DEGRADATION MODELLING ON TEMPERATURE UPON BURST CAPACITY OF COMPOSITE REPAIRED PIPELINE

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ABSTRAK

Saluran paip adalah cara yang paling selamat, cekap, dan ekonomi untuk pengangkutan minyak dan gas untuk jarak yang jauh. Ia tertakluk kepada kemerosotan dan kerosakan, yang boleh mengurangkan kekuatan dan integriti struktur. Komposit polimer diperkuat gentian *(FRP)* digunakan untuk membaiki paip keluli yang rosak dan ia telah terbukti berkesan kerana ia dapat memulihkan kapasiti muatan paip keluli. Walau bagaimanapun, *FRP* komposit terdedah kepada beberapa faktor persekitaran yang mengakibatkan degradasi seperti suhu, kelembapan, radiasi ultraungu, kitaran haba, dan keletihan mekanikal. Degradasi komposit *FRP* dijangka mengurangkan kapasiti galas beban paip diperbaiki oleh komposit. Oleh itu, tujuan kajian ini adalah untuk mengkaji kesan suhu terhadap degradasi E-kaca / Vinylester ke atas paip diperbaiki komposit melalui analisis unsur terhingga *(FEA)*. Komposit E-kaca / Vinylester tertakluk kepada suhu yang berbeza iaitu 23 ° C, 60 ° C, dan 95 ° C pada 0-hari, 360-hari, 1080-hari, dan 1440-hari. Sepuluh model unsur terhingga telah dihasilkan untuk mensimulasikan kesan degradasi komposit terhadap tekanan letus saluran paip diperbaiki komposit. Keputusan menunjukkan bahawa tekanan letus paip keluli diperbaiki komposit menurun dengan ketara sebanyak 10.09% dan 11.62% dalam masa 360 hari pada 60°C dan 95°C. Sementara itu, pengurangan tekanan letus sebanyak 7.29% diperhatikan pada 1080-hari apabila paip diperbaiki komposit adalah tertakluk kepada 23°C. Kesimpulannya, degradasi komposit E-kaca / Vinylester dari masa ke masa mempunyai kesan ke atas kapasiti galas beban paip keluli diperbaiki komposit. Pengurangan kekuatan tegangan dalam komposit telah mengurangkan kapasiti letus saluran paip diperbaiki komposit. Penemuan ini boleh menjadi sangat berguna dalam memahami ketahanan jangka panjang paip keluli diperbaiki komposit.

ABSTRACT

Pipelines are the safest, efficient, and economic way for oil and gas transportation over a long distance. It is subjected to deterioration and damage, which can reduce their strength and structural integrity. Fiber-Reinforced Polymer (FRP) composites are used to repair defective steel pipes and it has been proven effective as it restored the loading capacity of steel pipe. However, FRP composites are susceptible to be degraded by several environmental factors such as temperature, moisture, ultraviolet radiation, thermal cycling, and mechanical fatigue. Degradation of FRP composites are expected to decrease the load bearing capacity of composite repaired steel pipe. Therefore, the purpose of this research is to study the effect of temperature towards the degradation of E-glass/Vinylester on composite repaired pipeline through finite element analysis (FEA). The E-glass/Vinylester composites were subjected to different temperatures which are 23°C, 60°C, and 95°C at 0-day, 360-days, 1080-days, and 1440-days. Ten finite element (FE) models were developed to simulate the effect of composite degradation upon the burst pressure of composite repaired pipeline. The results show that burst pressure of composite repaired steel pipe dropped significantly by 10.09% and 11.62% within 360-days at 60°C and 95°C, respectively. Meanwhile, a reduction of burst pressure by 7.29% at 1080-days was observed when the composite repaired pipe was subjected to 23°C. As a conclusion, degradation of E-glass/Vinylester composites over time has the effect on load bearing capacity of composite repaired steel pipe. Reduction of tensile strength in composite had reduced the burst capacity of composite repaired pipeline. This finding can be very useful in understanding the long-term durability of composite repaired steel pipe.

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LIST OF SYMBOLS

E1	Hoop Tensile Modulus
E2	Axial Tensile Modulus
E3	Radial Tensile Modulus
G	Shear Modulus
T_g	Glass Transition Temperature
v	Poison Ratio
σ_a	Axial Tensile Stress
σ_h	Hoop Tensile Stress

LIST OF ABBREVIATIONS

CFEP	Carbon Fiber-Epoxy Polymer
CFRP	Carbon Fiber Reinforced Polymer
CFPP	Carbon Fiber-Polyester Polymer
FEA	Finite Element Analysis
FRP	Fiber Reinforced Polymer
GFEP	Glass Fiber-Epoxy Polymer
GFRP	Glass Fiber Reinforced Polymer
GFPP	Glass Fiber-Polyester Polymer
MCU	Moisture Cured Urethane
PGU	Peninsular Gas Utilisation
RMB	Renminbi
R&D	Research & Development
SSGP	Sabah-Sarawak Gas Pipeline
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nowadays, pipelines are considered as the safest, efficiency and economic way to transport natural gas, petroleum, refined products in a large quantity over a long distance. Pipelines are subjected to internal and external damage caused by several factors such as material and construction defects, natural forces, corrosion, and third-party damage (Yusof *et al.*, 2014; Lim *et al.*, 2015). Steel pipeline is susceptible to corrode with the presence of water. Corrosion rate will be faster under harsh environment compared to the common environment. Damaged or corroded pipelines can degrade its mechanical properties and reduce its strength throughout service life (Nakamura *et al.*, 2006; Ossai *et al.*, 2015). Eventually, these pipelines are potentially subjected to failure such as leaking and explosion. Failure of pipelines can cause significant negative impact such as loss of live, destruction of private and public property, and serious environmental damage.

In June 10, 2014 an explosion of Sabah-Sarawak Gas Pipeline (SSGP) in Lawas, Sarawak was reported where the main reason of explosion is believed due to leaking of pipeline (Ismail, 2014). This explosion results a temporary shutdown of pipeline operation that is worth with RM 4 billion that owned by national oil giant, Petronas (Then, 2014). Another explosion of underground gas pipeline in Kaohsiung, Taiwan happened on July 31,2014 has caused fatality of 32 people and almost 321 people were injured due to leaking of propylene gas (Chen *et al.*, 2016). Incident on November 22, 2013 occurred at Donghuang, China where direct economic lost is approximately 751,720,000 RMB, 136 people are injured and 62 people are died due to pipeline leakage and explosion (Gong and Li, 2018). Failure of pipeline will only give negative impacts to public and environment. Therefore, maintenance and repairing for pipeline system are necessary to prevent failure.

For years, a range of technique are available for rehabilitation of damaged pipeline on offshore or onshore. The most common method for repairing damaged pipeline is to remove the defective segment and replace it with new pipeline. Shutdown or isolation and depressurization are necessary for the defective segment of pipeline in this repair method (Jakso *et al.*, 2006). A temporary shutdown will affect the operation and cause significant loss for company. Other than this method, installation of full-encirclement steel sleeves is another widely used rehabilitation method where steel sleeves are used to cover the defective segment. This method is generally suitable for straight pipeline and it is difficult to be applied on bended pipeline. Both methods which involves welding or clamping of pipeline is hard to be done in limited workplace such as in underground environment (Lim *et al.*, 2015).

Recently, there is a trend of the application of Fiber Reinforced Polymer (FRP) composite as rehabilitation technique in different fields of engineering such as aircraft, structural buildings, aerospace and etc. This FRP composite application is used in pipeline repair method and it has been proven effective for repairing defective pipeline and other steel structures (Duell *et al.*, 2008; Chan *et al.*, 2015). However, FRP composite still have several issues regarding to the behaviour and performance of composite repair system are not fully understood. These issues consist of complexity of surface preparation, delamination and de-bonding between steel pipe and composite, performance and contribution of the infill material, load transfer mechanisms, effect of defect geometries, and conservativeness in existing design codes (Lim, 2017). Thus, pipeline rehabilitation techniques and repair method always are the concern for researchers to study in order to have a better understanding on the behaviour of composite repair system, and subsequently improve its efficiency.

1.2 Research Problem

Fiber Reinforced Polymer (FRP) composite materials in pipeline rehabilitation consist of three parts which are FRP composite wrap, infill material, and adhesive. FRP composite wrap provides additional strength to defective pipeline and it acts as a protection layer to putty as well. The role of infill material is to fill the damaged part of pipeline and give a smooth surface for composite layer while adhesive is used to bond the composite layer with the infill material and damaged pipeline. Combination of those materials has been proven effective for pipeline repair system (Duell *et al.*, 2008; Chan *et al.*, 2015).

Fiber Reinforced Polymer (FRP) is a composite made of polymer matrix reinforced with fibers. Glass, carbon or aramid are typically fiber where they provide strength and stiffness to composite. Polymer matrix generally are thermoplastic or thermosetting resin such as epoxy, vinyl ester or polyester where it has the function of transfer load between fibers and protect fibers from environment (Liao *et al.*, 1998). FRP composite has unique properties such as high specified stiffness, high strength, high resistance against corrosion, high fatigue endurance limit, and lightweight (Liao *et al.*, 1998; Farooq, 2009; Hagihara *et al.*, 2018; Vieira *et al.*, 2018).

However, the mechanical properties of FRP composite are significantly degraded over time under various factors such as temperature, ultraviolet (UV) light, moisture content, and oxygen (Jawaid *et al.*, 2016). Degradation of FRP composite layer will potentially results a reduction in strength and durability of a composite repaired pipeline. Reduction in strength and durability of FRP composite increase possibility of pipeline failure prior to its design life. The degradation rate is different under various factors. Therefore, this research aims to study the effect of temperature towards the degradation of composite repaired pipeline.

1.3 Objectives

The main concern of this research is to study the effect of temperature towards the degradation of composite repaired pipeline through finite element analysis (FEA). The objectives of this study are as follows:

1. To study the strength degradation of FRP composite subjected to different temperatures.
2. To simulate the effect composite degradation upon the burst pressure of composite repaired pipeline.

1.4 Scope of Research

This study utilizes numerical simulation to study the effect of temperature towards the strength degradation of FRP composite and subsequently the burst capacity of composite repaired pipeline. No experimental test was conducted in this study. Previous research's data were used to developed ten finite element models to simulate the burst capacity of repaired pipeline under several conditions, which are the composite repaired pipeline that is subjected to 23°C, 60°C and 95°C at 0-days, 360-days, 1080-days, and 1440-days respectively. Other parameters such as moisture content and wavelength are not considered in this study.

1.5 Significance of Research

Long-term durability and performance of composite repaired steel pipe has always become the concern of oil and gas industry and investors, as well as researchers. There are various factors that can cause the service life of composite repaired pipeline to be reduced, which it included of environmental factors. Based on previous literature, researchers found that composite material lose their mechanical properties when subjected to a critical environment throughout its service life. An elevated temperature, higher moisture content, ultraviolet are several environmental factors that can cause the alteration in structural integrity of composite material and thus it causes the material to be degraded. By conducting this research, a better understanding on the effect of environmental factor (temperature) over time towards the long-term durability and performance of composite repaired steel pipe can be achieved. This research also is like a stepping stone in understanding the long-term durability and performance of composite repaired steel pipe as there are limited information related to degradation of composite repaired steel pipe by environmental factors. Other than that, prediction of remaining life for composite repaired steel pipe is another contribution by this research. For instance, the predicted remaining life can be obtained by comparing the simulated burst pressure with the operating pressure.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter covers the issues related to fiber reinforced polymer (FRP) composite in pipeline rehabilitation. The information of conventional repair methods for damaged pipelines is presented and followed by the current rehabilitation techniques which is the application of composite materials. Each component of FRP composite was presented in this chapter. Moreover, the information related to composite material degradation by environmental factors also were discussed in this chapter.

2.2 Overview

Pipelines are known as the safest, economical and efficiency way to transport oil, natural gas and refined products over a long distance (Shamsuddoha, 2014; Noor *et al.*, 2016; Lim, 2017; Guo *et al.*, 2018). Based on data provided by Central Intelligence Agency, United States of America owned the longest span of pipeline which is 2225032 km (2013), followed by China with 828606 km pipeline (2015), Russia with 251800 km pipeline (2016), and Canada with 110000 km pipeline (2017) while Malaysia owned a total span of 9025 km pipeline (2013). In addition, Peninsular Gas Utilisation (PGU) operated 2521 km pipeline for salesgas transportation in West Malaysia, whereas they also transport small volumes of salegas in Miri and Bintulu, Sarawak and Kimanis, Sabah (Petronas Gas Berhad, 2016). These pipelines are subjected to damage caused by material and construction defects, natural forces, corrosion and third-party damage (Alexander, 2007b; Noor *et al.*, 2016; Lim, 2017). Deterioration of pipelines are common and serious problem as it can degrade the structural integrity and reduce the strength of pipeline throughout the service life (Nakamura *et al.*, 2006; Ossai *et al.*, 2015).

Corrosion is a natural process for offshore steel structures where it happened with the presence of metal, water, and oxygen. Corrosion is a common and serious problem to pipeline industry where it is one of the most predominant causes of pipeline failure as it can degrade the structural integrity (Ossai *et al.*, 2015). In United States, there are more than 2 billion dollars was loss due to corrosion of offshore pipeline (Duell *et al.*, 2008). More than 70% of oil and gas fields being developed around the world are highly corrosive, this cost will be increased to manage the facilities in corrosive environment (Ossai *et al.*, 2015). In fact, when a corroded or damaged pipeline appeared on the pipeline, an assessment or evaluation will be done in order to determine the safety of structural integrity caused by defective part of pipeline. Then, company will make decision to repair or replace the defective pipeline in order to minimize the loss to company. There are various rehabilitation techniques and repair methods have been developed to extend the lifetime of the defective pipelines. However, these repair methods are along with their own drawbacks.

2.3 Conventional Rehabilitation Techniques

Traditionally, the most common and reliable method to repair the damaged pipelines is to remove the defective segment of pipeline and replace it. Before the work is carry out, the operating system should be shut down or isolation and depressurization should be conducted (Jakso *et al.*, 2006). These actions are to ensure that there is no leaking of oil or natural gas from other segment of pipelines during the pipeline replacing. Shutdown of system will cause the loss to company where the longer the shutdown period, the greater the loss to company.

Besides, there is another way to repair damaged pipeline which is installation of full-encirclement steel sleeve to cover circularly the defective part of pipeline. Full-encirclement steel sleeve has been widely developed and used for general repair for onshore pipelines since early 1970s (Reliable Pipes & Tubes Limited, 2017). This method consists of Type A sleeve and Type B sleeve. Type A sleeve provides reinforcing to the defective part of pipeline by welding the sleeve halves longitudinally without welding the end to the pipeline (Figure 2.1). Type B sleeve has the same manner as Type A sleeve but it is completely welded to the pipe (Figure 2.1) and it is suitable for leaking defective pipeline (Reliable Pipes & Tubes Limited, 2017).

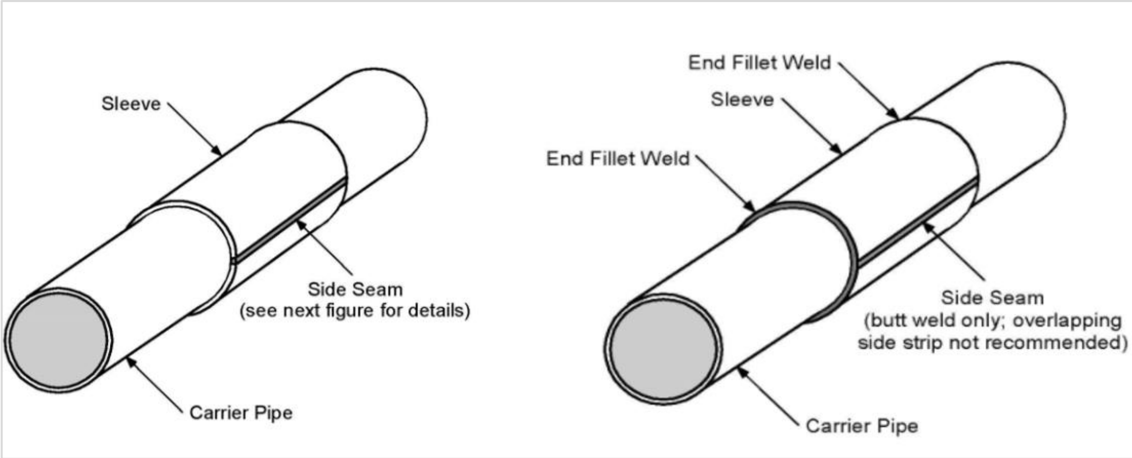

Figure 2.1 Type A sleeve (left) and Type B sleeve (right)
Source: Hoie (2015)

Other than that, clamp technique is another rehabilitation technique for damaged pipelines by using bolts to join two halves clamp together Figure 2.2. The damaged surface of pipeline must be perfectly smooth in order to seal properly before the clamps are installed (Hoie, 2015). Moreover, grouted clamp is one of the clamp repair techniques where there is an additional epoxy filling applied on the damaged surface of pipeline before the clamps are installed Figure 2.3.

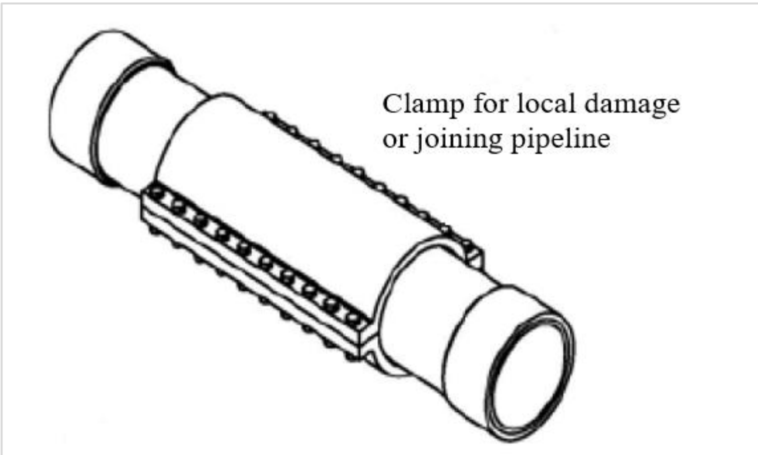

Figure 2.2 Typical mechanical bolt-on clamp
Source: Hoie (2015)

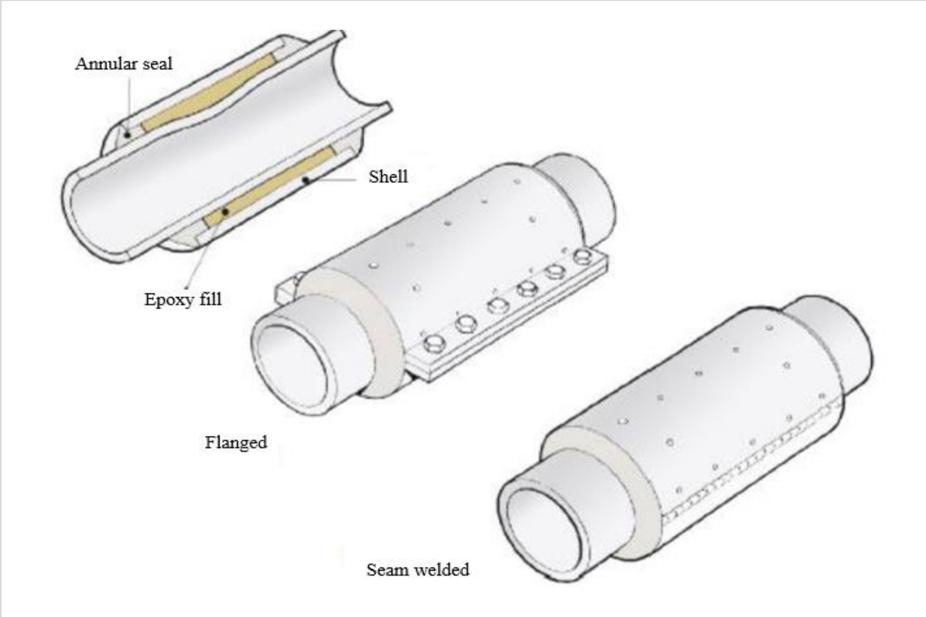

Figure 2.3 Grouted clamp
Source: Hoie (2015)

Besides, there is a more advanced technique of clamp rehabilitation technique which is flexible grouted clamp repair. Flexible grouted clamp cover the same features as grouted clamp and it is more advanced as it can be applied on bended area that grouted clamp cannot be done (Hoie, 2015). The grout is filled between the gap of clamp and surface of pipeline in order to allow the load transfer more efficient.

By using the conventional repair methods to repair the damaged pipeline, the strength of pipeline can be restored and thus the pipeline can sustain the pressure and operates under safe condition. Basically, the repair methods used in pipeline repair is based on the type of damage and damage condition on pipeline. The conventional repair methods discussed above except of cut and weld repair method, offer the advantage that repair work can be conducted without shutting down the operation. Meanwhile, clamp used in repair method has the ability to surround damaged section of the pipe with an enclosed and pressure tight environment. By filling the grout at angular gap, it can prevent the metal loss growth to the pipe wall. Besides, the cost of material used for these conventional repair methods are low as steel is the main element for the repair work. Steel is the material with excellent properties such as high strength, ductile, malleable, high durability, and excellent in heat and electricity.

Despite discussing the advantages and benefits of those conventional repair methods, there are some weakness or disadvantages by using it. The repair techniques mentioned above except of flexible grouted clamp, they are mostly suitable for straight damaged pipeline and have limited application on bended and jointed area. Sometimes, the repair work is difficult to be done as the workplace is limited which will cause the welding and clamping activities become more complex and more hazardous. Welding activities involved hot works which it has the potential to lead the fire and explosion. Hence, a temporary shutdown is required to ensure the safety issues. In some case, the use of steel clamp required mobilization of heavy structures from one platform to another platform which it is costly. Moreover, steel sleeve and steel clamp will be subjected to corrosion latter, and so the same repair work is required again. Therefore, the alternative materials that is lightweight, flexible, easily applicable, and can be an effective repair solution are required. So, this had led to the rapid growth and development of fiber reinforced polymer (FRP) composites in pipeline repair.

2.4 Pipeline Repair by Using Composite Materials

Composite is the material that made of two or more types of materials with different properties in order to improve or develop the properties for the material (Bagherpour, 2012; Jose *et al.*, 2012; Alberto, 2013; Saeed, 2015). Fiber reinforced polymer (FRP) is one type of composites that made of polymer matrix reinforced with fibers. Fibers are used to provide strength and stiffness to composite while polymer matrixes are used to transfer the load between fibers and protect fibers from environmental attack (Bagherpour, 2012; Alberto, 2013; Saeed, 2015). FRP composites offer various specified properties such as low density, high specified stiffness, high strength, high resistance against corrosion, and high fatigue endurance limit (Alexander, 2007b; Bagherpour, 2012; Jose *et al.*, 2012; Alberto, 2013; Saeed, 2015; Melander and Österberg, 2016). Moreover, FRP composites have been proven effective in repair system such as building, pipelines, steel risers, and other steel structures due to its unique properties (Alexander, 2007b; Duell *et al.*, 2008; Shamsuddoha, 2014; Chan *et al.*, 2015; Chan, 2017; Lim, 2017). In pipeline rehabilitation, the use of FRP composite offers more advantages over the conventional repair methods. The advantages include of lower cost, easier installation, faster application, and longer durability.

Advanced composite material has been used in the early age of 1960s with the development of high-modulus whiskers and filaments (Alexander, 2007a). While the composite made of whiskers has poor quality, but the filaments reinforcing epoxy was very successful to be used for fighter aircraft and later sport equipment (Saeed, 2015) . Then, the uses of composites had migrated to oil and gas applications, including pipeline repair. In fact, the use of composite in pipeline rehabilitation is introduced in the late of 1980s. Clock Spring® (refer Figure 2.4), is the first recognized composite repair product that was widely used to repair pipelines. Clock Spring® was verified through the most comprehensive pipeline repair study ever commissioned where it had been proven that the pressure can be up to 8000 psi and is expected to last 50 years and longer (Clock Spring Company, 2017). Since the composite repair method is recognized in the late of 1980s, various institutions and companies had put a lot of effort in developing their own research and development (R&D) to pursue commercial composite repair products. For years, the composite made of carbon fiber, aramid fiber, and hybrid fiber composite have been introduced in the pipeline rehabilitation for the applications that required higher performance in term of strength, stiffness, and thermal properties.

Figure 2.4 Clock Spring®
Source: Clock Spring Company (2017)

Other than that, the use of composite materials together with infill materials are effective in steel pipelines rehabilitation (Alexander and Pitts, 2005; Alexander, 2007b; Chan *et al.*, 2015; Chan, 2017). The study by Lam *et al.* (2011), they found that the number of cycles of loading for cracked steel pipeline was increased by about 21.6 times with the use of CFRP in repair system. Furthermore, Lukács *et al.* (2010) proved that external reinforcing was effective for different dimension of pipelines when subjected to quasi-static or cyclic loads and concluded that a small number of carbon-fiber reinforced polymer (CFRP) layers to repair a very deep flaw of defected area.

Besides, FRP composites offer more advantages than the other methods used in pipeline repair. A survey conducted by Chan (2017) showed that the overall cost can be reduced by 24% if using composite material instead of welded steel sleeves, while the cost can be further reduced by approximately 73% when compared to the cut and replace method. Low-weight feature for FRP composite can ease the repair process and reduce the transportation cost as it does not require heavy machineries for mobilization like the steel clamp repair method. FRP composite pipelines repair method can prevent the loss of cost due to temporary shutdown of operating system like the replacing method. Generally, pipeline repair by using FRP composite materials is considered safer as it does not involve any welding activities that has higher potential to cause explosion due to fire (Jakso *et al.*, 2006; Alexander, 2007a; Alexander, 2007b; Hoie, 2015; Saeed, 2015). Moreover, fibre orientation can be designed to provide optimum strength/stiffness to strengthen pipelines in a specific direction. At the same time, higher strength/stiffness allows to reduce the uses of FRP layer and thus to reduce the congestion of repaired structures (Lim, 2017).

Nowadays, there a various type of FRP composite materials commercial at market. They are researchers said that FRP composites has been proven effective in pipeline rehabilitation (Alexander, 2007b; Duell *et al.*, 2008; Shamsuddoha, 2014; Chan *et al.*, 2015; Chan, 2017; Lim, 2017). Although there are different types of FRP composite produced by numerous companies, industries, and research institutions, but they share the same principle in the composite repair system where it must consist of these 3 parts which are (i) infill material that transfer the load from pipeline to composite layer, (ii) adhesive material that bond the infill material and composite layer, (iii) composite layer that provide strength. Moreover, the composite repair method can be categorized into four systems which are flexible wet lay-up, pre-cured layered, pre-impregnation, and composite spit sleeve.

2.4.1 Composite Repair System

In the mid-1990s, wet lay-up system has been appeared and started to be used as a preferred composite repair system (Saeed, 2015). Flexible wet lay-up system is intensively used for pipeline repair where the defective pipeline that involve with various angles and bends. This repair system utilizes the flexible fiber reinforced fabric that is wetted with an uncured resin matrix on-site and create a stiff shell around the damaged part of pipeline after curing (Shamsuddoha, 2014; Chan, 2017; Lim, 2017). Then, a composite layer will cover the damaged area in order to increase loading capacity. Clock Spring, a well-known company that promote composite repair product for defective pipeline had promoted two products based on flexible wet lay-up system which are DiamondWrap® SubSea™ that used for offshore piping system and BlackDiamond® that used for onshore piping system (Clock Spring Company, 2017). Both products utilised carbon fiber to rehabilitate and restore original operational strength to defective pipeline where the carbon fiber provide reinforcement in the hoop and axial direction. Other than that, Armor Plate® Pipe Wrap (Armor Plate Inc, 2018), REINFORCEKiT® 4D (3X Engineering, 2018), and HydraWrap® (Hydra Tech LLC, 2017) are other products based on flexible wet lay-up repair system that is available on the market. Since the matrix resin is applied and cured in-situ, the quality of curing is not under controlled. The matrix resin that under-curing or non-uniform curing can reduce the capacity of the adhesive to transfer load and subsequently weaken the overall strength of the repaired pipeline (Shamsuddoha, 2014; Noor *et al.*, 2016; Lim, 2017).

Bonding of pre-manufactured fiber-reinforced composite materials that bonded to defective pipeline and held together by using an adhesive is known as pre-cured layered system. Clock Spring Company, the company who is the pioneer in the development of composite repair system designed a product by using pre-cured layered system which is Clock Spring®. Clock Spring® utilises E-glass/Polyester material with a methacrylate adhesive to bond the pre-cured composite layer (Clock Spring Company, 2017). Figure 2.5 shows the component of pre-cured layered repair system used in Clock Spring® where (1) is composite sleeve, (2) is interlayer adhesive, and (3) is infill material. In this system, the pre-manufactured composite layer which is a coil of high strength composite materials. Thus, the composite layer is able to wrap securely around the pipeline. Then, the composite layer is bond to the pipeline by interlayer bonding adhesive. Meanwhile, the defective area of pipeline is filled with infill material in order to assist with the load transfer prior to installation. Besides, PermaWrap™ and WeldWrap™ (Wrap Master Inc, 2014) are also the product using pre-cured layered system in pipeline rehabilitation. This repair system able to prevent defect failure through load transfer and restraint (Shamsuddoha, 2014; Lim *et al.*, 2015; Lim, 2017). However, this repair system has the limitation to designated pipeline size and straight pipeline section (Noor *et al.*, 2016; Chan, 2017; Lim, 2017). In the water condition, this repair system is challenging as it involved in-situ adhesive application for layered system. This had led to reduce bonding between layers and even the performance of the system.

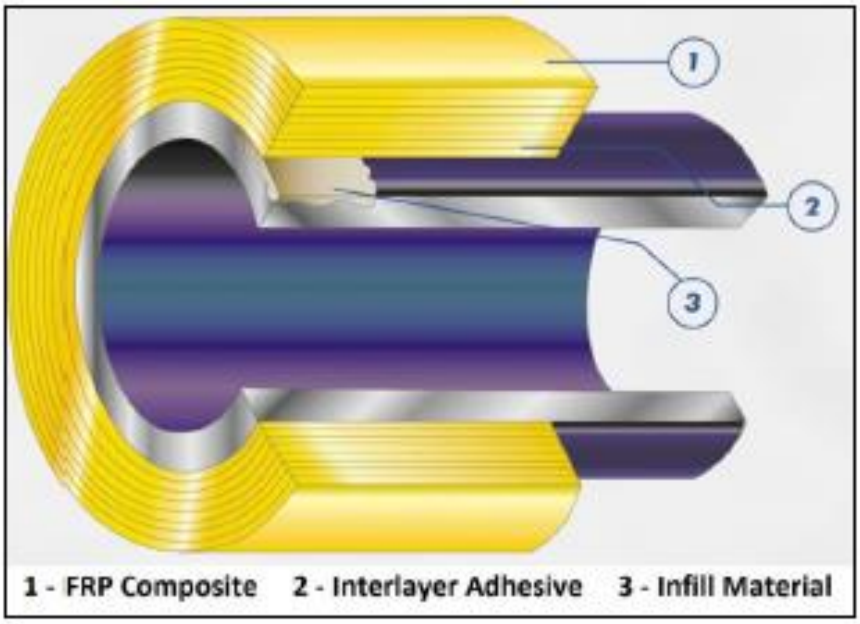

Figure 2.5 Clock Spring® components
Source: Clock Spring Company (2017)

Pre-impregnation repair system is to prevent the fibre with resin matrix from curing before its application. This repair system can be water-activated, temperature-activated, or UV-activated (Chan, 2017). In contrast with flexible wet lay-up system that apply resin matrix with fiber on-site, the fiber is pre-impregnated with resin matrix under a controlled environment. This controlled environment ensure that the quality of product is consistent. Hence, it can restore the optimum strength of repaired pipeline. However, the product is required to keep in a specific environment prior to repair. This unique condition had led the logistic and handling process become more challenging especially for the remote area such as offshore applications. Meanwhile, ProAssure™ Wrap Extreme and PRT Aquawrap® are some examples of the product developed based on pre-impregnation system that available in the market. PRT Aquawrap® consists of high strength fiberglass that is impregnated with a Moisture Cured Urethane (MCU) resin system which stored in nitrogen filled bag. The curing process is started and the process is around 30 minutes to be dry and touch once activated by water (Tolde SRL).

Split composite sleeve system is the repair system that provide higher structural integrity than the other repair system such as pre-cured layered, wet lay-up, and pre-impregnation. This system is able to permanently restore the original strength, contains leaks, and support axial load of the pipeline (Shamsuddoha, 2014; Lim, 2017). There is a product that using this system which is ProAssure™ Clamp (Figure 2.6) that made of advanced composite material (Merit Technologies Sdn Bhd). In this system, infill material is used to give a smooth surface to the damaged area of pipeline. Hence, a continuous support is provided by the introduced infill layer which minimizes the radial deformation and transfers the load from the pipeline to the outer shell. The principle of this system is largely depending on the performance of infill. At the same time, split composite sleeve system has some drawbacks or disadvantages such as limitation on straight section defective pipeline. Moreover, the joining of the split sleeves is very challenging in this repair system, especially underwater and restricted area.

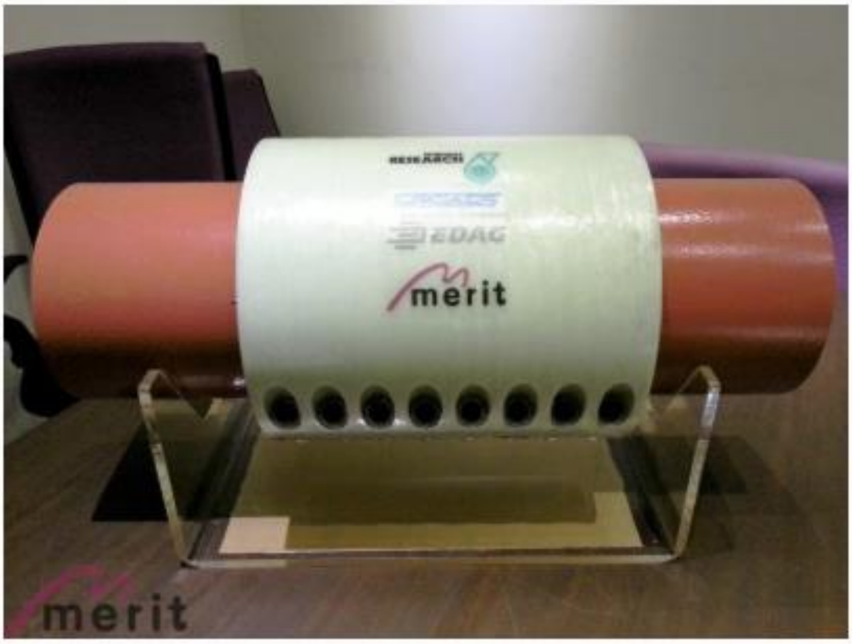

Figure 2.6 ProAssure™ Clamp
Source: Merit Technologies Sdn Bhd

2.5 Fiber-Reinforced Polymer (FRP) Composites

Fiber reinforced polymer composite composed of two or more elements where the high strength and stiffness fibers is embedded in a polymer matrix with distinct interfaces between them (Bagherpour, 2012; Jose *et al.*, 2012; Alberto, 2013; Saeed, 2015). In this composite, both fibers and polymer retains their own physical and chemical properties. Fibers act as main load bearing constituent, while the polymer keeps the fibers intact in their positions and desired orientations (Bagherpour, 2012; Alberto, 2013; Saeed, 2015). FRP composites offer more specific unique properties, which are high specific strength and stiffness, high fracture resistance, good abrasion and impact resistance, high resistance against corrosion, high fatigue resistance, low density and low cost (Alexander, 2007b; Bagherpour, 2012; Jose *et al.*, 2012; Alberto, 2013; Saeed, 2015; Melander and Österberg, 2016).

2.5.1 Fiber Reinforcement

Fiber are the primary load carrying component of composite material. Fibers arrangement decide the directional strength and stiffness for any particular applications. The typically fibers used in FRP composite are glass, carbon, aramid, baron or polyester, but natural fibers have been used for sometimes. Glass fibers are low cost, easily available, and more compatible with resin but they have low stiffness and durability where it is more compatible to fatigue, creep, and rupture (Giancaspro *et al.*, 2010). Meanwhile, carbon fibers exhibit low density, high strength and stiffness, and excellent fatigue performance than glass fibers, but they are relatively expensive due to their manufacturing process (Giancaspro *et al.*, 2010; Melander and Österberg, 2016). For aramid fibers, it provide high strength, high modulus and low density which is lower than glass fibers (Saeed, 2015), but it has low compressive properties and higher water absorption as well as low melting temperature (Melander and Österberg, 2016). Hausrath and Longobardo (2010) provided a comparative summary of the properties for glass, carbon and aramid fibers which is presented in Table 2.1 along with the advantages and disadvantages respectively. Toutanji and Dempsey (2001) found that carbon fiber reinforced polymer (CFRP) has higher strength than those reinforced with aramid or glass fibers, as demonstrated in Figure 2.7. This figure showed the different type of fiber reinforcement in term of circumferential stress against internal pressure, and CRFP repaired defected pipeline showed the higher internal pressure among the others.

Table 2.1 Summary of fiber properties

Property	Glass		Carbon	Aramid
	E-glass	S-2 Glass®	T700SC	K49
Density (gm/cc)	2.58	2.46	1.80	1.45
Tensile strength (MPa)	344.5	4890	4900	3000
Tensile modulus (GPa)	72.3	86.9	230	112.4
Comp. strength (MPa)	1080	1600	1570	200
Strain to failure (%)	4.8	5.7	1.5	2.4
CTE (10-7/°C)	54	29	-38	-48.6
Softening point (°C)	846	1056	>350	>150
Advantages	Low cost, easily available and more compatible		Low density, high strength and stiffness, low density and superior fatigue performance	High impact performance, flame resistant and resistant to chemicals
Disadvantages	Low modulus and susceptible to fatigue, creep and stress rapture		High cost, availability and compatibility	Low transverse and compressive strength. Susceptible to UV and degrade in moisture

Source: Hausrath and Longobardo (2010)

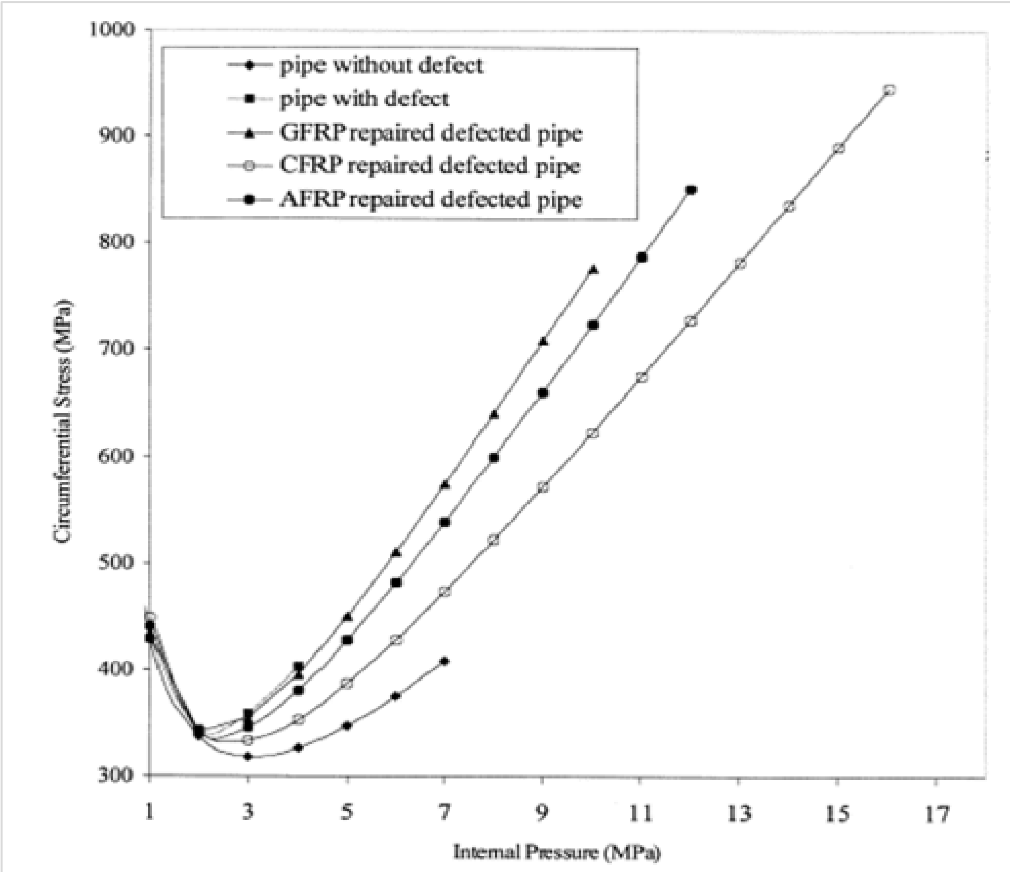

Figure 2.7 Comparison between circumferential stress and internal pressure in the pipe without defect, pipe with defect, and repaired damaged pipes

Source: Toutanji and Dempsey (2001)

Besides, hybrid fibers is another type of fiber that combining natural fiber and synthesis fiber in order to enhance the properties of fibers to against the environmental impacts. Alexander (2007b) had developed the multilayer hybrid composite sleeve where the inner layer and outer layers were introduced by E-glass to cover circumferential carbon fibres in the reinforcement thus eliminating galvanic corrosion. Moreover, Alexander (2007b) found that the strength provided by the sleeve layout orientation was sufficient in both longitudinally and circumferentially against hoop and flexural loading. Further, Yu *et al.* (2008) found out that the reinforcement composed of outside glass fibers and inside jute mats was effective for underground pipeline rehabilitation where the strength requirements is achieved.

2.5.2 Polymer

Polymer also is known as resin which is another major component in composite. Resin acts as matrix for fibers to transfer and distribute the load between fibers by binding the fibers together as well as protect them from environmental attacks and impacts (Shamsuddoha, 2014; Melander and Österberg, 2016). The mechanical performance of the composite can be affected by the properties of resin such as transverse stiffness and strength together with shear and compressive properties (Melander and Österberg, 2016). In pipeline rehabilitation, there are two types of polymer available which are thermoplastics and thermosets.

Thermoplastics consist of polyethylene, polystyrene, polyether imide, and etc, where thermoplastic can be reshaped by application of pressure and heat (Jose *et al.*, 2012). However, thermosets are more prefer and common to be used than thermoplastics due to their superior properties. Thermosets typically used are epoxy, polyester, vinyl ester, phenolics, and etc. Table 2.2 showed a comparative summary of advantages and disadvantages for epoxy, polyester, and vinyl ester. Epoxy is widely used in composite due to its superior properties which are thermal stability, excellent bonding, and their mechanical properties (Shamsuddoha, 2014).

Table 2.2 Advantages and disadvantages of resin

Property	Epoxy	Polyester	Vinylester
Advantages	Superior physical and mechanical properties, low cure shrinkage, better adhesion, wide range of adaptability, better compatibility with carbon fibers, good moisture and chemical resistance	Low cost, available and easily applicable	Better strain and strength performance than polyester, low cost
Disadvantages	Higher cost, may possess corrosive contents and may degrade under UV	Moderate strength, low durability, high cure shrinkage, low strain prior to failure and less compatible with carbon fibers	High shrinkage and exothermic temperature during curing, may require post curing, low strain and carbon compatibility than epoxy

Source: Shamsuddoha (2014)

2.5.3 Degradation of FRP Composite

FRP composites offer the advantage of higher resistance against corrosion, but degradation of FRP composites still can occur under critical environment throughout the service life. Degradation occurred due to the alteration in the integrity of FRP composite's components which are fibers, polymer matrix or interaction bonding of between fibers and matrix (Farooq, 2009; Shilpa *et al.*, 2010; Sethi, 2014; Frigione and Lettieri, 2018). This may including breaking of fibers, debonding which is separation of fibers and matrix, microcracking of matrix, and delamination (Shilpa *et al.*, 2010). Fibers-matrix interface is the region of synergy in composite where can affect the mechanical properties of the composite. The damage at fibers-matrix interface can alter the mechanical properties and reduce the lifetime of composite. Hence, the quality of fibers-matrix interface directly determines the performance of composite in term of load transferring. In fact, the environmental conditions such as temperature, ultraviolet (UV) radiation, and moisture content have influence on the durability of FRP composites (Nakamura *et al.*, 2006; Shilpa *et al.*, 2010; Sethi, 2014; Frigione and Lettieri, 2018).

2.5.3.1 Thermal Effect

FRP composites are relatively sensitive to elevated temperature especially the polymer constituents. Delamination and microcracking are developed when the polymer composite exposed to critical temperature (Shilpa *et al.*, 2010; Sethi, 2014). Normally, degradation of composite can be accelerated under an elevated temperature compared to room temperature. Previous studies proved that the mechanical properties of composite decreased under an elevated temperature (Davies *et al.*, 2005; Mourad *et al.*, 2010; Correia *et al.*, 2013). Besides, differential temperature that induce thermal stresses at interface region which lead to the formation of microcracks at the fibers-matrix interface (Shilpa *et al.*, 2010; Sethi, 2014). The residual stresses will weaken the fibers-matrix interface which will lead to microcracking and debonding issue. Meanwhile, the crack formation allows water ingress through fibers-matrix interface to adversely degrade the integrity and performance of composite. Other than that, glass transition temperature, T_g of FRP composite is an important concern when it is subjected to an elevated temperature. Generally, resin matrix has its own glass transition temperature, T_g. Amorphous regions of resin matrix are transformed from hard to viscous when the ambient temperature exceed T_g (Sethi, 2014; Frigione and Lettieri, 2018). This had led to the reduction in integrity of composite as well as the mechanical properties. In contrast, the mobility of resin matrix has been restricted when the ambient temperature is below T_g to maintain its solid state.

Previous studies had showed that the durability of FRP composites can be degraded under an elevated temperature and higher temperature variation throughout its service life. From the study of long-term behaviour of epoxy-anhydride/glass composite tubes exposed to hydrothermal ageing, Davies *et al*. (2005) found that the glass transition temperature was dropped from 124°C to 86°C after 7 years immersion, while there is a dramatic fall of lifetime for the tubes with the temperature immersion of 80°C after 1-year tested. In previous study, Mourad *et al.* (2010) obtained the result where the tensile strength of glass/polyurethane composite was decreased by 19% after 1-year exposure to seawater environment at room temperature, and 31% after under the same environment but at 65°C. Plasticization due to moisture absorption leads to ductile failure in the matrix. Correia *et al.* (2013) conducted an experiment to observe the mechanical behaviour of pultruded glass fibre reinforced polymer composites at vary temperatures from 20°C to 250°C, and they found that the tensile strength, shear strength, and compressive strength retained at elevated temperature is about 54%, 11%, and 5% respectively.

2.5.3.2 Moisture Effect

Most of FRP composite are able to absorb little water, but excessive amount of moisture if under a water environment. This had led FRP poses a drawback when immersed in water which the fibers-matrix interface can be degraded by hydrolysis reaction of unsaturated groups within resin. In fact, resin matrix is more sensitive to water than fibers. Hence, water ingression results the swelling and plasticization of resin matrix, and debonding at fibers-matrix interface. Destructive at interface region can reduce the mechanical properties of FRP composites (Farooq, 2009; Mourad *et al.*, 2010; Bagherpour, 2012; Sethi, 2014; Hagihara *et al.*, 2018). In addition, durability of FRP composites is degraded when it is immersed in water with a prolonged period which is humid ageing effect. This is due to excessive amount water absorption that can change the thermophysical, mechanical and chemical properties of resin matrix by hydrolysis and plasticization. Hence, humid ageing is considered as one of the main causes of long-term failure for FRP composites where it can cause the (1) changing in dimension (swelling), (2) reduction in glass transition temperature of resin, and (3) reduction in mechanical properties (strength, stiffness, and hardness). Residual stresses can be generated by swelling due to moisture absorption, where the residual stresses can cause the formation of crack at interface region. Finally, the structural integrity of composite is degraded as well as the durability. Besides, moisture ingression via fibers-matrix interface create a new phase at the interface region with its own glass transition temperature, T_g that different from its bulk matrix phase. Moreover, the degradation of FRP composites caused by moisture effect can be accelerated at an elevated temperature.

Gu (2009) concluded that the tensile strength of 4-layer laminate composite was gradually decreased with prolonged seawater immersion time, which is presented in Figure 2.8, due to the materials that had experienced the physical damage or irreversible chemical degradation which cause the fibers-matrix interface damage. The resin matrix is swell and crack due to excessive water absorption as the water react with the function group in the matrix and filaments. Fang *et al.* (2017) had studied the effect of seawater ageing in GFRP composites and revealed that the glass transition temperature, tensile strength, and flexural strength of GFRP decreased by 2.5%, 13.8%, and 9.8%, respectively after 6 months of immersion in seawater. This mechanical degradation is due to hydrolysis of resin and debonding at the interface. Other than that, Yan and Chouw (2015) conducted an experiment to test the effect of flax fabric/epoxy immersed in water, seawater, and alkaline solution for 365 days, the results of retained tensile strength and flexural strength are presented in Figure 2.8 and Figure 2.9. They also found that the formation of crack at interfacial region after the specimens is immersed for 365 days.

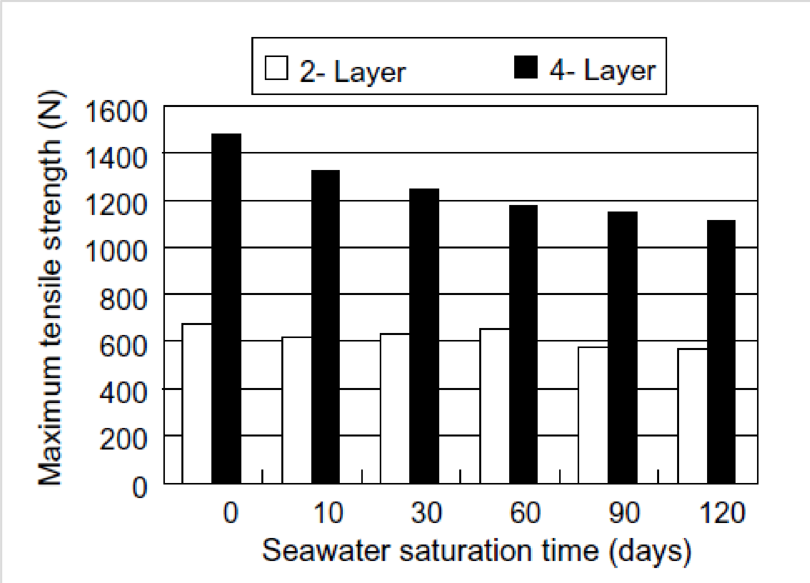

Figure 2.8 Tensile strength of seawater treated samples

Source: Gu (2009)

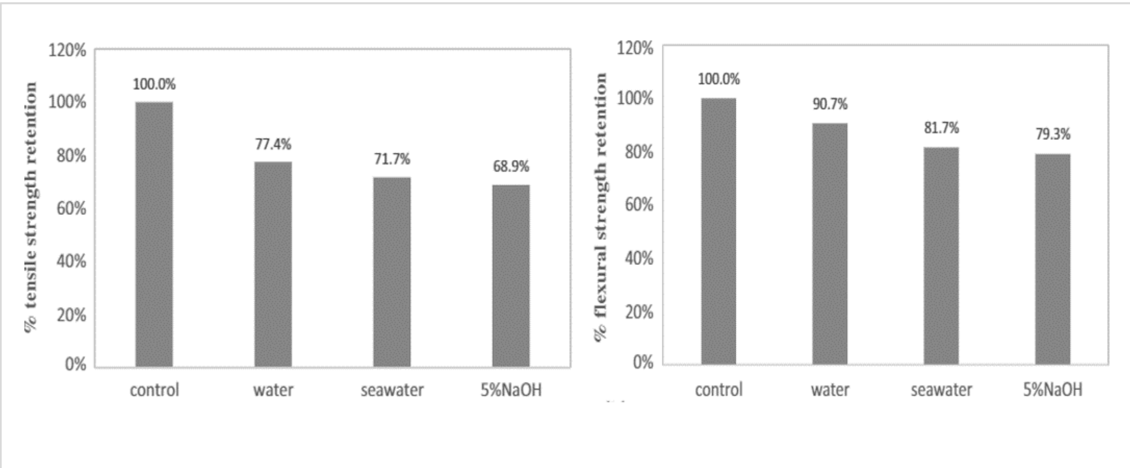

Figure 2.9 Percentage of tensile strength (left) and flexural strength (right) retained for flax fabric/epoxy composites after 365 days immersion

Source: (Yan and Chouw, 2015)

2.5.3.3 Ultraviolet (UV) Radiation

Ultraviolet (UV) radiation is an electromagnetic radiation with wavelength of 290 nm to 400 nm which it can be found under sunlight. UV radiation with atmospheric oxygen will lead to chemical changes in the epoxy polymer matrix which is relatively a complex process, photo-oxidation (Kumar *et al.*, 2002; Shokrieh and Bayat, 2007; Sethi, 2014; Hagihara *et al.*, 2018). Photo-oxidation process in polymer depends on the diffusion of oxygen. Photo-oxidation process cause the changing in mechanical properties of the composite materials. The covalent bond in the polymers are dissociated and formed free radical due to the effect of UV wavelength by absorbing the chromophore group of polymers, then molecular cross linking and chain scission occurred (Sethi, 2014). UV radiation which is contain light photons that will react with polymer chains lead to instability in mechanical properties of composite. UV radiation with shorter wavelength normally have more light photons which it will increase the breaking of chemical bonds between molecular compounds. FRP composite that absorbing the light photons due to UV radiation cause photo-oxidation process which can change the chemical structures of polymer. UV radiation normally destruct at fibers-matrix interface region due to high permeability of oxygen. Other than that, FRP composites that exposed to UV radiation under seawater environment at an elevated temperature poses a more severe degradation of composite.

In the study of degradation of carbon fiber-reinforced epoxy composites by ultraviolet radiation and condensation, Kumar *et al.* (2002) observed that the transverse tensile strength is decreasing by 29% after 1000 hours exposed to UV radiation. Moreover, Shokrieh and Bayat (2007) had studied the effect on mechanical properties of glass/polyester composites after 100-hours exposed to ultraviolet radiation, they found that average failure strain, ultimate strength and tensile modulus is decrease by 15%, 30%, and 18% respectively.

2.6 Effect of FRP Composite Degradation

Although FRP composite has various specific properties, degradation of composite can occurred along their service life when it is exposed to a critical environment. Temperature, moisture, and UV radiation, which are the environmental factors that can gradually reduce the integrity of composite as well as its residual strength (Nakamura *et al.*, 2006; Shilpa *et al.*, 2010; Sethi, 2014; Frigione and Lettieri, 2018). Normally, the degradation of composite is due to the poor quality of interaction between fibers reinforcement and resin matrix. Poor interaction between fiber reinforcement and resin matrix disturb the load transfer which the load is unable to be transferred from resin matrix to fibers. This had greatly impact on the performance of composite as well as its durability.

In pipeline repair application, FRP composite is used to repair damaged pipelines and it had been proven effective in repair system (Alexander, 2007b; Duell *et al.*, 2008; Shamsuddoha, 2014; Chan *et al.*, 2015; Chan, 2017). FRP composite is vital in repair system as it provides additional strength to the pipelines. However, the strength of composite repaired pipeline may be reduced with the degradation of composite as the additional strength that provided by composite is reduced. Moreover, reduction of strength in composite repaired pipeline will gradually decrease the burst pressure of the pipeline and increase the risk of explosion during its service life. Explosion will occur when the operating pressure exceed the strength of composite repaired pipeline. Degraded composite will potentially exhibit a poor performance in composite repaired pipeline in term of load transferring. The failure of pipeline brings a lot of negative impacts to public and environment as well as the investors. Therefore, the long-term performance and durability of composite repaired pipeline always is a concern to pipeline industries.

2.7 Concluding Remark

The use of FRP composite in pipeline rehabilitation has offer various advantages over than conventional repair method, due to its unique properties such as low density, high specific strength and stiffness, high resistance against corrosion, and high fatigue endurance limit. Whereas the advantages of using FPR composite in pipeline rehabilitation consist of (i) shorter duration to complete the repair work, (ii) eliminate the risk of explosion due to cutting and welding, and (iii) undisrupted operating process during repair work. Although the use of FRP composite promote benefit to pipeline rehabilitation, certain issues related FRP composite repair system should be concern. One of the issues is the long-term durability of composite repaired pipeline under its service environment. Based on previous literature, it had showed that FRP composite is effective to be used for pipeline repair material, but there is scarce detailed data related to the long-term durability of the composite repaired pipeline under the effect of environmental impacts. Previous literature only revealed that the composite can be degraded under temperature effect. Yet, the effect of environmental factors overtime towards the durability and performance of composite repaired steel pipe only has limited information. Hence, this study aims to providing the information pertaining to the environmental effect (temperature) on FRP composite repaired pipeline upon the burst capacity.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter presents the details of research methodology to study the effect of temperature upon burst pressure capacity of composite repaired pipeline. The research methodology is divided into two stages which include the development of base model and parametric study. Stage 1 involved development of finite element base model and its validation. The validated base model was used as a benchmark in Stage 2 to study the objectives of this research. Stage 2 was designed to simulate the actual conditions on composite repaired steel pipe using collected data of composite material that is subjected to various temperature.

3.2 Overview of Overall Research

ABAQUS® v6.12-1, a commercial finite element modelling software was used to simulate the previous experimental tests. Stage 1 is one of the important stages in this research where a base model of composite repaired steel pipe was developed. Validation was carried out by comparing the experimental and simulated burst pressure to check the margin of error. Previous researchers suggested the margin of error to be less than 10% between the simulated and experimental results (Shouman and Taheri, 2011; Chan *et al.*, 2015). Thus, the finite element model is validated and considered to simulate the actual behaviour of composite repaired steel pipe.

The validated finite element model generated in Stage 1 was utilized in Stage 2 which is parametric study. The validated base mode was used as a benchmark to study the effect of temperature over time towards burst pressure of composite repaired steel pipe by modifying the material strength. Hence, this stage is considered as the core of the research to achieve the objectives of this research.

3.3 Finite Element Modelling

As mentioned in previous section, ABAQUS® v6.12-1 software was used in this research to study the effect of temperature over time towards burst pressure of composite repaired steel pipe. This software was utilised to create models, generate mesh, and perform finite element calculation. Finite element modelling process has several stages before the analysis is started. It was started by modelling the geometries of individual parts of the structures that similar to previous experimental work. In this research, three main individual parts were created which are defective steel pipe, composite wrap, and infill material followed by modelling the material properties. The related material properties of respectively parts were assigned as inputs for the models. All created parts were assembled as an integrated structure for analysis in the later stage. Next, the interaction between all parts of composite repaired pipe such as bonding properties were modelled followed by assigning the boundary conditions and applying the internal pressure. A proper meshing size was assigned in order to generate mesh for all parts. The model is the ready to be analysed in order to determine the burst pressure of the models. The results of finite element analysis were compared with the published experimental tests. Validation was carried out by comparing the experimental and simulated results where the margin of error should be less than 10%. However, if the error exceeds 10%, the model is modified until it is validated. The validated model was used for parametric study in stage 2. The validated finite element model was used as a benchmark to achieve the objectives of this research by modifying the material strength. For instances, the material is exposed to temperature of 23°C, 60°C, and 95°C at duration of 0-days, 360-days, 1080-days, and 1440-days. Therefore, ten finite element models were generated. Apart from study the effect of temperature over time towards burst pressure of composite repaired steel pipe, prediction of remaining life for repaired pipeline was carried out. Figure 3.1 presents a flow chart of overall research methodology in order to achieve the objectives on this study.

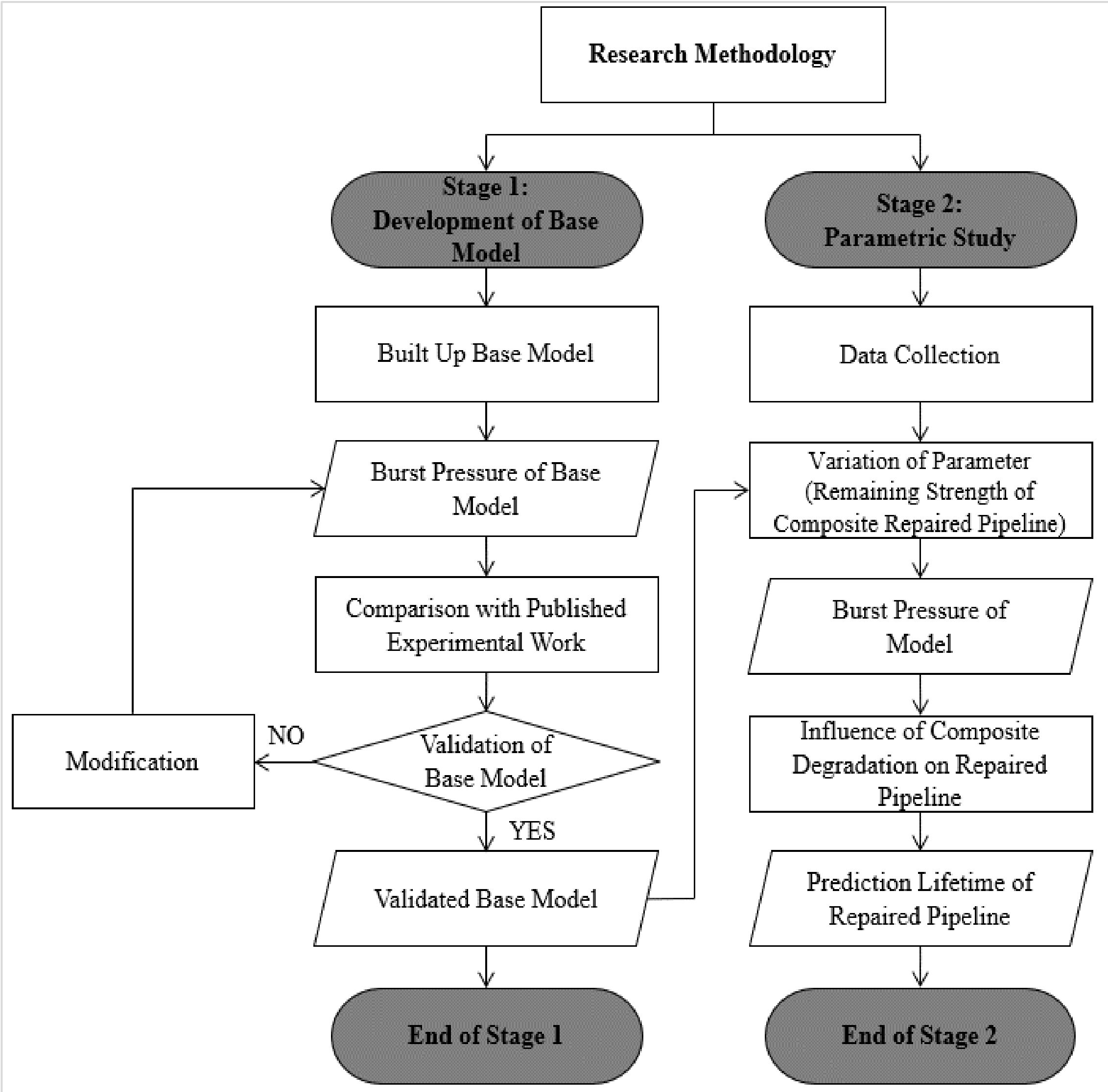

Figure 3.1 Flow Chart of Overall Research Methodology

3.4 Stage 1: Development of Base Model

Stage 1 involved two major steps which are development of finite element model for a composite repaired steel pipe and its validation. A complicated modelling process will be involved in this section to create a finite element base model, which is composite repaired steel pipe. There are three main solid parts are required to be created in this section which were defective steel pipe, composite wrap, and infill material. Then, the material properties for each component are assigned as the inputs to develop this model. Mesh generation for each component was carried out to create finite element model. It was followed by assembling three components into an integrated structure. Besides, modelling of contact is required for this model as there are three contacts between the interfaces of steel pipe, composite wrap, and infill material. Then, the burst pressure obtained from finite element analysis was compared with the burst pressure of experimental test for the validation purpose.

3.4.1 Modelling Composite Repaired Steel Pipe

The finite element modelling process of corroded steel pipe was presented in this section. By referring to previous experimental work, a three-dimensional deformable solid part with 168.3mm diameter and 1200mm length was generated to simulate the physical properties of the steel pipeline. It was followed by generating another solid part and cutting through the whole length of the first part. The second solid part has a diameter of 154.08mm which it was considered as the inner diameter of the steel pipe. By using second part to cut through the first part, a hollow steel pipe with dimension of 168.3mm outer diameter, 7.11mm thickness, and 1200mm length was generated. However, in order to model a defective steel pipe, a two-dimensional defect geometry with an arc length in the hoop direction of 100mm and the depth of 3.555mm was sketched onto the middle of the steel pipe. This sketch was then extruded to cut a 100mm defect in axial direction in order to completely model the defective geometry.

Similar to the development of steel pipe part, a three-dimensional deformable solid part was generated to simulate the physical properties of infill material. Since it is designed to cover that defect region, the geometry of putty was modelled same as the defect region which is 100mm in hoop direction, 100mm in axial direction, and 3.555mm in depth. Besides, translation of the location for infill material was carried out in order to allow the infill material to be modelled at the exact location. This action was done through a built-in feature which is called as translate instances.

It was then followed by modelling the part of composite wrap. A three-dimensional deformable shell part was chosen to model a composite wrap with 168.3mm diameter and 300mm length. Then, the thickness of composite was modelled by generating a composite shell section. Three layers of composite shell was modelled with 1mm thick for each layer to simulate the experimental composite wrap. The composite shell was modelled out of the repaired region same as infill material. Hence, the similar location translation technique that was used in infill material was applied to transfer the composite wrap to repair region.

Once all three individual parts were completely created, they were assembled into a single model to form an integrated structure. The default coordinate system used in ABAQUS was converted into cylindrical coordinates. Cylindrical coordinate system can accurately determine the information of analysis in pressure vessel such as the information in hoop, axial and radial directions. Figure 3.2 shows the geometry of entire composite repaired steel pipe model (bottom right) and its components which are defective steel pipe (top left), composite wrap (top right), and putty (bottom left).

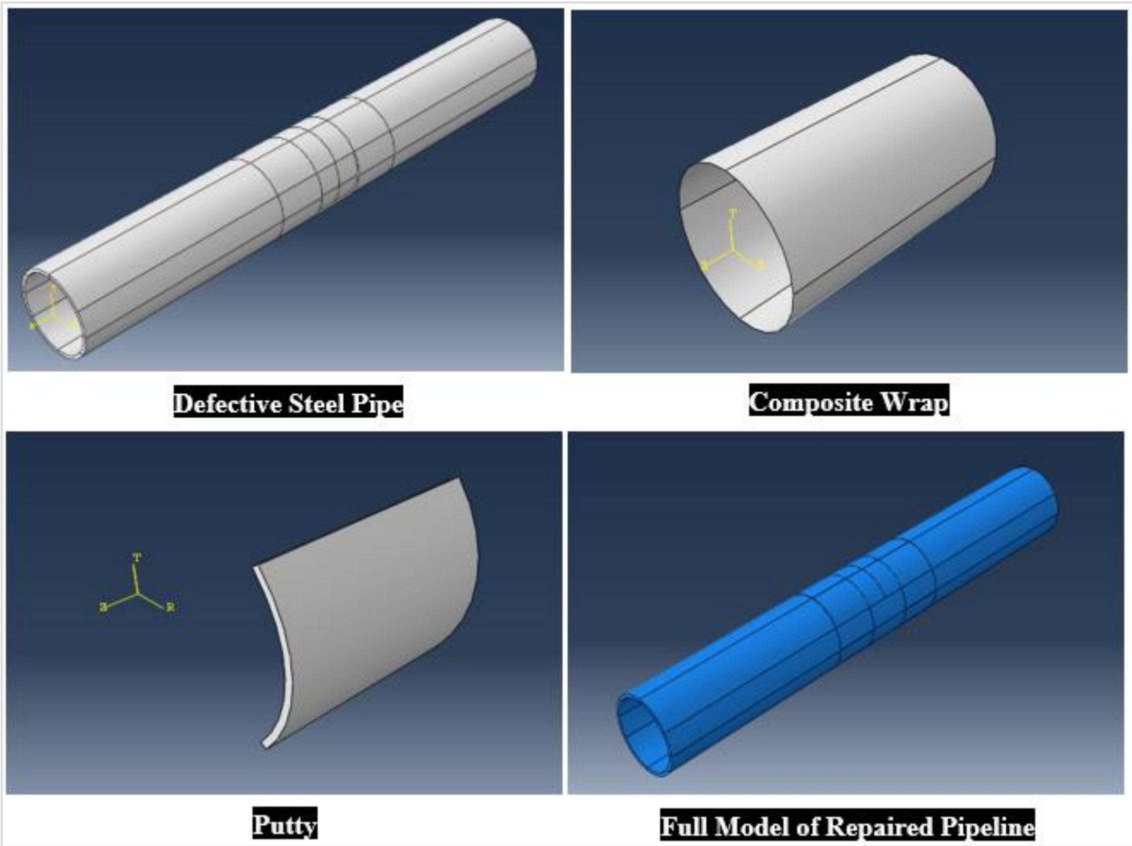

Figure 3.2 Geometry of defective steel pipe, composite, putty and integrated structure (full model-composite repaired steel pipe)

3.4.2 Material Properties Assignment

Once the geometry of all parts composite repaired steel pipe (corroded steel pipe, composite wrap, and infill material) are completely created, material properties assignment as inputs are next action in modelling process. The basic properties of steel pipe and infill material that was assigned in this model include of Young’s modulus, Poisson’s ratio, and stress-strain curve. Besides, the composite wrap properties were modelled by using the Engineering Constant Model from the material model library in

ABAQUS. In this model, nine elasticity properties are required which are E_1, E_2, E_3, v_{12}, v_{13}, v_{23}, G_{12}, G_{13}, and G_{23}. Poisson ratio of the composite is denoted as v, while tensile and shear modulus of the composite are denoted as E and G respectively. Other than that, Hashin Failure Criteria was employed to model the failure of the FRP composite. The data of strength in term of tensile, compressive, and shear for both longitudinal and transvers directions are required as inputs to simulate the composite wrap.

3.4.3 Load and Boundary Conditions Assignment

After the material properties assignment was completed, the material model was then assigned to the steel pipe, and the assignment of simulation duration was next action to creating the analysis. As the loading rate in experimental test is approximately 0.1MPA/s, the analysis duration was assigned to be 500s with a linear increase in 50MPa pressure that applied onto internal wall surface of the pipe. The pressure was applied by ramp amplitude to ensure that a loading rate of 0.1MPa/s can be simulated throughout the analysis duration.

3.4.4 Interaction Bond between Components

Modelling the interactions between all bonded interfaces were carried out. There are three main bonded interfaces which are (i) infill material to steel pipe, (ii) infill material to composite, and (iii) composite to steel pipe. A tie constraint option was selected to bond all the interfaces. Figure 3.3 shows the bonding interaction between putty-pipe (top left), putty-composite (top right), and composite-steel (bottom).

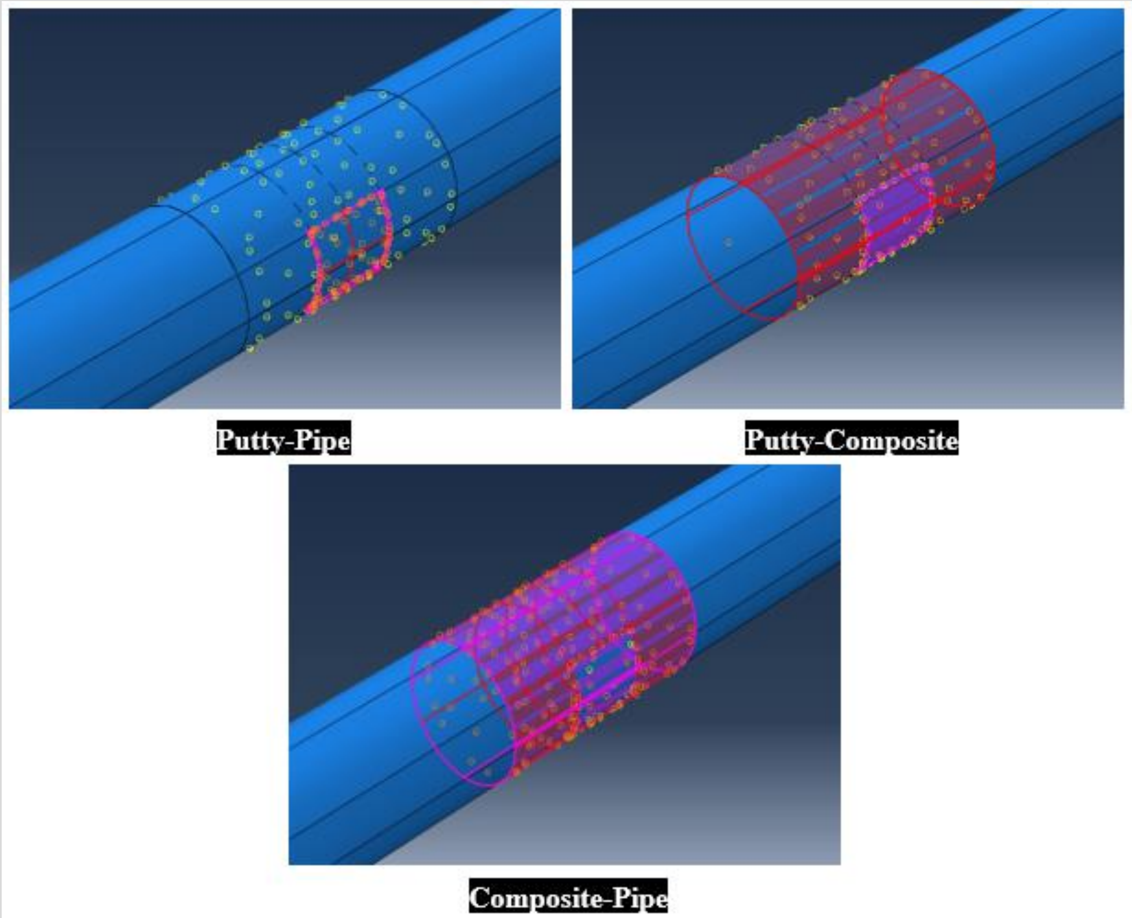

Figure 3.3 Bonding between putty-pipe, putty-composite, and composite-steel

3.4.5 Meshing of Composite Repaired Steel Pipe Model

The ABAQUS three-dimensional reduced integration, eight-node linear solid element (C3D8R) was selected to produce the mesh of steel pipe and infill material. Meanwhile, reduced integration of four-node shear element (S4R) will be used to model the composite shell. A good mesh is essential in most of the finite element analysis in order to obtain an accurate result and to shorten the analysis duration. Figure 3.4 presents the meshing of each components which are defective steel pipe, composite wrap, putty, and full model of repaired pipe.

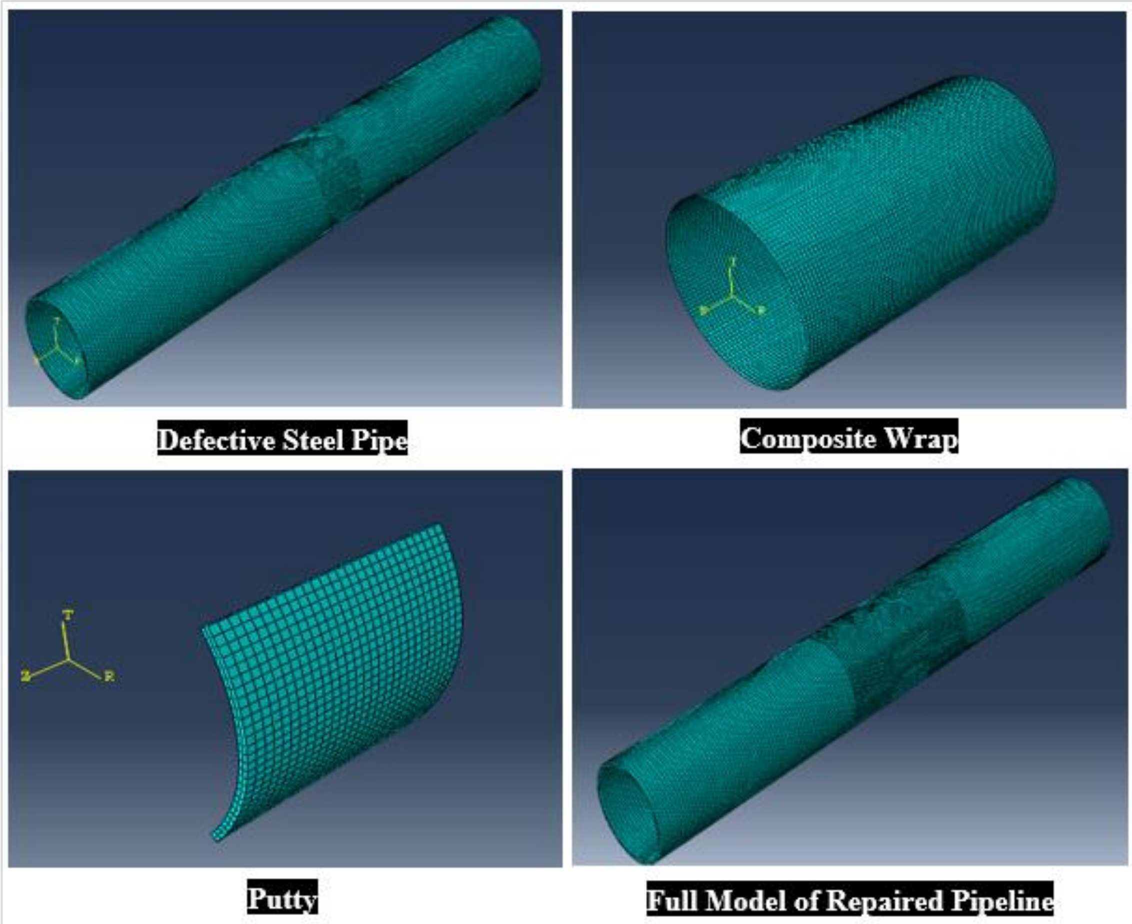

Figure 3.4 Meshed model of defective steel pipe, composite wrap, putty, and full model repaired pipe

3.4.6 Validation of Composite Repaired Pipe Model

Once the mesh is generated, the model development is considered completed and finite element analysis was conducted then. Finite element analysis was carried out to determine the burst pressure of the model for validation purpose. The burst pressure result from numerical simulation was compared with the previous experimental test. A variation of 10% difference between the simulated and experimental is considered acceptable and the model is regarded as capable to simulate the behaviour of experimental work. However, if the margin of error between the simulated result and experimental result is greater than 10%, the finite element model will be modified until the error is less than 10%. Hence, the validation was completed and the validated finite element model will be used in later stage for parametric study.

3.5 Stage 2: Parametric Study

The purpose of parametric study is to investigate the influence of composite degradation on burst capacity of composite repaired steel pipe under different temperatures. Data collection and parametric analysis are conducted in this stage. Data collection involves of searching previous literature that related to degradation of material under temperature effect. Then, the collected data were compared based on certain criterion in order to select the most suitable experiment result for parametric study. After this, the validated base model developed in Stage 1 and the data collected from previous literature were used to generate ten finite element models to achieve the objectives of this study.

3.5.1 Data Collection

In the stage of data collection, the data of previous experimental test related to temperature effect on composite material degradation were collected. The data collected from previous literature were compared based on the type of fiber reinforced polymer (FRP) composite used and the experimental duration in order to choose the most suitable data. In this research, the priority of FRP composite used are glass fiber-epoxy polymer (GFEP) composite as the composite material behaviour is same as the composite material in the validated base model. In case of limited information related to GFEP composite degradation experiment, then another composite can be used which it includes of carbon fiber-epoxy polymer (CFEP), glass fiber-polyester polymer (GFPP) composite, and carbon fiber-polyester polymer (CFPP). After this, the data was selected based on the closer behaviours and longer experimental duration as it allows to study the long-term durability of composite repaired steel pipe.

Generally, the greater stress experienced by a pressurized pipe is hoop stress. The data collected from previous literature are only included tensile strength and tensile modulus of composite material, and thus the tensile strength and tensile modulus of the composite material are known as the hoop tensile strength (σ_h) and hoop tensile modulus (*E1*). However, composite material properties in finite element model required more detail data rather than hoop tensile strength and hoop tensile modulus. For instance, axial tensile strength (σ_a), axial tensile modulus (*E2*), and radial tensile modulus (*E3*). By obtaining these data, several calculations are required as shown in Equation Eq. 3.1, Eq. 3.2, and Eq. 3.3.

$$\sigma_a = 70\% \times \sigma_h \qquad \text{Eq. 3.1}$$

$$E2 = 70\% \times E1 \qquad \text{Eq. 3.2}$$

$$E3 = 50\% \times E2 \qquad \text{Eq. 3.3}$$

The collected data were used in the later stage for parametric study in order to investigate the influence of composite material degradation upon burst pressure capacity of composite repaired steel pipe.

3.5.2 Parametric Variation Analysis

Parametric variation analysis is the most important stage which is the process to achieve the objectives in this study by study the effect of temperature on composite material degradation upon burst pressure of composite repaired pipeline. The validated base model developed in Stage 1 and the data collected from previous literature were used in parametric variation analysis.

The validated base model was utilized as the benchmark to simulate the behaviour of composite repaired steel pipe. Several finite element models were generated to simulate the burst pressure of composite repaired steel pipe with different degradation strength. The base model was duplicated and the composite material properties were modified in order to simulate the burst pressure of repaired pipeline under the specified conditions. Figure 3.5 shows the material properties that need to be modified which is longitudinal tensile strength (hoop tensile strength) and transverse tensile strength (axial tensile strength) in Hashin Damage under material behaviour. Meanwhile, other parts that need to be modified is *E1*, *E2*, and *E3* which is under elastic material behaviour that presented in Figure 3.6. Several finite element models were developed based on degradation strength under different exposure duration with specified temperature.

Once the finite element models were completely generated, finite element analysis was carried out in order to obtain several results such as burst pressure and stress experienced by each component. Based on the results obtained, the effect of temperature over time towards the burst pressure of composite repaired steel pipe were discussed.

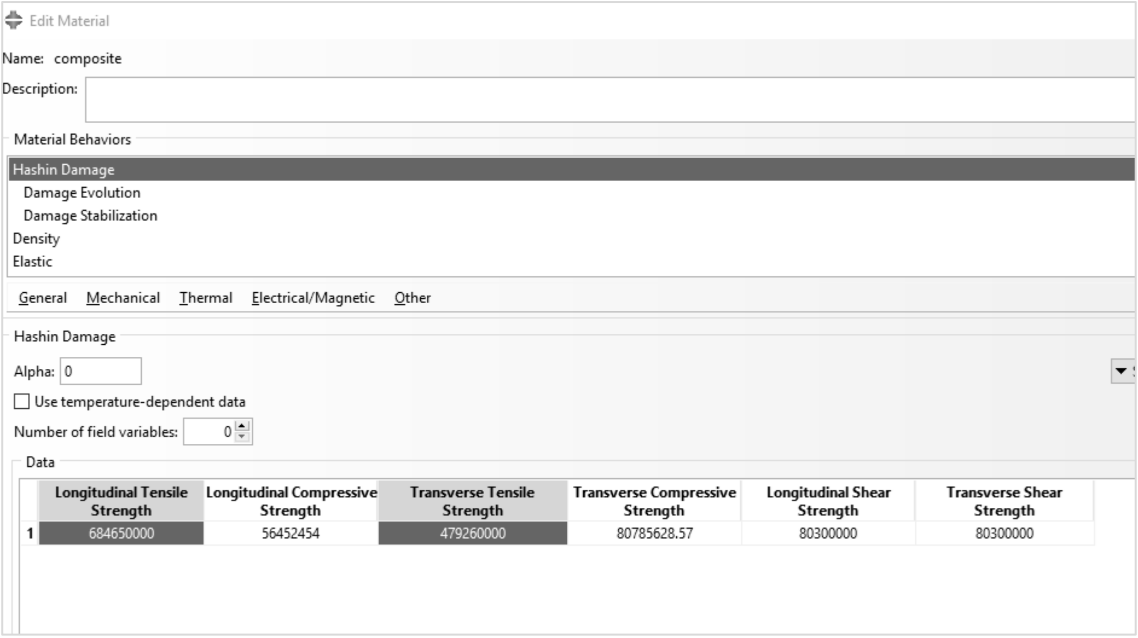

Figure 3.5 Modification of material properties in term of longitudinal tensile strength and transverse tensile strength

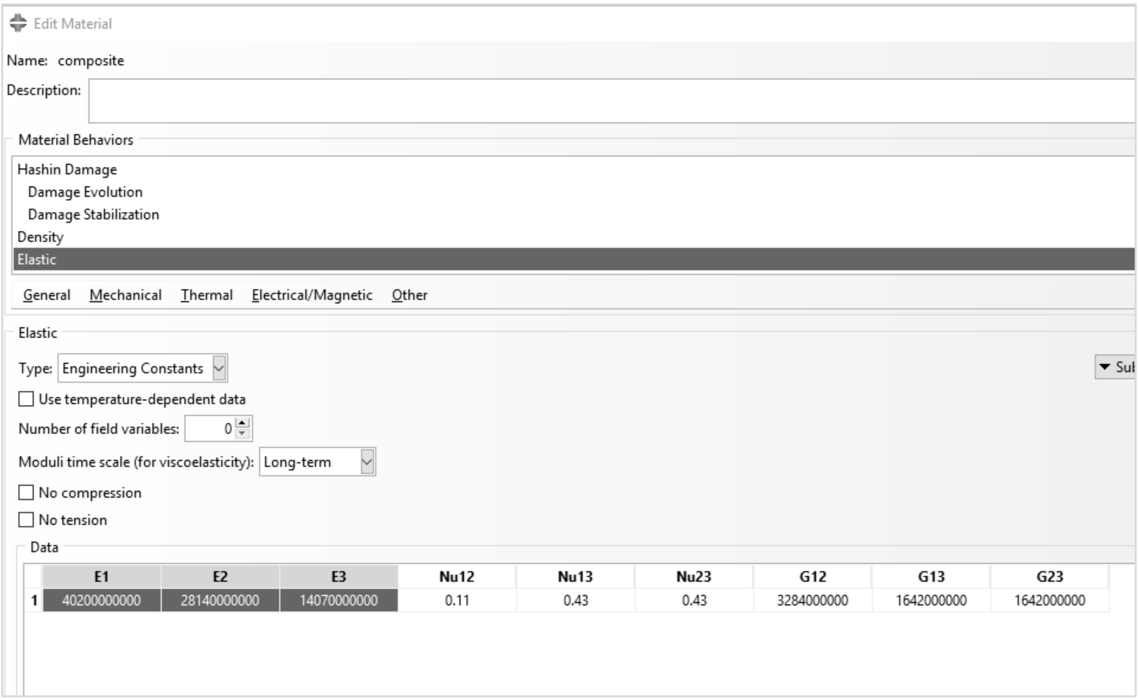

Figure 3.6 Modification of material properties in term of hoop tensile modulus, axial tensile modulus, and radial tensile modulus

3.6 Concluding Remark

This chapter presents the research methodology to simulate the degradation modelling of temperature upon burst pressure capacity of composite repaired steel pipe. Two stages were involved which are base model development and parametric study. It is important to develop a base model for validation purpose to ensure the behaviour of base model simulated is same as the actual model. The validated base model was used as benchmark for parametric study in order to achieve the objectives of this study. In parametric study, several finite element models with different degradation strength were created in order to simulate behaviour of composite repaired steel pipe under different exposure duration with specified temperature. Therefore, the influence of temperature over time on burst pressure capacity can be discussed from the finite element analysis's results.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results of finite element analysis are presented in this chapter followed by the discussion of the findings. A finite element model was developed for validation by comparing the result of burst pressure with previous literature and finite element calculation. The validated base model was utilized as a benchmark for parametric variation analysis to investigate the effect of temperature over time towards the burst pressure of composite repaired steel pipe. The composite material properties were collected from previous literature to develop ten different finite element models under different conditions which are in terms of temperature and duration. Burst pressure results generated by finite element analysis were presented in this chapter. Then, it was followed by the discussion on effect of temperature towards degradation of composite repaired steel pipe. Prediction of remaining life for composite repaired steel pipe is also discussed in this chapter.

4.2 Development and Validation of Base Model

A base model was developed to validate the previous experiment test based on burst pressure. The result of finite element model developed is validated by the burst pressure with the margin of error less than 10%. The finite element model shows 31.77MPa of burst pressure result, which is lower than the experimental result, 33.00MPa. The difference between the burst pressure result of finite element analysis and experiment test was 3.73%. As the margin of error is less than 10%, the finite element model was validated to simulate the behaviour of composite repaired steel pipe. The validated finite element model was referred as a benchmark for the later stage, which is parametric variation study in order to investigate the effect of temperature over time upon burst pressure of repaired pipeline.

4.3 Fiber-Reinforced Polymer (FRP) Composite Material

4.3.1 Data Collection – Material Properties

In the study of Surathi and Karbhari (2006), the experiment results of tensile strength and tensile modulus of E-glass/Vinylester over time were collected as the properties of material composite in parametric study. The tensile strength and tensile modulus of composite material was collected where the composite material subjected to temperature of 23°C, 60°C, and 95°C, within 1440 days.

As mentioned before, the greater stress experienced by a pressurized pipe is hoop stress. Thus, the tensile strength and tensile modulus of the composite material are known as the hoop tensile strength, and hoop tensile modulus, *E1* in the simulation as the largest stress applied on the circular pipe is hoop stress. Other than that, due to limited information in previous experiment, the axial tensile strength was calculated with 70% of σ_h, whereas axial tensile modulus, *E2* of composite material are known as the 70% of *E1*. Meanwhile, the value of radial tensile modulus, *E3* of composite material is 50% of *E2*. Table 4.1 listed the properties for E-glass/Vinylester composite material that were used for parametric sensitivity analysis which the purpose is to understand the effect of temperature over time upon burst pressure of composite repaired steel pipe.

Table 4.1 Properties of E-glass/Vinylester composite.

Temperature (°C)	Time (days)	Hoop Tensile Strength (MPa)	Axial Tensile Strength (MPa)	Hoop Tensile Modulus, E1 (GPa)	Axial Tensile Modulus, E2 (GPa)	Radial Tensile Modulus, E3 (GPa)
23	0	684.65	479.26	40.20	28.14	14.07
	360	642.94	450.06	39.85	27.90	13.95
	1080	550.34	385.24	38.68	27.08	13.54
	1440	515.94	361.16	38.27	26.79	13.39
60	0	648.65	479.26	40.20	28.14	14.07
	360	311.58	218.11	38.20	26.74	13.37
	1080	279.31	195.52	36.68	25.68	12.84
	1440	262.90	184.03	36.54	25.58	12.79
95	0	648.65	479.26	40.20	28.14	14.07
	360	210.77	147.54	35.23	24.66	12.33
	1080	182.16	127.51	31.37	21.96	10.98
	1440	172.03	120.42	31.23	21.86	10.93

Source: Surathi and Karbhari, 2006

4.3.2 Tensile Strength of Composite Material

Figure 4.1 presents the degradation curve of hoop tensile strength of E-glass/Vinylester composite over time when subjected to temperature of 23°C, 60°C, and 95°C. As mentioned before, hoop stress is the largest stress among three principal stresses generated by internal pressure on pipe and thus the discussion on the hoop tensile strength are mainly focused in this study. Based on Figure 4.1, the tensile strength of composite is reduced over time under exposure of all tested temperature. At first year, the retention tensile strength in composite are approximately 93.91%, 45.51%, 30.79% of its initial strength under temperature exposure of 23°C, 60°C, and 95°C, respectively. Then, it was observed that the tensile strength retained in composite decreased over time under all temperature. At 1080-days, tensile strength retained in composite material are 80.38%, 40.8%, and 26.61%, when the composite is subjected to 23°C, 60°C, and 95°C, respectively. At 1440-days, the tensile strength in composite only retained 75.36%, 38.40%, and 25.13% when composite is subjected to 23°C, 60°C, and 95°C, respectively. Other than that, it was observed that the tensile strength of composite retained is less than half of its initial strength when the composite is subjected to elevated temperature such as 60°C and 95°C. It can be explained that the degradation of composite is faster when it exposed to higher temperature compared to room temperature, which is in line with previous literatures (Davies *et al.*, 2005; Mourad *et al.*, 2010; Correia *et al.*, 2013; Sethi, 2014).

Reduction in tensile strength of composite material due to degradation over time can destroy the structural integrity of material. Fibers-matrix interface is the region of synergy in composite where can affect the mechanical properties of the composite. Hence, the damage at fiber-matrix interface can alter the mechanical properties such as reduction of tensile strength in composite. These damage may include of breaking of fibers, debonding, microcracking of matrix, and delamination (Shilpa *et al.*, 2010). Moreover, the structural integrity of resin matrix is reduced when ambient temperature exceeds the glass transition temperature, T_g of composite as amorphous regions of resin matrix are transformed from hard to viscous (Sethi, 2014; Frigione and Lettieri, 2018). Alteration in resin matrix has influenced the overall performance of composite and its durability as well. Therefore, the durability and performance of composite material are decreased when temperature is higher. Degradation in composite material has the direct influence towards the performance of composite repaired steel pipe as well as its long-term durability, which it is discussed in the later section.

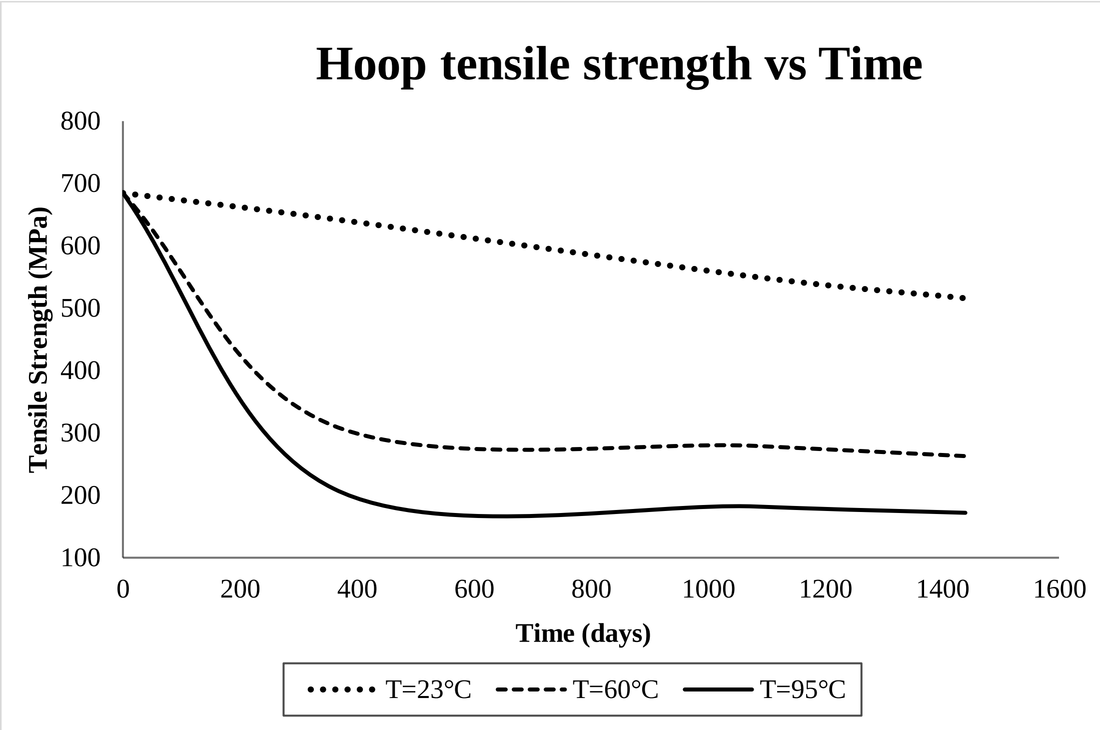

Figure 4.1 Hoop tensile strength of E-glass/Vinylester composite over time when subjected to 23°C, 60°C, and 95°C

4.4 Finite Element Analysis

4.4.1 Stress Contour Plot

Figure 4.2 illustrates the stress contour plot for the entire composite repaired pipe with all components, where this pipe is simulated with initial material model (0-days). The image at the top left represents the assembled model, top right is defective steel pipe, and followed by putty and composite wrap. When a pipe is pressurized internally, three principal stresses are generated, which are hoop stress, axial stress, and radial stress. The greatest stress experienced by a pressurized pipe is hoop stress and thus the stress contour plot presented by steel pipe is only hoop stress. The value of stress is expressed by the colour gradient, where red colour indicates the highest stress experienced by each component. From the image of defective steel pipe, it can be observed that highest stress concentrations are at both edges of defect region along the axial direction, which is the predicted failure location after burst test. Meanwhile, the stress at the centre of the defect was lower than at the edge of defect along the axial direction. Whereas almost entire putty experienced highest stress when the pipe is pressurized internally. Other than that, the higher stress experienced by the composite wrap was found that along the hoop direction at the edge of defect area underneath the composite wrap. The highest stress experienced by defective pipe, putty, and composite wrap are 557.7MPa, 20.1MPa, and 753.4MPa, respectively under initial condition. Moreover, Figure 4.3, Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7 show the stress contour plot of the finite element models under different conditions.

In addition, it was observed that the highest stress experienced by defective steel pipe and putty are constant for all conditions, whereas the highest stress experienced by composite wrap has decreased when it exposed to its service environment for longer duration. It was observed that the highest stress experienced by the composite wrap has decreased from 753.4MPa (0-days) to 661.2MPa (1440-days) under temperature of 30°C. Similar condition was observed on the composite wrap for the temperature of 60°C where the highest stress experienced by the composite wrap has decreased from 753.4MPa (0-days) to 350.8MPa (360-days) and 321.8MPa (1440-days). Moreover, it was also observed that the stress sustainability of composite wrap dropped from 753.4MPa (0-days) to 230.5MPa (1080-days) and 222.6MPa (1440-days) under temperature of 95°C. Hence, it explained that the stress sustainability of composite wrap reduces over time.

Meanwhile, it was also found that the highest stress sustained by the composite wrap has reduced when the temperature increased. At 1440-days, the highest stress sustained by composite wrap is 661.2MPa (23°C), 321.8MPa (60°C), and 221.6MPa (95°C). Similar conditions were observed on the highest stress sustained by composite wrap at duration of 360-days and 1080-days. Hence, the stress sustainability of composite wrap reduced when temperature increased.

The stress experienced by the composite wrap has reduced due to degradation of composite material over time under temperature effect. Composite degradation reduced composite's mechanical properties and structural integrity, and thus its ability to sustain the stress is decreased. At the same moment, the reduction in stress experienced by the composite wrap due to higher temperature is caused by the degradation rate. Higher temperature can accelerate the degradation rate, and thus the stress sustained by the composite wrap is lower at higher temperature compared to room temperature.

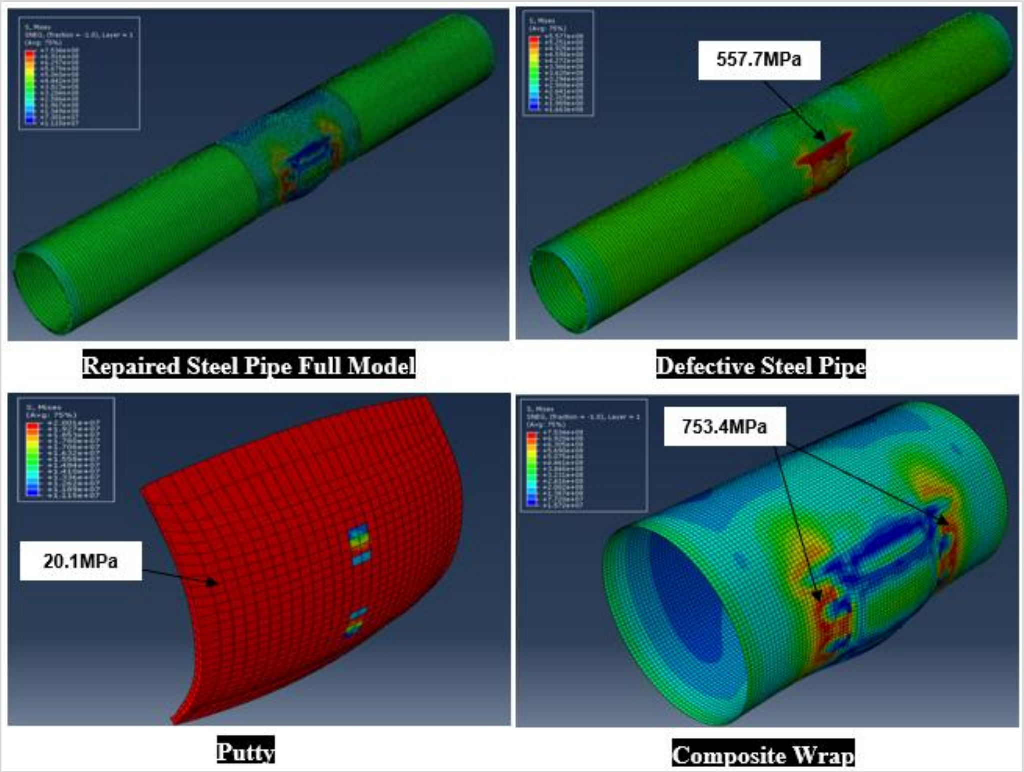

Figure 4.2 Contour stress plot for initial material pipe model (0-days)

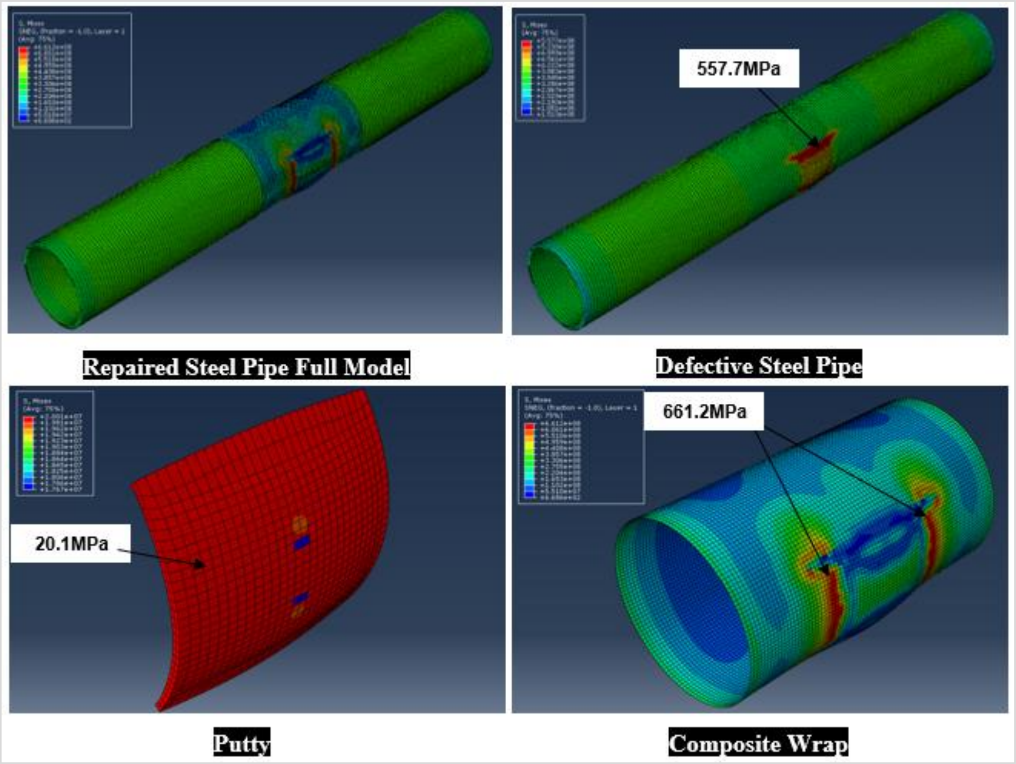

Figure 4.3 Contour stress plot of repaired pipe subjected to 23°C at 1440-days

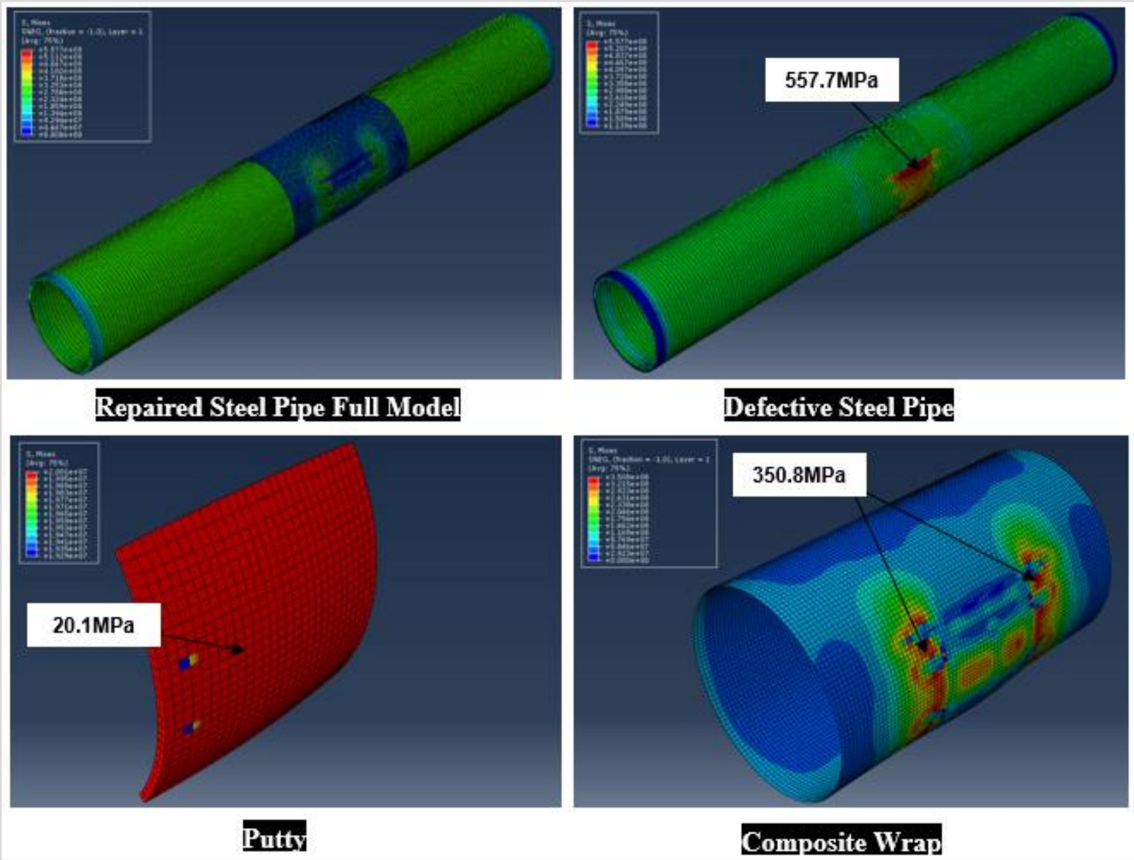

Figure 4.4 Contour stress plot of repaired pipe subjected to 60°C at 360-days

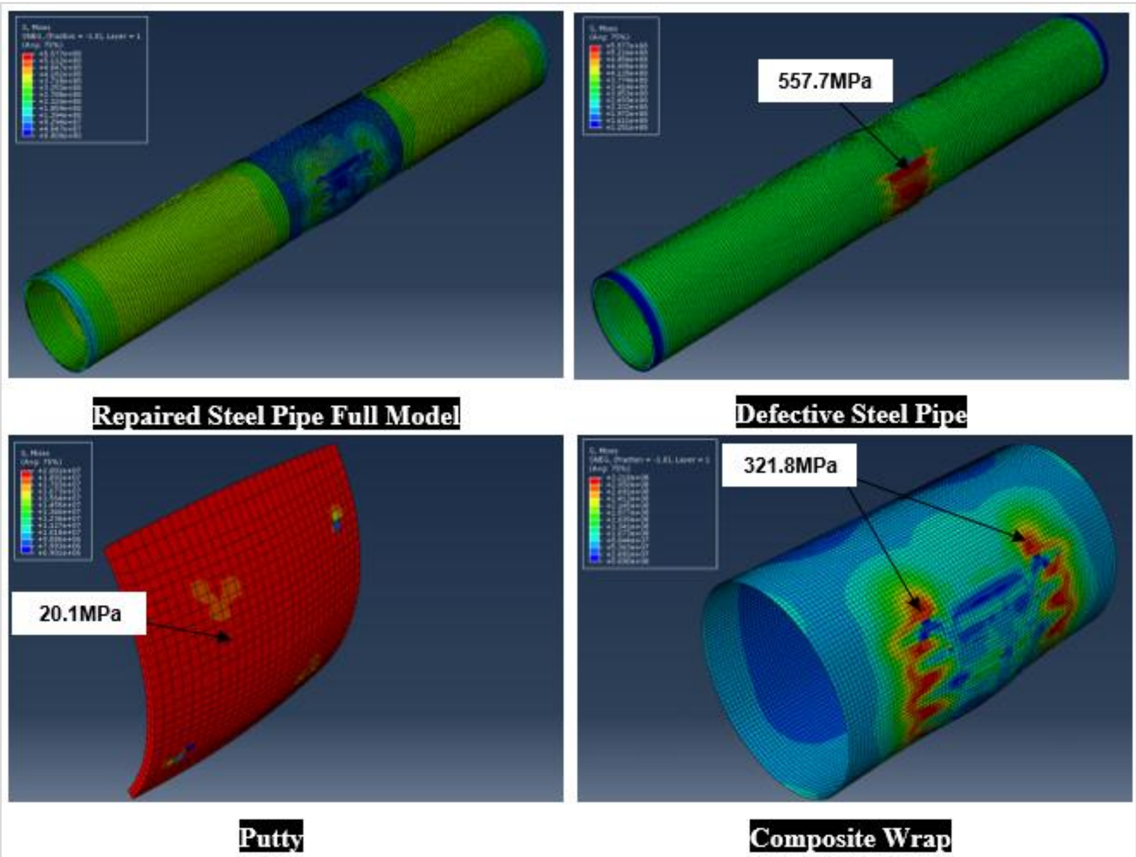

Figure 4.5 Contour stress plot of repaired pipe subjected to 60°C at 1440-days

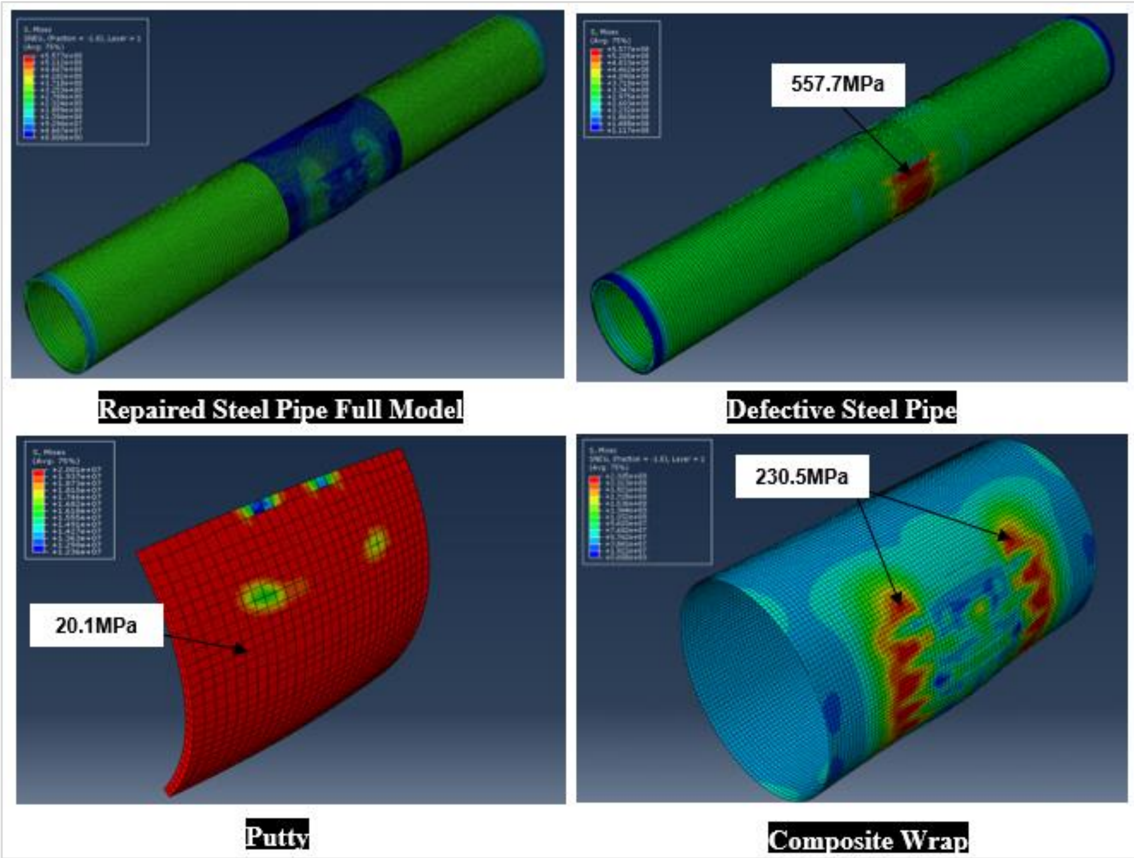

Figure 4.6 Contour stress plot of repaired pipe subjected to 95°C at 1080-days

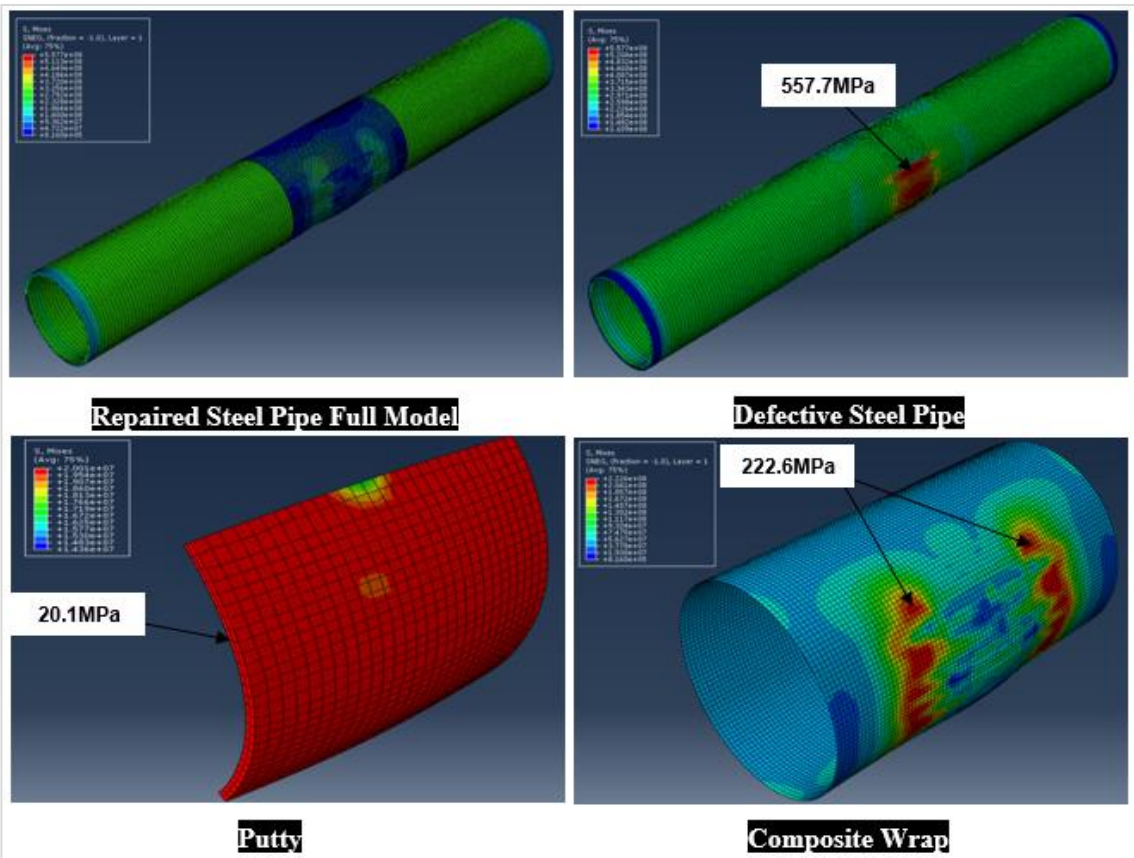

Figure 4.7 Contour stress plot of repaired pipe subjected to 95°C at 1440-days

4.4.2 Effect of Temperature over Time upon Burst Pressure of Repaired Pipeline

The purpose of finite element analysis in parametric study is to investigate the effect of temperature over time towards the burst pressure of composite repaired steel pipe. Table 4.2 listed the result of the burst pressure of composite repaired steel pipe over time under temperature effect. The burst pressure of composite repaired steel pipe at 0-days is regarded as benchmark in evaluating the performance of composite repaired steel pipe over time, due to the initial properties of composite material. In addition, the results were plotted into a degradation curve which is presented in Figure 4.8.

Table 4.2 Burst pressure of composite repaired steel pipe under temperature of 23°C, 60°C, and 95°C.

Temperature (°C)	**Time (days)**	**Burst Pressure (MPa)**	**Difference (%)**
23	0	37.17	-
	360	36.00	-3.15
	1080	34.46	-7.29
	1440	34.40	-7.45
60	0	37.17	-
	360	33.42	-10.09
	1080	33.4	-10.14
	1440	33.34	-10.30
95	0	37.17	-
	360	32.85	-11.62
	1080	32.43	-12.75
	1440	32.22	-13.32

*Note: Difference = $\frac{(Initial\ BP - other\ BP)}{Initial\ BP} \times 100$

Figure 4.8 presents a typical degradation trend in burst pressure when the composite is subjected to 23°C, 60°C, and 95°C. Moreover, the burst pressure of composite repaired steel pipe has a decrease trend where the burst pressure has dropped noticeably within a specified range, then declined insignificantly afterward. The burst pressure of repaired pipe has decreased gradually for composite subjected to 23°C. Meanwhile, the burst pressure has reduced sharply for the composite subjected to temperature of 60°C and 95°C. When the composite is subjected to 23°C, the burst pressure has decreased gradually within approximately 1080 days, whereas the burst pressure has dropped dramatically within approximately 400 days for the composite that exposed to 60°C and 95°C.

The burst pressure of composite repaired steel pipe is decreased under 23°C, 60°C, and 95°C. The burst pressure of composite repaired steel pipe, 37.17MPa has dropped by 3.15% (360-days), 7.29% (1080-days), and 7.45% (1440-days), when the composite is subjected to 23°C. Whereas, a reduction of burst pressure by 10.09% (360-days), 10.14% (1080-days), and 10.30% (1440-days), when the composite is subjected to 60°C. When the composite is exposed to elevated temperature of 95°C, the burst pressure of composite repaired steel pipe has decreased by 11.62% (360-days), 12.75% (1080-days), and 13.32% (1440-days).

The burst pressure of composite repaired steel pipe is obviously decreased by the degradation of composite material. Whereas, the degradation of material is caused by the reduction in tensile strength of composite over time for all tested temperature. Degradation of composite material had influenced its structural integrity where it can be fibers breaking, debonding between fibers and matrix resin, and delamination (Shilpa *et al.*, 2010). Fibers-matrix interface is the region of synergy in composite where can affect the mechanical properties of composite. Mechanical properties of composite material are important as the composite will provide additional strength to repaired pipe to sustain the pressure. Hence, degradation of composite reduced the mechanical properties of composite; thus, the burst pressure of composite repaired steel pipe is reduced as the load bearing capacity is decreased. Therefore, the durability and performance of composite repaired steel pipe is affected by the mechanical properties and structural integrity of composite material. The degradation of mechanical properties of composite reduces its structural integrity and subsequently reduces the load bearing capacity of composite repaired steel pipe as well as its burst pressure.

Based on Figure 4.8, it was also observed that the degradation rate in burst pressure is increased when the composite is subjected to 60°C and 95°C as compared to 23°C. It is more obvious within 400 days, where the composite repaired steel pipe with burst pressure of 37.17MPa has dropped by 3.15%, 10.09%, and 11.62%, when the composite is subjected to 23°C, 60°C, and 95°C, respectively for 360-days. At 1080-

days, a reduction of 7.29%, 10.14%, and 12.75% in burst pressure was recorded when the composite is subjected to 23°C, 60°C, and 95°C, respectively. When the composite is subjected to 23°C, 60°C, and 95°C at 1440-days, the burst pressure of repaired pipe has reduced by 7.45%, 10.30%, and 13.32%, respectively.

It indicates that the reduction in burst pressure of composite repaired steel pipe is faster when it is subjected to higher temperature. The higher the exposure temperature, the lower the burst pressure of composite repaired steel pipe. The lower burst pressure of composite repaired steel pipe is due to the reduction in mechanical properties of composite material that caused by higher temperature. Hence, it can be said that higher temperature accelerates the degradation in mechanical properties of composite material. Previous studies also stated that the rate of degradation is faster when the material is exposed to higher temperature compared to room temperature (Davies *et al.*, 2005; Mourad *et al.*, 2010; Correia *et al.*, 2013; Sethi, 2014). As mentioned before, degradation of composite's mechanical properties reduces the additional strength provided to repaired pipe and thus the load bearing capacity of composite repaired steel pipe as well as its burst pressure is decreased.

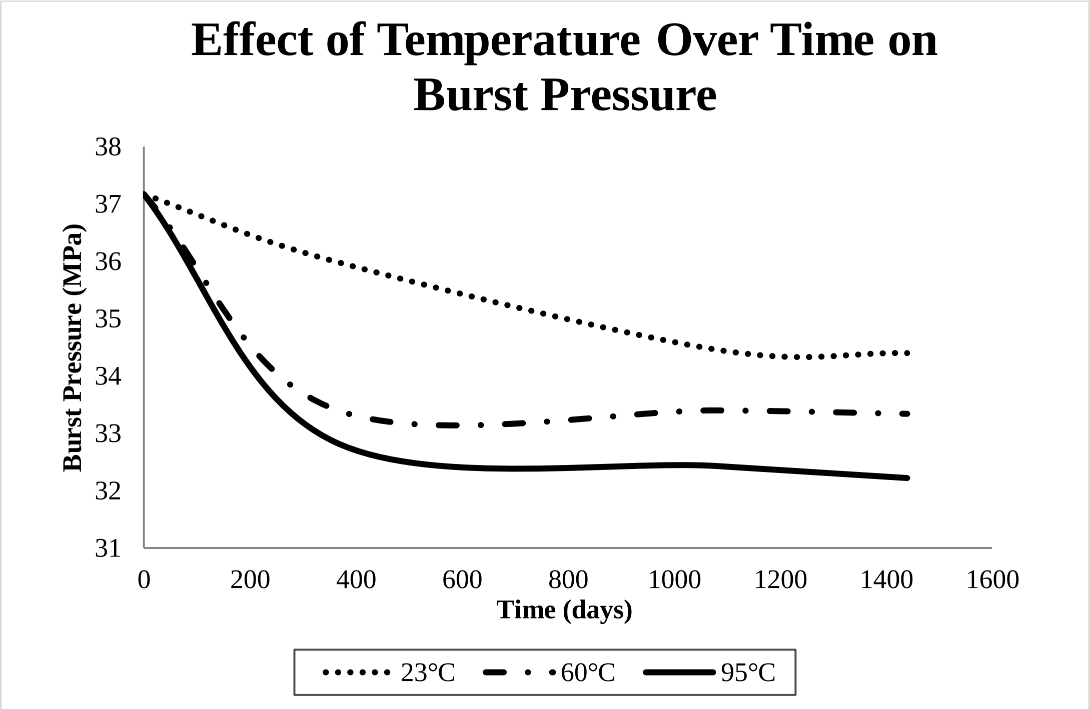

Figure 4.8 Effect of temperature over time when subjected to 23°C, 60°C, and 95°C

4.5 Prediction Remaining Life of Repaired Pipeline

The results generated by finite element analysis on burst pressure of composite repaired steel pipe over time can be used to predict the residual service life for the repaired pipe under the specified environment. By comparing the operating pressure with the burst pressure result of finite element models under the specified environment, the residual service life of the repaired pipe can be predicted. For instance, the current study obtained the result of burst pressure of repaired pipe over time under 23°C, 60°C, and 95°C. Figure 4.9 presents an example of predicted service life of composite repaired steel pipe, which is about 800 days, if the operating pressure of the repaired pipe is 35MPa under room temperature of 23°C. Meanwhile, the remaining life of composite repaired pipeline that is subjected to temperature of 60°C become much shorter which is less than 200 days when same operating pressure is applied. The remaining life of composite repaired pipeline will continue to be reduced when the temperature increased to 95°C. Hence, the remaining life of composite repaired pipeline reduces when temperature increases.

By comparing the operating pressure with the simulated burst pressure of repaired pipe, pipeline owner can estimate the residual service life of the repaired pipe, and thus they can determine whether is worth to repair or replace the damaged pipeline. Otherwise, company can reduce the operating pressure to extend the service life time of repaired pipeline.

However, current study has only investigated the burst pressure of repaired pipe by simulating the conditions. The simulated burst pressure needs to be validated by conducting experiment to ensure the reliability. Other than that, current study only considered the temperature effect within 1440-days on burst pressure of repaired pipe, while there are other parameters that can influence the burst pressure of repaired pipe such as moisture content, ultraviolet light, impact loading, and etc. Hence, combination of the various parameters should be considered to increase the accuracy of burst pressure in repaired pipeline. Besides, the duration tested is required to be extend to obtain the long-term data in repaired pipeline performance as well as its durability.

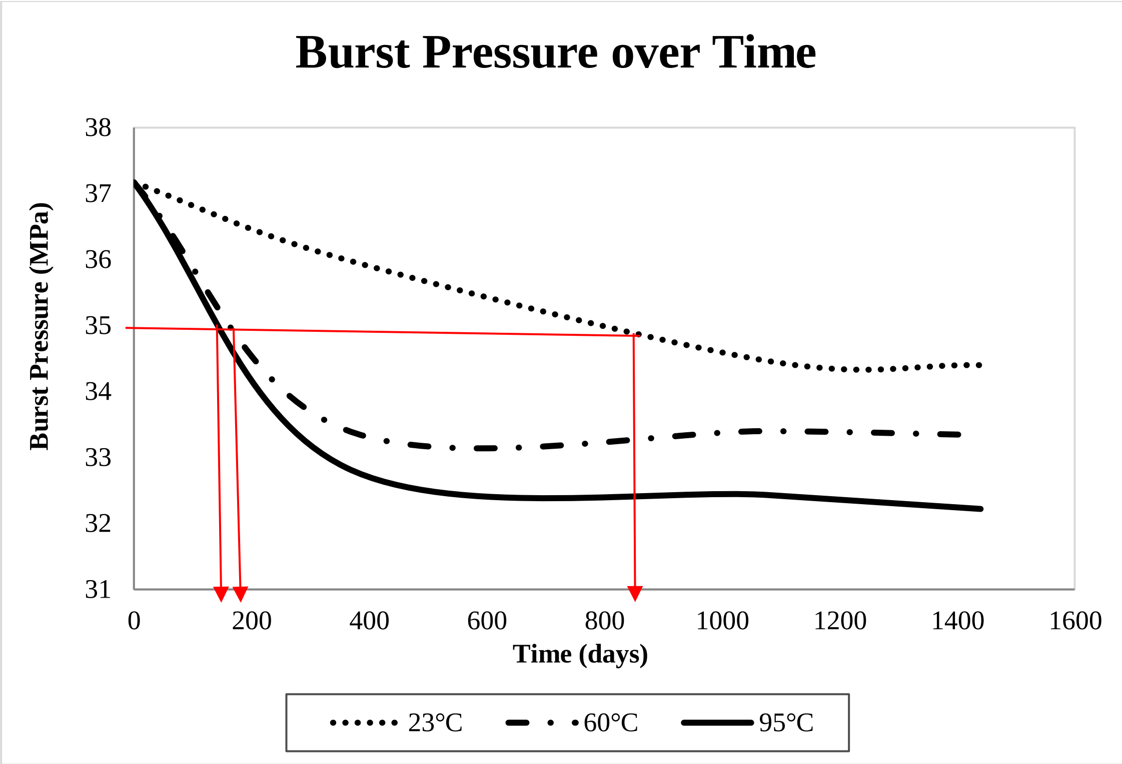

Figure 4.9 Prediction residual service lifetime of repaired pipe

4.6 Concluding Remark

Most of the previous studies only provide information on degradation of composite over time caused by various environmental factors, but there is really rare to have the information on effect of degradation material towards the composite repaired steel pipe. Hence, the current study is like a stepping stone with the aim to investigate the effect of material degradation caused by temperature upon the burst pressure of composite repaired steel pipe. Ten finite element models were analysed with different degradation strength where the strength of composite material is tested when it is subjected to 23°C, 60°C, and 95°C, tested at 360-days, 1080-days, and 1440-days, respectively. Tensile strength of composite material decreased over time which is known as degradation. Based on the findings, it was observed that degradation of the composite has effect on burst pressure of composite repaired steel pipe as the load bearing capacity of the repaired pipe is reduced. The results show that the burst pressure of composite repaired steel pipe has a degradation trend that almost same as the degradation trend in tensile strength of composite material, which the degradation of composite reduced the burst pressure of composite repaired steel pipe. Moreover, it was also found that the degradation of composite repaired steel pipe in burst pressure are accelerated by higher temperature. Other than that, prediction residual service life of composite repaired steel pipe can be carried out by comparing the actual operating pressure with the simulated burst pressure.

CHAPTER 5

CONCLUSION

5.1 Introduction

The main purpose of this study is to investigate the effect of temperature towards the degradation of composite repaired steel pipeline through finite element analysis. Ten finite element models that simulate the material model with temperature of 23°C, 60°C, and 95°C at 0-days, 360-days, 1080-days, and 1440-days were developed to determine the burst pressure of composite repaired steel pipe. It has been successfully performed in accomplishing the two objectives, which are (i) to study the strength degradation of FRP composite subjected to different temperatures and (ii) to simulate the effect composite degradation upon the burst pressure of composite repaired pipeline. This chapter presents the conclusion of the findings of this research, followed by the significance of study and recommendation which can be served as motivation for future research in long-term durability of composite repaired steel pipe.

5.2 Conclusions

The following are the conclusions based on two research objectives:

1. Degradation of FRP composite reduced tensile strength of composite material especially at elevated temperature. Tensile strength of composite was less than half of initial strength when subjected to temperature of 60°C, and 95°C compared to 23°C. Higher temperature accelerates the strength degradation of FRP composite was found in this study.
2. Degradation of composite material has the effect upon burst pressure of composite repaired steel pipe, where the burst pressure is reduced when the composite is degraded. In this research, the simulated burst pressure of composite repaired steel

pipe subjected to temperature of 60°C and 95°C have a significant reduction of about 10.09% and 11.62%, respectively within roughly 400 days, then dropped insignificantly afterward. Whereas, the simulated burst pressure of composite repaired steel pipe under temperature of 23°C is decreased linearly by 7.29% within 1080-days, and dropped insignificantly afterward.

5.3 Significance of Research Contribution

The finding in this research is important as it can be a stepping stone to study the long-term durability and performance of composite repaired pipeline by simulating the burst pressure under the temperature effect over time. Throughout the simulation testing, the effect of temperature over time on burst pressure of composite repaired steel pipe was determined. Thus, oil and gas company can predict the remaining life of a composite repaired steel pipe by comparing the simulated burst pressure with the actual operating pressure. By knowing the remaining life of a composite repaired steel pipe, company can decide whether it is worth to repair or replace a defective steel pipe. Meanwhile, they can adjust the operating pressure to extend the remaining life of composite repaired pipeline based on the simulated result of burst pressure over time. Other than that, the finding in this study may provide the information to pipeline operators, manufacturer of composite repair system and researchers in exploring the long-term durability and performance of composite repaired steel pipe under the condition of temperature effect over time.

5.4 Recommendations

In this study, it has been found that degradation of composite by temperature effect has the influence to burst pressure of composite repaired steel pipe by finite element analysis. There are some recommendations are given for future investigation to improve the research:

1. Experimental investigation on composite degradation by temperature effect should be conducted to validate the simulated burst pressure as well as other parameters such as stress-strain of composite material.
2. As current study only involved the duration of 1440-days, it is suggested to extend the experiment duration to obtain more data and thus to predict the remaining life of repaired pipe for a longer time.

3. Degradation should be considered to other component such as putty as the temperature effect may also have the effect on putty rather than composite wrap only.
4. In order to obtain a more accuracy predicted remaining life of a composite repaired steel pipe, other degradation factors should be considered when conducting experiment or simulation. For instance, impact loading, cyclic force, etc, as well as other environmental factors such as moisture content, ultraviolet light, etc.

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