive review of the chemical hazardous applications where FRP wraps could be used would be necessary.

Ability to restrain propagation of corrosion
On some occasions, especially during internal corrosion, a repair measures with a FRP wrap will not prohibit further propagation of corrosion. If the repair is intended to last long term, the pipe must simply be replaced.

Fire resistance
Swedish authorities, particularly MSB, set high standards on work environment. Limited availability to research on how FRP wraps resist fire have led to uncertainty within the industry, further commented in chapter 5.2.4 - "Aspects of construction". This issue requires further clearance but is not covered within the scope of this thesis.

Temperature resistance
Operators have expressed their concern that FRP wraps will not withstand sufficiently high temperatures. This problem has been acknowledged by FRP wrap manufacturers during recent years, a development briefly discussed in chapter 5.2.4 - *"Aspects of construction"*. Today, some products withstands service temperatures above 200 °C allowing for a wider spectrum of use.

Environmental friendliness
Today the industry claim they have high ambitious on limiting their environmental impact. Components such as plastics and epoxies are traditionally not regarded as the most promising in that aspect. Therefore, some argue that FRP wraps are already an outdated technique. However, the possibility to, during operation, prolong the service life of pipe speaks on the contrary. Some research can be found on this matter. Notwithstanding, in order to properly address the environmental impact of FRP wraps further research via Life Cycle Assessment would be feasible.

Exaggerated disbelief of the quality of the technic from regulating actors
Despite the possibility to overcome or disregard some of the above mentioned challenges, regulating actors such as network owners, inspection bodies and authorities tend to exaggerate their disbelief towards the technic. Not seldom the disadvantages are presented habitually without obvious motives. This behavior could possibly be because of lack of knowledge and uncertainty towards something still not conventional.

Exaggerated promotion of the quality of the technic from contractors and manufacturers
On the other hand, actors that would obviously benefit from of a greater use of FRP wraps, such as contractors and manufacturers, tend to be simplistically positive. The researchers believe that these actors would achieve greater trustworthiness with a more nuanced promotion of the technic. If challenges would be openly discussed maybe solutions could be found together with other opposing parties. With the current approach from contractors and manufacturers, mistrust easily occurs.

Limited knowledge of international advancements
Recent advancements on the international arena with regard to improvements of the FRP wraps as a repair method is not closely followed by the Swedish industry. The progress, sometimes verified by renowned foreign inspection bodies such as DNV-GL and TÜV Rheinland, is therefore not acknowledged. The Swedish industry would probably benefit from greater international interaction.

Jurisdictional aspects

Confusing applicability
As presented in chapter 7.6.3 -*"Where FRP wraps can be used and how"* there are pipes on which the technique is perfectly okay to use. However, the distinction between when they are allowed or not can be difficult to fully understand. This confusion lay ground for several of the following issues that will be described here under "Jurisdictional aspects" and under the forthcoming "Social aspects".

Gaps and inconsistencies in regulations

Chapter 7.6.1 - *"Governing regulations for FRP wrap repair"* provides a brief guidance to how the governing regulations for FRP wrap repairs could be interpreted. Evidently, there are several inconsistencies still to be resolved. Most significantly, the national regulations lack paragraphs on how to handle repairs. Currently, new regulations are developed on this area but if this matter is addressed remain unanswered.

SS-EN ISO 24817 is not a harmonizing standard

Yet another issue introduced in chapter 7.6.1 - *"Governing regulations for FRP wrap repair"* is the fact that *SS-EN ISO 24817* is not a harmonizing standard. Because of this reason, the legitimacy of the standard is limited. Therefore, designs based on *SS-EN ISO 24817* must undergo further verification than elsewise.

Interpretation of regulations

An observation made in the semi-structured interviews was the way in which the contractors related to the jurisdictions. Often contractors referred to the jurisdictions as if they were written in such a way that they *specifically restricted* the use of FRP wraps. Moreover, it is commonly assumed that it is an authorial decision that prohibits FRP to be used. With this mindset it is believed that it is adequate with a simple change of standpoint from the authorities in charge, such as *Arbetsmiljöverket* (AV) or *Myndigheten för Samhällskydd och beredskap* (MSB). However, as explained in chapter 7.6.1 - *"Governing regulations for FRP wrap repair",* the actual convention is not this elementary. Unless some substantial advancements are made on the technical area it is likely that the current situation will remain for some time. For a more permissive handling of FRP wrap to be possible, it is plausibly required that the governing regulations are rewritten. Though, a rewriting of an AV regulation is a hefty task not made swiftly. Moreover, it is not likely that an update is made only to allow for FRP wraps to be used. Although, the obvious general need for competitive solutions for quick and simple in-situ pipe repairs may motivate changes in the current regulations.

Social aspects

Different viewpoints on division of responsibility

A common viewpoint among contractors is that they are unjustly treated and not given equitable feedback from inspection bodies and authorities. Contractors request guidance on when, where and how they can use FRP wraps. In a way they claim a right to know exactly how the regulations should be interpreted. On the other side, neither *AV* nor *MSB* are interested in discussing single cases. They argue that their role in this matter is to provide and maintain the regulations, not interpret them on contractors' behalf. However, it may be justified with a slightly more informative approach from the authorities to facilitate a more efficient use of the regulations. Middle hands in this constellation are the inspection bodies. In their role they communicate with both parties, thus aware of the conflicting viewpoints. However, being independent profit-making actors these companies naturally expect return on their services. Today, inspection bodies offer the industry different sorts of guidance packaged in education programs. Collaborative experience exchange on such courses or similar events could ease the current frustrated situation. Up until today, the researchers have not heard of such events.

As a result of their uncertainty, contractors have a tendency to approach the issue of not knowing how to interpret regulations through trial and error. Hence, they suggest or even perform FRP wrap pipe repairs only then to realize that it will not be accepted by inspection bodies.

Insufficient communication and guilt mentality
Unconsidered language lay ground for misinterpretations. When working with the action research the researchers often received conflicting statements. In the situation that has arisen regarding the limited use of FRP wraps for pipe repairs in Sweden people tend to air their frustration by guilting others. Unfortunately, uncalled for accusations seems to have created an atmosphere where renounced responsibility is justifiable. In the current situation actors seem to wait on others to make progressive moves instead of attacking the problem themselves.

Lack of economic incentives
The reason why very few actors are willing more thoroughly investigate how FRP wraps could be further implemented depends on the believed lack of economic incentives. Swedish operators and network owners seem to have been unwilling to invest money in research. International manufacturers have been able to easily implement their products abroad and are perplexed by the hindrances in the Swedish regulations. However, few actions are taken to address this matter. The actors that most actively strive for change are the national Swedish contractors. In the semi-structured interviews they clearly expressed an urge for development. As mentioned in above paragraphs they currently lack understanding of the regulations and consider themselves as unfairly treated. Moreover, being rather small companies they also seem to lack finical strength to undertake research on their own. If funding were to be found, an appropriate first step would be to consult inspections bodies to investigate the technique in relation to the regulations and give a clearer judgment on its future outlook. Similar research could naturally also be undertaken by other instances, such as universities.

Further research
In addition to the comments on future research given in the paragraphs above, some more recommendations will now be suggested.
First and foremost, additional investigation of the first research question should be conducted. This research has approached the question holistically. To further explore the question, favorably, experts of each field should investigate it more thoroughly. Special attention should be given to the concluding remarks listed previously in this chapter.
From an academic viewpoint, further research could for example aim to develop distinct guidelines for the use of FRP wraps for pipe repairs. A future project should include:

- Tools to ensure a reproductive method with continuous quality. Establishment of common measurements for quality assurance to be standardized for the entire construction cycle, stretching from material testing in lab, to application procedures and inspection routines. *SS-EN ISO 24817:2015* provide such measurements but must be customized and verified to meet governing regulations.
- Complete investigation of the technical issues listed under the headline *Technical obstacles with FRP wraps for pipe repair* above.
- Publish guidelines on how to use FRP wraps in a accessible and user friendly format. The end user in the industry should directly be able to implement the guidelines in their work routines.

PART III – CASE STUDY

8 CASE STUDY

To illustrate how the design procedure for FRP wraps in pipe repair works, a case study was performed. Moreover, the case study aims to support and facilitate the analysis of the second research question: *What would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?*

The case study was made in cooperation with *Göteborgs Kretslopp och Vatten*, the department responsible for drinking water and sewage in Gothenburg. The standard used to perform the design was *SS-EN-ISO 24817:2015*; the Swedish adaption of the international code EN-ISO 24817. The material properties for the rehabilitated pipe were treated in accordance with Eurocode ”*DIN-EN-1561 Gray Cast Iron*”.

The configuration of the defect addressed in this case is developed to represent a real defect. Despite the fact that the defect is fictive, it is designed as an accurate estimation of a frequently occurring damage in the given environment.

8.1 Background

The pipe to be repaired was constructed in the 1960's and is situated in a water tower in the Gothenburg urban area. The tower is about 20 meter high and located around 150 m above sea level. Until the 1970's a majority of the water distribution pipe networks was constructed of casted iron (Malm, et al., 2011). In this case the pipe is made of gray iron, a casted iron consisting of about 3-4 % coal. The classification of this gray iron is EN-GJL-300. This class gives the material properties for the original pipe and are used in the calculations designing the pipe.

Table 10 Shows the material properties of the pipe

Tensile strength	300 MPa
0.1 % proof stress	195 MPa
Compressive strength	960 MPa
0.1 % Compression yield strength	390 MPa
E-modulus	108 GPa
Linear expansion coefficient	10,0 µm (-100 to 20°C) 11,7 (20 to 200°C)
Density	1,7·1000 kg/m^3

The pipe in the water tower transports drinking water to the reservoir in the top of the water tower. The media transported in the pipe is clean water with temperatures between 0-20°C. The ambient temperature follows the outdoor temperature. The pipe has due to several years of service in a humid surrounding started to corrode externally and must be maintained, within a near future, to ensure the serviceability. The dimensions of the pipe is shown in the figure below.

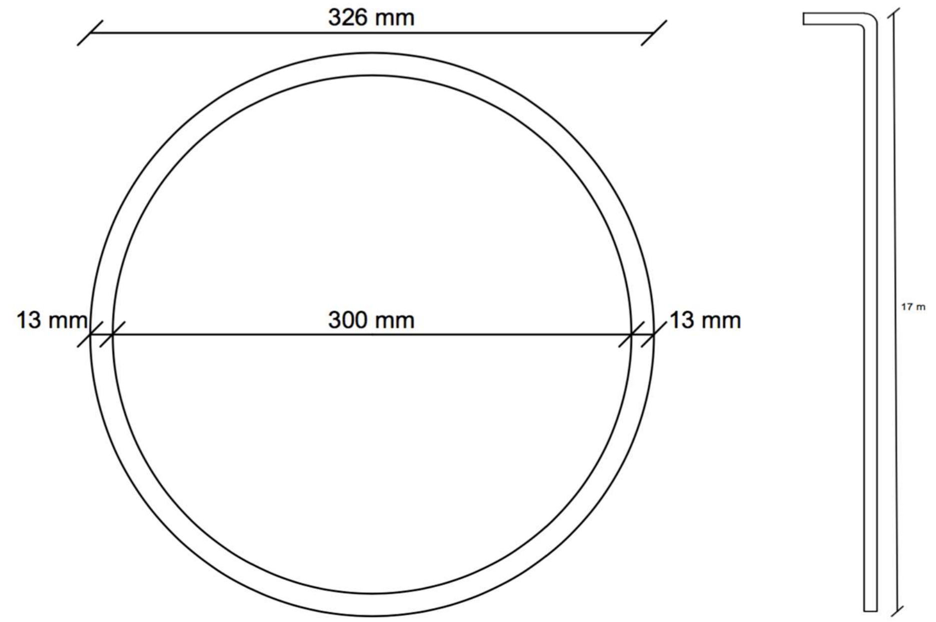


Figure 27 Shows the original pipe geometry with measurements. To the left – cross section. To the right the total extrusion of the pipe is illustrated.

Since the pipe stretches vertically, a conventional repair methods is difficult to perform. Due to the height in the water tower and the length of the pipe a contractor with experience of altitude work has to be hired. With the traditional method, i.e. cutting and refitting with new pipes, the work takes long time and requires advanced equipment to lift in the new pipes. If FRP wraps would to be used instead, the time of the pipe's off-service would be decreased to zero in the same time as the repair time would be decreased, thus reducing costs for the pipe owner.

8.2 Design of the repair

Due to the low pressure in the pipe, there is no need for a wrap with particularly high tensile strength. The E-module of the gray iron pipe is lower than for normal construction steel which decrease the significance of the fiber stiffness. In fact, all the three fiber types presented in chapter 3.1.1 - *"Fibers"* could potentially meet the mechanical perquisites. Consequently, the determining factor becomes economical. On this matter, under these conditions, glass fibers offer the highest cost efficiency.

The repair solution was chosen to a GFRP manufactured by *Neptune Research Inc. (NRI)* (Neptune Research, 2016). *NRI* are known for their complete products with high quality. The different components in a repair kit must interact efficiently, something provided by a wrap solution called *Syntho Glass XT*. The product was chosen to make this assessment as close to the reality as possible. Many of the contractors working with FRP in Gothenburg area are today use NRI's products. Hence, if a similar repair was to be made with FRP wraps, there is a large possibility that this product would be used.

Except for the fiber fabric, the system consist of:

- Filler: Syntho-Poxy™HC
- Anti-Corrosion Primer: Syntho-Subsea™LV Epoxy
- UV protection: Syntho-Glass®UV
- Compression Film

The repair kit is designed to meet the recruitments in the international standard for FRP wraps, *ISO TS24817*.

The product's full technical datasheet is found in Appendix D. The data used in this repair assessment, can be found in the table below. The hand calculations referred to in this chapter are found in Appendix C.

Table 11 Shows the input data for the laminate

E-Modulus – Circumferential direction	30.5 GPa
E-Modulus – Axial direction	15.8 GPa
Thermal Expansion Coefficient – circumferential direction	$10.3 \cdot 10^{-6}$ /°C
Thermal Expansion Coefficient – axial direction	$15.14 \cdot 10^{-6}$ /°C
Laminate thickness	0.33 mm
Poisson Ration	0.133
Lap shear strength	129.05 MPa
Heat deflection temperature	195 °C
Glass transition temperature	133 °C

8.2.1 Assumptions and limitations

Iron pipes may deviate from its straightness up to 0.15% of its length (Gustavbergs Rörsystem, 2014). Based on this guidance, a similar estimation is considered to be fairly representative for the case studied. Therefore, it is estimated that the pipe has an initial imperfection of 8.5 mm which leads to a bending moment on the pipe. This axial bending moment is calculated to 0,127 kN. The torsional bending moment is assumed to be so low that it can be neglected in this calculation. The defect is assumed to be caused by external corrosion and is estimated to be of circular shape with a diameter of 200 mm and maximum depth of 12 mm.

8.2.2 Defect

In the calculations, the maximum defect depth, 12 mm, is considered to extend all over the circular defect. This is a conservative assumption which means that the result of the design assessment will be on the safe side. Below, illustrations of the defect are presented. The defect is located 0.5 meters above the floor of the water tower. The remaining 16.5 meters above the defect is assumed to be in a condition without urgent repair needs.

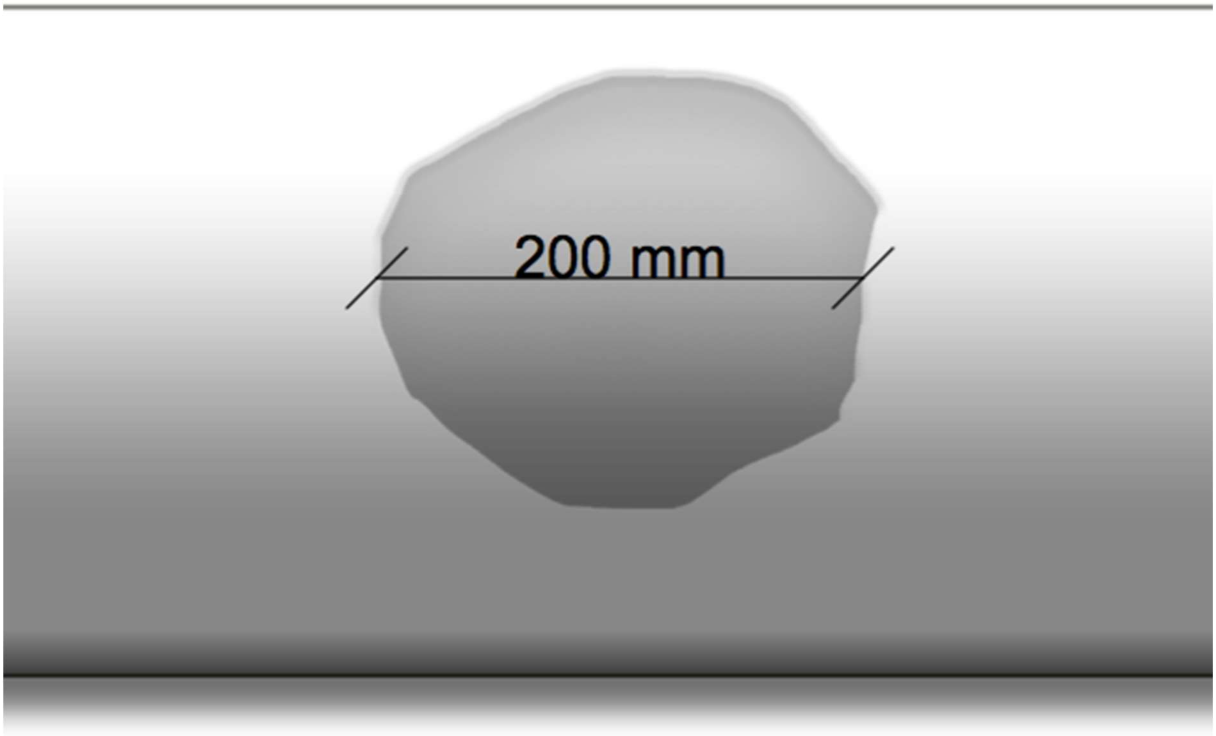


Figure 28 Illustrates the damage of the pipe from the side

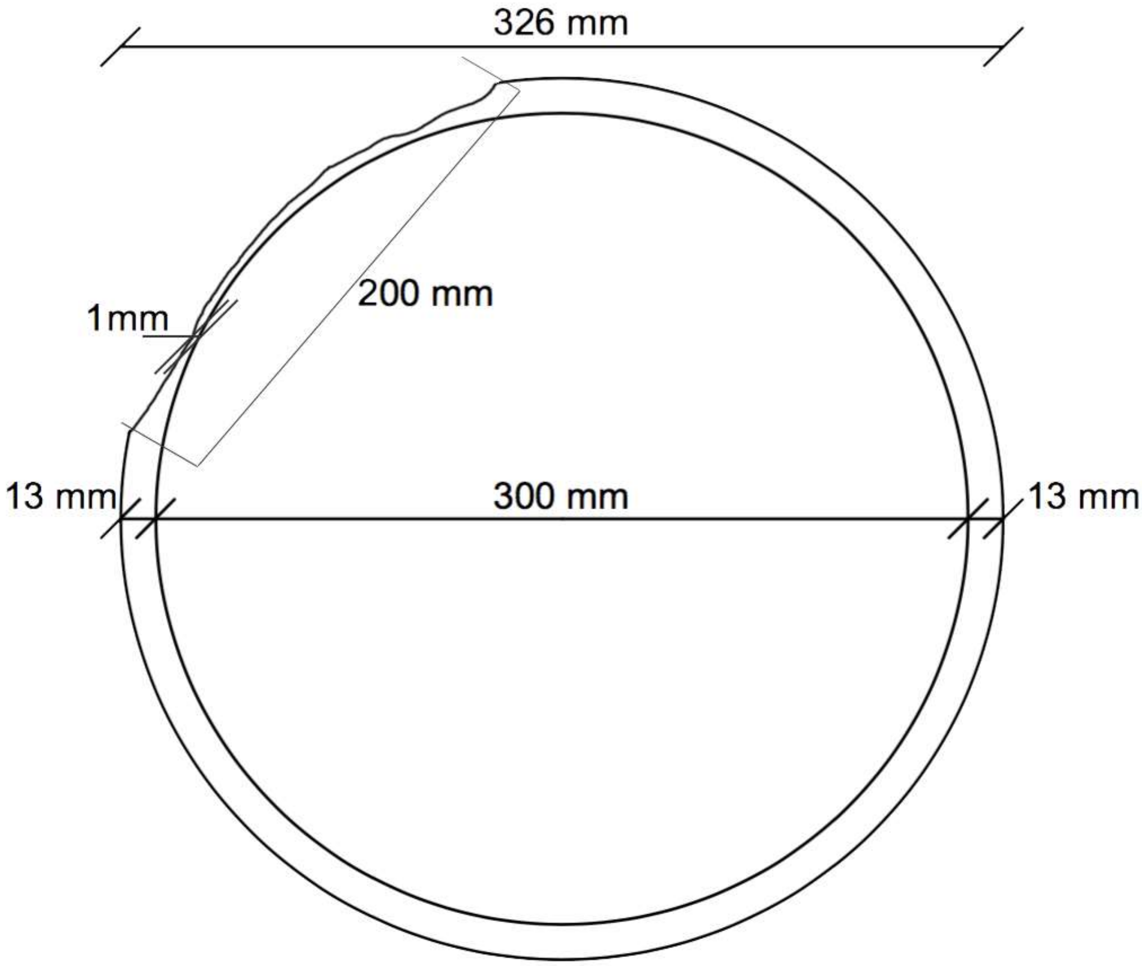


Figure 29 Shows the section of the damaged pipe

8.2.3 Boundaries

The pipe is casted into a concrete fundament at the bottom of the pipe. Thereafter it stretches upward 17 m vertically. In the upper end the pipe is attached to the water reservoir with a rubber gasket. The pipe's boundary condition is, as mentioned above, assumed to be simply supported. This prevents the pipe from moving vertically and horizontally, but do redistribute moments in the supports. The conditions are described in the picture below.

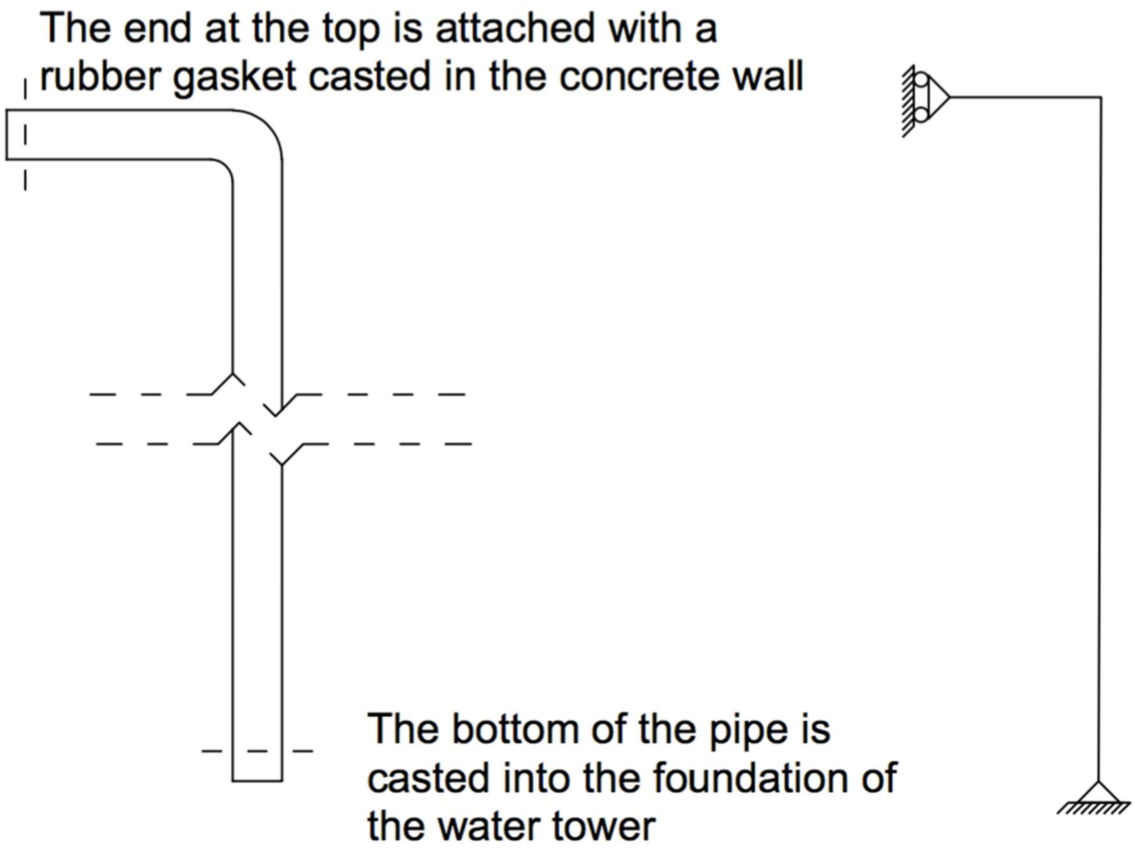


Figure 30 Shows the attachments and the boundaries of the pipe.

8.2.4 Loads

The loads acting on the pipe are mainly loads perpendicular to the pipe wall, i.e. pressure. The load in the pipe is proportional to the height of the water tower. With a height of 20 meter the pressure inside the pipe was calculated form the fact that 1 m water pillar equals 9.8 kPa. Therefore, the water pressure at the location of the defect is approximately 0.2 MPa. This means that the pipe is not affected with the limitations in the PED or national regulations discussed in the previous chapters. In combination with this, the pipe is subjected to an axial force from the self-load. The pipe material has a density of 7250 kg/ m^3. With a sectional area of 0.013 m^2 and a height of 16.5 m the total volume is 0.211 m^3 which gives a total weight of 1529 kg. The total load in the bottom of the pipe can then be calculated to 15 kN. The pipe is assumed to have an initial imperfection which leads to a bending moment on the pipe. The axial load will due to the initial imperfection results in a shear load. This has the magnitude of 45 N, which is a considerably low value.

8.2.5 Hand calculations

The defect is of Type-A (not through wall). Since the pressure in the pipe is moderate, the class of the repair is Class 1 (<2 MPa and <40 °C). The loads acting on the pipe are described above.

From these loads and pressure equivalent forces and pressures were calculated taking all different loads in consideration. The standard has a certain procedure to follow depending on what type of repair to be done. This is described in chapter "6.1 - Design procedure". The procedure for this case study is shown in Figure 31 below.

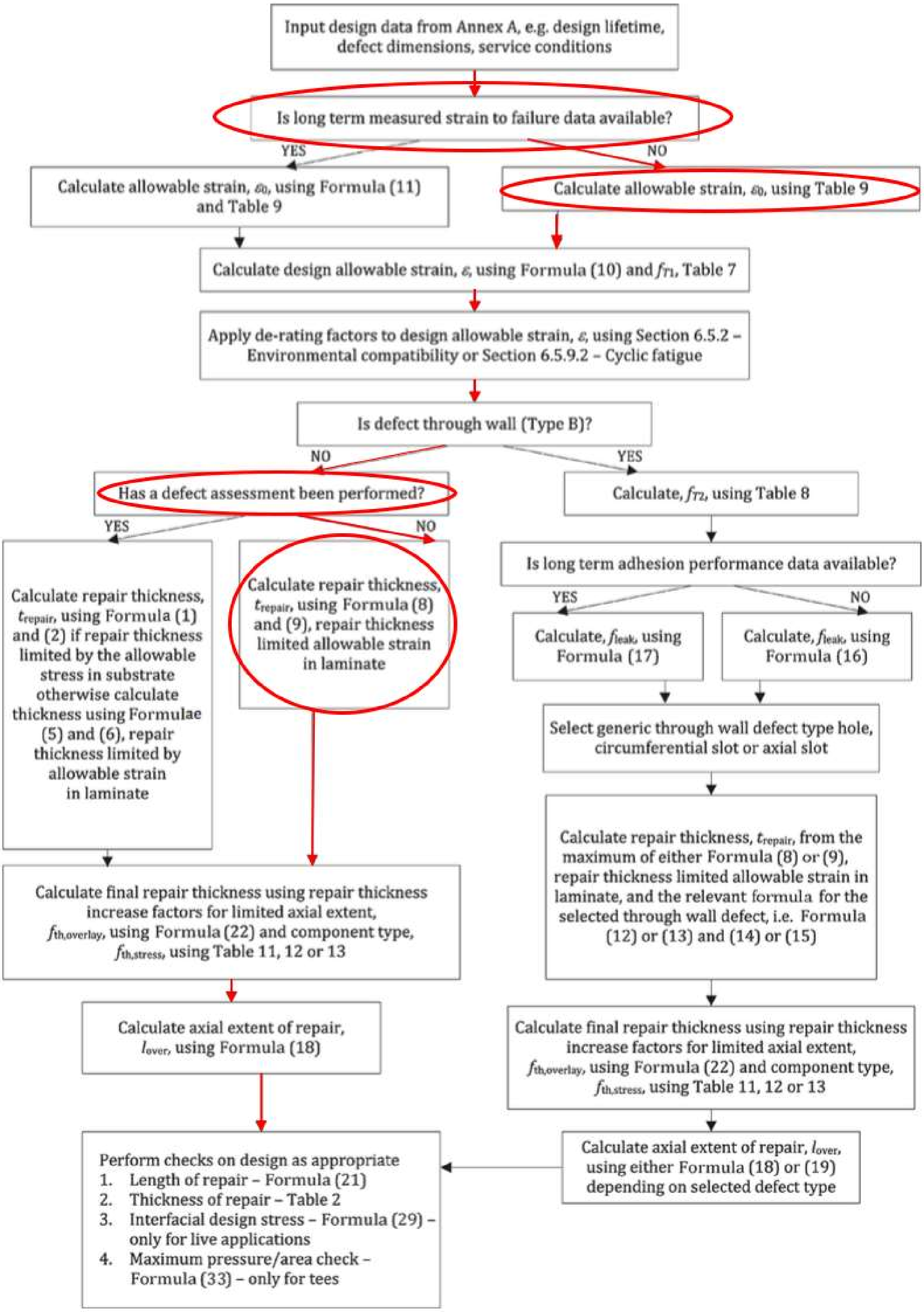


Figure 31 Illustrates the design procedure for the case study. The steps taken are marked in red.

The first step in the assessment handles the allowable strain for the repair. This was calculated to $5.313 \cdot 10^{-3}$ mm/mm and $5.217 \cdot 10^{-3}$ mm/mm for the circumferential and axial direction respectively. With these two values a minimum thickness for the repair was calculated using the equivalent loads and pressures and geometrical and material properties data for the pipe. The minimum thickness was calculated to 0.359 mm. With the laminate thickness of 0.33 mm, 2 layers of wraps were required. The axial extent of the repair was calculated to 0.645 m. The intended wrap is 30 cm wide. When wrapped around the pipe an overlap of half of the width is recommended. With a pipe diameter of 326 mm the circumference is about 1 m. The wrap is wound in two layers which means that the total length of the wrap will be about 12 m.

8.3 Cost analysis

In this part of the case study the cost of a conventional repair method and repair with FRP wraps are compared. This comparison is made to investigate and illustrate the economic aspect of using FRP-wraps.

8.3.1 FRP wrap repair

A step-by-step description of the repair procedure is given in chapter 5.1 - *"Repair procedure"*. Considering that the defect of the pipe is located only 0.5 m from the floor and that the axial extent of the repair is 0.625 m, the accessibility allows for a simple installation without need for scaffolding. The repair is assumed to be conducted by two construction workers during half a day - 4 hours.

The wrap repair is made with the Syntho-Glass XT kit. The components of the system are:

- Wrap (Fiber fabric) SG430
- Epoxi GS02
- Wulk rubber WG3

All required equipment are provided by the entrepreneur included in the unit price of the workmanship. If needed, the repair could have been conducted on the pressurized pipe in service. However, it is likely that the repair is made during hours of down time. Moreover, the repair is assumed to be able to stop any further progression of corrosion at the location of the defect.

8.3.2 Conventional repair method

The conventional repair example is chosen to a pipe replacement. The method is commonly employed and naturally restores the pipe to its original standard. However, an entire pipe section, stretching 6m from floor and up, must be removed and refitted. The operation causes downtime on service. The weight of the pipe section to be replaced is estimated to 600 kg. Recycling is assumed to be made without costs, except for transportation. The new pipe section is a Tyton-system in cast iron (Gustavsbergs Rörsystem, 2016). The components of the system are:

- Tyton N pipe, 6m, DN 300
- Anchor ring Tyton N, DN 300
- Anchor bolts

The weight of the section is approximately 500 kg. The combined work of dismantling and installation is estimated to be conducted by two construction workers during two days. The reservoir is normally refilled during nighttime. Therefore, if the installation is completed on schedule, there will be one night on which the reservoir cannot be refilled. Apparently, buffer capacity and resilience within the drinking water distribution network can allow for this. This may cause some cost for inconvenience and rescheduling, however, disregarded in the cost calculation. The weight of the pipes as well as the height require the work to be carried out by lifting machinery. This setup includes: vertical mast lift, chain hoist, pipe lifter hook, harness, harness safety inspection and impact wrench.

8.3.3 Comparison of construction costs

Table 12 FRP wrap cost calculation

Material				**4650**
Wrap (Fiber fabric) SG430	1	1400	SEK/pc	1400
Epoxi GS02	1	2300	SEK/pc	2300
Wulk rubber WG3	1	950	SEK/pc	950
Equipment				**0**
No additional equipment required				
Transport				**624**
Service vehicle	1	624	SEK/day	624
Labor				**3460**
Construction workers incl. basic tools	8	432,5	SEK/h	3460
Total				**8734**
Reference:				
Olofsson, Said. Project Manager, SMC-Sweden. Mail 20160821				

Table 13 Conventional repair - Pipe replacement cost calculation

Material				**14000**
Pipe section	6	1500	SEK/m	9000
Anchor ring	1	5000	SEK/pc	5000
Equipment				**3110**
Chain hoist	2	266	SEK/day	532
Impact wrench	2	160	SEK/day	320
Pipe lifter hook	2	309	SEK/day	618
Vertical mast lift	2	578	SEK/day	1156
Harness	2	142	SEK/day	284
Harness safety inspection	1	200	SEK/pc	200
Transport				**3430**
Delivery of equipment	2	715	SEK/way	1430
Transport of pipes with crane lorry	2	1000	SEK/way	2000
Labor				**13840**
Construction workers incl. basic tools and service vehicle	32	432,5	SEK/h	13840
Total				**34380**
Reference:				
Andersson, Peter. Sales Manager Gustavsberg Rörsystem AB. Phone interview 2016-08-15				
Torstensson, Mikael. Salesman, Cramo AB. Mail 2016-08-15				

The cost of the FRP wrap repair respectively the pipe replacement are calculated to 8734 SEK respectively 34380 SEK. Evidently, the FRP wrap repair is approximately one fourth of the cost of the conventional. To further analyze the result, each cost category are commented.

Material
The material cost of the FRP wrap repair is roughly one third of the cost the conventional. Yet, the conventional method provide a brand new pipe and its higher material cost is therefore reasonable.

Equipment
Some additional equipment and machinery are required to conduct the conventional pipe replacement. For the FRP wrap, however, it is sufficient with the basic tools included in the labor cost.

Transport
Both of the pipes as well as the additional machinery and equipment must be transported by trucks. On the contrary, all the required components for the FRP wrap repair can easily be transported in the service vehicle.

Labor
In total it is estimated that the FRP wrap repair can be made in one fourth of the time as the conventional. The repair procedure is less extensive and consists of fewer steps.

8.4 Discussion

In this chapter the case study is summarized and the findings made discussed. Firstly, the design phase is commented, thereafter the cost analysis is briefly addressed.

Design of the repair
The hand calculations show that only a few layers of wrap will be required to repair the pipe to withstand the loads acting on the pipe. This may indicate that the pipe is not in urgent need of repair and that the calculated number of wraps just originate from uncertainties and safety margins in the standard. However, the corrosion of the pipe is an ongoing process and the repair could be justified to ensure that the pipe can provide service for several years to come. Another aspect of this kind of repair is the ability to keep the pipe in service during the repair. This could motivate an early repair, thus avoiding walls through cracks, making the repair procedure less complicated.

An objective of the case study was to support the analysis of the second research question: *What would be required to assure a liable implementation of FRP wraps as a pipe repair method in Sweden?* The question is more directly addressed in the conclusion of the Action research but a short comment can be made also in this context.

Demonstrated in the case study is how not only the installation of the repair is straightforward but also the design calculations. The standard *SS-EN ISO 24817:2015* presents easily followed design steps including necessary verifications. A liable implementation should therefore be made in accordance with this standard. For further research, proposed in chapter 7.6.4 - *"Conclusion and further research"*, this standard could serve as a proper base.

Construction cost analysis

In the cost analysis two different approaches of managing the corrosion defect are compared. The outcome of the repairs are different considering that the conventional repair provides a whole new pipe section and the FRP wrap does not. Hence, it could be questioned if such a comparison is appropriate. It is obvious that a pipe replacement is preferable in some cases. For example, when the general condition of the pipe is derogated and overall rehabilitation is required. On such a case, a pipe replacement would probably prolong the life time of the repair considerably. However, there are several cases where pipe replacements cannot be justified when alternatives such as FRP wraps exist and yet, it is often employed. This case is an example of such a case. The defect, described in chapter 8.2.2 – *"Defect"*, is concentrated to a limited area and the progression of the corrosion is assumed to be hindered as a result of the operation. Through the FRP wrap repair, the service life of the pipe section is prolonged. Thus, this method is selective measure that efficiently solves the considered issue and is therefore the suitable option.

One could wonder whether the cost findings made in this case could be generalized onto others or not. The cost ratio 1:4 could possibly be a valid rough estimation, however, this one case study alone cannot be seen as proof, merely an indication. Although this case proved to have considerably lower construction costs, it is likely that in other scenarios, FRP wraps can be even more appealing. The time aspect is more significant on repairs of larger scale where the labor cost become more decisive. As mentioned serval times previously, the repair method would be particularly efficient where it enables the pipe to be kept in service.

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10 APPENDICES