Behaviour of Corroded Oil and Gas Pipes Rehabilitated with BFRP Wrap

Behrouz Chegeni

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Behaviour of Corroded Oil and Gas Pipes Rehabilitated with BFRP Wrap

by

Behrouz Chegeni

A Dissertation
Submitted to the Faculty of Graduate Studies through the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the University of Windsor

Windsor, Ontario, Canada
2018

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Behaviour of Corroded Oil and Gas Pipes Rehabilitated with BFRP Wrap

by

Behrouz Chegeni

APPROVED BY:

_______________________________________
S. Adeeb, External Examiner
University of Alberta

_______________________________________
N. Zamani-Kashani
Department of Mechanical, Automotive and Materials Engineering

_______________________________________
S. Bhattacharjee
Department of Civil and Environmental Engineering

_______________________________________
S. Cheng
Department of Civil and Environmental Engineering

_______________________________________
S. Das, Advisor
Department of Civil and Environmental Engineering

_______________________________________
R. Carriveau, Co-Advisor
Department of Civil and Environmental Engineering

September 7, 2018
DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this dissertation incorporates material that is result of joint research, as follows:

This dissertation is a result of a research undertaken under the supervision of Dr. S. Das and co-supervision of Dr. R. Carriveau. Testing of five specimens were completed jointly by the author and Mr. Sachith Jayasuriya.

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ABSTRACT

Corrosion in oil and gas pipelines is a major integrity problem for pipeline operators. Throughout their lifespan, pipelines experience a variety of loads including internal pressure, external pressure, bending, and axial loads. These load combinations along with corrosion defect make the pipes vulnerable to failure. Traditional corrosion repair techniques require hot work and can be very expensive. In recent years, researchers have been exploring the possibility of using new techniques and materials to repair defective sections of pipelines. Carbon and glass fibre-reinforced polymers have been proven to enhance the burst strength of corroded pipes. However, few studies were found in the literature that investigated the effectiveness of using composites to restore the bending performance of the corroded pipes. Basalt is a natural rock and hence, a green material and abundant in nature. Basalt fibre is produced from Basalt rock. The mechanical properties of basalt fibre are better than glass, while it is much cheaper than carbon. Although it has been effectively used to repair several structural elements, however, no research was found to use BFRP composite to repair corroded pipelines. The purpose of this research is to experimentally and numerically investigate the feasibility and effectiveness of using BFRP composite wrap on restoring the behaviour of the pressurized corroded pipes while subject to bending load. The experimental study was conducted in two phases: Phase A and phase B. Seven full-scale laboratory experiments were tested in phase A and five full-scale specimens were tested in phase B. Several finite element model-based parametric studies were performed using ABAQUS software. Based on experimental and numerical results, it was found that biaxial BFRP composite can effectively rehabilitate and restore the bending capacity of the corroded pipes and prevent wrinkle formation.
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Chapter 1: Introduction

1.1 General

Pipelines are the most important tools for transferring oil, gas and other petroleum products from oil sources to consumers. Due to unfavorable terrains and harsh weather conditions, buried pipelines develop imperfections such as corrosions, wrinkles, gouges, wearing, dents, cracks, spalling, and/or a combination of these defects. Among these different types of imperfections, metal loss and corrosion are the worst defects in steel pipeline (Frankel, 1998; Francis, 1994). Due to the high importance of their structural integrity, the pipeline industry is required to ensure that the operation of the pipelines does not pose a risk to the safety of the environment and habitants. Therefore, the pipeline industry has to tackle the problem of corrosion by repairing the defective sections or in the worst-case scenario to cut and replace the defective section.

In recent years, numerous attempts have been made towards the development of repair methods for defective energy pipelines. Patch clamps and encircling sleeves are traditional repair techniques currently used in the pipeline industry. However, these techniques involve hot work and interrupt the operation of the pipeline during the repair (Rohem et al., 2016). Having effective performance on repairing other structural components, the possibility of FRP composites to rehabilitate the defective pipes have been investigated and documented. Carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP), and aramid fibre reinforced polymer (AFRP) are the most typical composite used in the pipeline industry (Alexander and Francini, 2006; Duell et al., 2008; Shouman and Taheri, 2011; Lim et al., 2016; Elchalakani et al., 2017).
Due to high demand for reducing the cost and facilitating the repairing process, researchers continue to investigate the possibility of new products and repairing techniques to tackle defects in pipelines. The objective of this research is to experimentally and numerically investigate the effects of corrosion on the performance of pipelines under load combination and to use a new composite material, basalt fibre reinforced polymer (BFRP), to repair the corroded pipes.

1.2 Corrosion

One of the main problems in pipeline industry is corrosion of the pipes which endanger the longevity and reliability of the pipes. Due to their devastating effects on the performance of the pipes, the corroded segments either need to be replaced or repaired which cost millions of dollars every year. The results of a two-year study from 1999 to 2001 conducted by CC Technologies Laboratories, Inc., with the support from the U.S. Federal Highway Administration (FHWA) and National Association of Corrosion Engineers (NACE) estimated that the total annual cost of corrosion in the U.S. is $276 billion, approximately 3.1% of the nation’s Gross Domestic Product (GDP). According to the report, the cost of corrosion on infrastructures including high-way bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads is $22.6 billion among which $7 billion is estimated to monitor, replace, and maintain gas and liquid transmission pipelines (NACE International, 2002). The annual corrosion cost in the Australian and New Zealand economy is estimated to be between $36B - $60B and $5.5B - $9.2B, respectively (Australian Corrosion Association, 2010).
1.3 Wrinkle

When the compressive limits of the pipe walls exceed beyond its yielding capacity, wrinkle or local buckling in the wall of the pipeline occurs. This phenomenon is a plastic deformation which can be formed as a result of a variety of reasons. However, the ground movement that introduces bending load to the pipe is the main reason of wrinkle formation in pipelines. The freeze-thaw cycle which can apply axial forces and induce volumetric strains in form of wrinkle or local buckling in the compressive side of the pipe is another reason of wrinkle formation. In the past two decades, a wealth of research has been conducted to investigate and document the wrinkle formation and its impact on the behaviour of pipelines (Kim and Park, 2002; Alexander and Kulkarni, 2008; Zhang and Das, 2008; Gresnigt and Karamanos, 2009; Limam et al., 2010; Yudo and Yoshikawa, 2015).

1.4 Statement of Problem

As mentioned earlier, the corrosion phenomenon is the main safety concern in the pipeline industry; any negligence to address the issue can lead to severe hazardous condition for the environment and to humans. Since traditional repair techniques might be dangerous during installation and may not be economical, researchers have recently employed CFRP and GFRP composite to rehabilitate the corroded pipes. However, the aforementioned composites have mostly been used to restore the burst pressure capacity of the corroded pipe. Basalt composite (BFRP) which is an environmental friendly product, has better mechanical properties than glass composite (GFRP), while it is cheaper than
carbon composite (CFRP). No studies were found in the literature to restore the bending capacity of pressurized pipes using BFRP composites.

1.5 Objectives and Scope

Considering the previously mentioned research, the objective of this study is to assess the structural performance and the effectiveness of rehabilitating corroded steel pipes using basalt fiber reinforced polymers (BFRP). A series of experimental tests, as well as a parametric study utilizing the commercially available finite element software, ABAQUS version 6.14.2, were conducted in this study. The followings are the objectives of this study:

- To conduct a test setup that could successfully create a wrinkle in the compressive side of the pipe as it typically occurs in the pressurized pipe in the field. The pipe should be able to maintain its integrity in the test setup without any out of plane movement under combined internal pressure and bending load.
- To determine the effect of different corrosion shapes and corrosion depths on a pipe specimen.
- To examine the performance of corroded pipes rehabilitated with a varying number of BFRP composite layers and their orientations.
- To model corroded and repaired specimens using finite element analysis and validate them with experimental results.
- To experimentally and numerically conduct parametric studies to determine the optimum thickness of BFRP composite needed for the rehabilitation of corroded pipes.
In this study, two types of pipes including NPS8 and NPS6 with different external diameters and thicknesses were used.

1.6 Organization of the Dissertation

This dissertation contains four major chapters (Chapters 2-5) and two small chapters (Chapters 1 and 6). The first chapter is an introduction to the performed research. Chapter 2 includes background information about wrinkles of the pipes and summarizes the available findings in the literature regarding experimental and numerical research on corrosion and FRP repair. Chapter 3 describes a detailed description of the full-scale test setup of phase A and phase B of the study and presents the experimental methodology undertaken during the tests. Chapter 4 discusses the experimental results obtained from the tested specimens. The numerical modeling of the full-scale test, detailed explanations, and the obtained results from the parametric studies are discussed in Chapter 5. Chapter 6 includes the general conclusion of the research and recommendations for the future works.
Chapter 2: Literature Review

2.1 General

Experimental and analytical tests have been performed to study the various failure modes exhibited by pipelines in service under different load combinations. The desire to reduce the cost and the urge to maximize the environmental protection have motivated researchers to explore the possibility of newer rehabilitation techniques. In the recent years, considerable investigations on the application of Fibre Reinforced Polymers (FRP) composite to restore different structural components have been conducted. Among those were studies aimed at the rehabilitation of defected pipelines using various FRP composites.

2.2 Corrosion and Local Buckling of Pipes

2.2.1 Corrosion Phenomenon

One of the main problems in oil and gas industry that endangers the integrity and longevity of the pipelines is corrosion. Corrosion is the root of about 30% of the hazardous incidents of liquid and gas pipes (NACE International, 2011). The term pipeline integrity refers to the concept that a pipeline is able to safely perform the tasks for which it is designed with no damaging effect on the environment around it. Based on the study released in 2002 by NACE International, the annual corrosion cost in the U.S. is about $276 billion among which $7 billion is the cost for gas and liquid transmission pipelines (NACE International, 2002).
Corrosion is defined as destruction or deterioration of a material through interaction with the environment. It is an inevitable phenomenon that happens naturally and can not be stopped completely. This is because essentially all the environments are corrosive to some degree. However, it can be controlled. There are many types of interrelated corrosions, some of the most problematic types are: uniform corrosion, crevice corrosion, localized corrosion, intergranular corrosion, selective leaching, erosion corrosion, stress corrosion cracking, hydrogen damage corrosion. Uniform corrosion is the most common type of corrosion which uniformly progresses over the whole exposed area of the metal. It can be reduced by using proper methods such as: coatings, inhibitors, or cathodic protection. Crevice corrosion frequently occurs within the crevices on metal surfaces. Localized corrosion or pitting corrosion is an extremely localized corrosion which creates holes in the metals. Intergranular corrosion is the result of impurities in the grain boundaries of the metals. Selective leaching is a type of corrosion in which the elements of a solid alloy separate in a special process. Relative movement between a metal surface and corrosive fluid results the acceleration of decomposition of the metal which causes erosion corrosion. Stress corrosion refers to the formation of cracks caused by the existence of both tensile stress and a particular corrosive medium. Hydrogen damage corrosion is the mechanical damage of a metal caused by the presence of hydrogen.

### 2.2.2 Local Buckling

Steel pipelines experience a variety of stresses and defects in service. Change in the loading and environmental conditions are the principal causes of these defects. Pipelines in arctic and sub-arctic regions are specifically vulnerable to local buckling. Subsurface geotechnical movements of the earth, changes in the temperature, freeze and thaw cycles,
as well as other influencing factors, induce compressive stresses beyond the yield strength of the pipe material resulting in wrinkle formation in the pipe walls. Extensive experimental and analytical studies have been conducted to assess the behaviour of corroded pipes under a variety of load conditions. Figure 2.1 shows a wrinkle in an experimental specimen test (Alexander and Kulkarni, 2008).

The height and the width of a wrinkle are the two main parameters that identify a wrinkle (Alexander and Kulkarni, 2008). The formation of a wrinkle depends on several factors among which are loading conditions, internal pressure, diameter-to-thickness ratio \((D/t)\), and the material properties of the pipe.

The loading condition is one of the main contributing factors in forming the wrinkle. Onshore and offshore pipelines experience different kinds of stresses and strains, depending on the type of applications for which they are used. Generally, onshore pipes are not subjected to external pressure, while in offshore pipelines, depending on the depth of their location can experience varying external pressure. Due to volumetric thermal changes or exposure to lateral bending loads such as ground movement, pipelines can be axially compressed. Essentially, cylindrical shells are susceptible to local buckling in compression (Timoshenko and Gere, 1963). Depending on the conditions, differential ground movements, terrain topography, and slopes put the pipelines in vulnerable positions. Freeze and thaw cycles in different seasons can act as fatiguing loads on the pipe. In all cases, the pipelines should be designed to accommodate the plastic buckling and strains beyond the yield point of the material.

Unlike thin cylindrical shells that elastically buckle, thick-walled shells, locally buckle after yielding of the pipe (Gresnigt and Karamanos, 2009). Strain-based design is a
limit state design. The purpose of the strain-based design is to make sure that pipelines continue to safely operate even after they yield (Liu et al., 2009). Defining the strain limit, the strain at which the local buckling occurs is very important. Several models have been developed for determining the critical buckling strain ($\varepsilon_c$). Tables 2.1 and 2.2 show the various critical buckling strain and critical buckling moment models, respectively.

Table 2.1: Critical buckling strain models

<table>
<thead>
<tr>
<th>Model</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_c = 0.5 \frac{t}{D}$</td>
<td>Murphy &amp; Langner</td>
</tr>
<tr>
<td></td>
<td>(1985)</td>
</tr>
<tr>
<td>$\varepsilon_c = 0.5 \frac{t}{D} - 0.0025$</td>
<td>Gresnigt</td>
</tr>
<tr>
<td></td>
<td>$D/t &lt; 120$</td>
</tr>
<tr>
<td>$\varepsilon_c = 0.2 \frac{t}{D}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D/t \geq 120$</td>
</tr>
<tr>
<td>$\varepsilon_c = 0.005 + 13 \left(\frac{t}{D_0}\right)^2$</td>
<td>Igland</td>
</tr>
<tr>
<td></td>
<td>(1993)</td>
</tr>
<tr>
<td>$\varepsilon_c = 15 \left(\frac{t_{nom}}{D_0}\right)^2$</td>
<td>BS PD 8010</td>
</tr>
<tr>
<td></td>
<td>(2004)</td>
</tr>
<tr>
<td>$\varepsilon_c = \frac{t}{D_0} - 0.01$</td>
<td>DNV</td>
</tr>
<tr>
<td></td>
<td>(2017)</td>
</tr>
<tr>
<td>$\varepsilon_c = 0.5 \frac{t}{D_0}$</td>
<td>ABS</td>
</tr>
<tr>
<td></td>
<td>(2014)</td>
</tr>
<tr>
<td>$\varepsilon_c^{crit} = 0.5 \frac{t}{D} - 0.0025 + 3000 \left(\frac{(P_l - P_s) D}{2tE_s}\right)^2$</td>
<td>CSA-Z662</td>
</tr>
<tr>
<td></td>
<td>(2015)</td>
</tr>
</tbody>
</table>
Table 2.2: Critical buckling moment models

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>$M_c = M_p(1 - 0.0024\frac{D_o}{t_{\text{min}}})$</td>
<td>$M_c = (D_o)^2 t_{\text{nom}}\sigma_y$</td>
<td>$M_c = M_p(1.05 - 0.0015\frac{D_o}{t})$</td>
</tr>
</tbody>
</table>

Internal pressure is another important element that affects the shape and strain localization of the wrinkle in a pipe. Typically, the operating pressure is measured in terms of a percentage of the Specified Minimum Yield Strength (SMYS). In the absence of internal pressure, instead of wrinkle formation, a pipe experiences a cross-sectional distortion in form of a diamond-shaped buckle. Figure 2.2 shows a local buckling failure in the absence of internal pressure. The presence of internal pressure tends to stabilize the structural performance of the pipe and increases its ductility (Limam et al., 2010; Shouman and Taheri, 2011).

When a pipe is subject to bending, the cylindrical cross-section distorts in an oval form. This ovalisation phenomenon creates bending stresses in the circumferential direction which in turn modifies the local curvature and thus, expedites the occurrence of wrinkle formation (Gresnigt and Karamanos, 2009). However, internal pressure tends to endure the distortional effects in the hoop direction, hence attenuating the ovalisation effect (Gresnigt, 1986; Limam et al., 2010; Kim and Park, 2002).

In this chapter, an overview of the available literature on corroded and repaired pipelines is provided with emphasis on recent researches of FRP composites used in the
industrial such as carbon, aramid, and glass. In order to document the structural behaviour of the defected pipe repaired with FRP, several experimental and numerical methodologies are also discussed.

2.2.3 Studies on the Effect of Corrosion on the Behaviour of Pipes

Nicolella and Smith (1997) studied the wrinkling behaviour of a corroded pipeline using non-linear finite element (FE) method. The objective of the study was to create a proper finite element model that can accurately simulate the behaviour of corroded steel pipelines under various load conditions. To that end, the FE program, ABAQUS was employed and the plasticity model proposed by Mroz (SwRI, 1992) was utilized to model the post yielding performance of the pipe material. The main parameters of the study were internal pressure, axial load, corrosion dimensions, and bending moment. A user developed material model was generated to properly determine the material constitutive behaviour used in the FE models in ABAQUS. In order to validate the analytical model, the study also conducted a test on a specimen, 48 inches in diameter, transferred from the Trans-Alaska pipeline. The length, nominal thickness, and the D/t ratio of the specimen were 208 in (5283 mm), 0.462 in (12 mm), and 104, respectively. The combined internal pressure, axial load, and bending moment were applied to the specimens. After development of a wrinkle, the axial load increased until the pipe ruptured. Based on the numerical studies and comparison with the experimental results, it was found that the model could accurately predict the behaviour of the pipe until just before the formation of a wrinkle. However, beyond the formation of a wrinkle, a discrepancy appeared between the experimental and the numerical results and the model predicted a much stiffer response than that observed in the tests. In order to match the experimental results, it was suggested to incorporate all
setup details and imperfections into the model and use the softening and hardening moduli of the actual pipe material properties.

Local wall thinning is one of the important reasons of pipeline failure in the nuclear power industry. Kim and Park (2002) conducted an experimental study on the failure behaviour of carbon steel pipelines used in nuclear power plants with local wall thinning. The purpose of the study was to examine the corrosion of wall thickness because of Flow Accelerated Corrosion. Axial thinning length, circumferential thinning angle, internal pressure, and different loading types were the main parameters of the investigation.

In order to simulate the corrosion, the wall thinning of the pipe was machined on the inner side of the pipe. The specimens were tested with and without internal pressure. For the specimens with internal pressure, they were first pressurized with water and nitrogen gas to an internal pressure of 10 MPa, and then gradually bent through the application of monotonic bending moment. The corroded region was either subjected to tensile or compressive stress. For the dimension of the corroded area, four different lengths in the circumferential direction measuring 0, 90, 180 and 360 degrees of the circumference and two corrosion lengths of 25 mm and 200 mm were considered. The wall thicknesses of the corroded area of all specimens reduced to 2 mm which was lower than the minimum thickness recommended by construction codes such as ANSI/ASME B31.1 (1995). The length of all specimens was 1200 mm. The thickness and nominal diameter of the pipes were 7.8 mm and 113.8 mm, respectively. A 4-point bending test in the displacement control method was conducted for all the pipe specimens. It was found that when the corroded region was under tensile stress, the increasing or decreasing of the load carrying capacity of the pipe was dependent on the circumferential angle of the corroded region.
Also, regardless of the thinning angle, as the axial thinning length increased, the ductility of the pipes increased. However, when the thinning area was under compressive stress, increasing the axial length of the corroded region caused the load carrying capacity of all specimens decreased.

Following the work done by Kim and Park (2002), Shim et al. (2002) reported the outcomes of a numerical study that was conducted to investigate the behaviour of full-scale corroded pipelines subject to combined pressure and bending moment. A three-dimensional finite element model was established using the experimental parameters of the previous work. A solid element was employed for this purpose and the geometrical non-linearity was used in order to properly simulate the corrosion patch. Then a parametric study was performed on 252 specimens and the effect of axial length of corrosion, circumferential thinning angle, internal pressure, and different loading types were investigated. Bending moment was applied to the specimens after applying internal pressure. The study confirmed the results of the previous work by Kim and Park (2002) and it was found that increasing the length and circumferential angle of the corrosion patch decreased the maximum moment capacity of the pipes. It was also concluded that except for the specimens with deep corrosion depth and long corrosion length, the internal pressure did not have a noticeable effect on the maximum moment capacity of the specimens.

Zhang and Das (2008) experimentally and numerically investigated the failure modes and the post wrinkling behaviour of X52 grade wrinkled energy pipelines under internal pressure and monotonic bending moment. The study contained two parts; experimental and numerical. Two NPS12 pipes with a 12 in. (304 mm) nominal diameter, 6.84 mm wall thickness, overall length of 1270 mm, and diameter-to-thickness ratio \( D/t \) of 45 were
tested in the experimental part of the study. The $D/t$ and internal pressure were the main parameters of the study. The specified minimum yield strength (SMYS) of the pipes was 358 MPa and they were pressurized to either 0.8 $P_y$ or 0.4 $P_y$. Then a compressive load and monotonically increasing bending moment were applied to the specimens. Finite element analysis was the second part of the study. A total of 180 specimens were analyzed in the parametric study with different internal pressures and $D/t$ ratios. The results of the study revealed that the X52 grade pipes could maintain their longitudinal and circumferential strains far beyond the maximum allowable strain suggested in the design standards (CSA, 2015; BSI, 2004; DNV, 2017). It was found that the rupture failure of the pipes occur only at the wrinkle location of compression face of the bent pipe and the tension face of the pipe does not experience any rupture. Finally, it was observed that generally, the X52 grade pipes exhibit a high ductile behaviour under monotonically increasing bending moments and do not fail in rupture but rather fail due to excessive cross-sectional distortion.

Limam et al. (2010) experimentally and numerically investigated the plastic buckling of small pipes under combined constant value of internal pressures and monotonically increasing bending moments. The research consisted of testing 15 specimens with a $D/t$ value of 52 and a diameter of 1.5 in. (38 mm). The overall length of the specimens varied from $11D$ at higher pressure to $17D$ at lower pressure. The constant values of internal pressures were applied to the specimens first and then gradually bending moment was increased. Using four-node shell elements in ABAQUS, a finite element model was developed to simulate the testing specimens and it was validated with the experimental results. The material properties were represented as anisotropic elastic-plastic and the initial geometric imperfections were simulated.
The results of Limam et al. (2010) were in agreement with the findings of Yoosef-Ghodsi et al. (2000) that when the compressional stresses of a buried pipe exceed beyond its maximum carrying capacity, a wrinkle forms. It was found that the internal pressure stabilizes the structural performance of the pipes and it can noticeably postpone the localization and collapse under bending moment. The results were in agreement with Ju and Kyriakides (1991) research which proved that the existence of internal pressure caused the expansion of the cross-section and it significantly reduced the ovalisation growth in the pipes. As can be seen in Figure 2.3, increasing the internal pressure increases the curvature capacity of the specimens.

Tajika et al. (2011) conducted an experimental study on 48-inch X82 pipes under combined bending moment and internal pressure to investigate the local buckling and post buckling behaviour of pipelines. Yield-to-Tensile strength ratio ($Y/T$) was the main parameter investigated in this study. A full-scale bending test was conducted to examine three line pipe specimens measuring 8 m in length with $Y/T$ ratios of 0.83, 0.82 and 0.91. The first two specimens were high strain pipes and the last specimen was a conventional steel pipe. In the first stage, 12 MPa (1740 psi) of internal pressure was applied to the pipe. Then bending moment was exerted on the pipe until it failed. The specimens were oriented in a way such that the longitudinal weld seams were not placed in the compression nor tension sides. It was found that the conventional pipe specimen ruptured at a maximum strain of 0.97% in tensile zone at 19.7 degrees of end rotation and it did not have any sign of a rupture in the compression zone. Also, it was found that the two high-strain line pipes had higher compressive and tensile strain capacities and could endure 18.8 and 18.1 degrees of end rotation to maintain their integrity and sustained the maximum compressive
strain of 1.67% and 1.51%. These results revealed that $Y/T$ ratio had a significant impact on the bending capacity of the pipes; the specimens with lower $Y/T$ ratio had higher critical strains for buckling.

2.3 Composite Repair Systems

A composite is a material fabricated by combining two or more constituent materials with different mechanical and chemical properties that form a material with different characteristics from the individual components. The initial elements remain separate and distinct within the new material (Fib Bulletin 40, 2007; El Maaddawy, 2004).

Fibre Reinforced Polymer composites (FRPs) are made of two parts; fibres and matrix. Fibres with high strength and high modulus of elasticity are bonded together and embedded in a low modulus polymeric matrix. The fibres can be made of a variety of materials that are fabricated through one of the traditional textile production methods, e.g. knitting, weaving, braiding, etc. A polymer is a large, organic, molecule constituted of a smaller repeated units called monomers. The polymeric matrix which plays an important role in the performance of the composite, should be physically and chemically compatible with the fibres. The main functions of a matrix are to bind the fibres together and protect their surfaces from damage, to disperse and separate the fibres, and to transfer stresses to fibres (ISIS Canada Corporation, 2006; Fib Bulletin 40, 2007).

Unlike steel, the FRP composites exhibit a linear elastic behaviour until failure. Generally, the modulus of elasticity of FRP composites is lower than steel, however, their ultimate strength is significantly higher. The failure mode of FRPs is brittle, without any
yielding of material, and they show little warning before failure (ISIS Canada Corporation, 2006).

Due to their extremely high strength-to-weight ratios, the application of FRP has been used in aerospace and automotive industries for half a century. In the past two decades, the application of FRP to rehabilitate the damaged concrete structures has been effectively increased (ISIS Canada Corporation, 2006; El Maaddawy, 2004; Iyer et al., 2015). Besides being used in concrete structures, researchers have worked on the possibility of repairing steel structures with FRP composites. Tavvakolizadeh and Saadatmanesh (2003) observed that carbon fibre-reinforced composite increased the flexural capacity of damaged steel-concrete composite girders. Liu et al. (2001) reported an increase in the bending stiffness of corroded steel beams. The application of FRPs to repair defected pipelines has been in use since the 1980s. Figure 2.4 shows some conventional FRP products used for repair and rehabilitation of structural elements.

There are several forms of typical commercially manufactured fibres such as: cloth wraps, laminates, rods, meshes, pultruded sections, and chopped fibres. While there are different methods for manufacturing FRPs, three rehabilitation techniques for structural engineers are wet lay-up system, pre-cured layered systems, and pre-impregnated systems (Lim et al, 2016).

In the wet lay-up system, the fabric is in form of woven fibres that is flexible before curing. After cleaning the intended section, the fabric is attached with a high-strength epoxy resin. The matrix impregnates and binds the fabrics to the structural member. This provides a great advantage over using steel repairing techniques, because it can be applied
to the sections with complex geometries e.g. bends and joints. The mechanical characteristics of the fabric are dependent upon the amount and orientation of fibres. Since the fabric is impregnated in the field, the binding properties of the matrix are responsible for attaching the fibres to the structural elements, which makes the FRPs a monolithic composite. The efficacy of this system is also dependent upon how well the layers adhere.

In a pre-cured layered system, a factory made pre-impregnated laminate is bonded to the structural member. The laminate is made of multiple layers of thin sheets of fibres bonded together. The amount of fibres oriented in the axial or transverse directions, as well as the strength of matrix used to achieve the bond between fibres mainly determine the strength of laminates. While laminates are an easier repairing technique, their rigidity, however, limits their applications to sections with complex geometries. However, compared to the wet lay-up system, the laminates have a better quality control, since they are pre-manufactured in the factory.

The pre-impregnated system is a combination of the wet lay-up and the pre-cured system. Unlike the wet lay-up system where the fibres get impregnated in the field, in the pre-impregnated system, the impregnation of the fibres with the resin is conducted in a factory. As a result, the product has better quality control. In contrast to the pre-cured system, since it is only partially cured, it is still flexible and can be applied to the sections with complex geometries. One of the drawbacks of this system is that since the fibres are pre-impregnated with resin, they need to be stored in sub-zero degree Celsius environment prior to applying to the structural elements.
2.3.1 Resins

Generally, the type of material used as the matrix for FRP composites can be divided into two groups: thermoplastics and thermosetting resins. Thermosetting resins have strong molecular bonds and they don’t melt and reshape. Thermoplastics resigns, however, are capable of being reformed and when exposed to temperature cycles, they repeatedly hardened and softened. Polyesters, vinylesters, and epoxies are three specific types of thermosetting resins that are typically used for manufacturing the matrix in composites. Due to their relatively low cost, polyesters are the most widely used polymers in the manufacturing of FRP composites. Vinylesters are considered as a type of polyesters which cost slightly more than polyesters. Since they are resistant to acids and alkalis, they are commonly used in the manufacturing the FRP reinforcing bars in concretes. Epoxies cost noticeably more than polyesters and vinylesters. However, due to their ability to cure well at room temperature and their better adhesion characteristics, they are often used in wet lay-up applications of FRP sheets (ISIS Canada Corporation, 2006; Fib Bulletin 40, 2007). Table 2.3 shows the typical mechanical properties of thermosetting materials (Fib Bulletin 40, 2007).
Table 2.3: Typical mechanical properties of thermosetting materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Polyester</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1200 - 1400</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>34.5 - 104</td>
</tr>
<tr>
<td>Longitudinal modulus (GPa)</td>
<td>2.1 – 3.45</td>
</tr>
<tr>
<td>Poisson’s coefficient</td>
<td>0.35 – 0.39</td>
</tr>
<tr>
<td>Thermal expansion coefficient (10⁻⁶/°C)</td>
<td>55 - 100</td>
</tr>
<tr>
<td>Moisture content (%)</td>
<td>0.15 – 0.60</td>
</tr>
</tbody>
</table>

2.3.2 Fibres

The strength and stiffness of a composite are derived from the fibres (ISIS Design Manual 4, 2001). Since the fibres used in a composite are continuous and are oriented in specified directions, FRP composites are typically orthotropic. Their high strength characteristic is primarily a result of the bonding between fibres and the matrix which happens on the microscopic level (El Maaddawy, 2004). The orientation of fibres, as well as the length-to-diameter ratio are fundamental factors in establishing the ultimate tensile strength of the FRP composite. When a fibre breaks within an FRP composite, the matrix transfers the forces to the neighbouring fibres through shear stresses that develop in the polymer, thereby resisting the failure of the whole FRP composite (ISIS Canada Corporation, 2006).

In civil engineering applications, the three typical fibre materials manufactured for FRPs are glass, carbon (graphite), and aramid. Having different mechanical properties,
every one of them has its own set of advantages and disadvantages. Figure 2.5 demonstrates the stress-strain diagrams of different fibres.

The most used fibre for construction purposes as well as the least expensive is glass. The diameter of glass fibres ranges from 3 – 25 microns and they are manufactured by a process called direct melting. Glass fibres, which are isotropic fibres, are often used in the manufacturing of FRP reinforcing bars, FRP wraps for seismic upgrades, and as a medium for application of carbon FRP on steel structures to prevent galvanic corrosion. There are several different grades of glass, but the main two grades are E-glass and S-glass. E-glass is an inexpensive fibre used in many different applications. S-glass, however, is expensive but has higher mechanical properties.

Carbon fibres are anisotropic materials and are manufactured by a method called controlled pyrolysis which includes oxidation, graphitization, and carbonization to fabricate carbon filaments with diameters ranging from 5-8 microns. Carbon fibres possess both a higher modulus of elasticity and higher ultimate strength than glass fibres. The manufacturing process of carbon fibres is complicated. Therefore, it provides a possibility to produce carbon fibres with an extensive range of mechanical properties with a modulus of elasticity between 250 to 1000 GPa (ISIS Design Manual 4, 2001; ISIS Canada Corporation, 2006). Although carbon fibres have very high mechanical properties, their relatively high cost, as well as low ductility act as major drawbacks of this type of fibre. Also, due to the potential of forming galvanic corrosion cells, there is a concern about using carbon fibres for repairing steel structures (Tavakkolizadeh and Saadatmanesh, 2001; Alexander and Ochoa, 2010).
Aramid is an anisotropic synthetic fibre which is manufactured from Aromatic Polyamide in a process called extrusion and spinning. In terms of costs and mechanical properties, Aramid fibres stand between glass and carbon fibres. They are distinguished by high strength, moderate stiffness, and low density. Because of the unique anisotropic properties of the fibres, the aramid fibre reinforced polymers (AFRPs) have low shear and compressive strength. Their low environmental and chemical resistance is one of the drawbacks of using Aramid fibres. (ISIS Canada Corporation, 2006). Table 2.4 shows some typical mechanical properties of common fibres and steel reinforcing bars (Fib Bulletin 40, 2007; Jayasuriya et al., 2018).

Table 2.4: Typical mechanical properties of common fibres and steel reinforcing bars

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel</td>
</tr>
<tr>
<td>Longitudinal modulus (GPa)</td>
<td>200</td>
</tr>
<tr>
<td>Longitudinal tensile strength (MPa)</td>
<td>450 to 700</td>
</tr>
<tr>
<td>Ultimate tensile strain (%)</td>
<td>5 to 20</td>
</tr>
</tbody>
</table>

Basalt, an aphanitic igneous rock, features a glassy matrix combined with minerals and composed of less than 20% quartz. The volcanic rock, basalt, is produced through the rapid cooling of lava (Hyndman, 1985). The naturally made rock, which is named by its mineral content and texture is usually grey to black in colour, has the average density of 3 gm/cm³, and rapidly weathers to brown or rust-red. Although often distinguished as "dark", due to their regional geochemical processes, basaltic rocks exist in a wide range of shading.
The most common occurrences of basalt on Earth are in the ocean floors which are almost completely made up of basalt. The largest basalt quarries are concentrated in Russia, Ukraine, Georgia, China, and U.S. A wealth of studies on the previously mentioned fibres and the ongoing exploration to find new, efficient and cheaper materials have led researchers to investigate the possibility of using Basalt to produce fibres.

Basalt fibres are manufactured through a simple process which involves melting crushed volcanic lava deposits (Fib Bulletin 40, 2007; Iyer, 2014). These fibres have superior mechanical and chemical characteristics than those of glass, yet they are significantly cheaper than carbon fibres. The main advantages of basalt fibres are: fire resistance, resistance to chemically active environments, significant capability of acoustic insulation and vibration isolation. Because of the high working temperature of 982°C and the melting point of 1450°C of basalt, it can be used as a fire-resistant textile in the construction industry.

Since basalt fibres are essentially natural rocks which are abundant in nature, the FRPs constructed from them are green products: inert, non-reactant, and environmentally-friendly. Having these environmentally-friendly features, as well as the previously mentioned beneficial characteristics promotes these fibres for a broader range of applications of the industry.

2.3.3 Studies on FRP Repaired Pipelines

Extensive studies were conducted to investigate the potential application of FRP for repair and rehabilitation of steel pipelines. In this section, the results of experimental and analytical studies are reviewed.
Toutanji and Dempsey (2001) conducted an analytical study to determine if FRP composites provide any structural benefit in the rehabilitation of corrosion damaged pipelines and if so, what type of composite materials (CFRP, GFRP, or AFRP) has a greater beneficial effect on ultimate internal pressure capacity. Internal pressure inside the pipe, soil loads, and traffic loads such as roadway and railway were the main sources of loading that were considered in the study. The authors made some simplifying assumptions since the models were complex. Bending stresses and hoop stresses were applied on the pipe through traffic loads, soil load, and internal pressure. Equations 2.1 and 2.2 were derived using the analytical results. These equations are able to calculate the maximum circumferential tensile stress in the elastic range.

\[ \sigma_m = \sigma_f + \sigma_s + \sigma_t \]  

\[ \sigma_m = \frac{pr}{(t_s - d)} \left[ 1 + \frac{E_{FRP} t_{FRP}}{E_t (t_s - d)} \right] + \frac{6k_w C_d \gamma B^2 d E_t r}{E_t^3 + 24k_d p r^3} + \frac{6k_w I_c F E_t r}{E_t^3 + 24k_d p r^3} \]  

In Equation 2.1, \( \sigma_f \) is hoop stress due to internal pressure, \( \sigma_s \) is bending stress due to soil load, and \( \sigma_t \) is bending stress due to traffic load. Based on the material properties of an FRP composite, Equation (2.2) is able to calculate the internal pressure of a repaired pipe and determine which type of composite allow the pipe to reach the highest internal pressure. It was found that FRP composites are able to restore the internal pressure capacity of corroded pipes, comparing the three common types of composites: Carbon, Glass and Aramid. It was also found that the Carbon fibre composites provide the maximum capacity to the pipe.
Alexander and Francini (2006) reviewed the application of available composites for rehabilitation of defected pipelines in the literature and design codes such as ASME B31.8 (ASME, 2016) and ASME B31.4 (ASME, 2016). In the past two decades, some outstanding products like Clock Spring®, ArmorPlate, and StrongBack were developed to effectively repair and restore the damaged line pipes. Generally, these products can be categorized into two groups: layered systems and wet lay-up systems. In the layered system, a stiff composite is bonded on to the pipe through adhesives. The Clock Spring® and PermaWrap systems are layered system products. The disadvantage of this system is that the whole system may not act monolithically and most of the load might be carried by the closer layers to the pipe. In a wet lay-up system, the composite fabric is impregnated with resin or a pre-impregnated cloth is used which is activated in the field with water. The advantage of this type of in-situ system is that it can easily conform to the contour of the surface with different geometries and provide a monolithic repair.

Freire et al. (2007) experimentally investigated the effect of glass composite repairs on the pressure capacity of the corroded pipelines. External and internal rectangular corrosion defects of 70% of the wall thickness measuring 500x97 mm were simulated at the mid-span of the pipe specimens. The test included a total of fourteen 3-m long, API 5L X60 pipe specimens (API, 2018). The specimens had a wall thickness of 14.3 mm and a diameter of 508 mm. A 25 mm thick composite fabric with fibre glass was used to repair the specimens in three forms: non-impregnated, pre-cured, and shape-cured with water. Depending on their ability to resist the internal pressures, four different pressure loadings were applied to the pipes. In this study, a finite element model was also developed to simulate the experimental tests. The results from the study showed that up to the start of
yielding at the corroded area, the elastic loading of the repaired pipe was carried only by the pipe itself due to the steel's high Young's modulus. The load started to transfer to the FRP composite at the post yielding phase of the pipe. Also, it was found that the strain distribution had a linear trend across the different materials in either elastic or plastic loading. It was found that even in the fractured pipes, none of the specimens underwent the composite delamination, and the failure was in the longitudinal direction of the specimens. Figure 2.6 shows a crack in the defected region.

Duell et al. (2008) conducted an experimental and numerical study to investigate the performance of carbon FRP composites on 6 in. (152 mm) diameter corroded pipes. Internal pressure and corrosion patch size were the main test parameters. The purpose of the study was to determine whether CFRP can rehabilitate corroded pipelines under internal pressure. In the experimental part of the study, a rectangular corrosion patch was manufactured on two 5-foot (1.52 m) pipe sections and then the specimens were repaired and pressurized until fracture. The \( D/t \) value of the pipes was 23.6. The axial length of the corrosion patches was 6 in. (152 mm) and the circumferential length was varied between 6 in. (152 mm) and the whole perimeter of the pipe. The thickness of all corrosion defects was 50% of the wall thickness of the pipe. A numerical model was also developed and validated with experimental tests using FE analysis method. Two different corrosion defects with 3×6 in. (76.2×152.4 mm) and 1×6 in. (25.4×152.4 mm) dimensions were modeled in the parametric study. The results of the experimental study showed that varying the internal pressure of the pipes did not change the maximum stress in the FRP composite. The numerical results revealed that varying the defect length in the circumferential direction had little impact on failure pressure of the repaired pipe. It was also found that
the proposed formula by ASME B31G (ASME, 2012) for calculating the required thickness of the wrap for safe operating conditions was conservative and the FE model was able to predict the burst pressure with a good accuracy. Figure 2.7 shows the burst pipe specimen repaired with carbon composite under monotonic static pressure loading.

Alexander and Kulkarni (2008) investigated the effect of wrinkle bends on pipeline behaviour. Two main parameters that identify a wrinkle are \( h \), the height of a wrinkle and \( L \), the distance over which the curvature of the wrinkle returns back to the original level of the pipe. The main parameters of the study were \( D/t \) ratios, the wrinkle severity ratios of, \( h/L \), and stress concentration factors. Three specimens with the same thickness of 0.312 in were considered. The diameters of the pipe specimens were either 22 in. (559 mm) (API grade of X42) or 30 in. (762 mm) (API grade of X52). The research was aimed at repairing the wrinkle bends with GFRP composite wraps oriented in both longitudinal and circumferential directions. Each specimen was designed to have two wrinkles, one of which was rehabilitated with 9 layers of GFRP composite wrap. Figure 2.8 shows a completed installation of composite wrap for a specimen. Following the repair, the specimens were subjected to a cyclic pressure load ranging from 0.68 MPa (98 psi) to 5.9 MPa (855 psi) until a failure occurred. Using the experimental results, a finite element model was also developed and validated. The parametric study by FEA showed that the number of cycles needed to fail the specimens was inversely proportional to the typical wrinkle severity ratio \( (h/L) \). Results exhibited that the GFRP wrap extended the fatigue life of the specimens and was effective in reinforcing the wrinkles. Also, the GFRP increased the fatigue life of the specimens when the presence of corrosion reduced it.
Most of the research conducted on repairing corroded pipelines using FRP found in literature are for pipes loaded under internal pressure. Shouman and Taheri (2009) numerically investigated the performance of repaired and unrepaired corroded pipelines under combined internal pressure and bending. The commercial FE cod, ABAQUS was utilized to model a 1.5-meter X52 API steel pipe. An eight-layer uniaxial Glass composite was simulated in the model, wrapped around the pipe with the fibres in the circumferential direction. It was assumed that there was a perfect bond between the composite wrap and the pipe. The results of the numerical investigation showed that up to the yielding of the steel in the corroded region, the steel pipe counteracted most of the stresses induced by applied load combination. However, after this point, the composite started to carry most of the stresses which was accordance with Freire et al. (2007) results.

It was found that Clock Spring’s GFRP repair system can restore the minimum specified strength of pipelines to its un-corroded values. It was found that the existence of internal pressure had a severe impact on the bending capacity of a pipe; as the pressure increased, the bending capacity decreased. Also, it was found that as the internal pressure increased, the curvature of the maximum moment decreased. Meaning that in specimens with higher internal pressures, the moment dropped immediately after reaching the maximum moment capacity. Also, the results of the experimental tests revealed that although FRP prevents the wrinkle formation in the corroded area, however, it made the area adjacent to the repaired zone susceptible to yielding. This is because use of FRP increases the stiffness of the repaired area which transfers the stresses to the less stiff regions adjacent to the repaired section. Based on the results found in this research, one
can say that an FRP composite is capable of repairing a defected region of a pipe, however, this will lead to local buckling on either side of the composite.

Riser pipes are among vital constituents used in offshore operations to transport liquid vertically from below the surface to the well head. Besides of being subjected to a variety of loads such as external pressure, internal pressure, tension and axial loads, risers are exposed to severe corrosive conditions. Alexander and Ochoa (2010) extended the study of repairing corroded onshore pipelines using CFRP composite to offshore riser pipes. The purpose of the study was to investigate the effectiveness of using composites in repairing corroded riser pipes as an appealing alternative to the conventional repairing techniques of using steel clamps that were either bolted or welded together. In this study, three full-scale experimental tests were conducted, and their results were used to validate the finite element model in ABAQUS. The thickness and diameter of the specimens were 10.3 mm and 219 mm, respectively. A corrosion patch measuring 50% of the wall thickness with 60.9 cm length was fabricated on the specimens. The composite repair scheme wrapped around the specimens was composed of three layers of CFRP and one innermost layer of GFRP to avoid galvanic corrosion. The results of the burst test revealed that fibres oriented in the hoop direction recorded the highest strains while the half-shells had relatively lower strain due to the fact that they were not loaded as much. Under the four-point bending test, until the bending load reached 89 kN, all strain gauges responded elastically. Having higher local stresses, the plastic hinge formed outside of the repair segment which was in agreement with the previous literature. Figure 2.9 shows the installation of carbon composites on an offshore steel riser.
Shouman and Taheri (2011) numerically and experimentally assessed the compressive strain limits of corroded steel pipes rehabilitated with FRP composites, comprised of 8 layers of glassy epoxy. The objective of the study was to investigate the effectiveness of FRP rehabilitated pipes, under combined internal pressure, axial loading, and bending, with different $D/t$ ratios. In the numerical part of the study, the 8-node linear solid element (C3D8R) was employed to model a 3-meter long API 5L X60 grade steel pipe in ABAQUS. The stress-strain relationship was simulated based on the Ramberg-Osgood material model expression. The parametric study varied combinations of different parameters for 45 specimens. The internal pressure was altered at increments of 20 between 0 and 80% of the yield stress in the hoop direction. $D/t$ ratios varied from 30 to 100 with an increment of 10. The axial loading was in the form of a tensile or a compressive load. The experimental part of the study was conducted on API 5L, X56 steel pipes with 1520 mm length. The corrosion depth of the specimens was 80% of the wall thickness. The defect cavities were filled with epoxy putty.

The authors made several conclusions based on the outcomes of this study. As the internal pressure increased, the ultimate moment capacity of the pipes decreased. However, the ductility of specimens significantly increased at higher pressure. As the $D/t$ ratio increased, the ultimate moment capacity decreased. Repairing the specimen with uniaxial FRP in the circumferential direction, did not have any noticeable impact on the moment-curvature response. While the pressurized pipes buckled outwardly, the unpressurized pipes buckled in the form of inward bulging, or diamond mold buckles which was in agreement with the literature (Kim and Park, 2002; Limam et al., 2010). Considering the length of the wrap, it was seen that increasing the length of the FRP wrap would increase
the ultimate moment capacity of the specimens and decrease the curvature. Same as the observations made by Alexander and Ochoa (2010), this study found that as the bending moment increased, the specimen tended to buckle in the area outside the repaired zone. The comparison of the local buckling shapes of the experimental test and numerical model can be found in Figure 2.10.

Despite numerous studies on the behaviour of composite repaired pipelines, there is an evident gap in the literature for long-term performance of the FRP repaired corroded pipes. Esmaeel et al. (2012) investigated the applicability of FRP repaired steel pipes subjected to internal pressure and environmental effects. The main purpose of the study was to examine the long-term deterioration of FRP composites subjected to harsh environmental conditions. In this study, six identical specimens were gouged and repaired with ten layers of unidirectional E-glass fibres. In order to pressurize the pipes, all the specimens were welded with end caps at their ends and then were pressurized until failure. An 89X12.7 mm corrosion patch with 80% of wall thickness depth was fabricated at the mid-span of the specimens. The diameter and the $D/t$ ratio of the specimens were 141.2 mm and 21.4, respectively. The pipes were sandblasted, and the defects were filled with auto body type filler so that the original shapes were restored prior to repair. For a period of 225 days, all the specimens were plunged in water with a salinity of 35 ppm. Three groups of specimens were constructed; the control, which was kept in a normal, environmental condition; one was subjected to hot cycling; and the last was exposed to moist and hot cycling. The range of thermal cycles was between +5 °C and + 55 °C.

The three-dimensional eight node solid elements (C3D8R) were used to model the specimens in ABAQUS and the models were validated with the experimental results. The
authors reported leakage in the welded plates due to the high internal pressure; as a result, the specimens did not reach the burst pressure capacity. It was found that the hot environment decreased the stiffness of the specimens. The worst-case scenario occurred when the specimens were exposed to an environment that was both hot and moist. It was also observed that in order for the finite element model to match the experimental strains, the modulus of elasticity of the FRP had to be degraded.

Elchalakani (2016) investigated the behaviour of corroded circular hollow sections made with mild steel grade ASTM A53 Schedule 30, rehabilitated with CFRP composite under 3-point bending. The diameter-to-thickness ratio of the specimens was in the range of 20.3 to 93.6. The corrosion was artificially simulated using CNC by reducing the wall thickness all around the circumference of the pipe. Four different corrosion severities including 20%, 40%, 60%, and 80% were considered in this study. The corrosion length-to-diameter ratio of the specimens was in the range of 1 to 3. Combined flexural and bearing strengths were applied on 31 specimens, including 12 bare and 19 repaired specimens without applying any internal pressure. The results of the tests revealed that using biaxial CFRP sheets wrapped around the pipe could increase the strength of specimens by an average of 97%. However, only the pipe section with corrosion measuring 20% of the wall depth could be repaired to meet its original capacity. As the corrosion depth increased, the repaired strength with respect to the original capacity decreased. It was concluded that for the pipes with 40% to 80% corrosion of the wall thickness, adding more CFRP layers may restore their capacities to the level of un-corroded specimen. Figure 2.11 compares the capacities of the control specimen with 20% and 40% corroded pipes and their repaired capacities.
Elchalakani et al. (2017) conducted their second series of tests on pipelines under 3-point bending. Like the previous study, four levels of severity of corrosion 20% (mild), 40% (moderate), 60% (severe), and 80% (very severe) were tested. However, in this series, the corrosion length was extended to almost the entire length of the pipe. By doing so, the slenderness limits of some of the pipes changed significantly from compact (un-corroded pipe) to slender section (80% corrosion pipes). Two series of tests were conducted, with 31 specimens in the first series and 12 specimens in the second series. In the second series, not only was the corrosion length extended, but also twice the number of CFRP layers were used in both horizontal and circumferential direction to strengthen the load-carrying capacity of the pipes. By doing so, the average gain in the strengthening series increased 74% more than the rehabilitation test results and the maximum gain was 434.1% for one of the specimens with 80% corrosion. Figure 2.12 compares the load-capacity of the control specimen with corroded and CFRP repaired specimens of 20% and 40% corrosion depth.

Rohem et al. (2016) experimentally examined the performance of a new Glass fibre reinforced polymer on pipelines under burst pressure. The study was designed and validated based on the ISO/TS24817 standard (ISO, 2017). ISO/TS24817 recommends two design cases for defective pipes. In this study, two types of defects based on the standard were investigated. In type A, the defect was machined into the pipe to simulate 80% external corrosion of the wall-thickness. According to the equation proposed in the standard, 16 mm repair thickness of GFRP which include 54 turns of laminates were applied to the pipe. Three modes of hydrostatic tests were conducted, including constant, cyclic, and failure pressure. The results of this type of defect showed that the composite repair could preserve the original design pressure to the point that plastic deformation
occurred at the end of the tube without any failure of the composite wrap. For type \( B \) defect, a circular hole with three different diameters was drilled into a pipe with 100 mm diameter. Based on the recommendations of ASTM D1599, the internal ramp pressure was applied until the composite layers were delaminated from the pipe. For this defect, the delamination of the pipe was in accordance with ISO/TS 24817 (ISO, 2017) which recommends the failure should be due to delamination failure mechanism and cannot happen along the thickness of the composite wrap.

Budhe et al. (2017) analytically continued their previous experimental research (Rohem et al. 2016) to find a simple yet accurate methodology to calculate the failure pressure of an FRP reinforced, corroded metallic pipeline. In this theoretical analysis, an elasto-plastic thin-walled cylinder with inner radius \( r_i \) and outer radius \( r_o \) was considered, which was subjected to an internal pressure \( P_i \) and external pressure \( P_o \). The following equation was proposed to calculate the theoretical failure pressure:

\[
P_f^{th} \left( \frac{r_i - \eta r_p}{r_p - r_i} \right) = \sigma_{flow} \tag{2.3}
\]

In the equation, \( P_f \) is the failure pressure, \( r_p \) is the outer radius of steel pipe at defect section, and \( \sigma_{flow} \) is flow stress which is defined as the required stress for the pipe to fail. Although the proposed equation only uses the elastic range of material properties of the pipe, filler, and composite, it yields a more conservative result than the ISO/TS 24817 failure pressure value and is suggested to be used for the structures with higher safety demand.

Typically, in the numerical and analytical studies for repairing pipelines using composites found in the literature including ASME PCC-2 (ASME, 2015) and CSA Z662
(CSA, 2015), it is assumed that the connection between FRP and pipe remains intact during the test. Using ABAQUS, Shadlou and Taheri (2017), conducted a numerical study to investigate the effect of cohesion between composite and pipe on the axial and bending capacity of the repaired pipelines. The authors employed finite-element analysis to examine the effects of a variety of parameters including having intact or unintact composite wrap (CW), tensile axial loading, compressive axial loading, bending, internal pressure, thickness, and length of the CW in their research. The Ramberg-Osgood model was used to define the stress-strain constitutive relationship. An indent with a dimension of 75×12 mm was simulated in an API 5L X52 steel pipe model. The results of their model under axial loading are depicted in Figure 2.13. As can be seen from the figure, not only increasing the composite thickness does not contribute to increasing the axial capacity of the pipe, but also it decreases the axial capacity which is in contrast with the ASME, CSA, and previous numerical studies about repairing pipelines in the literature. The rationale behind their results is that in reality, the connection between composite wrap and pipe does not remain intact during the test. Moreover, as the thickness of the CW increases, its axial stiffness, and thereby, its contribution to the applied axial load increases which may cause the premature failure of the adhesive interface.

It was also found that the condition of composite wrap interface does not have any noticeable influence on ultimate bending capacity of the pipe, when it is under combined internal pressure and bending moment.

Use of composites for repairing water pipeline began in 1990’s. Ojdrovic and Pridmore (2017) studied the performance of CFRP on the behaviour of internally repaired
buried pipelines. This study was a continued work by Zarghamee et al, 2013, 2014, 2015, and 2016 on repairing water pipeline with CFRP.

The uniaxial layers of CFRP were employed to provide stiffness and strength to the pipes and biaxial GFRP layers were used to prevent galvanic corrosion and provide a barrier against water in the pipeline. The purpose of the study was to investigate the importance of requirements, quality of products, qualification of installers, and inspection during and after construction on the performance of the pipelines. To that end, four types of imperfections including voids between CFRP layers, waviness in the orientation of fibres, distance between the CFRP rolls, and fabric with improper saturated zones were investigated. It was found that CFRP can be used to effectively increase the reliability and longevity of large diameter water pipes. It was suggested that although small imperfections such as waviness in the orientation of fibres and small voids do not have a significant effect on the structural performance of the pipe, however in order to utilize the maximum advantage of CFRP, material and installation procedures should be followed based on industry standards by experienced installers and engineers.

2.4 Codes and Standards

2.4.1 ASME B31G

ASME B31G (ASME, 2012) Manual for Determining the Remaining Strength of Corroded Pipelines was first published in 1984. Based on the 1991 version of the code, the maximum allowable longitudinal extent of the corroded area is calculated from:

\[ L = 1.12B\sqrt{Dt} \]
The value of the factor $B$, which should not exceed 4 is determined either through Equation 2.5 or an existing graph in the code.

$$B = \sqrt{\left(\frac{d}{t}\right)^2 - 1}$$  \hspace{1cm} (2.5)

The depth of a corrosion pit is calculated as a percent of the nominal uncorroded wall thickness of the pipe:

$$\% \text{ Pit depth} = 100 \frac{d}{t}$$  \hspace{1cm} (2.6)

Where

$d = \text{measured maximum depth of the corroded area}$

$t = \text{nominal wall thickness of the pipe}$

$D = \text{nominal outside diameter of the pipe}$

If the length of the corroded area is greater than the value calculated in Equation 2.4 and the maximum corrosion depth is between 10% to 80% of the nominal wall thickness, ASME B31G recommends lowering the pressure to $P'$ which is the safe maximum pressure for the corroded area; otherwise, the corroded area should be either repaired or replaced.

In order to calculate $P'$, first, factor $A$ should be determined.

$$A = 0.893 \left( \frac{L_m}{\sqrt{D_t}} \right)$$  \hspace{1cm} (2.7)

$P'$ for the values of $A$ less than or equal to 4 is:
\[ P' = 1.11P \left[ \frac{1 - \frac{2}{3} \left( \frac{d}{t} \right)}{1 - \frac{2}{3} \left( \frac{d}{t \sqrt{A^2 + 1}} \right)} \right] \]  

(2.8)

Where \( P \) is the greater of either MAOP (Maximum allowable Operating Pressure, psi) or \( P = 2StFT / D \).

\[ P' \] for the values of \( A \) greater than 4 is:

\[ P' = 1.1P \left[ 1 - \frac{d}{t} \right] \]  

(2.9)

2.4.2 DNV RP-F101

DNV RP-F101 (DNV, 2017) which is a result of co-operation between BG (British Gas) Technology and DNV, was first published in 1999. BG conducted more than 70 burst tests on pipes containing machined corrosion defects and 3D non-linear finite element analysis to generate a database of line pipe performance and their material properties. The DNV database included 12 burst tests on corroded pipes subjected to the axial and bending loads as well as 3D non-linear finite element analysis. DNV RP-F101 (DNV, 2017) provides recommendations for assessing corroded pipes under:

1) Internal pressure loading only

2) Internal pressure loading combined with longitudinal compressive stresses

Internal corrosion in the base material, external corrosion in the base material, corrosion in seam welds, corrosion in girth welds, colonies of interacting corrosion defects,
and metal loss due to grind repairs are the types of corrosion defects that can be assessed in this code.

The DNV RP-F101 simplified capacity equation for a single rectangular corrosion shape defect is:

\[
P_{\text{cap}} = 1.05 \frac{2t\sigma_u}{(D-t)} \left(1 - \frac{d/t}{Q}\right) \left(1 - \frac{d/t}{Q}\right)
\]

Where

\[
Q = \sqrt{1 + 0.31 \left(\frac{L}{\sqrt{Dt}}\right)^2}
\]

(2.10)

(2.11)

2.4.3 CSA Z662

CSA Z662 (CSA, 2015) is a standard provided by Canadian Standard Association for oil and gas pipelines in Canada. Based on the standard, a pipe that does not have a corroded area located in dents, and the depth of corrosion is between 10% to 80% of the nominal wall thickness of the pipe, can be used providing:

a) The longitudinal length of the corroded area does not exceed the maximum allowable longitudinal extent determined as specified in ASME B31G; or
b) The Maximum Operating Pressure is equal to or less than the factored failure pressure of the pipe containing the corroded area, as seen in the following expression:

\[
MOP \leq P_{\text{fail}} \times (F \times L \times J \times T)
\]

(2.12)
Where

\[ F = \text{design factor} \]
\[ L = \text{location factor} \]
\[ J = \text{joint factor} \]
\[ T = \text{temperature factor} \]

\( P_{\text{fail}} \) is the failure pressure of a pipe containing a corroded area determined in the 0.85\( dL \) method or the effective area method. The design factor value is 0.8 and the values of \( L, J, \) and \( T \) are less than or equal to 1 which makes the Maximum Operating Pressure more conservative.

2.4.4 ISO/TS 24817

The objective of ISO/TS 24817 standard (ISO/TS, 2017) is to ensure that the composite repairs on pipelines meet the specified performance requirements. The requirements and recommendations of the standard are for external application of composite repairs to the corroded or damaged pipelines in the petroleum, petrochemical and natural gas industries. The design methodology of the standard is for two types of defects, type \( A \) and type \( B \). The defect type \( A \) is within the substrate, not through-wall and not expected to become through-wall within the lifetime of the repair system. This type of defect only requires structural reinforcement. In defect type \( B \), the substrate requires structural reinforcement and sealing the leaks. Based on the standard, the length of the composite should extend beyond the damaged region by the larger of 50 mm or \( L_{\text{over}} \), where \( L_{\text{over}} \) is determined by:

For slot type defects:
\[ L_{\text{over}} = 2\sqrt{Dt} \]  

(2.13)

For circular type defects:

\[ L_{\text{over}} = 4d \text{ where } d < 0.5\sqrt{Dt} \]  

(2.14)

The total axial length of the repair is determined by:

\[ L = 2L_{\text{over}} + L_{\text{defect}} + 2L_{\text{taper}} \]  

(2.15)

Equations 2.15 is also provided by ASME PCC-2 (ASME, 2015).

2.4.5 ASME PCC-2

ASME PCC-2 (ASME, 2015) provides technical information and recommendations for repair of pressure equipment and piping. This standard provides the repair information including welding repairs, mechanical repairs, and non-metallic composite repair systems. The design methodology for the composite repair systems in ASME PCC-2 includes two design cases: Type A design case, where the components do not leak and only require structural reinforcement and type B design case, where the components leak through-wall defects and require sealing and structural reinforcement.

The minimum thickness of the composite repair provided in this standard depends on the contribution of the component in the calculation for load-carrying capacity. When the underlying substrate does not yield, the minimum repair thickness required to support hoop stresses due to internal pressure is calculated by:

\[ t_{\text{min}} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot (P - P_s) \]  

(2.16)
And the minimum repair thickness to support the axial stresses due to internal pressure, bending, and axial thrust is calculated by:

\[
t_{\text{min}} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(\frac{2F}{\pi D^2} - P_s\right)
\]  
(2.17)

When the underlying substrate does yield, the minimum thickness required to support hoop strains due to internal pressure is calculated by:

\[
t_{\text{min}} = \frac{1}{\varepsilon_s E_c} \left(\frac{P_D}{2} - s \varepsilon_s\right)
\]  
(2.18)

And the minimum repair thickness to support the axial stresses is calculated by:

\[
t_{\text{min}} = \frac{1}{\varepsilon_a E_a} \left(\frac{P_D}{4} - s \varepsilon_a\right)
\]  
(2.19)

Equations 2.16, 2.17, and 2.18 are also provided by ISO/TS 24817 (ISO/TS, 2017). Other pipeline standards such as BS 7910 (BSI, 2016) and API 579 (API, 2007) do not have any recommendations about the minimum thickness of the composite repair.

### 2.5 Summary

The literature presented in this chapter elaborates on the corrosion phenomenon and its effect on the performance of pipelines. Traditional repair mechanisms to repair corroded pipelines include patch clamps and encircling sleeves that have their own disadvantages. Due to the cost-effectiveness, ease of use, and convenient application, researchers have explored the possibility of using FRP composites to repair and rehabilitate defected oil and gas pipe sections. It was found from the literature that CFRP and GFRP can be used to increase the burst strength of the corroded pipes.
Despite the extensive research conducted on these commercially available FRP composites, no experimental data was found in the literature of using BFRP to repair corroded pipes. Basalt FRPs (BFRPs) are green products, abundant in nature, and have been effectively proven to enhance the performance of concrete structures. Most of the research conducted on repairing corroded pipes with FRP composites have focused on burst strength capacity of the pipelines and only few studies were found to investigate the impact of FRP repairs on the bending capacity of pipes.

The study conducted by Shouman and Taheri (2011) revealed that increasing the length of the FRP wrap can increase the ultimate moment capacity of the specimens and decrease the curvature. Through experimentally testing unpressurized pipes under three-point bending load, Elchalakani (2016) found that CFRP was able to fully restore the bending load-carrying capacity of low level corroded pipes with 20% corrosion depth. Elchalakani et al. (2017) extended the previous study by increasing the number of CFRP layers. It was observed that in order to restore the capacity of corroded pipe with a higher level of corrosion depth, a higher number of CFRP layers needs to be used. Considering the previously mentioned studies, a research is necessary to investigate the performance of corroded pipes rehabilitated with BFRP composite under four-point bending.
Figure 2.1: Local buckling of pipes (Alexander and Kulkarni, 2008)

Figure 2.2: Local buckling of a pipe with no internal pressure (Sen et al., 2011)
Figure 2.3: Ovalisation vs. curvature (Limam et al., 2010)

Figure 2.4: Conventional FRP products (ISIS Canada Corporation, 2006)
Figure 2.5: Stress-strain curves of typical reinforcing fibres (Fib Bulletin 40, 2007)

Figure 2.6: Burst specimens of API 5L X60 pipe (Freire et al., 2007)
Figure 2.7: Burst carbon composite repaired vessel (Duell et al., 2008)

Figure 2.8: Installation of composite wrap (Alexander and Kulkarni, 2008)
Figure 2.9: Installation of Carbon composite (Alexander and Ochoa, 2010)

Figure 2.10: Experimental and numerical buckling shapes (Shouman and Taheri, 2011)
Figure 2.11: Effect of CFRP repair on corroded pipes (Elchalakani, 2016)

Figure 2.12: Effect of CFRP repair on corroded pipes (Elchalakani et al., 2017)
Figure 2.13: Normalized axial force of pipe (Shadlou and Taheri, 2017)
Chapter 3: Experimental Program

3.1 Introduction

As discussed in the previous chapter, basalt composite is a new type of fibre and this fibre has not been used by the pipeline industry to repair and rehabilitate defective pipe sections. There is a large number of research in the literature about the use of CFRP and GFRP composites to rehabilitate and strengthen corroded pipes under burst pressure. However, no research was found to use BFRP composite to improve bending capacity of the corroded pipelines or to repair any kind of defect in oil and gas pipeline. The purpose of this study was to determine the effectiveness of BFRP composite in restoring the bending capacity of corroded pipelines.

The experimental part of this study was conducted in two phases. The specimens in phase A were manufactured from an 8 in. (203 mm) diameter pipe. The actual outside diameter, thickness (t), and D/t ratio of these specimens were 220 mm, 6 mm and 36.6, respectively. In phase B of the study, 6 in. (152 mm) diameter pipes were used with actual outside diameter, thickness, and D/t ratio of 168 mm, 3.4 mm and 50, respectively. This chapter presents the test specimens, material properties, test setup, and the instrumentations used in this study.

3.2 Preparation of the Specimens

The length of the specimens in phase A and phase B were approximately 2124 mm and 1760 mm, respectively. The specimens from each phase were cut from the same pipe separately. Two ends plates with a dimension of 330×330 mm and the thickness of 25 mm
were welded to the end of each pipe to be able to pressurize the pipe. The plates were drilled, threaded, and fitted with valves in order to fill the pipe with water. The pipes had a longitudinal seam from the ERW (Electric Resistance Welding) process. In order to reduce the effects of stress concentration of the seam weld on the failure, the pipes were oriented in a way such that the weld seam of the pipes was not oriented in the top (compression) or bottom (tension) side of the specimens; it was 90° degree from the top side or at 3 O’clock position. For each phase of the experiment, a computer numerical control (CNC) machine was used to manufacture the desired corrosion patch with different shapes, depths, and dimensions on the midpoint of the top side of the specimens.

3.3 Corrosion Repair

Four specimens in phase A and one specimen in phase B were repaired by BFRP composite using the wet lay-up method. As explained in the previous chapter, in the wet lay-up system, the epoxy resin is mixed and applied to a flexible woven fabric. First, the corroded zone of the pipe was cleaned of any dirt or oil with a grinder (Figure 3.1). Then, it was wiped with acetone to remove the remaining dust. Except specimen 5 in phase A (A40R20B) where three strain gauges were installed in the corroded area (Figure 3.2), all repaired specimens were attached with one horizontal strain gauge in the centre of the corroded area to measure the behaviour of the wrinkle (Figure 3.3). Then, a 100 mm strain gauge wire was soldered to the strain gauge. After installing the strain gauge to the pipe, the MasterBrace P 3500 type of primer was applied to the substrate of the pipe. Based on the instruction of the primer, it was prepared by mixing the two parts of A and B with the ratio of 100 (part A):60 (part B) by weight. Part A was first mixed separately. Then, part B was added to the part A and they were mixed for three minutes. After curing the primer,
the epoxy was applied to the pipe within the following 24 hours of the application of the primer. Figure 3.4 illustrates the application of epoxy during repairing a corroded specimen and Figure 3.5 shows the specimen after repairing with BFRP composite. The epoxy, MasterBrace SAT 4500 was prepared by mixing two parts at a ratio of 100 (part A):30 (part B) (Figure 3.6).

For the specimens with 20% and 40% corrosion depth, 10 and 20 layers of BFRP composite were used, respectively to repair the corroded zones. Each BFRP dry fabric is 0.45 mm thick. Only uniaxial BFRP fabric was used in this study. Depending on the depths and shapes of the corrosion patches, several pieces of BFRP composite were impregnated with resin and used to fill simulated corroded patches (Figure 3.7). As mentioned in Chapter 2, the minimum required length of the corrosion patch recommended in the standard (ISO/TS 24817 and ASME PCC-2) is as follows.

\[
L = 2L_{\text{over}} + L_{\text{defect}} + 2L_{\text{taper}}
\]  

(3.1)

Where \( L \) is the required total length of the composite, \( L_{\text{over}} \) is the overlap length, \( L_{\text{defect}} \) is the length of the defect, and \( L_{\text{taper}} \) is the taper length. In the specimens with 75×75 mm dimension of the corrosion patch, the recommended repair length based on these standards is 223.4 mm and 179.5 mm for the specimens in phase A and B, respectively. Based on the studies done by Deng and Lee (2007) and Haghani and Al-Emrani (2012) on rehabilitation of steel beam with CFRP composite, it was found that tapering the laminates can reduce the effects of stress concentration at the ends of the CFRP laminates and prevent debonding. Therefore, it was decided to implement the end tapering of the composite layers by gradually reducing the length of the layers from the bottom to the top. The length of the
repair used for the corroded 8 in. (203 mm) diameter specimens in phase A tapered from 348 mm for the bottom layer to 312 mm for the top layer (Figure 3.8 (a)). For the 6 in. (152 mm) diameter corroded specimens in phase B, the length of the composite repair tapered from 200 mm for the substrate layer to 180 mm for the top layer (Figure 3.8 (b)).

3.4 Material Properties

3.4.1 Steel

In order to determine the material property of the pipes, four coupon specimens of the pipe in phase A and five coupon specimens of the pipe in phase B were cut from the pipes using a water-jet cutter (Figures 3.9 and 3.10). The recommendation of tension testing of metallic materials of the ASTM E8/E8M-16a (ASTM, 2016) was followed to prepare and test the steel coupon specimens in direct tension. In order to eliminate the stress concentration effects of the weld seam, the coupons were cut from the pipe in the longitudinal direction away from the weld seam. The coupons were gripped by the MTS machine with wedge type grips and were subjected to the tensile loading until rupture (Figures 3.11 and 3.12). A 50 mm gauge length extensometer was mounted on the coupon specimens to measure the displacement between the two jaws of the extensometer. The engineering strain values were determined by dividing the displacement values by 50. The engineering stress values were calculated by dividing the load values of the MTS machine load-cell by the cross-sectional area of the coupon specimens. The average yield strength, ultimate strength, and modulus of elasticity of the specimens in phase A were found to be 403 MPa, 448 MPa, and 185 GPa, respectively. Hence, this pipe specimen was X46 grade as per API 5L (API, 2018). The average yield strength, ultimate strength, and modulus of
elasticity of the specimens in phase $B$ were found to be 404 MPa, 476 MPa, and 185 GPa, respectively. Hence, it was X46 grade pipe in accordance with API 5L (API, 2018). Figure 3.13 shows the engineering stress-strain diagrams of the specimens in phases $A$ and $B$, and BFRP fabric.

### 3.4.2 Basalt Fibre Fabric

Tensile properties of the BFRP composite were determined by testing coupon specimens in accordance with the ASTM D3039/D3039-17 (ASTM, 2017). The standard suggests using tab at the ends of the coupon specimens to reduce stress concentration at the ends of the grip and ensure that the load is distributed evenly to the coupon. In order to prepare the BFRP coupon specimens, first, two tabs made of glass composite board were placed on a plastic sheet. Then, the plastic and the tabs were covered with epoxy. Next, a uniaxial BFRP composite sheet with a thickness of 0.45 mm was placed on the tabs and it was immersed in epoxy. At the end, two tabs were placed at the ends of the impregnated BFRP sheet and allowed to dry. Once the fabric was cured, the coupons were cut from the BFRP fabric. The non-contact optical metrology called Digital Image Correlation (DIC) was utilized during the test to analyze the BFRP coupon specimens (Figure 3.14). The average modulus of elasticity, ultimate stress, and ultimate strain of the tensile uniaxial BFRP specimens were found to be 25 GPa, 550 MPa, and 0.022, respectively (Figure 3.13). Also, the shear and compressive properties of the BFRP composites were obtained by fabricating, testing, and analyzing coupon specimens in collaboration with a co-doctoral student, Mr. Amirreza Bastani. Figure 3.15 shows several coupon specimens before the test and Figure 3.16 displays ruptured basalt coupon specimen after the shear test.
3.5 Test setup

The schematic of the test setup for phase A and B specimens are shown in Figure 3.17. Figures 3.18 and 3.19 show the real test setup of the specimens in Phase A and B, respectively. The exact details of each phase of the specimens are sketched in Figures 3.20 and 3.21. In order to have a firm symmetrical four-point bending setup, two large and heavy steel rigid supports were bolted to the concrete floor (Figure 3.17). A custom-made mechanism was designed to allow the specimens to rotate in one direction. Two plates having two protruding cylinders with balled ends each were bolted to the large steel rigid supports. A bottom support with two half-cylindrical holes was placed on the plate with the two ball studs. The purpose of having two ball studs is to have a stable setup while preventing any out of plane bending of the pipe.

Next, the specimens were lifted upright with a crane so that while it was filled with water from the bottom valve, the top valve was open to allow the air to go out (Figure 3.22). After that, the pipe was lowered and placed on the bottom supports. A hose was used to connect one side of the pipe to a fluid pump to pressurize the pipe to a constant level of internal pressure. A pressure transducer was installed to the other side of the pipe to monitor the internal pressure during the test.

A hydraulic jack was bolted vertically to a strong steel reaction frame and it was positioned exactly at the centre of the pipe. A steel spreader beam was placed between the pipe and the hydraulic jack to transform the three-point bending load to four-point bending load through two top supports. The top supports were located between the spreader beam and the pipe. Similar to the mechanism of the bottom supports, four protruding cylinders
were bolted to the bottom side of the spreader beam (Figure 3.17) so that they can rotate inside the half-cylindrical holes of the top supports. The span length of the spreader beam was 500 mm for both phases of the specimens.

Three Linear Variable Differential Transformers (LVDTs) were placed at 1/4\textsuperscript{th} of span length under the pipe (Figure 3.17) and two LVDTs were installed on the top load cell to measure the deflection that the pipe underwent by the hydraulic jack (Figures 3.17, 3.18, and 3.19). Five small magnets were placed between the pipe surface and the tip of each LVDTs to prevent any slippage of the LVDTs during the test. Six collars were put around the pipe; two at the external edge of each top support and one in the internal edge of them to prevent unwanted wrinkle formation. Two inclinometers were installed at the ends of the pipe to measure the curvature of the pipe. Loctite 401 glue was used to install several strain gauges at the top of the pipe in the area between two internal collars, where a wrinkle was expected to form.

3.6 Test Procedure

Once the setup was completed, a laser levelling device was used to make sure everything was symmetrically aligned, and the hydraulic jack was exactly in the centre of the pipe to prevent any out of plane movement of the pipe and the spreader beam. Also, an electronic level was used to check if the pipe, spreader beam, and the large steel rigid supports were perfectly horizontal. Then, the LabVIEW program was launched to check if all the data collecting instruments connected to the data acquisition system were working. Next, all the values in the program were set to zero. The two valves at the ends of the pipe were opened and the pipe was pressurized by the hydrostatic pump to reach the desired
internal pressure, 670 psi (4.6 MPa) for the specimens in phase A and 960 psi (6.6 MPa) for the specimens in phase B. These pressures correspond to 0.2p_y and 0.4p_y, respectively.

Once everything was ready, the load was gradually applied to the specimen through the hydraulic jack using displacement control method. The four-point bending load was continued until a small wrinkle was visually inspected in the mid-span of the pipe (Figure 3.23). Then the pipe was unloaded in order to safely remove all collars around the pipe. Next, the specimen was reloaded to pass the previous loading point and continued until the formation of a full wrinkle (Figure 3.24).

3.7 Phase A of the specimens

3.7.1 Details of the specimens

The test matrix of phase A is shown in Table 3.1. The test parameters in this phase are the depth of the corrosion (20% or 40% of total wall thickness), number of BFRP fabric layers (10 or 20 layers), and orientation of BFRP fabrics (uniaxial or biaxial) used in rehabilitation of corroded pipe specimens. Hence, the length, diameter, wall thickness, grade of pipe, and corrosion shape were kept unchanged in all specimen of this phase. In this phase of the study, seven specimens measuring 2124 mm were cut from a longer NPS 8 X46 pipe. All specimens were pressurized to an internal pressure of 670 psi (4.6 MPa), equivalent to 0.2p_y of the pipe. The p_y is the pressure that is required to yield the pipe in the circumferential direction which can be calculated using Barlow’s formula:

\[ p_y = \frac{2\sigma_y t}{D} \]  

(3.2)

Where
\[ \sigma_y = \text{yielding stress} \]

\[ t = \text{wall-thickness} \]

\[ D = \text{inner diameter} \]

All corroded specimens were machined to have a square 75×75 mm corrosion patch (Figure 3.25). As can be found in Figure 3.26, in order to reduce stress concentration, the edges of the corrosion patch were machined to have fillet. The corrosion patch was located away from seam weld and seam weld was at 3 O'clock location. All these specimens had an external diameter and wall thickness of 220 mm and 6 mm and thus, the D/t of 36.6. The first specimen (A0C) was an un-corroded pipe to establish a reference for the performance of the virgin (un-corroded) pipe under combined bending and internal pressure and compare the results of other specimens with it. The second specimen (A20C) was manufactured to have a corrosion patch with a depth of 1.2 mm (20% of the wall-thickness of the pipe) (Figure 3.26). The third specimen (A20R10U) was manufactured the same as the second specimen. However, it was repaired with 10 layers of uniaxial BFRP wrap to test whether it can restore the bending capacity of the pipe to the level of the un-corroded (virgin) pipe. The fourth specimen (A40C) was manufactured to have a corrosion patch with a corrosion depth of 2.4 mm (40% of the pipe wall thickness). The fifth specimen (A40R20U) was manufactured the same as the fourth specimen, except 20 layers of uniaxial BFRP wrap was used to repair its corrosion patch with 40% depth of the wall-thickness. In order to have consistency between the number of BFRP layers used for repair and the depth of the specimens, 10 layers of BFRP were used to repair the specimens with
20% corrosion depth and 20 layers of BFRP were used to repair the specimens with 40% corrosion depth.

The objective of testing specimen number three and specimen number five was to examine whether uniaxial BFRP composite can restore the bending capacity of corroded pipes to the level of the un-corroded specimen and whether it can prevent the wrinkle formation in the corroded area. In the subsequent two rehabilitated specimens, BFRP fabrics were used in both directions: half of the BFRP fabric layers were placed in the longitudinal direction and the remaining layers were placed in the circumferential direction. Specimen 6 (A20R10B) was manufactured to have a corrosion patch with the depth of 20% of the wall thickness. In this specimen, 10 layers of biaxial BFRP composite were employed to repair the corroded area. Specimen 7 (A40R20B) was made to have a corrosion patch with 40% depth of the wall-thickness and rehabilitated with 20 layers of biaxial BFRP composite.
Table 3.1: Test matrix of phase A specimens

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Corrosion Depth (%)</th>
<th>Dimension (mm)</th>
<th>Shape</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
<th>Specimen Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>75×75</td>
<td>Square</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
<td>A0C</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>75×75</td>
<td>Square</td>
<td>No</td>
<td>10</td>
<td>0.2p_y</td>
<td>A20C</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>75×75</td>
<td>Square</td>
<td>Yes</td>
<td>0</td>
<td>0.2p_y</td>
<td>A20R10U</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>75×75</td>
<td>Square</td>
<td>No</td>
<td>20</td>
<td>0.2p_y</td>
<td>A40C</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>75×75</td>
<td>Square</td>
<td>Yes</td>
<td>10</td>
<td>0.2p_y</td>
<td>A40R20U</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>75×75</td>
<td>Square</td>
<td>Yes</td>
<td>(5+5) Biaxial</td>
<td>0.2p_y</td>
<td>A20R10B</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>75×75</td>
<td>Square</td>
<td>Yes</td>
<td>(10+10) Biaxial</td>
<td>0.2p_y</td>
<td>A40R20B</td>
</tr>
</tbody>
</table>

Note: Specimens 1-5 were tested jointly by Sachith Jayasuriya and Behrouz Chegeni.

3.7.2 Designation of the Specimen

In Table 3.1, the first letter A, represents the phase A of the tests which includes the specimens with 8 in. (203 mm) nominal diameter. The following number stands for the depth of the corrosion patch in a percentage of the wall thickness which was varied to 0, 20, and 40. The text letter indicates whether a specimen is repaired (R) or it is a control (C) specimen. The following number exists only for the repaired specimens (R) and this number represents the number of BFRP layers used for repairing the specimen. The last letter is either B or U. The letter B indicates that the specimen was repaired with biaxial
fabrics (longitudinal and circumferential). The letter $U$ denotes that the BFRP fabric is used in the uniaxial (longitudinal) direction only. For example, A40R20B, is a specimen with 8 in. (203 mm) nominal diameter and 40% corrosion depth of the wall thickness which was repaired with 20 layers (10 layers in longitudinal direction and remaining 10 layers in the circumferential direction) of BFRP composite in biaxial directions. It should be noted that for biaxial fabrics, the direction of the fabric was altered in each subsequent layer. Hence, bottommost fabric was in the longitudinal direction and the next fabric was in the circumferential direction.

3.8 Phase B of the specimens

3.8.1 Details of the specimens

Table 3.2 displays the test matrix of the specimens in phase B. In this phase of the study, five specimens were cut from a long NPS 6 X 46 pipe. The length, thickness, and outer diameter of the specimens were 1760 mm, 3.4 mm, and 84.7 mm, respectively. The shape of corrosion (circular or square or rectangular) was the test parameter in this phase of study (See Figures 3.26, 3.27, and 3.28). All specimens were pressurized to 960 psi (6.6 MPa) which is 0.4$p_y$. The depth of the corrosion patch in all corroded specimens was 1.36 mm (40% of the wall thickness of the pipe).

In this phase of the study, the first specimen (B0C) was tested on an un-corroded pipe to obtain the bending performance of the pipe. The data from this test was used as a reference to compare with the other 6 in. (152 mm) corroded specimens. The second specimen (B40CS) was machined to have a square 75×75 mm corrosion patch (Figure 3.27). The third specimen (B40CC) was designed to have a circular corrosion patch with a
diameter of 84 mm (Figure 3.28). The fourth specimen (B40RS20B) had a square 75×75 mm corrosion patch, the same as the second specimen. However, it was repaired with 20 layers of biaxial BFRP composite. The fifth specimen (B40CR) was machined to have a rectangular corrosion patch with 45 mm longitudinal length and 125 mm circumferential width (Figure 3.29). The dimensions of the corrosion patch of the fifth specimen were chosen so that the area of the corrosion was the same as that of specimens 2, 3, and 4. The purpose of this phase of the study was to investigate the impact of different corrosion shapes on the bending performance of the corroded and repaired specimens.

Table 3.2: Test matrix of phase B specimens

<table>
<thead>
<tr>
<th>Test</th>
<th>Depth</th>
<th>Dimension (mm)</th>
<th>Shape</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
<th>Specimen Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>No</td>
<td>0</td>
<td>0.4p_{y}</td>
<td>B0C</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>75×75</td>
<td>Square</td>
<td>No</td>
<td>0</td>
<td>0.4p_{y}</td>
<td>B40CS</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>D84</td>
<td>Circle</td>
<td>No</td>
<td>0</td>
<td>0.4p_{y}</td>
<td>B40CC</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>75×75</td>
<td>Square</td>
<td>Yes</td>
<td>20 (10+10) Biaxial</td>
<td>0.4p_{y}</td>
<td>B40RS20B</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>45×125</td>
<td>Rectangular</td>
<td>No</td>
<td>0</td>
<td>0.4p_{y}</td>
<td>B40CR</td>
</tr>
</tbody>
</table>

### 3.8.2 Designation of the Specimen

In the specimen tags provided in Table 3.2, letter B represents the phase B of tests which includes specimens with 6 in. (152 mm) nominal diameter. The second number
indicates the depth of corrosion in a percentage of the wall thickness which was either 0% or 40%. The third letter indicates whether a specimen was repaired (R) or it was a control (C) specimen. The next letter represents the shape of the corrosion: S (Square), or C (Circle), or R (rectangular). The following number of the name represents the number of layers that were applied to repair the specimens. The last letter, B indicates that the specimen was repaired with fibers in biaxial directions (10 longitudinal and 10 circumferential). For example, B40RR20B, describes a 6 in. (152 mm) nominal diameter specimen with a rectangular corrosion patch (45×125 mm) and 40% corrosion depth of the wall thickness which was repaired with 20 layers of BFRP composite in biaxial directions.

3.9 Instrumentation

3.9.1 Hydraulic Jack

A hydraulic jack equipped with a load cell by AEP transducer was used to apply the load to the specimens. The load transducer was able to measure compression and tension loads up to 3 MN and 2.5 MN, respectively. A loading plunger cylinder with a stroke length of 500 mm inside the jack operated by a ZE4440SB hydraulic electric pump enabled it to apply force from the steel reaction frame to the specimens.

3.9.2 Collars

The 4-point bending process caused severe stress concentration on the pipe, near the loading points. In order to prevent local deformation of the pipe under the top supports, six collars were used for setup in phase A of specimens and 4 collars were used in phase B of the specimens, as the pipe sections used in phase B were smaller. The collars used in each
phase of specimens were made by cutting off a ring from the same size pipe. Then, each ring was cut into two semi-circular halves. Next, two punctured steel angles with the same width of the ring were welded to each semi-circular half. Before starting the tests, the collars were fastened using bolts and nuts.

### 3.9.3 Fluid Pump

A constant internal pressure was applied to the specimens by a P300 series hydrostatic pump with a maximum capacity of 10,000 psi throughout the entire of the test. In phase A, the applied internal pressure was 670 psi (4.6 MPa); in phase B, it was 960 psi (6.6 MPa). The pump takes in water and pressurized air, and pumps out pressurized water to the specimens. The pressure value could be monitored throughout the test in three ways: by the reading the pressure gauge of the pump, the pressure gauge connected to the pipe, and LabVIEW data through a calibrated pressure transducer connected to the pipe.

### 3.9.4 Inclinometers

An inclinometer is a device for measuring angles of slope of a structural element. Two inclinometers were fixed with bands at the two ends of each specimen to measure the rotation of the ends of the pipe (Figure 3.17).

### 3.9.5 Linear Variable Differential Transformer (LVDT)

A linear variable differential transformer (LVDT) is a type of electrical transformer used to measure linear movement. The LVDT transforms a linear mechanical movement to a relative electrical signal information. Five LVDTs were installed in the setup to
measure the deflection of each specimen. Two LVDTs were placed on the load cell and three were located under the pipe (Figure 3.17).

3.9.6 Electrical Resistance Strain Gauges

A strain gauge is a device used to collect the strain values in a localized area of an element. The strain gauges were made of a metallic grid which stretch or compress as the pipe deforms under internal pressure and bending load, causing it to become narrower and longer or broader and shorter. As long as the strain gauge doesn’t break or tear off, these changes increase or decrease its electrical resistance, resulting in measuring the local strains of the pipe. Several electrical resistance Kyowa strain gauges of type KFG-5-120-C1-11 were installed at the top of the pipe in the area between two internal collars, where a wrinkle was expected to form. The strain gauges had a resistance of 120 Ω and a length of 5 mm.

Loctite 401 instant glue was used to attach the strain gauges to the pipe. For the control corroded specimens, the strain gauges were installed in the corroded region because it was obvious that the wrinkle forms in that weakened area. In the repaired specimens, one strain gauge was installed in the centre of the corrosion patch on the steel surface of the pipe and a few strain gauges were installed on the cured basalt composite above the corroded patch.

3.9.7 Data Acquisition System (DAQ)

DAQ which is an abbreviation of Data acquisition system was used to monitor and collect all the data of load cell, Linear Variable Differential Transformer (LVDTs), strain
gauges, pressure transducer, and inclinometers during the test. Since in the control specimens around 14 strain gauges were installed, two NI-9235 bridge input modules with 8 channels each were installed to collect the strain gauge data during the test. LabVIEW platform which is a visual programming language from National Instruments was employed to record the data from all the attached instruments. A program was written in LabVIEW to show all data and draw the load-deflection graph of the pipe and load-strain at the centre of the wrinkle which was expected to occur in the corrosion patch. The real-time monitoring data provides this opportunity to observe the behaviour of the pipe during the test.

3.10 Summary

This chapter discussed the preparation of the specimens, rehabilitation technique of the corroded specimen, test setup, details of the specimens in both phase A and B, and the instrumentations used in this study.
Figure 3.1: Cleaning the corroded zone of a specimen before repairing with BFRP

Figure 3.2: Installation of three strain gauges on A40R20U
Figure 3.3: Installation of one strain gauge on A20R10B

Figure 3.4: Application of BFRP composite on a corroded specimen
Figure 3.5: The repaired specimen A20R10U

Figure 3.6: Mixing parts A and B of the epoxy MasterBrace SAT 4500
Figure 3.7: Pieces of BFRP composite to fill the corrosion patch

Figure 3.8: Tapering of BFRP composite fabric (a) phase A (b) phase B
Figure 3.9: The coupon specimens from the 8-inch pipe before the test

Figure 3.10: The coupon specimens from the 6-inch pipe after the tensile test
Figure 3.11: Steel coupon specimen inside the MTS machine

Figure 3.12: Ruptured steal coupon specimen under tensile loading
Figure 3.13: Engineering stress-strain diagrams of specimens in phases A and B, and BFRP composite

Figure 3.14: Testing of BFRP coupon in shear
Figure 3.15: BFRP coupon specimens before testing

Figure 3.16: Basalt coupon specimen after the shear test
Figure 3.17: Schematic of the test setup (mm)
Figure 3.18: Test setup of the specimens in phase $A$

Figure 3.19: Test setup of the specimens in phase $B$
Figure 3.20: The details of the specimens in phase A (mm)

Figure 3.21: The details of the specimens in phase B (mm)
Figure 3.22: Filling a specimen with water
Figure 3.23: Initiation of wrinkle

Figure 3.24: Fully developed wrinkle
Figure 3.25: 75×75 mm square corrosion patch on specimens in phase A

Figure 3.26: Fillet at the edges of corrosion patch

Figure 3.27: 75×75 mm square corrosion patch on B40CS in phase B
Figure 3.28: Circular corrosion patch with 84 mm diameter on B40CC

Figure 3.29: 45×125 mm rectangular corrosion patch on B40CR in phase $B$
Chapter 4: Experimental Results

4.1 Phase A

In this phase of the experimental study, seven NPS 8 grade X46 pipes with D/t of 36.6 were tested. The purpose of testing these specimens was to examine the performance of corroded specimens rehabilitated with BFRP composite under combined internal pressure and bending load. Internal pressure was kept unchanged, however, bending load was increased gradually using a displacement control method. Table 4.1 shows the results of the specimens in phase A. Hence, the test parameters were: the depth of the corrosion (20% or 40% of total wall thickness), number of BFRP fabric layers (10 or 20 layers), and orientation of BFRP fabrics (uniaxial or biaxial) used in rehabilitation of corroded pipe specimens. The ductility of the specimens was measured in two methods: energy ductility and displacement ductility. In the energy ductility method, the area under the load-displacement curve was measured until the load dropped to 0.9F_u. The displacement ductility was measured as the displacement of the specimens when the load drops to 90% of the ultimate load (F_u). In this table, the global yield load was determined a point in the load-displacement graph of the specimens where it deviates from the straight line in the elastic zone and goes toward the plastic zone. The wrinkle initiation strain referred to a strain at which a wrinkle began to form. At this point, the strain value of the load-strain graph began to reverse back toward the positive (tension) values of the diagram which implied the initiation of the wrinkle formation. The wrinkle initiation load, which was corresponding to the wrinkle initiation strain referred to a load at which a wrinkle began to form.
Table 4.1: Experimental values of the parameters tested in phase A

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<tr>
<td>Specimen Name</td>
<td>A0C</td>
<td>A20C</td>
<td>A20R10U</td>
<td>A40C</td>
<td>A40R20U</td>
<td>A20R10B</td>
<td>A40R20B</td>
</tr>
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<td>Global Yield Load (kN)</td>
<td>300</td>
<td>244</td>
<td>300</td>
<td>208</td>
<td>214</td>
<td>300</td>
<td>300</td>
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<td>Local Yield Load (kN)</td>
<td>250</td>
<td>142</td>
<td>260</td>
<td>142</td>
<td>156</td>
<td>250</td>
<td>212</td>
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<td>Yield Displacement (mm)</td>
<td>10</td>
<td>7.6</td>
<td>10</td>
<td>6.2</td>
<td>6</td>
<td>9.5</td>
<td>9.5</td>
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<tr>
<td>Ultimate Load (kN)</td>
<td>412</td>
<td>350</td>
<td>408</td>
<td>328</td>
<td>356</td>
<td>411</td>
<td>405</td>
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<tr>
<td>Ultimate Displacement (mm)</td>
<td>62.3</td>
<td>36.5</td>
<td>50</td>
<td>16.7</td>
<td>26</td>
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<td>Strain at Ultimate Load (%)</td>
<td>2.17</td>
<td>0.98</td>
<td>1.92</td>
<td>0.46</td>
<td>-</td>
<td>0.98</td>
<td>0.72</td>
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<td>Elastic Stiffness (kN/mm)</td>
<td>33.8</td>
<td>33.2</td>
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<td>33</td>
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</tr>
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<td>Wrinkle Initiation Load (kN)</td>
<td>411</td>
<td>347</td>
<td>408</td>
<td>313</td>
<td>326</td>
<td>No Wrinkle</td>
<td>No Wrinkle</td>
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<tr>
<td>Wrinkle Initiation Strain (%)</td>
<td>2.71</td>
<td>1.45</td>
<td>1.92</td>
<td>1.25</td>
<td>-</td>
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</tr>
<tr>
<td>Energy Ductility (kN-mm)</td>
<td>31600</td>
<td>18083</td>
<td>24860</td>
<td>13592</td>
<td>16560</td>
<td>26452</td>
<td>25822</td>
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<td>Displacement Ductility (mm)</td>
<td>87</td>
<td>59</td>
<td>70</td>
<td>48</td>
<td>54</td>
<td>73</td>
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4.1.1 Specimen 1 (A0C)

Specimen A0C refers to NPS8 grade X46 pipe without a corrosion defect that was used as the control (virgin) specimen. The purpose of testing this specimen was to determine the performance of corroded specimen and compare the performance with other specimens. As can be seen in Figure 4.1, specimen A0C displayed elastic behaviour until the displacement of the pipe reached approximately 10 mm. The displacement here refers to the displacement of the LVDT that was located at the bottom mid-span of the pipe (Figure 3.17). The global yield load at this point reached a load of 300 kN. The global yielding of the pipe is considered to have occurred at the yielding point of the load-displacement graph, as opposed to the local yielding of an area. After the yielding point, specimen A0C continued to take an increased load and displayed significant strain hardening behaviour. The specimen continued to bend without any wrinkle formation until it reached a load of 407 kN, corresponding to a displacement of 56 mm. At this point, a small wrinkle was visually identified. The loading continued until it reached its ultimate load of 412 kN at 62.3 mm displacement. After this point, the load resisted by the pipe gradually decreased until the wrinkle continued to grow (Figure 4.2). The loading was stopped, and the test was discontinued at a displacement of 89 mm, corresponding to a load of 362 kN and the load was withdrawn gradually.

As can be seen in Figure 4.3, at the end of the test, the wrinkle grew to an amplitude of 16 mm at the crest of the wrinkle and the length between two feet of the wrinkle was 65 mm. The location at the mid-height of a wrinkle, where the stress condition on outer wall surface is tensional is called the crest of wrinkle. The two ends of a wrinkle, where the stress condition on the outer pipe surface is compressional is called the foot of wrinkle. The
length of the wrinkle was determined by measuring the distance between the two feet of the wrinkle and the amplitude of it was calculated by measuring the vertical distance from the foot to the crest of the wrinkle.

**Strain Behaviour**

Figure 4.3 shows the strain gauge location map with respect to the crest and feet of the wrinkle. The strain behaviour of specimen A0C is shown in Figure 4.4. Although the setup of the test was symmetric, however, the wrinkle did not occur at the mid-span of the specimen. It is assumed that the effects of stress concentration at the collars, and defects within the pipe material caused the wrinkle to form 25 mm off centre, near to one of the internal collars. The strain behaviour of specimen A0C, shown in Figure 4.4, was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle, that is strain gauge 5 in Figure 4.3.

As can be seen in Figure 4.4, the wrinkle location of specimen A0C showed elastic behaviour until it reached a load of 250 kN. After this point, the specimen showed plastic behaviour and the load increased with a decreasing rate until it reached an ultimate load of 412 kN, corresponding to -0.0271 strain. At this point, the strain value began to reverse back toward the positive (tension) values of the diagram which implied the initiation of the wrinkle formation. Once the wrinkle starts to form, the area around the wrinkle expands, therefore, the accumulated compressive strain in that zone decreases and the stress at the crest of the wrinkle transforms from compression to tension. As the displacement of the specimen increased, the wrinkle grew, the load gradually decreased, and the strain values at the crest of the wrinkle approached zero, towards tension. The reason of decreasing load
after developing a full wrinkle is that when a wrinkle grows, it acts as a plastic hinge and allows the specimen to easily bend, thereby, reducing the stiffness of pipe. After the formation of the plastic hinge, increasing the displacement do not result in increasing the load.

4.1.2 Specimen 2 (A20C)

Specimen A20C is a control corrosion specimen and it had a square corrosion patch of 75×75 mm with 1.2 mm corrosion depth equal to 20% of the specimen wall-thickness. The purpose of testing this specimen was to determine the performance of a corroded specimen with a square corrosion patch measuring 75×75 mm under both internal pressure and bending load. Figure 4.5 compares the load-displacement diagram of specimen A20C with A0C. As can be seen in the figure, specimen A20C showed elastic behaviour until it reached a load of 244 kN, corresponding to 7.6 mm displacement at the mid-span of the specimen. Having a corrosion patch measuring 20% of the wall thickness reduced 56 kN of the yielding load, which is about 19% (244 kN vs. 300 kN) of the yielding load of the un-corroded specimen (300 kN).

After yielding, the specimen continued to take a higher load until it reached a load of 350 kN, corresponding to 36.5 mm displacement, which is lower (15%) than that of specimen A0C (412 kN). After reaching its ultimate load, the loading continued until the wrinkle of desired shape developed. At this stage, the displacement reached about 59 mm and load value dropped to about 317 kN. The ultimate load-carrying capacity reached by specimen A20C was 15% (350 kN vs. 412kN) less than the capacity of specimen A0C. Also, the ultimate displacement corresponding to the ultimate load decreased 41.4% (36.5
mm vs. 62.3 mm) as compared to the control specimen. A picture of specimen A20C at the end of the test can be seen in Figure 4.6. The displacement ductility at yield and ultimate loads of specimen A20C were 76% and 59.6% of specimen A0C.

**Strain Behaviour**

As can be found in Figure 4.7, several (8 in longitudinal direction and 4 in circumferential direction) strain gauges were installed longitudinally in and around the corrosion patch, between the two internal collars of specimen A20C. The wrinkle formed exactly at the mid-span of the simulated area of corrosion patch. Therefore, the strain behaviour of the wrinkle of specimen A20C was obtained from the strain gauge that was located at the mid-length of the corrosion patch (strain gauge 5 in Figure 4.8). Figure 4.9 compares the load-strain diagram of specimen A20C and A0C. It should be noted that the strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3). Specimen A20C showed elastic behaviour until it reached a load of 142 kN. It should be noted that the local yielding load occurred at a lower load compared to the global yielding load which occurred at 244 kN. The local yielding implies yielding at the crest of the wrinkle while the global yielding refers to the yielding behaviour of the whole specimen. After this point, the area at the top of the specimen continued to compress until the strain at the middle of the corrosion patch reached -0.0145, corresponding to 347 kN load. At this point, a wrinkle started to form at the centre of the corrosion patch, causing the behaviour of the area to change from compression to tension. As the wrinkle grew, the compressive strain drastically decreased toward the tensile strain values. In this corroded specimen, the wrinkle load which refers to the load at which a wrinkle begins to form, dropped 15.6% as
compared to the control virgin specimen (A0C). Also, the wrinkle strain which refers to the strain at which a wrinkle occurs dropped 46.6%.

### 4.1.3 Specimen 3 (A20R10U)

The purpose of testing specimen A20R10U was to study the performance of the repaired corroded specimen with BFRP composite under combined internal pressure and bending load. Similar to specimen A20C, specimen A20R10U had a 1.2 mm deep square corrosion patch measuring 75×75 mm at the top mid-span of the specimen. In this specimen, ten layers of uniaxial BFRP composite (fibres oriented in the longitudinal direction) were wrapped around the corroded area using the wet lay-up method to repair the corroded specimen. Figure 4.10 compares the load-displacement of specimen A20R10U with the control virgin specimen (A0C) and control corrosion specimen (A20C). As can be observed in the figure, similar to specimen A0C, specimen A20R10U showed elastic behaviour until it reached a load of 300 kN, corresponding to 10 mm displacement of the pipe. The load-displacement curve in specimen A20R10U continued to match its corresponding control virgin specimen (A0C) until it reached its ultimate load-carrying capacity of 408 kN, corresponding to 50 mm displacement. However, post-ultimate load–displacement behaviour of A20R10U was slightly softer than specimen A0C and much stiffer than specimen A20C. Hence, it was found that the ten layers of uniaxial BFRP composite improved the ultimate load-carrying capacity of the corroded specimen by 17% (350 kN vs. 408 kN) and it reached 99% (408 kN vs. 412 kN) of the capacity of the control virgin specimen (A0C). The ultimate displacement of the corroded specimen (A20C) also increased by 37% (36.5 mm vs. 50 mm). After reaching the ultimate load, several horizontal cracks appeared in the BFRP composite which caused the load to drop at a
displacement smaller than the un-corroded virgin specimen (Figure 4.11). Figure 4.12 shows a picture of specimen A20R10U after testing and removing its BFRP composite. As can be seen in this figure, although the BFRP composite improved the bending capacity of the corroded specimen, however, it could not prevent the formation of a wrinkle in the corroded area.

Strain Behaviour

The strain behaviour of specimen A20R10U was obtained from the strain gauge that was installed at the centre of the square corrosion patch (strain gauge 5 in Figure 4.8) on the outer surface of the steel pipe. Figure 4.13 compares the load-strain diagram of specimen A20R10U with specimens A0C and A20C. It should be noted that the strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3). As can be seen in Figure 4.13, specimen A20R10U displayed local elastic behaviour until the steel at that spot reached its local yield load of 260 kN, at the location of the strain gauge. Compared to the corroded specimen (A20C), the BFRP composite increased 83% (142 kN vs. 260 kN) the local yielding load. After this point, the specimen demonstrated strain hardening behaviour until the load reached 395 kN, corresponding to 0.47% strain. Since the modulus of elasticity of BFRP composites is much lower than steel, specimen A20R10U did not show a significant difference in global elastic behaviour compared to specimen A0C. However, the local elastic behaviour in the corroded area of specimen A20R10U showed a stiffer local elastic behaviour than A0C in the corroded area. Since the BFRP composite was located at the corroded area, it only increased the local stiffness of the repaired zone, without affecting the global stiffness.
The corroded zone of the specimen continued to be under increased compressive stress until it began to develop a wrinkle at a load of 408 kN, corresponding to 50 mm displacement, and -0.0192 strain. At this point, the compressive strain at the corroded area began to decrease. As the wrinkle under the BFRP composite continued to grow, several longitudinal cracks on the BFRP composite developed along the length of the pipe and hence, the load capacity gradually reduced.

4.1.4 Specimen 4 (A40C)

Similar to specimen A20C, specimen A40C is a control-corrosion specimen. However, it has thickness loss of 40% due to corrosion formation. This specimen was tested to examine the performance of the corroded specimen when the depth of the corrosion increases to 40% of the wall-thickness. Same as the previous specimens, the dimension of the corrosion patch was 75×75 mm. However, its depth increased from 1.2 mm to 2.4 mm. Figure 4.14 compares the load-displacement diagram of specimen A40C with specimens A0C and A20C. As can be seen in the figure, specimen A40C displayed an elastic behaviour until it reached a load of 208 kN, corresponding to 6.2 mm displacement. It can be seen that the global yield load of specimen A40C is only 69% (208 kN vs. 300 kN) of that of specimens A0C, 15% (208 kN vs. 244 kN) lower than A20C.

After yielding, specimen A40C reached its ultimate load-carrying capacity of 328 kN much faster than specimens A0C and A20C. The ultimate load-carrying capacity of specimen A40C was 328 kN, which was 79% of the ultimate load of control virgin specimen A0C (412 kN), corresponding to 16.7 mm. The ultimate displacement of 16.7 mm was only 27% (16.7 mm vs. 62.3 mm) and 45.7% (16.7 mm vs. 36.5 mm) of the
ultimate displacement of specimen A0C and A20C, respectively. The severe negative
effect of the corrosion can be confirmed from the reduction in ductility. After reaching its
ultimate load, the load-carrying capacity decreased at a faster rate as the displacement
increased. Loading was stopped, and the test was abandoned at 287 kN, corresponding to
55 mm displacement. As can be found in Figure 4.15, a large wrinkle formed at the mid-
length of the corrosion patch of the specimen at the end of the test.

**Strain Behaviour**

The strain data of specimen A40C was extracted from the strain gauge that was
installed at the centre of the corrosion patch (strain gauge 5 in Figure 4.8). The wrinkle
occurred at the middle of the corrosion patch. Figure 4.16 compares the load-strain
relationship of specimen A40C with specimens A0C and A20C. It should be noted that the
strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain
gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3).
As can be found in Figures 4.13 and 4.15, although the global stiffness of the three
specimens up until the global yielding point of specimen A40C were the same, however,
the local stiffness of the three specimens differed; specimen A40C with the deepest
corrosion depth had the lowest local stiffness. Since the corroded area was a very small
part of the pipe, it did not have a noticeable effect on the performance of the pipe before
reaching the global yielding point. However, after yielding and wrinkle formation, the
corroded zone acted as a plastic hinge and drastically reduced the load-carrying capacity
of the corroded specimen. Figure 4.16 shows that the local stiffness of the corroded area
was directly related to the thickness of the pipe at the corroded zone. Therefore, specimen
A40C with the most corrosion depth had the least local stiffness.
As can be found in Figure 4.16, specimen A40C displayed elastic behaviour until it reached a load of 142 kN. After this point, the specimen continued to resist increased load and this resulted in increased compressive stress in the corrosion patch until it reached a load of 313 kN, corresponding to 0.0125 local strain. At this point, a wrinkle began to form, and the direction of strain began to reverse, toward tension. Having a corrosion patch with 2.4 mm depth caused the strain needed for initiation of the wrinkle in specimen A40C to be 46% of the strain capacity of the un-corroded specimen (A0C). Next, the load continued to increase, and the load-strain diagram reversed toward the tensile strain values. The recorded strain value corresponding to the ultimate load was 0.46%.

4.1.5 Specimen 5 (A40R20U)

Similar to specimen A40C, specimen A40R20U had a 75×75 mm square corrosion patch with a depth measuring 40% of the wall-thickness. However, it was repaired with 20 layers of uniaxial BFRP composite with the fibres oriented in the longitudinal direction. Figure 4.17 compares the load-displacement diagram of specimen A40R20U with specimens A0C and A40C. Although specimen A40R20U was repaired with 20 layers of BFRP composite wrap, its elastic stiffness in terms of load-displacement behavior was same as specimen A0C and A40C.

Specimen A40R20U showed elastic behaviour until it started to yield at a load of 214 kN, corresponding to 6.2 mm of displacement. Adding 20 layers of uniaxial BFRP composite could only increase the yield load of the corroded specimen (A40C) by 3% (208 kN vs. 214 kN). The specimen continued to resist load until a loud cracking sound was heard at a load of approximately 240 kN, at a displacement of 7.6 mm, which caused a
small drop in the load. The sound might be related to the debonding of BFRP and the pipe. After that, the specimen had a second small drop in the load at 335 kN which coincided with another loud cracking sound. The specimen continued to carry load until it reached its ultimate load capacity of 356 kN, corresponding to 26 mm displacement. At this point, a much louder cracking sound was heard and the BFRP composite split open along the longitudinal direction (Figure 4.18), causing the load to drop to 337 kN. Since the resisted load was still higher than that of specimen A40C, it is obvious that part of the BFRP composite was still contributing to the load-carrying capacity. The load gradually decreased until the test was stopped at 327 kN load and 51.5 mm displacement.

In Figure 4.18, a large and wide longitudinal crack can be seen in the BFRP composite. Since the uniaxial fibres were used only in the longitudinal directions, the ovalisation of the cross-section caused the BFRP composite to crack along the direction of the fibres. Therefore, it was realized that use of BFRP composite in the circumferential direction may help to reduce the ovalisation of the pipe and thus, may result in higher load capacity and ductility. Figure 4.19 shows the specimen after testing and removing the 20 layers of biaxial BFRP composite.

**Strain Behaviour**

As it was shown in Figure 3.2, three strain gauges were installed in the corrosion patch on the surface of the pipe, under BFRP composite wraps. The strain behaviour discussed in this section was obtained from the strain gauge that was installed at the centre of the corroded zone (strain gauge 5 in Figure 4.8). Since this strain gauge failed at a strain
of -0.02, probably due to de-bonding of BFRP composite wrap from the pipe, data regarding the initiation and growth of the wrinkle was not obtained.

Figure 4.20 compares the load-strain diagram of the specimen A40R20U with specimens A0C and A40C. It should be noted that the strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3). The local stiffness of the repaired specimen (A40R20U) was close to the control virgin specimen (A0C), and higher than the un-repaired corroded specimen (A40C). Specimen A40R20U showed elastic behaviour until it reached a local yield load of 156 kN. The local yield load of specimen 5 (A40R20U) reached 62% (156 kN vs. 250 kN) of the local yield load of the un-corroded virgin specimen (A0C).

4.1.6 Specimen 6 (A20R10B)

Similar to specimens A20C and A20R20U, specimen A20R10B had a 1.2 mm deep square corrosion patch measuring 75×75 mm. However, specimen A20R10B was repaired with 10 alternate layers of biaxial BFRP composite oriented in both directions. In order to have biaxial composite, the direction of the uniaxial composite sheets was alternated in the longitudinal and circumferential directions. It was observed that several horizontal (longitudinal) cracks occurred in specimen A20R10U and a large horizontal (longitudinal) crack also occurred in specimen A40R20U, both of which were repaired using uniaxial BFRP composite with fibres oriented in the horizontal directions. The purpose of specimen A20R10B was to examine if the biaxial BFRP composite can improve the bending capacity
of the corroded specimen, and prevent wrinkle formation in the corroded area, and delay or possibly eliminate the crack formation in the BFRP composite.

Figure 4.21 compares the load-displacement diagram of specimen A20R10B with specimens A0C, A20C, and A20R10U under combined internal pressure and bending load. As can be seen in this figure, specimen A20R10B displayed elastic behaviour until it reached a load of 300 kN, corresponding to 9.5 mm displacement. This means that using 10 layers of biaxial BFRP composite could restore 100% the global yielding load of specimen A20C to the level of the un-corroded specimen, A0C. Beyond this point, the specimen continued to take load until it reached its ultimate load of 411 kN, corresponding to 45 mm displacement.

Although the ultimate load-carrying capacity of specimen A20R10B was not much higher than specimen A20R10U, as can be seen in Figure 4.22, the biaxial repair was able to prevent the formation of the wrinkle and thus, eliminate the rupture or crack formation in the BFRP composite. Four short and very fine cracks occurred at the two ends of the BFRP repair, but they did not expand throughout the whole composite. There was no delamination between the composite and the steel pipe. As can be seen in Table 4.1, specimen A20R10B showed more ductility comparing to specimen A20R10U that was repaired with the same number of uniaxial BFRP layers.

**Strain Behaviour**

Similar to specimen A20R10U, the local strain behaviour of specimen A20R10B was obtained from a strain gauge that was installed horizontally along the length of the specimen at the centre of the corroded area on the steel surface. Figure 4.23 compares the
load-strain diagram of specimen A20R10B with specimens A0C, A20C, and A20R10U. It should be noted that the strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3). As can be observed in Figure 4.23, specimen A20R10B showed elastic behaviour similar to the un-corroded virgin specimen, A0C. It displayed elastic behaviour until it reached a local yield load of 250 kN. After this point, the corroded specimen continued to resist the load until it reached its ultimate load of 411 kN, corresponding to -0.0098 strain.

As can be seen in Figure 4.23, unlike the other specimens, the strain values of the corroded zone of specimen A20R10B did not reverse toward the tensile values. This shows that no wrinkle formed in the corroded area and the compressive strain of the area did not decrease in the same fashion as the other repaired specimens due to initiation and formation of a wrinkle. Having 5 layers of BFRP composite circumferentially wrapped around the pipe in the corroded area reduced the ovalisation effect due to the bending of the pipe, reinforced the composite, prevented wrinkle formation and thus crack formation in the BFRP composite, and created a perfect bonding between the BFRP composite and the pipe. In order to make sure if any wrinkle was formed under the BFRP composite, the fabric was cut using a grinder. As can be seen in Figure 4.24, there was no sign of wrinkle formation in the repaired area. It should be mentioned that even after cutting the BFRP composite by a grinder, there was a perfect bonding between the fabric and the pipe. The small drop in load and strain values in the load-strain diagram of specimen A20R10B in Figure 4.23 could be related to the deformation of the pipe under the top supports. Once the area outside the repaired zone, under the top supports yielded, the load-carrying capacity of the
specimen decreased. The deformation of the pipe outside the repaired zone reduced the stress level in the corroded zone, causing the small drop in the strain values.

4.1.7 Specimen 7 (A40R20B)

Similar to specimens A40C and A40R20U, specimen A40R20B was machined to have a square corrosion patch, measuring 75x75 mm with a depth measuring 40% of the wall-thickness. However, specimen A40R20B was repaired with 20 layers of biaxial BFRP composite wrapped around the corroded area. The 20 layers were installed alternatively in the longitudinal and circumferential directions in the wet lay-up system method. It was noticed with specimen 5 (A40R20U) that 20 layers of uniaxial BFRP composite oriented in the longitudinal direction could not restore the bending capacity of the 40% wall-thickness corroded specimen (Figure 4.17). Therefore, the purpose of specimen 7 (A40R20B) was to examine if the biaxial BFRP composite was capable to restore the bending capacity of the 2.4 mm (40%) corroded specimen and prevent wrinkle formation in the corroded area.

Figure 4.25 compares the load-displacement diagram of specimen A40R20B with specimens A0C, A40C, and specimen A40R20U. As can be seen in the figure, specimen A40R20B had a similar elastic behaviour compared with the un-corroded specimen. In this specimen, the global yield load was 300 kN, which was the same as A0C. After yielding, the specimen demonstrated a good strain hardening behaviour and continued to take load until it reached its ultimate load of 405 kN, corresponding to 45 mm displacement. Having 20 layers of biaxial BFRP composite increased the ultimate load-carrying capacity of the 40% wall-thickness depth corroded specimen by 23.5% (328 kN of specimen A40C vs.
405 kN of specimen A40R20B), while the same number of uniaxial BFRP composite layers oriented in the longitudinal direction increased the ultimate load-carrying capacity only 8.5% (328 kN vs. 356 kN). Also, the biaxial composite increased 170% (16.7 mm vs. 45 mm) in the displacement corresponding to the ultimate load, while the uniaxial composite in specimen A40R20U could only increase 56% (16.7 mm vs. 26 mm) in the displacement as compare to the control corrosion specimen, A40C. After this point, the load decreased gradually until the load application was stopped at a load of 352 kN, corresponding to 85 mm. As can be seen in Figure 4.26, unlike specimen A40R20U, the BFRP composite of specimen A40R20B did not crack at all and the whole repaired composite remained intact after the test, which caused increasing the ductility of the specimen (Table 4.1).

**Strain Behaviour**

Strain behaviour of specimen A40R20B was obtained from the strain gauge that was installed at the centre of the corroded zone, on the steel surface of the pipe. Figure 4.27 compares the load-strain diagram of specimen A40R20B with specimens A0C, A40C, and A40R20U. It should be noted that the strain behaviour of the wrinkle of specimen A0C was obtained from the data of a strain gauge that was located 3 mm from the crest of the wrinkle (strain gauge 5 in Figure 4.3). As can be observed in Figure 4.27, specimen A40R20B displayed elastic behaviour until it reached a load of 212 kN. Having 20 layers of biaxial BFRP composite, the local yield load increased by 49% (142 kN vs. 212 kN). After reaching the yielding load, the centre of the corroded zone continued to be under increased compressive stress until it reached a strain of -0.0072. However, compressive strain was not large enough to initiate a wrinkle. Similar to specimen A20R10B, using biaxial BFRP composite reduced the ovalisation effects of bending load; prevented the wrinkle formation.
in the repaired area. At this point, the area outside the repaired zone, under the top supports, yielded and deformed (dented) due to high stress concentration where load was applied; causing the load-carrying capacity of the specimen to drop. After yielding of the area outside the repaired zone and under the loading supports, the stress level in the corroded area decreased; causing the strain value to decrease along with decreasing the load-carrying capacity of the specimen. It should be noted that this reduction in compressive stress level of specimen A40R20B is not due to initiation of a wrinkle.

4.2 Phase B

The purpose of undertaking tests of phase B was to investigate the effects of different shapes of corrosion on the bending behaviour of the corroded and repaired pipes. In this phase of the study, five NPS 6 grade X46 pipes with $D/t$ ratio of 50 were tested. The shape of corrosion (circular or square or rectangular) was the test parameter in phase B of study (Table 3.2). The internal pressure was kept unchanged at 960 psi (6.6 MPa) which is $0.4p_y$ and the depth of corrosion was also kept unchanged at 40% in all these specimens. Table 4.2 shows the summary of results of the specimens in phase B. The LVDT located at the mid-span underneath the specimen is used to plot all load-displacement plots.
Table 4.2: The experimental results of the specimens in phase B

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Name</td>
<td>B0C</td>
<td>B40CS</td>
<td>B40CC</td>
<td>B40RS20B</td>
<td>B40CR</td>
</tr>
<tr>
<td>Global Yield Load (kN)</td>
<td>124</td>
<td>110</td>
<td>111</td>
<td>124</td>
<td>75</td>
</tr>
<tr>
<td>Local Yield Load (kN)</td>
<td>82.6</td>
<td>44</td>
<td>43</td>
<td>113</td>
<td>44</td>
</tr>
<tr>
<td>Yield Displacement (mm)</td>
<td>10.5</td>
<td>10</td>
<td>10</td>
<td>11</td>
<td>5.7</td>
</tr>
<tr>
<td>Ultimate Load (kN)</td>
<td>169</td>
<td>127</td>
<td>127</td>
<td>177</td>
<td>105</td>
</tr>
<tr>
<td>Ultimate Displacement (mm)</td>
<td>62.5</td>
<td>30</td>
<td>37</td>
<td>57</td>
<td>15</td>
</tr>
<tr>
<td>Strain at Ultimate Load (%)</td>
<td>0.0055</td>
<td>0.003</td>
<td>0.0023</td>
<td>0.0047</td>
<td>0.0019</td>
</tr>
<tr>
<td>Elastic Stiffness (kN/mm)</td>
<td>14</td>
<td>13.7</td>
<td>13.7</td>
<td>14.1</td>
<td>13.5</td>
</tr>
<tr>
<td>Wrinkle Initiation Load (kN)</td>
<td>151.5</td>
<td>79.5</td>
<td>76</td>
<td>No Wrinkle</td>
<td>75</td>
</tr>
<tr>
<td>Wrinkle Initiation Strain (%)</td>
<td>1.25</td>
<td>0.8</td>
<td>0.63</td>
<td>No Wrinkle</td>
<td>0.44</td>
</tr>
<tr>
<td>Energy Ductility (kN-mm)</td>
<td>11550</td>
<td>7866</td>
<td>8824</td>
<td>11600</td>
<td>3311</td>
</tr>
<tr>
<td>Displacement Ductility (mm)</td>
<td>79</td>
<td>70</td>
<td>76</td>
<td>77</td>
<td>37</td>
</tr>
</tbody>
</table>

4.2.1 Specimen 1 (B0C)

Specimen B0C was an un-corroded or control virgin specimen. The purpose of this specimen was to examine the behaviour of 6 in. (152 mm) specimen with $D/t$ ratio of 50 under combined 960 psi (6.6 MPa) internal pressure and four-point bending load to have a reference to compare the behaviour of the rest of the specimens with it. Figure 4.28 shows the load-displacement diagram of specimen B0C. As can be found in the figure, the specimen showed elastic behaviour until it reached its global yield load of 124 kN, corresponding to 10.5 mm displacement. Beyond this point, the specimen resisted increased load until it reached its ultimate load-carrying capacity of 168 kN, corresponding
to 62.5 mm. After reaching its ultimate load, the load gradually decreased. The loading was discontinued at a load of 134 kN, corresponding to 100 mm.

**Strain behaviour**

Before testing specimen B0C, several strain gauges were installed in the longitudinal direction on the top surface of the pipe between two internal collars to cover the whole area prone to the wrinkle formation. The strain behaviour of the specimen was obtained from the strain gauge that was placed at the crest of the wrinkle (strain gauge 5) which is shown in Figure 4.8. Figure 4.29 shows the load-strain diagram of specimen B0C. As can be seen in the figure, the specimen showed an elastic behaviour until it reached a load of 82.6 kN. After this point, the local plastic compressive strain increased until the specimen reached a load of 151.5 kN, corresponding to a wrinkle initiation strain of -0.0125. At this point, a wrinkle started to form close to one of the internal collars. Although it was expected to have a wrinkle in the mid-span of the pipe, the stress concentration effects of the internal collars caused the wrinkle to be formed off-centre. The strain values at the crest of the wrinkle reversed toward the tensile strains. As the wrinkle grew, the strain values decreased, and the specimen continued to take load until it reached an ultimate load of 169 kN, corresponding to -0.0055 strain and displacement of 62.5 mm. Figure 4.30 shows a picture of specimen B0C after the test.

**4.2.2 Specimen 2 (B40CS)**

Specimen B40CS was machined to have a 1.36 mm (40% wall-thickness) deep square corrosion patch, measuring 75×75 mm. The purpose of testing specimen was to study the behaviour of a corroded specimen with a square corrosion shape under internal
pressure and four-point bending load. Figure 4.31 compares the load-displacement diagram of specimen B40CS with the un-corroded control specimen (B0C). As can be found in this figure, specimen B40CS showed elastic behaviour until the load reached a global yield load of 110 kN, corresponding to 10 mm. Beyond this load point, the specimen continued to take a higher load until it reached an ultimate load of 127 kN, corresponding to a 30 mm displacement. The corrosion caused the ultimate load-carrying capacity of specimen B0C to drop by 25% (127 kN vs. 169 kN). Unlike specimen B0C, specimen B40CS did not exhibit a large strain hardening behaviour. After reaching the ultimate load, the load gradually dropped until the test was stopped at a load of 113 kN, corresponding to 70.5 mm displacement. At this point, a large wrinkle had formed in the corroded zone. Figure 4.32 shows specimen B40CS at the end of the test.

**Strain Behaviour**

The strain behaviour of specimen B40CS was obtained from the strain gauge that was horizontally installed at the centre of the square corrosion patch. As can be seen in Figure 4.32, the wrinkle formed at the mid-length of the corroded zone and hence, this strain gauge was located at the crest of the wrinkle (strain gauge 5 in Figure 4.8). Figure 4.33 compares the strain-load diagram of specimen B40CS with the un-corroded control specimen (B0C). As can be seen in the figure, specimen B40CS showed an elastic strain behaviour until it reached a local yield load of 44 kN. The specimen continued to take load until it reached a load of 79.5 kN, corresponding to a wrinkle initiation strain of -0.008. At this point, the wrinkle began to form and the direction of the strain reversed toward the tensile zone. After that, the load increased gradually while the strain values decreased until it reached an ultimate load of 127 kN, corresponding to a strain value of -0.003. Having a
square corrosion patch with a depth measuring 40% of the wall-thickness caused specimen B40CS to reach the strain needed to form the wrinkle 36% (0.8 vs. 1.25) earlier than the un-corroded control (virgin) specimen.

4.2.3 Specimen 3 (B40CC)

As can be seen in Figure 4.34, specimen B40CC was machined to have a circular shape corrosion patch in the mid-span of the specimen. The dimensions of the circle were chosen so that the area of the circle was equal to the area of the square corrosion patch. The diameter of the circle was 84 mm. Specimen B40CC was tested to compare the effect of a circular corrosion patch and compare its performance with specimens with square and rectangular shapes of corrosion. Figure 4.35 compares the load-displacement diagram of specimen B40CC with specimens B0C and B40CS. As can be seen in the figure, specimen B40CC had a very similar behaviour as specimen B40CS. It displayed elastic behaviour until it reached a global yield load of 111 kN, corresponding to 10 mm displacement. Past this point, the specimen continued to take load until it reached its ultimate load-carrying capacity of 127 kN, corresponding to 37 mm. Afterwards, the load gradually decreased until a large wrinkle was formed at the centre of the corrosion patch. The test was stopped at a load of 119 kN, corresponding to 70 mm displacement.

Strain Behaviour

The wrinkle formed exactly at the centre of the circular corrosion patch. The strain behaviour of the wrinkle location (strain gauge 5 in Figure 4.8) of specimen B40CC was obtained from the strain gauge that was located on the crest of the wrinkle and at the centre of the corrosion patch. Figure 4.36 compares the load-strain diagram of specimen B40CC
with specimens B0C and B40CS. As can be seen in the figure, specimen B40CC with a circular corrosion patch had a strain behaviour similar to specimen B40CS with a square corrosion shape. Specimen B40CC showed elastic behaviour until it reached a local yield load of 43 kN. After this point, the corroded zone continued to have increased compression strain and take load until it reached a load of 76 kN, corresponding to a wrinkle initiation strain of -0.0063. At this point, the wrinkle started to form at the centre of the corrosion patch. The compressive strain started to decrease and reverse toward the tensile strain values while the load continued to increase until it reached the ultimate load of 127 kN, corresponding to a strain of -0.0023. The loading process was stopped at a strain of -0.001 at which point a large wrinkle formed at the middle of the corrosion patch. Figure 4.37 shows specimen B40CC after the four-point bending test.

Hence, the study found that the shape of corrosion (square vs. circular) does not affect the load-displacement behaviour of the corroded pipe if the area and the depth of corrosion are not varied.

**4.2.4 Specimen 4 (B40RS20B)**

Similar to specimen B40CS, specimen B40RS20B had a 40% deep square corrosion depth, however, it was repaired with 20 layers of alternate biaxial BFRP composite. The purpose of testing specimen B40RS20B was to examine the effect of basalt composite repair on the corroded specimen with square corrosion patch and compare it with the other specimens with different corrosion shapes. Figure 4.38 compares the load-displacement curves of specimen B40RS20B with specimens B0C and B40CS. As can be observed in this figure, the elastic behaviour of specimen B40RS20B is very similar to specimen B0C.
Specimen B40RS20B had a global yield load of 124 kN, corresponding to 11 mm displacement. After yielding, the specimen demonstrated strain hardening and continued to take load until it reached an ultimate load of 177 kN, corresponding to a displacement of 57 mm. Compared to specimen B40CS, the ultimate load-carrying capacity of specimen B40RS20B increased 39% (127 kN vs. 177 kN). Also, having 20 layers of biaxial BFRP composite caused the load-carrying capacity of specimen B40RS20B to increase 5% beyond the capacity of the un-corroded control (virgin) specimen (B0C). After reaching the ultimate load, the load gradually decreased while the deflection of the pipe increased until the test was stopped at a load of 152 kN, corresponding to 80 mm displacement. Figure 4.39 shows the specimen after the test. As can be seen in the figure, no wrinkle formed in the repaired section and the specimen yielded and deformed in the area outside the repaired zone.

**Strain behaviour**

The local strain behaviour at the centre of specimen B40RS20B was obtained from the strain gauge that was installed at the centre of the corroded zone, on the surface of the steel, under the BFRP composite. Figure 4.40 compares the load-strain diagram of repaired specimen B40RS20B with specimens B0C and B40CS. As can be seen in the figure, the local stiffness (in terms of load-displacement values) displayed by specimen B40RS20B is even higher than the un-corroded control (virgin) specimen. The specimen showed elastic behaviour until the load reached a local yield load of 113 kN. Having 20 layers of biaxial BFRP composite increased the local yield load of the corroded control specimen by 157% (44 kN vs. 113 kN), reaching 137% (82.6 kN vs. 113 kN) of the un-corroded strength. After local yielding, the load continued to increase, and the corrosion patch compressed until it
reached an ultimate load of 177 kN, corresponding to a strain of -0.0047. As can be found in Figure 4.40, unlike other specimens, the load-strain diagram of specimen B40RS20B did not reverse back toward the tensile strains, which shows that no wrinkle even initiated in this specimen. In order to make sure that no wrinkle was formed under the repaired zone, the BFRP composite was cut with a grinder. As can be seen in Figure 4.41, no wrinkle formed in the repaired area and it remained totally intact. It should be mentioned that even after cutting the BFRP composite, it could not easily be separated from the pipe, there was a perfect bonding between the composite and the pipe.

Since the specimen with circular corrosion (B40CC) patch had a very similar load-displacement and load-strain behaviour to the specimen with square corrosion patch (B40CS), no specimen was tested to examine the performance of the repaired specimen with circular corrosion patch.

**4.2.5 Specimen 5 (B40CR)**

Since the circular and square corrosion patch exhibited a similar behaviour, before doing any experimental tests, a finite element model in ABAQUS was created to simulate the 6 in. (152 mm) nominal diameter pipe with different corrosion shape. The purpose of the model was to find which corrosion shape with the same area caused the most reduction in the load-carrying capacity of the specimen and to examine the performance of that specimen after repairing with 20 layers of biaxial BFRP composite.

The results of this numerical model will be presented in Chapter 5. Using the results of the numerical model, it was decided that extending the corrosion in the circumferential direction would provide the most critical shape to repair. Specimen B40CR was machined
to have a circumferentially oriented rectangular corrosion patch, measuring 45×125 mm (Figure 3.28). The depth of the corrosion patch was 40% of the specimen wall-thickness.

Figure 4.42 compares the load-displacement diagram of specimen B40CR with the specimens B0C and B40C. As can be observed in this figure, specimen B40CR displayed elastic behaviour until it reached a global yield load of 75 kN, corresponding to 5.7 mm. A rectangular corrosion patch along the circumferential direction reduced the global yield load of specimen B40CR to 60.5% (75 kN vs. 124 kN) of the un-corroded specimen B0C (68% of B40CS). After yielding, specimen B40CR continued to take a higher load until it reached an ultimate load of 105 kN, corresponding to 15 mm displacement. Specimen B40CR had even less strain hardening comparing to specimen B40CS. After reaching its ultimate load, the load gradually decreased until the test loading process was stopped at a load of 95 kN, corresponding to 36 mm.

**Strain Behaviour**

The strain behaviour of specimen B40CR was obtained from the strain gauge that was installed at the centre of the corrosion patch (strain gauge 5 in Figure 4.8). Figure 4.43 compares the load-strain diagram of specimen B40CR with specimens B0C and B40CS. As can be seen in the figure, specimen B40CR displayed elastic behaviour until it reached a load of 44 kN. Beyond this load point, the specimen continued to take a higher load until it reached a load of 75 kN, corresponding to a compressional strain of -0.0044, at which point, a wrinkle started to form at the mid-length of the corrosion patch. Figure 4.44 shows that a wrinkle has started to form in the mid-span of specimen B40CR. After wrinkle formation, the strain reversed toward the tensile strains and the specimen continued to take
load until it reached its ultimate load of 105 kN, corresponding to a strain of -0.0019. The rectangular corrosion patch in specimen B40CR caused the strain value that was needed to form the wrinkle to decrease by 65% (0.44 vs. 1.25) and 45% (0.44 vs. 0.8) compared to specimens B0C and B40CS, respectively.

4.3 Analytical Validation

In this section, the theoretical equations are used to validate the experimental results for the uncorroded specimen in phase A (A0C) in the elastic range. The bending moment that is required to onset the yielding at the top external surface of the pipe was calculated in both theoretical and experimental methods. Since the pipe was under both bending load and internal pressure, the compressive stress at the external surface of the pipe section can be calculated by theoretical Equation 4.1.

\[
\sigma_x = \frac{M_z y}{I_z} - \frac{p D}{4t}
\]  

(4.1)

where

\( \sigma_x \) = bending stress

\( M_z \) = moment about the neutral axis

\( y \) = perpendicular distance from the neutral axis

\( I_z \) = second moment of area about the neutral axis

\( p \) = internal pressure

\( D \) = inner diameter
The yielding stress of the specimens in phase A, obtained from the uniaxial coupon tensile test was 403 MPa. However, since the pipe was under both internal pressure and bending load, the Maximum-Distortion-Energy or von Mises Criterion was used to calculate the axial stress at the top surface of the pipe using Equation 4.2.

\[
\sigma_y = \sqrt{\frac{(\sigma_a - \sigma_h)^2 + (\sigma_a)^2 + (\sigma_h)^2}{2}}
\]  

(4.2)

where

\(\sigma_y\) = yield stress

\(\sigma_a\) = axial stress

\(\sigma_h\) = hoop stress

The hoop stress can be calculated by Barlow’s formula:

\[
\sigma_h = \frac{pD}{2t}
\]  

(4.3)

Specimen A0C was pressurized to 4.6 MPa (0.2p_y), which caused a 79.8 MPa hoop stress. After plugging in the hoop stress and the yield stress (403 MPa) values into Equation 4.2, it returned the axial stress required to yield the top external surface of the pipe as 357.1 MPa in compression or 436.9 MPa in tension. The compressional axial stress of 357.1 MPa can be used in Equation 4.1 to calculate the theoretical value of bending moment.
Table 4.3: Theoretical bending moment

<table>
<thead>
<tr>
<th>Equation</th>
<th>Values</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \sigma_x = \frac{M_z y - pD}{I_z} ]</td>
<td>( \sigma_x )</td>
<td>357.1 MPa</td>
</tr>
<tr>
<td></td>
<td>( y )</td>
<td>110 mm</td>
</tr>
<tr>
<td></td>
<td>( I_z )</td>
<td>23,109,668 mm(^4)</td>
</tr>
<tr>
<td></td>
<td>( p )</td>
<td>4.6 MPa</td>
</tr>
<tr>
<td></td>
<td>( D )</td>
<td>214 mm</td>
</tr>
<tr>
<td></td>
<td>( t )</td>
<td>6 mm</td>
</tr>
<tr>
<td></td>
<td>[ \frac{I_z}{4} ]</td>
<td>83,404,895 (N\cdot mm)</td>
</tr>
</tbody>
</table>

The second moment of area in Table 4.3 was calculated by the second moment of area formula for the hollow cylindrical cross sections as:

\[ I_z = \frac{\pi}{4}(r_o^4 - r_i^4) \]  

(4.4)

The experimental bending moment that is required to cause yielding at the top external surface of the pipe can be calculated by Equation 4.5.

\[ \text{Moment} = 680 \times \text{Load/2 (N.mm)} \]  

(4.5)

In the above equation, “Load” is the local yield load shown in Table 4.1 and 680 mm is the distance between the bottom rigid support and the top support in Figure 3.17.

Table 4.4: Experimental bending moment

<table>
<thead>
<tr>
<th>Equation</th>
<th>Values</th>
<th>Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \text{Moment} = 680 \times \text{Load/2} ]</td>
<td>Local yield load</td>
<td>85,000,000 (N\cdot mm)</td>
</tr>
<tr>
<td></td>
<td>250,000 N</td>
<td>680 mm</td>
</tr>
</tbody>
</table>
\[
\% \text{Error} = \frac{|83404895 - 85000000|}{83404895} \times 100 = 1.9\% \quad (4.6)
\]

As can be seen in Equation 4.6, the percent error of the two theoretical and experimental methods is 1.9%, which shows that there is a good agreement between the theoretical and experimental results.

### 4.4 Summary

In the experimental part of this study, two phases of specimens were tested. In phase A, seven NPS 8 X46 grade pipe specimens with \(D/t\) ratio of 37 were tested. The purpose of phase A specimens was to study the effects of BFRP composite on the performance of corroded pipes and to examine if it can be used to restore and rehabilitate the bending capacity of corroded pipes. The purpose of phase B was to investigate the effect of different corrosion shapes on the performance of the corroded and repaired specimens with the biaxial BFRP composite. In this phase, five NPS 6 X46 grade pipe specimens with \(D/t\) ratio of 50 were tested under combined internal pressure and bending load. Several observations and conclusions are made by analyzing the experimental data from the tested specimen:

- Increase in the corrosion depth drastically decreases the bending capacity of the corroded specimens.
- Having 20% and 40% square corrosion patch in the specimens in phase A reduced the global yielding loads by 19% and 30.7%, respectively.
- The 20% and 40% corrosion patch reduced the ultimate load-carrying capacity of the un-corroded control (virgin) specimen by 15% and 20%, respectively. Also, the
ultimate displacements corresponding to the ultimate load decreased by 41.4% and 73%, respectively.

- The elastic stiffness of all specimens in each phase of A and B was the same.
- In the corroded specimens, the wrinkle formed exactly at the middle of the corrosion patch. In the 20% and 40% corroded specimens, the strain at which the wrinkle formed reduced by 46.5% and 54%, respectively.
- Using ten layers of uniaxial BFRP composite improved the bending capacity of the 20% corroded specimen, however, it did not prevent wrinkle formation in the corroded area and several horizontal cracks occurred along with the orientation of the fibres.
- The attempt to repair the 40% corroded specimen with 20 layers of uniaxial BFRP composite failed and a full wrinkle was formed under the composite. It was observed that a large horizontal crack occurred at the top of the composite. It caused the composite to be de-bonded from the pipe and the load-carrying capacity of the specimen drastically dropped. It was observed that the horizontally oriented fibres in the BFRP composite could not resist the ovalisation effects of the specimen under bending load.
- Using biaxial BFRP composite not only improved the bending capacity of the corroded specimens to the level of the un-corroded specimen, but it also prevented the wrinkle formation in the corroded zone. It was found that the circumferential fibres in the biaxial BFRP composite resisted the ovalisation of the cross-section and prevented the fibres to be pulled apart. Also, using biaxial BFRP composites
noticeably increased the ductility of the corroded specimens comparing to the uniaxial BFRP composites.

- In phase \( B \) of the specimens, it was found that the square and circular corrosion patch had the same influence on the load-displacement and load-strain behaviour of the corroded specimen.

- The ultimate load-carrying capacity of the square and circular corroded specimen with 40% wall-thickness depth was 75% of the ultimate load of the un-corroded control specimen. The displacement corresponding to the ultimate load in the corroded specimen with the square shape was 48% of the displacement of the un-corroded specimen.

- It was observed that the circumferentially oriented rectangular corrosion patch caused the most drop in the bending capacity of the corroded specimens. The ultimate load-carrying capacity of the rectangular corrosion shape specimen was 17% less than the capacity of the specimen with the square or circular corrosion shape.
Figure 4.1: Load-displacement diagram of specimen 1 (A0C)

Figure 4.2: Wrinkle forming on specimen 1 (A0C)
Figure 4.3: Location of strain gauges for specimen A0C

Figure 4.4: Strain behaviour diagram at crest of wrinkle of specimen 1 (A0C)
Figure 4.5: Load-displacement diagrams of specimens A0C and A20C

Figure 4.6: Specimen A20C after testing
Figure 4.7: Installation of strain gauges on specimen A20C

Figure 4.8: Location of strain gauges for specimens with symmetric wrinkle
Figure 4.9: Strain behaviour at crest of wrinkle of specimens A0C and A20C

Figure 4.10: Load-displacement diagrams of various specimens
Figure 4.11: Horizontal cracks in specimen A20R10U

Figure 4.12: Specimen A20R10U after removing the BFRP
Figure 4.13: Strain behaviour at crest of wrinkle of various specimens

Figure 4.14: Load-displacement diagrams of various specimens
Figure 4.15: Specimen A40C after testing

Figure 4.16: Strain behaviour at crest of wrinkle of various specimens
Figure 4.17: Load-displacement diagrams of various specimens

Figure 4.18: Longitudinal crack in specimen A40R20U after testing
Figure 4.19: Specimen A40R20U after testing

Figure 4.20: Strain behaviour at crest of wrinkle of various specimens
Figure 4.21: Load-displacement diagrams of various specimens

Figure 4.22: Specimen A20R10B after testing
Figure 4.23: Strain behaviour at crest of wrinkle of various specimens

Figure 4.24: Specimen A20R10B after testing
Figure 4.25: Load-displacement diagrams of various specimens

Figure 4.26: Specimen A40R20B after testing
Figure 4.27: Strain behaviour at crest of wrinkle of various specimens

Figure 4.28: Load-displacement diagram of specimen B0C
Figure 4.29: Strain behaviour diagram at crest of wrinkle of specimen B0C

Figure 4.30: Specimen B0C after testing
Figure 4.31: Load-displacement diagrams of specimens B0C and B40CS

Figure 4.32: Specimen B40CS after testing
Figure 4.33: Strain behaviour at crest of wrinkle of specimens B0C and B40CS

Figure 4.34: Circular corrosion patch of specimen B40CC
Figure 4.35: Load-displacement diagrams of various specimens

Figure 4.36: Strain behaviour at crest of wrinkle of various specimens
Figure 4.37: Specimen B40CC after testing

Figure 4.38: Load-displacement diagrams of various specimens
Figure 4.39: Specimen B40RS20B after testing

Figure 4.40: Strain behaviour at crest of wrinkle of various specimens
Figure 4.41: Cutting BFRP of specimen B40RS20B after testing

Figure 4.42: Load-displacement diagrams of various specimens
Figure 4.43: Strain behaviour at crest of wrinkle of various specimens.

Figure 4.44: Specimen B40CR after testing.
Chapter 5: Finite Element Analysis

5.1 General

Experimental methods are the most reliable techniques to investigate the performance of engineering structures. However, due to the high level of cost and time-consuming nature of experimental studies, they are not practical for wide-ranging parametric studies. In this study, a nonlinear finite element analysis using a commercially available finite element platform ABAQUS/EXPLICIT version 6.14.2 (SIMULIA, 2014) was employed to conduct a comprehensive parametric study on the performance of corroded pipelines rehabilitated with BFRP composite. The FE model was validated with the results of the experimental tests.

There are three stages in finite element analysis including pre-processing, processing, and post-processing. ABAQUS is designed to perform all three stages. In the pre-processing stage, part geometries, material properties, assembly, boundary conditions, loading, and meshing are defined. The analysis of the FE model takes place in the processing stage. In the post-processing stage, ABAQUS is capable of presenting the results of the analysis in several ways including visualizing the results in 2D or 3D space or providing the animation of the deformation of the model.

5.2 Model

5.2.1 Assembly

In order to simulate the experimental test setup in ABAQUS, thirteen part instances were modeled, defined with proper material properties, and these parts were then
assembled together. The part instances include the pipe specimen, two end plates, six collars, two bottom supports, and two top supports. The FE model was generated to represent the experimental setup as accurately as possible. Coaxial constraints were used between the outer surface of the pipe and inner surface of the collars and supports so that there was no gap between them. In order to simplify the model and reduce the running time, all parts were merged together. As can be seen in Figure 5.1, the pipe was modeled with 8-node linear brick solid elements, C3D8R, with reduced integration and three translation degrees of freedom in each node to properly simulate the corrosion defect.

After modeling the pipe and validating it with the experimental data, the BFRP composite was modeled with four-node conventional shell elements S4R (Figure 5.2). S4R is a general purpose (thick and thin) linear element which has six degrees of freedom in each node: three translational and three rotational. The properties of each layers of a BFRP composite were assigned separately with a specific thickness and fibre orientation. Similar to the experimental tests and the recommendations of ISO/TS 24817 standard (ISO/TS, 2017), in the assembly module, a cylindrical composite was placed between the two internal collars to cover the corrosion patch and extend over it. A tie constraint was used to define the interaction between the BFRP composite and the pipe.

5.2.2 Loads and Boundary Conditions

Similar to the experimental setup, bending load was applied to the top supports in displacement control method. Prior to applying displacement, an internal pressure load was defined to simulate the applied internal pressure inside the pipe due to the pressurized water in the experimental tests. In the experimental setup, the pipe could slide on the bottom
supports and move along the length of the pipe. In the numerical model, since all the parts were combined together, as can be seen in Figure 5.3, the bottom supports were modeled as pin-roller. The top supports were allowed to rotate and translate in the horizontal and vertical directions.

5.2.3 Material Properties

5.2.3.1 Pipe

Depending on the type of materials and the nature of tests, ABAQUS requires the user to define true stress-strain curve and elastic material properties in order to achieve accurate results. The material properties of the pipe were obtained from testing coupon specimens based on ASTM E8/E8M-16a (ASTM, 2016). Two separate material properties were defined for steel pipe. As can be seen in Table 5.1, Young’s modulus of elasticity and Poisson’s ratio were used to define the elastic behaviour of the pipe. The elastic behaviour of the pipe was defined as isotropic in ABAQUS.

Table 5.1: Elastic material properties of the pipe.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>185 GPa</td>
</tr>
<tr>
<td>µ</td>
<td>0.3</td>
</tr>
</tbody>
</table>

In order to define the plastic behaviour of the pipe in ABAQUS, true stress and logarithmic strain for isotropic material were calculated based on Equations 5.1 and 5.2, respectively.
\[ \sigma_{\text{true}} = \sigma_{\text{nom}} (1 + \varepsilon_{\text{nom}}) \]  

(5.1)

\[ \varepsilon_{\text{ln}}^p = \ln(1 + \varepsilon_{\text{nom}}) - \frac{\sigma_{\text{true}}}{E} \]  

(5.2)

where \( \sigma_{\text{true}} \) is the true stress, \( \sigma_{\text{nom}} \) is the nominal or engineering stress, \( \varepsilon_{\text{ln}}^p \) is the logarithmic or true plastic strain, and \( \varepsilon_{\text{nom}} \) is the nominal strain or engineering strain. Tables 5.2 and 5.3 display the plastic material properties used to model the specimens of phases A and B, respectively. Figure 5.4 shows the true stress-true plastic strain diagrams of the specimens in phases A and B.

Table 5.2: Plastic material properties of the specimens in phase A

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Plastic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>403.2</td>
<td>0</td>
</tr>
<tr>
<td>419.7</td>
<td>0.010091</td>
</tr>
<tr>
<td>433.7</td>
<td>0.020994</td>
</tr>
<tr>
<td>446.2</td>
<td>0.031624</td>
</tr>
<tr>
<td>457.0</td>
<td>0.042284</td>
</tr>
<tr>
<td>466.5</td>
<td>0.053059</td>
</tr>
<tr>
<td>474.8</td>
<td>0.063974</td>
</tr>
<tr>
<td>482.3</td>
<td>0.074988</td>
</tr>
<tr>
<td>489.0</td>
<td>0.086118</td>
</tr>
<tr>
<td>495.2</td>
<td>0.097362</td>
</tr>
<tr>
<td>500.7</td>
<td>0.108744</td>
</tr>
<tr>
<td>505.7</td>
<td>0.120268</td>
</tr>
<tr>
<td>509.7</td>
<td>0.131958</td>
</tr>
<tr>
<td>515.1</td>
<td>0.182638</td>
</tr>
</tbody>
</table>
Table 5.3: Plastic material properties of the specimens in phase $B$

<table>
<thead>
<tr>
<th>Stress (MPa)</th>
<th>Plastic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>404.1</td>
<td>0</td>
</tr>
<tr>
<td>406.3</td>
<td>0.000615</td>
</tr>
<tr>
<td>408.8</td>
<td>0.002248</td>
</tr>
<tr>
<td>416.6</td>
<td>0.00465</td>
</tr>
<tr>
<td>425.4</td>
<td>0.008292</td>
</tr>
<tr>
<td>436.6</td>
<td>0.01397</td>
</tr>
<tr>
<td>442.9</td>
<td>0.017566</td>
</tr>
<tr>
<td>457.4</td>
<td>0.026716</td>
</tr>
<tr>
<td>480.2</td>
<td>0.045013</td>
</tr>
<tr>
<td>523.6</td>
<td>0.095028</td>
</tr>
<tr>
<td>554.3</td>
<td>0.145031</td>
</tr>
<tr>
<td>576.6</td>
<td>0.195036</td>
</tr>
</tbody>
</table>

5.2.3.2 BFRP

In order to properly define the behaviour of the BFRP composite, its material properties such as: elastic behaviour, damage initiation, and damage evolution were defined in ABAQUS. Then, depending on the purpose of each specimen, the thickness, orientation of fibres, and the material properties of each layer (ply) were assigned separately in the composite layup. A local coordinate system was used to assign the orientation of fibres in each ply. The longitudinal direction of the fibre was considered as local direction 1, the transverse direction of the fibres was considered as local direction 2, and the normal direction of the composite sheet was considered as the local direction 3.
The stress-strain diagram of the BFRP composite was shown in Figure 3.12. Table 5.4 shows the material properties of the BFRP composite. Using the amount of energy required to damage the BFRP composite, the fracture energy parameter ($G_c$) was defined (Table 5.4). Hashin damage theory based on work done by Hashin and Rotem (1973), and Hashin (1980) was used to detect the onset of damage in BFRP composite fabric. This model considers four different damage initiation criteria: fibre tension, fibre compression, matrix tension, and matrix compression. The general forms of the damage initiation criteria are as follows:

\[
\text{Fibre tension} = \left( \frac{\sigma_{11}}{X_T} \right)^2 + \alpha \left( \frac{\tau_{12}}{S_L} \right)^2
\]

\[
\text{Fibre compression} = \left( \frac{\sigma_{11}}{X_C} \right)^2
\]

\[
\text{Matrix tension} = \left( \frac{\sigma_{22}}{Y_T} \right)^2 + \left( \frac{\tau_{12}}{S_T} \right)^2
\]

\[
\text{Matrix compression} = \left( \frac{\sigma_{22}}{Y_C} \right)^2 + \left[ \left( \frac{Y_C}{S_T} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y_C} + \alpha \left( \frac{\tau_{12}}{S_L} \right)^2
\]

where

$X_T$: longitudinal tensile strength

$X_C$: longitudinal compressive strength

$Y_T$: transverse tensile strength

$Y_C$: transverse compressive strength

$S_T$: longitudinal shear strength
$S^T$: transverse shear strength

$\sigma_{ij}$: principal stress components for the lamina

$\alpha$: coefficient of contribution of the shear stress to the fibre tensile criteria

Table 5.4: Material properties of the BFRP composite

<table>
<thead>
<tr>
<th>E1 (MPa)</th>
<th>E2 (MPa)</th>
<th>$\nu_{12}$</th>
<th>G12 (MPa)</th>
<th>G13 (MPa)</th>
<th>G23 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25000</td>
<td>10000</td>
<td>0.3</td>
<td>4800</td>
<td>4800</td>
<td>4800</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Longitudinal Tensile Strength (MPa)</th>
<th>Longitudinal Compressive Strength (MPa)</th>
<th>Transverse Tensile Strength (MPa)</th>
<th>Transverse Compressive Strength (MPa)</th>
<th>Longitudinal Shear Strength (MPa)</th>
<th>Transverse Shear Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>550</td>
<td>45</td>
<td>60</td>
<td>35</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Longitudinal Tensile Fracture Energy</th>
<th>Longitudinal Compressive Fracture Energy</th>
<th>Transverse Tensile Fracture Energy</th>
<th>Transverse Compressive Fracture Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td>26</td>
<td>0.67</td>
<td>13</td>
</tr>
</tbody>
</table>

5.3 Mesh Convergence Study

A mesh convergence study was conducted to determine an optimum element size to be used in modelling the specimens. The mesh convergence study was performed on the middle part of the pipe, between the two internal collars, as that was the main area of interest. The rest of the specimen was modeled with 15×15 mm mesh size to reduce the running time of the model. Four different mesh sizes including 15×15 mm, 10×10 mm, 5×5
mm, and 3×3 mm were considered in this study. As the mesh size reduced, the running time of the model in ABAQUS increased. Table 5.5 outlines the results of mesh convergence study. In order to have a better understanding of the study, the results are displayed in Figure 5.5.

As can be seen in the figure, the von Mises stress on the compression side of the pipe vs. the mesh density of each mesh size is shown in the figure. As the element size decreased, the stress converged to a close value in the mesh sizes of 5×5 mm and 3×3 mm. Therefore, the mesh size of 5×5 mm was selected to use in the mid-part of the specimens.

<table>
<thead>
<tr>
<th>Element Size (mm)</th>
<th>Number of Elements</th>
<th>von Mises Stress (MPa)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3×3</td>
<td>7868</td>
<td>521</td>
<td>0</td>
</tr>
<tr>
<td>5×5</td>
<td>4730</td>
<td>539</td>
<td>3.3</td>
</tr>
<tr>
<td>10×10</td>
<td>3051</td>
<td>647</td>
<td>24.1</td>
</tr>
<tr>
<td>15×15</td>
<td>1438</td>
<td>840</td>
<td>60.9</td>
</tr>
</tbody>
</table>

**5.4 Validation of the Model**

**5.4.1 Control Virgin and Control Corrosion Specimens**

The experimental results presented in Chapter 4 were used to validate the numerical (FE) model. Figures 5.6 – 5.8 compare the numerical and experimental results of specimens A0C, A20C, and A40C, respectively. As can be seen in the figures, there is a good correlation between the experimental and numerical results.
5.4.2 Repaired Specimen

After validating the numerical model of the corroded specimens with the experimental results, the BFRP composite was simulated in the model. The results of specimens A40R20U and A40R20B were utilized to validate the model of a repaired specimen. Figures 5.9 and 5.10 compare the numerical and experimental results of specimens A40R20U and A40R20B, respectively.

5.5 Parametric Studies

5.5.1 Effect of Internal Pressure on Corroded Control Specimens

In order to investigate the effect of internal pressure on corroded specimens, six specimens with different internal pressures were modeled in ABAQUS. All the specimens had a 75×75 mm square corrosion patch. NPS 8 API 5L grade X46 specimen was chosen for this parametric study (API, 2018). The depth of the corrosion patch in all specimens was 40% of the wall-thickness. The internal pressure was varied in between 0 and 1.0$p_y$. Table 5.6 shows the matrix of this part of parametric studies. Similar to the experimental part of the study, the specimens were under combined internal pressure and four-point bending load. First, the required internal pressure was applied to the specimens. Next, the bending load was applied in the displacement control method. Figure 5.11 shows the specimen with 1.0$p_y$. As can be found in this figure, the corrosion patch of the specimen bulged in the pressure stage and hence, bending load could not be applied and thus, the analysis did not continue to the next loading stage. Figure 5.12 shows the 40% corroded specimen at the end of applying 100 mm displacement. The load-displacement diagrams of these 5 specimens are displayed in Figure 5.13.
Table 5.6: Effect of internal pressure on corroded control specimens

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Shape &amp; Dimension (mm)</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A40CP0</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.0p_y</td>
</tr>
<tr>
<td>2</td>
<td>A40CP20</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
<tr>
<td>3</td>
<td>A40CP40</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.4p_y</td>
</tr>
<tr>
<td>4</td>
<td>A40CP60</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.6p_y</td>
</tr>
<tr>
<td>5</td>
<td>A40CP80</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.8p_y</td>
</tr>
<tr>
<td>6</td>
<td>A40CP100</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>1.0p_y</td>
</tr>
</tbody>
</table>

In order to have a better understanding of the effect of internal pressure on the performance of the specimens, the yield load vs. internal pressure and the ultimate load vs. internal pressure of these specimens are displayed in Figures 5.14 and 5.15. The yield load was assumed a point in the load-displacement graph of the specimens where it deviates from the straight line in elastic zone and goes toward the plastic zone. The ultimate load was determined from a point in the load-displacement graph where the load reaches its maximum value. Similar to the experimental tests in Chapter 4, the internal pressure was applied to the internal face of the pipe, as well as to the end plates in the model. It was expected that the yield load and the ultimate load would increase at lower pressures (0.2p_y, 0.4p_y). However, as can be seen in Figure 5.14, as the internal pressure increased from 0 to
0.2\(\text{p}_y\), the yield load decreased by 2 kN and it remained constant as the internal pressure increased to 0.4\(\text{p}_y\). After that, the yield load of the specimens decreased with increasing the internal pressure until the yield load reached the lowest point in the specimen with 0.8\(\text{p}_y\).

The behaviour of the ultimate load-carrying capacity of the specimens slightly differed from the yield load of the specimens. As can be seen in Figure 5.15, although the maximum ultimate load-carrying capacity of the specimens occurred in the specimen with 0.2\(\text{p}_y\), it did not noticeably differ in the specimens with internal pressures of 0.0, 0.2, 0.4, and 0.6\(\text{p}_y\). However, in the specimens with the internal pressure of 0.8\(\text{p}_y\), the ultimate load-carrying capacity significantly dropped.

5.5.2 Effect of Internal Pressure on Repaired Specimens

In the second phase of the parametric study, the effects of internal pressure on the corroded specimens with 40\% corrosion depth, rehabilitated with 20 layers of biaxial BFRP composite was investigated. NPS8 API 5L grade X46 specimen was chosen for this parametric study. It was found in Chapter 4 that the uniaxial BFRP composite could not prevent wrinkle formation and restore the bending capacity of the corroded pipes to the level of uncorroded virgin specimen (Figure 4.18). On the other hand, the biaxial BFRP composite not only prevented the wrinkle formation and restored the bending capacity of the corroded pipes to the level of uncorroded virgin specimen, but no debonding or rupture occurred in the fabric. Therefore, it was decided to model the biaxial BFRP composite in the parametric study.

The depth of corrosion was kept unchanged at 40\% of the wall-thickness because it was found in Chapter 4 that it had more severe effect on the bending capacity of the pipes
than 20% corrosion (Figure 4.13). Six specimens were simulated in ABAQUS similar to the first parametric study. However, the specimens were repaired with a biaxial BFRP composite. Table 5.7 shows the matrix of this parametric study. The load-displacement curves of these specimens are shown in Figure 5.16. Figures 5.17 and 5.18 show the yield load and the ultimate load-carrying capacity of each specimen, respectively. It can be noted that the specimen with 1.0$p_y$ did not form the wrinkle and hence, bending load could be applied in the repaired specimen. This was not possible for unrepaired specimen.

Table 5.7: Effect of internal pressure on repaired specimens

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Shape &amp; Dimension (mm)</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A40R20BP0</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>0.0$p_y$</td>
</tr>
<tr>
<td>2</td>
<td>A40R20BP20</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>0.2$p_y$</td>
</tr>
<tr>
<td>3</td>
<td>A40R20BP40</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>0.4$p_y$</td>
</tr>
<tr>
<td>4</td>
<td>A40R20BP60</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>0.6$p_y$</td>
</tr>
<tr>
<td>5</td>
<td>A40R20BP80</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>0.8$p_y$</td>
</tr>
<tr>
<td>6</td>
<td>A40R20BP100</td>
<td>40</td>
<td>Square 75×75</td>
<td>Yes</td>
<td>20</td>
<td>1.0$p_y$</td>
</tr>
</tbody>
</table>

As can be observed in Figures 5.17 and 5.18, the yield load vs. internal pressure and the ultimate load-carrying capacity vs. internal pressure have similar behaviour. In Figure
5.17, the diagram started from a yield load of 267 kN of the specimen without internal pressure. It increased to a load of 295 kN of the specimen with 0.2\(p_y\). It remained unchanged when internal pressure was increased to 0.4\(p_y\). The yield load decreased with increasing the internal pressure to 0.6\(p_y\) and it continued to decrease until it reached its minimum value in the specimen with 1.0\(p_y\). The ultimate load vs. internal pressure diagram of the specimens started from the specimen with zero internal pressure (Figure 5.18). It increased in the specimens with 0.2\(p_y\) and 0.4\(p_y\). Similar to the yield load behaviour of the specimens, the ultimate load decreased with increasing the internal pressure until it reached its minimum value in the specimen with 1.0\(p_y\).

Since internal pressure stabilises the behaviour of a pipe, it is expected that at lower pressures (as the internal pressure increases from 0 to 0.4\(p_y\)), the bending behaviour of the pipe will improve due to the internal pressure. This improvement can be seen in the repaired specimens but not in the unrepaired ones. The formation of the wrinkle in the unrepaired specimens may account for the difference in behaviour.

### 5.5.3 Effect of Corrosion Depth on Corroded Control Specimens

In the third parametric study, the effect of corrosion depth on the performance of the corroded specimens was investigated. NPS8 API 5L grade X46 pipe specimen was chosen for this parametric study. All these specimens had same square corrosion shape measuring 75×75 mm. However, the corrosion depth of the specimens varied from 0\% to 80\% at an increment of 20\% as shown in Table 5.8. The internal pressure in all specimens was kept unchanged at 0.2\(p_y\). Table 5.8 shows the matrix of this parametric study.
Table 5.8: Effect of corrosion depth on corroded control specimens

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Shape &amp; Dimension (mm)</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A0CP20</td>
<td>0</td>
<td>-</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
<tr>
<td>2</td>
<td>A20CP20</td>
<td>20</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
<tr>
<td>3</td>
<td>A40CP20</td>
<td>40</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
<tr>
<td>4</td>
<td>A60CP20</td>
<td>60</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
<tr>
<td>5</td>
<td>A80CP20</td>
<td>80</td>
<td>Square 75×75</td>
<td>No</td>
<td>0</td>
<td>0.2p_y</td>
</tr>
</tbody>
</table>

Figure 5.19 shows the load-displacement diagram of the specimens. As can be seen in the figure, except the un-corroded control (virgin) specimen that displayed a large strain hardening behaviour (A0CP20), all corroded specimens reached to their ultimate load soon after reaching yield load. Figures 5.20 and 5.21 show the yield load vs. corrosion depth and the ultimate load vs. corrosion depth of the specimens, respectively. The un-corroded control (virgin) specimen exhibited the maximum yield load. As the depth of the corrosion increased, the yield load decreased until the yield load reached its minimum value for the specimen with the 80% corrosion depth. The behaviour of the ultimate load-carrying capacity was similar to the yield load behaviour. The maximum value of the ultimate load occurred in the un-corroded control (virgin) specimen. As the corrosion depth of the
specimens increased, the ultimate load decreased until it reached its minimum value in the specimen with 80% corrosion depth.

5.5.4 Effect of Number of BFRP Layers

In this parametric study, the effect of the number of BFRP layers on the structural behaviour and the ultimate load-carrying capacity of the corroded specimens were investigated. NPS8 of API 5L X46 grade pipe was chosen for this parametric study. Eight FE models with 0, 10, 16, 20, 26, 40, 80, 120 layers of biaxial BFRP composite were simulated in ABAQUS. All these pipe specimens have 40% corrosion depth and same square corrosion shape of 75×75 mm. The purpose of this parametric study was to determine the optimum number of biaxial BFRP composite layers required to restore the ultimate load-carrying capacity of the pipe to the level of un-corroded control (virgin) specimen. The other objective was to study if increasing the number of layers will prevent wrinkle formation in the corroded region. Table 5.9 shows the matrix of this parametric study.
Table 5.9: Effect of number of BFRP layers on 40% corroded specimen

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Shape &amp; Dimension (mm)</th>
<th>Repaired</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A40CP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>No</td>
<td>0</td>
<td>0.2py</td>
</tr>
<tr>
<td>2</td>
<td>A40R10BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>10</td>
<td>0.2py</td>
</tr>
<tr>
<td>3</td>
<td>A40R16BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>16</td>
<td>0.2py</td>
</tr>
<tr>
<td>4</td>
<td>A40R20BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>20</td>
<td>0.2py</td>
</tr>
<tr>
<td>5</td>
<td>A40R26BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>26</td>
<td>0.2py</td>
</tr>
<tr>
<td>6</td>
<td>A40R40BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>40</td>
<td>0.2py</td>
</tr>
<tr>
<td>7</td>
<td>A40R80BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>80</td>
<td>0.2py</td>
</tr>
<tr>
<td>8</td>
<td>A40R120BP20</td>
<td>40</td>
<td>Square 75x75</td>
<td>Yes</td>
<td>120</td>
<td>0.2py</td>
</tr>
</tbody>
</table>

Figure 5.22 outlines the results of this parametric study. As can be seen in the figure, 18 layers of BFRP composite could restore the ultimate load of the 40% corroded specimen to the level of the un-corroded specimen. The specimens with 80 and 120 layers of BFRP composite were simulated to determine the effect of using a large number of layers on the corroded specimens. It was found that using too many layers of BFRP composite could barely increase the ultimate load of the corroded specimen; as the ultimate load began to converge approximately at 40 layers of biaxial BFRP composite.
Figure 5.22 also displays the number of layers recommended by ASME PCC-2 (ASME, 2015) and ISO/TS 24817 (ISO/TS, 2017) standards. As can be seen in this figure, 60 layers are recommended by ASME PCC-2 and 71 layers are recommended by ISO/TS 24817 in the axial direction. Although increasing the number of layers beyond what is needed increases the factor of safety of the repaired pipe, however, it might increase the material cost of the repair by a magnitude of three, which is not economical. The difference between the required numbers of repair in each standard is due to the method of calculating the axial forces ($F_a$) in each standard.

As discussed in Chapter 2, ISO/TS 24817 (ISO/TS, 2017) and ASME PCC-2 (ASME, 2015) standards are the main standards for rehabilitation of oil and gas pipes. Both standards recommend similar equations for calculating required thickness of FRP composites. Other pipeline standards such as API 579 (API, 2007), CSA Z662 (CSA, 2015), and BS 7910 (BSI, 2016) do not have any recommendations about the required thickness of the composite based repair of oil and gas pipes. There are two series of equations recommended by these two standards for calculating the required circumferential repair thickness ($t_{min,c}$) and the required axial repair thickness ($t_{min,a}$). In one series of equations it is assumed that the underlying substrate of steel pipe yields, and in the other series, the equations are derived based on the assumption that the underlying substrate of the steel pipe does not yield. Table 5.10 outlines the repair equations of these standards. It should be mentioned that the equations of the two standards are identical, except when the underlying substrate is assumed to have yielded, ISO/TS 24817 standard only considers hoop loading for determining a composite repair.
Table 5.10: Equations provided by ASME PCC-2 and ISO/TS 24817 for FRP repair

<table>
<thead>
<tr>
<th>Underlying substrate</th>
<th>$t_{\text{min},c}$</th>
<th>$t_{\text{min},a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>does not yield</td>
<td>$t_{\text{min},c} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_c} \right) \cdot (P - P_s)$ (5.7)</td>
<td>$t_{\text{min},a} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_a} \right) \cdot \left( \frac{2F_a}{\pi D^2} - P_s \right)$ (5.8)</td>
</tr>
<tr>
<td>yields</td>
<td>$t_{\text{min},c} = \frac{1}{\varepsilon_c E_c} \left( \frac{PD}{2} - s t_s \right)$ (5.9)</td>
<td>$t_{\text{min},a} = \frac{1}{\varepsilon_a E_a} \left( \frac{PD}{4} - s t_s \right)$ (5.10)</td>
</tr>
</tbody>
</table>

where,

$t_{\text{min},a} =$ required repair thickness of composite in the axial (longitudinal) direction

$t_{\text{min},c} =$ required repair thickness of composite in the circumferential direction

$D =$ outside diameter, mm (in.) = 220 mm

$E_s =$ tensile modulus for the substrate material, N/m$^2$ (psi) = 185 GPa

$E_c =$ tensile modulus for the composite laminate in the circumferential direction, N/m$^2$ (psi) = 10 GPa

$E_a =$ tensile modulus for the composite laminate in the axial direction, N/m$^2$ (psi) = 25 GPa

$F_a =$ sum axial tensile loads due to pressure, bending, and axial thrust, N (lb) = 2391.8 kN and 2566 kN calculated by equations provided by ASME PCC-2 and ISO/TS 24817, respectively.

$P =$ internal design pressure, N/m$^2$ (psi) = 4.6 MPa

$P_s =$ MAWP/MAOP/MOP for the component, N/m$^2$ (psi) = 20.1 MPa

$s =$ SMYS (Specified Minimum Yield Strength), N/m$^2$ (psi) = 400 MPa

$t_s =$ minimum remaining wall thickness of the component, mm (in.) = 3.6 mm

$\varepsilon_a =$ allowable repair laminate axial strain = 0.175

*Only exist in ASME PCC-2
\[ \varepsilon_c = \text{allowable repair laminate circumferential strain} = 0.28 \]

\[ P_s, F_a, \varepsilon_a, \text{and} \varepsilon_c \text{ were calculated based on the equations and data provided by ASME PCC-2 and ISO/TS 24817.} \]

\[ P_s = \frac{2t}{D} \left(1.1 \sigma_t \right) \left\{ \frac{1 - \frac{2d}{3t}}{1 - \frac{2d}{3tM_t}} \right\} \]

\[ M_t = \sqrt{1 + \frac{0.8L^2}{Dt}} \]

The Equations 5.7 to 5.12 are not restricted to either imperial or metric units. Either system of units can be used as long as the units are consistent with each other.

According to ASME PCC-2 equations, the minimum thickness would be:

Underlying substrate does not yield:

\[ t_{min,c} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(P - P_s\right) = -77.9 \text{ mm} \]  

(5.7)

\[ t_{min,a} = \frac{D}{2s} \cdot \left(\frac{E_s}{E_c}\right) \cdot \left(\frac{2F_a}{\pi D^2} - P_s\right) = 23.7 \text{ mm} \]  

(5.8)

Underlying substrate yields:

\[ t_{min,c} = \frac{1}{\varepsilon_c E_c} \left(\frac{PD}{2} - st_s\right) = -0.093 \text{ mm} \]  

(5.9)

\[ t_{min,a} = \frac{1}{\varepsilon_a E_a} \left(\frac{PD}{4} - st_s\right) = -0.169 \text{ mm} \]  

(5.10)
The design repair thickness shall be the maximum value of $t_{\text{min}, \text{c}}$ and $t_{\text{min}, \text{a}}$ which is 23.7 mm. Since the thickness of each BFRP layer was 0.4 mm in this study, the required number of BFRP layers in the axial (longitudinal) direction would be 60.

According to ISO/TS 24817 equations, the minimum thickness would be:

Underlying substrate does not yield:

$$
t_{\text{min}, \text{c}} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_c} \right) \cdot (P - P_s) = -31.2 \text{ mm} \tag{5.7}
$$

$$
t_{\text{min}, \text{a}} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_c} \right) \cdot \left( \frac{2F_a}{\pi D^2} - P_s \right) = 28.4 \text{ mm} \tag{5.9}
$$

Underlying substrate yields:

$$
t_{\text{min}, \text{c}} = \frac{1}{E_c} \left[ \frac{PD}{2} - ss_s \right] = -0.037 \text{ mm} \tag{5.10}
$$

Hence, the design repair thickness recommended by ISO/TS 24817 was 28.4 mm, which corresponded to 71 layers of uniaxial BFRP in the axial (longitudinal) direction.

It should be noted that the specimens in the parametric study were pressurized to only 0.2$p$ (Table 5.9). Since the main focus of the study was to determine the performance of the pressurized pipe under bending load. As a result of this low design pressure in the pipes, the internal pressure of the specimens was much lower than the maximum allowable operating pressure (MAOP) of the pipe. Thus, none of the standards recommended using FRP composite in the circumferential direction. Using low internal pressure in the circumferential repair thickness equations (Equations 5.3 and 5.5) in Table 5.10 resulted in negative values. This is in contrast with the experimental results that were found in this study which proved that the circumferential reinforcement was necessary to resist the
ovalisation effect of the pipe while it bends. Therefore, it seems that the ASME PCC-2 and ISO/TS 24817 standards should modify the equations to better incorporate the effects of ovalisation that occur when bending.

In Chapter 4 it was demonstrated that using 20 layers of biaxial BFRP composite could prevent wrinkle formation in the corroded zone of the 40% corroded specimen (specimen A40R20B) as shown in Table 4.1. Figure 5.23 shows a 40% corroded specimen of NPS8 of API 5L X46 grade pipe rehabilitated with four different number of layers of biaxial BFRP composite including 10, 16, 20, and 26. It is apparent that as the number of layers increased to 20 layers, the wrinkle formation was prevented.

5.5.5 Effect of Fibre Orientation

In this section, the effect of three different fibre orientations is discussed. Table 5.11 shows the matrix of these specimens used in this parametric study. The corrosion depth in all specimens was 40% of the wall-thickness and the internal pressure was 0.2p. NPS8 API 5L grade X46 specimen was chosen for this parametric study.
Table 5.11: Effect of the orientation of fibres

<table>
<thead>
<tr>
<th>Specimen no</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Shape &amp; Dimension (mm)</th>
<th>Fibre Orientation</th>
<th>Number of BFRP Layers</th>
<th>Internal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A40R20BP20F0/90</td>
<td>40</td>
<td>Square 75×75</td>
<td>0/90</td>
<td>20 Biaxial</td>
<td>0.2(p_y)</td>
</tr>
<tr>
<td>2</td>
<td>A40R20BP20F45/45</td>
<td>40</td>
<td>Square 75×75</td>
<td>45/45</td>
<td>20 Biaxial</td>
<td>0.2(p_y)</td>
</tr>
<tr>
<td>3</td>
<td>A40R20UP20F90</td>
<td>40</td>
<td>Square 75×75</td>
<td>90</td>
<td>20 Uniaxial</td>
<td>0.2(p_y)</td>
</tr>
<tr>
<td>4</td>
<td>A40CP20</td>
<td>40</td>
<td>Square 75×75</td>
<td>-</td>
<td>-</td>
<td>0.2(p_y)</td>
</tr>
</tbody>
</table>

Figure 5.24 shows the orientation of fibres in this parametric study. The first specimen was repaired with 20 layers of biaxial BFRP composite oriented in both longitudinal (0°) and circumferential (90°) directions (Orientation 1- A40R20BP20F0/90). For the second specimen as well, 20 layers of biaxial BFRP composite were used. However, the layers were oriented at ±45° and hence, the fibres were oriented at 90° from each other and at 45° from the longitudinal axes of the pipe (Orientation 2- A40R20BP20F45/45). In the third specimen, 20 layers of uniaxial BFRP composite were placed at 90° to the longitudinal axis and hence, they were placed circumferentially around the pipe (Orientation 3- A40R20UP20F90). Since it was observed in the experimental test that the uniaxial BFRP composite oriented in the longitudinal direction fractured and could not prevent wrinkle formation in the 40% corroded specimen, therefore, it was not considered in this study. The results of all three specimens were compared with the corroded un-repaired specimen (A40CP20).
Figure 5.25 shows the results of this parametric study. It was found that the specimen with the biaxial fibres oriented at ±45° with the longitudinal axes had the lowest improvement on the performance of the corroded specimen. It had the lowest ultimate load and softest post wrinkling behaviour. This may be due to the fact that the fibres were not placed in either the longitudinal direction to increase the stiffness of the specimen, nor they were located on the circumferential direction to resist ovalisation of the specimen and prevent wrinkle formation. Hence, a wrinkle occurred in the corroded zone of this specimen (Figure 5.26).

The specimen with biaxial BFRP composite oriented in the longitudinal and circumferential directions (Orientation 1) and the specimen with the uniaxial fibres oriented in the circumferential direction (Orientation 3) had a similar behaviour. Based on the results of Figure 5.25, and the fact that it is able to resist the hoop stress as twice as Orientation 1, it appeared that Orientation 3 may be better than Orientation 1 to repair corroded pipe under bending. However, there is a concern regarding the ability of the composite to resist the longitudinal stress of the pipe wall resulted from bending load. Since the fibres are oriented only in the circumferential direction, the tensile strength of the matrix - which is significantly weaker than the tensile strength of the fibre - is the only component that withstands the longitudinal moment of the pipe.

In order to address this issue, the longitudinal strain values at the tensile section of the BFRP composite of the two Orientations 1 (biaxial) and 3 (uniaxial) were analyzed (Figure 5.27). Table 5.12 shows the results of this comparison. It was found that the longitudinal strain observed at the base of the uniaxial BFRP composite (0.84%) in the FE model exceeded its ultimate strain of 0.45% for BFRP composite (that was obtained from
experimental coupon tests) at the maximum deflection of the specimen. However, the longitudinal strain experienced by the biaxial composite remained below one-third of its maximum strain capacity.

Table 5.12: Longitudinal strains of biaxial and uniaxial composites

<table>
<thead>
<tr>
<th></th>
<th>Ultimate Strain</th>
<th>Observed FEA Strain</th>
<th>Safe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial (90°)</td>
<td>0.45%</td>
<td>0.84%</td>
<td>No</td>
</tr>
<tr>
<td>Biaxial (0°/90°)</td>
<td>1.56%</td>
<td>0.42%</td>
<td>Yes</td>
</tr>
</tbody>
</table>

5.5.6 Effect of Dimensions of Rectangular Corrosion Shape

In section 4.2 of Chapter 4, it was found that square and circular corrosion shapes with the same corrosion area had the same effect on the load-displacement behaviour of the NPS6 API 5L X46 grade pipe under combined internal pressure and bending load. The internal pressure was maintained at 0.4$p_y$ level and depth of corrosion in all these specimens was also kept unchanged at 40%. Before manufacturing a specimen with a rectangular corrosion shape, it was decided to perform a finite element study to determine the dimensions of the rectangular corrosion shape that would have the most effect on the performance of the specimen. A parametric study was conducted in two parts. In part I, the width (circumferential dimension or $B$) of the rectangle was kept constant to 45 mm and the length of the rectangle (longitudinal dimension or $L$) varied between 45, 90, 125, and 180 mm. In part II, the length of the rectangle (longitudinal dimension or $L$) was kept constant at 45 mm and the width (circumferential dimension or $B$) of the rectangle varied between 45, 90, 125, and 180 mm. Tables 5.13 and 5.14 show the dimension of the rectangular corrosion patch and the ultimate load-carrying capacity of each specimen of
parts I and II. Figure 5.28 shows a sketch of the four rectangular corrosion shapes used in Tables 5.13 and 5.14.

Table 5.13: Rectangular corrosion shapes with 45 mm width and varying lengths

<table>
<thead>
<tr>
<th>Specimen no</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Dimensions B×L (mm)</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B0C</td>
<td>0</td>
<td>-</td>
<td>168.3</td>
</tr>
<tr>
<td>2</td>
<td>B40CR45×45</td>
<td>40</td>
<td>45×45</td>
<td>161.1</td>
</tr>
<tr>
<td>3</td>
<td>B40CR45×90</td>
<td>40</td>
<td>45×90</td>
<td>152.0</td>
</tr>
<tr>
<td>4</td>
<td>B40CR45×125</td>
<td>40</td>
<td>45×125</td>
<td>156.0</td>
</tr>
<tr>
<td>5</td>
<td>B40CR45×180</td>
<td>40</td>
<td>45×180</td>
<td>155.9</td>
</tr>
</tbody>
</table>

Table 5.14: Rectangular corrosion shapes with varying widths and 45 mm length

<table>
<thead>
<tr>
<th>Specimen no</th>
<th>Specimen Name</th>
<th>Corrosion Depth (%)</th>
<th>Corrosion Dimensions B×L (mm)</th>
<th>Ultimate load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B0C</td>
<td>0</td>
<td>-</td>
<td>168.3</td>
</tr>
<tr>
<td>2</td>
<td>B40CR45×45</td>
<td>40</td>
<td>45×45</td>
<td>161.1</td>
</tr>
<tr>
<td>3</td>
<td>B40CR90×45</td>
<td>40</td>
<td>90×45</td>
<td>137.4</td>
</tr>
<tr>
<td>4</td>
<td>B40CR125×45</td>
<td>40</td>
<td>125×45</td>
<td>125.9</td>
</tr>
<tr>
<td>5</td>
<td>B40CR180×45</td>
<td>40</td>
<td>180×45</td>
<td>117.0</td>
</tr>
</tbody>
</table>

Figure 5.29 shows the results of specimens in part I. As can be seen in this figure, by keeping the circumferential length equal to 45 mm and increasing the longitudinal length
of the corrosion patch \((L)\), the ultimate load-carrying capacity of the pipe decreased until it reached a load of 152 kN, corresponding to the length \((L)\) of 90 mm. However, the trend reversed in the specimen with a length \((L)\) of 125 mm which had a higher ultimate load of 156.7 kN. In the next specimen with the highest length of the corrosion patch, the ultimate load decreased to 155.9 kN. It is evident from the figure that there is no clear relationship between increasing the longitudinal length of the rectangular patch \((L)\) and the load-carrying capacity.

Figure 5.30 displays the ultimate load-carrying capacity of the specimens in part \(II\). As can be seen in the figure, the ultimate load-carrying capacity starts from 168.3 kN of the un-corroded control (virgin) specimen and it decreases with increasing circumferential \((B)\) length of the corrosion patch until it reaches 117 kN, the ultimate load of the specimen with the maximum circumferential length of the corrosion patch. As can be seen in this figure, it is clear that by keeping the longitudinal length of the corrosion patch the same and increasing the circumferential length, the ultimate load-carrying capacity of the specimens decreases. The reason could be related to the fact that as the corrosion shape expands in the circumferential direction, the moment of inertia decreases. However, expanding the corrosion shape in the longitudinal direction does not have any effect on the moment of inertia. Hence, when the moment of inertia decreases, the pipe which is under a four-point bending load would reach a higher stress at a lower moment.
5.6 Summary

In this chapter, FE models were developed and validated using test data. The FE models were then used for undertaking several parametric studies using ABAQUS version 6.14.2 software to study the performance of corroded specimens, rehabilitated with BFRP composite. The results of these studies are as follow:

- Increasing the internal pressure reduced the yield load of the corroded specimens.
- Increasing the internal pressure from 0 to $0.6p_y$ did not have a noticeable effect on the ultimate load of the corroded specimens. However, after that, the ultimate load dropped.
- Increasing the internal pressure from 0 to $0.2p_y$ and $0.4p_y$ increased the yield load and the ultimate load of the repaired specimens. However, after that, the yield load and the ultimate load dropped.
- Increasing the corrosion depth of the specimens reduced the yield load and the ultimate load of the corroded specimens.
- Increasing the number of biaxial BFRP composite beyond the optimum number did not have a noticeable impact on the ultimate load-carrying capacity of the specimen.
- The recommended numbers of repair BFRP layers by ASME PCC-2 and ISO/TS 24817 standards are highly conservative.
- The recommendation of the standards about not using circumferential fibres in the low level pressurized pipes leads to the fracture of the composite due to ovalisation.
- Using 20 layers of BFRP composite prevented wrinkle formation in the corroded zone.
• Using biaxial BFRP composite with fibres oriented in the longitudinal and circumferential directions has the best influence on restoring the performance of the corroded specimens.

• Corrosion in the circumferential direction causes the most reduction in the ultimate load-carrying capacity of the pipe, compared to the corrosion in the longitudinal direction which its relationship between increasing the longitudinal length and the reduction of the ultimate load-carrying capacity did not have any pattern.

Figure 5.1: A 40% corroded specimen modeled with solid elements
Figure 5.2: The FRP composite modelled with shell elements

Figure 5.3: Boundary conditions of the bottom supports
Figure 5.4: True stress-true plastic strain diagrams of specimens in phases A and B.

Figure 5.5: Diagram of stress vs. mesh density
Figure 5.6: Load-displacement diagram of specimen A0C

Figure 5.7: Load-displacement diagram of specimen A20C
Figure 5.8: Load-displacement diagram of specimen A40C

Figure 5.9: Load-displacement diagram of specimen A40R20U
Figure 5.10: Load-displacement diagram of specimen A40R20B

Figure 5.11: Bulging of corrosion of A40CP100 due to internal pressure

Figure 5.12: Specimen A40CP20 at the end of loading
Figure 5.13: Effect of internal pressure on corroded control specimens

Figure 5.14: Effect of internal pressure on yield load of corroded control specimen
Figure 5.15: Effect of internal pressure on ultimate load of corroded control specimen

Figure 5.16: Effect of internal pressure on repaired specimen
Figure 5.17: Effect of internal pressure on yield load of repaired specimen

Figure 5.18: Effect of internal pressure on ultimate load of repaired specimen
Figure 5.19: Effect of corrosion depth on corroded un-repaired specimen

Figure 5.20: Effect of corrosion depth on yield load of corroded specimen
Figure 5.21: Effect of corrosion depth on ultimate load of corroded specimen

Figure 5.22: Effect of number of BFRP layers on ultimate load
Figure 5.23: Wrinkle behaviour with increasing number of layers

Figure 5.24: Orientation of fibres
Figure 5.25: Effect of fibre orientation on load-displacement behaviour

Figure 5.26: Wrinkle formation
Figure 5.27: Longitudinal strain on the FRP composite

(a) biaxial (0°/90°) composite  (b) uniaxial (90°) composite

Figure 5.28: Rectangular corrosion shapes
Figure 5.29: Rectangular corrosion shapes with 45 mm width and varying lengths

Figure 5.30: Rectangular corrosion shapes with varying widths and 45 mm length
Chapter 6: Conclusions and Recommendations

6.1 Summary

BFRP is a green product and it has been established to be an effective composite material for repair of various defected structures like concrete and steel beams. A large number of studies on repair of corroded pipes using carbon and glass fibres composite are available in the literature. However, no research on rehabilitation of corroded pipe using basalt fibre reinforced polymer (BFRP) was found in the literature. Literature review also revealed that most of the research on repairing the corroded pipes using CFRP and GFRP focused on strengthening the burst pressure of the pipe and only a few studies addressed the bending behaviour of corroded pipelines.

In this research, detailed experimental as well as numerical studies were conducted to investigate the effectiveness of BFRP in rehabilitating corroded steel pipes used in oil and gas transportation. The experimental part of the study was completed in two phases. In phase A, seven full-scale laboratory experiments, and in phase B, five full-scale specimens were tested. The results of the experimental tests were used to validate the finite element models used in the numerical study. Several parametric studies were performed using ABAQUS software to examine the performance of corroded specimens, rehabilitated with BFRP composite.

6.2 Conclusions

The following conclusions are made based on the current study and hence, these conclusions may be limited to the scope of the current study.
1. Increase in the corrosion depth reduces the bending capacity of the corroded pipes and the reduction may be considerable to significant depending of the depth of corrosion.

2. Corrosion reduces the strain hardening of the pipe material and hence, it results in reaching its ultimate load at a lower deflection.

3. The uniaxial BFRP composite may restore the bending capacity of the corroded specimens when the level of corrosion is limited to 20% of the wall thickness. However, it is not able to resist ovalisation of the pipe and it fails to prevent wrinkle formation.

4. Using uniaxial composite in the longitudinal direction results in longitudinal fracture in the composite due to tension caused by ovalisation.

5. Use of biaxial BFRP composite can restore bending capacity of the corroded specimens, resist ovalisation of the cross-section, and prevent wrinkle formation in the corroded zone without any de-bonding or fracture in the composite.

6. The repair thickness recommended by ISO/TS 24817 and ASME PCC-2 standards depends on the Maximum Allowable Working Pressure (MAWP). Therefore, for a pipe with the internal pressure lower than MAWP, the recommendations of the two standards may not be applicable.

7. The recommended axial repair thicknesses by ASME PCC-2 and ISO/TS 24817 standards are conservative since number of layers of BFRP required as per these two standards are much larger than the number of BFRP layers needed and found from the experimental study. On the other hand, the recommended
circumferential repair thicknesses for the low-pressure pipes (up to 20% internal pressure) is zero which is in contrast with the experimental results.

8. Increase in the number of BFRP composite layers beyond the experimentally achieved optimum number might slightly increase the ultimate load. However, the cost of repair far outweighs its benefit.

9. Square and circular corrosion patch with the same area have a similar effect on the bending performance of corroded specimen.

10. Circumferentially located rectangular corrosion patch causes the most reduction in the ultimate load-carrying capacity of the corroded specimens. Corrosion increasing in the circumferential direction causes a steady reduction in the ultimate load-carrying capacity, whereas increasing corrosion in the longitudinal direction does not show correlation with reducing load.

### 6.3 Recommendations

Basalt fibre and BFRP are new materials and they have not been used in pipeline industry for repair and rehabilitation of any damaged pipeline. Therefore, many experimental and numerical studies are needed to investigate and document the effectiveness of this environmentally friendly composite on rehabilitating the defected oil and gas pipelines. The recommended repair thickness by ASME PCC-2 and ISO/TS 24817 for the corroded specimens having an internal pressure lower than MAWP is not applicable. Thus, a comprehensive study is needed to generate equations of repair thickness that better take into account the effects of bending loads.
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VITA AUCTORIS

NAME: Behrouz Chegeni

PLACE OF BIRTH: Khorramabad, Iran

YEAR OF BIRTH: 1986

EDUCATION:
Azad University, B.Sc. – Mechanical Engineering, Khorramabad, Iran, 2008

Malayer University, M.Sc. – Structural Engineering, Malayer, Iran, 2012

University of Windsor, Ph.D. – Civil Engineering, Windsor, ON, 2018