DEGRADATION MODELLING ON THE INFLUENCE OF MOISTURE CONTENT UPON BURST CAPACITY OF COMPOSITE REPAIRED PIPELINE

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DEGRADATION MODELLING ON THE INFLUENCE OF MOISTURE CONTENT UPON BURST CAPACITY OF COMPOSITE REPARIED PIPELINE

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ABSTRAK

Saluran paip adalah cara yang paling digemari untuk mengangkut gas/cecair dalam kuantiti yang besar. Sepanjang perkhidmatan sistem saluran paip keluli, ia digunakan dalam persekitaran yang berbeza yang akan menyebabkan kemerosotan paip keluli. Kini, komposit polimer deperkuat gentian (*FRP*) semakin pesat digunakan untuk membaiki saluran paip keluli dan ia telah terbukti berkesan. Apabila sistem pembaikan komposit terdedah kepada persekitaran yang agresif, terdapat pelbagai faktor yang boleh menjejaskan kekuatan komposit termasuk kelembapan, suhu, keasidan, kebakaran dan ultraviolet. Oleh itu, kajian ini bertujuan untuk menentukan ketahanan komposit serat tikar cincang kaca-epoksi (*chopped strand mat glass fibre/epoxy*) dibawah kesan penyerapan kelembapan dengan menggunakan simulasi analisis unsur terhingga (*FEA*). Komposit direndam dalam air selama 28 hari berturutan pada suhu bilik. Kandungan lembapan komposit berada pada 1.078%, 2.758%, 3.693%, 4.100% dan 4.121% dalam masa 1, 7, 14, 21, dan 28 hari. Terdapat lima model unsur terhingga telah dihasilkan untuk mengkaji kesan kelembapan ke atas tekanan letus. Dapatan dari analisa unsur terhingga (*FE*) menunjukkan sedikit penurunan tekanan letus iaitu 31.663MPa (penurunan sebanyak 0.994%) pada 28 hari dengan kandungan lembapan sebanyak 4.121%. Kekuatan tegangan yang rendah daripada komposit membawa kepada kekurangan sumbangan ketahanan tekanan. Kesan kelembapan komposit kurang jelas ditunjukkan dengan menggunakan serat tikar cincang kaca-epoksi. Walaupun hasil kajian menunjukkan kelembapan tidak banyak memberi kesan terhadap tekanan letus, namun terdapat trend yang menunjukkan penurunan tekanan letus apabila kandungan kelembapan bertambah. Peningkatan kandungan kelembapan akan mengurangkan kekuatan tegangan komposit dan mengakibatkan penurunan tekanan letus. Satu ramalan jangkahayat perkhidmatan paip keluli dibaiki komposit telah dilakukan untuk meramal baki hayat perkhidmatan bagi tujuan menunjukkan bagaimana keputusan dalam kajian ini boleh digunakan oleh pengendali saluran paip. Tekanan letus dijangka berkurangan sebanyak 53.097% berbanding dengan model kawalan iaitu dari 31.981MPa kepada 15MPa selepas 178 hari.

ABSTRACT

Pipelines are most favored mode of transportation of gas/liquid in large quantities. Along the service life of steel pipeline system, it exerted in different condition of surrounding which cause deterioration of steel pipeline. There is a rapid growth in the application of Fibre-Reinforced Polymer (FRP) composites wrap where the method has been proven effective for repairing steel pipelines. When composite repair system exposed to aggressive environment, there are various factors which may affect the strength of composite include moisture, temperature, acidity, fire and ultraviolet. This study aims to determine the durability of chopped strand mat glass fibre/epoxy composite under the effect of moisture absorption using finite element analysis (FEA) simulation. The composite was immersed into water for 28 days at room temperature. The moisture contents of composite were 1.078%, 2.758%, 3.693%, 4.100%, and 4.121% on immersion time of 1, 7, 14, 21, and 28 days, respectively. Five finite element models were developed to study the moisture effect toward burst pressure. The FE result shows a slightly drop for burst pressure on 28-days which was 31.663MPa (0.994% drop) with moisture content of 4.121%. The low tensile strength of composite lead to less contribution toward stress sustainability. The moisture effect of composite was not obviously shown by using chopped strand mat glass fibre-epoxy. Although the result shows not much effect of moisture toward the burst pressure, but there was a trend shows the decreasing of burst pressure when moisture content increases. The increase of moisture content decreases the tensile strength of composite and resulted in decreasing of burst pressure. A prediction of long-term service life of composite repaired steel pipe was performed to forecast its remaining service life to demonstrate how the results in this study can be used by the pipeline operators. The burst pressure was predicted to reduce by 53.097% compared to control model which drop from 31.981MPa to 15MPa after 178 days.

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LIST OF SYMBOLS

E	Young’s Modulus
G	Tensile modulus
v	Shear modulus

LIST OF ABBREVIATIONS

PG&E	Pacific Gas and Electric Company
FRP	Fibre-Reinforced Polymer
UV	Ultraviolet
UTS	Ultimate tensile strength
TTS	Time-temperature superposition
FEA	Finite Element Analysis
USA	The United States of America
BP	Burst pressure
FE	Finite Element

CHAPTER 1

INTRODUCTION

1.1 Overview

Pipelines function as blood vessels serving to transport life-necessities such as water or natural gas, oil and to take away life waste like sewage (Central Intelligence Agency, 2018). Pipeline are also considered to be the most favoured mode of transportation of gas/liquid in large quantities (Kishawy and Gabbar, 2010). According to a database published by the United State of America's Central Intelligence Agency, there are over one million kilometres of pipelines laid around the world to transport oil and natural gas (Central Intelligence Agency, 2018). Along the service life of steel pipeline system, it exerted in different condition of surrounding such as aggressive environments with high pressures and high temperatures which cause deterioration of steel pipeline. The degradation of pipeline may lead to leaking, fire and explosion. In regard to urban natural gas pipeline accidents, corrosion is one of the major causes (Muhlbauer, 2004). Pipeline failure due to corrosion attack can cause hazards involving multiple fatalities, serious financial loss, bad economic implications, and significant environmental damage (Yahaya et al., 2009).

As reported by the National Transportation Safety Board (2011), an explosion of a natural gas pipeline in San Bruno, California, owned by Pacific Gas and Electric Company (PG&E), killed eight people, injured 58 others, destroyed 38 houses, and damaged 70 more in a residential neighbourhood. According to The Star Online, there is a fire broke out on Tukau B drilling platform with 60m-deep underwater inside the vicinity of the Tukau Oilfield, located 31km from the Miri shoreline that belonging to Petronas in deep waters in the South China Sea. There were 16 peoples on board doing maintenance work on the platform during the fire had been successfully evacuated and the fire was doused in an hour (Stephen, 2012). In preventing the risk and hazardous to occur, maintenance, checking by using pigging and safety are very significant to carry out. There is more than 35% of Malaysia local onshore pipeline are more than 30 years old (Petronas Gas Berhad, 2014). Therefore, in order to ensure the serviceability of pipeline system to continue safely, rehabilitation of structurally compromised pipelines is needed.

There is a wide range of rehabilitation techniques and repair methods available for onshore and offshore pipelines. To repair corroded steel pipeline, several method can be used such as, applying grout, installing full-encirclement steel sleeve or steel clamp, or remove the entire corroded pipe to replace a new pipe if condition is critical (Noor et al., 2016). Apart from that, there is a rapid growth in the development and application of FRP composites wrap recently where the method has been proven effective for repairing steel structures such as risers and pipelines (Duell et al., 2008; Leong et al., 2011; Alexander, 2014; Chan et al., 2015).

1.2 Problem Statement

Fibre-Reinforced Polymer (FRP) composite wrap is increasingly used as rehabilitation technique of pipeline system. In order to optimise the design of composite repair system, the load bearing capacity of FRP composite wrap is important. However, the performances of FRP composite wrap in various environment conditions are not fully understood. Their durability and integrity in various service environments depends of the response of its constituents i.e., fibre, polymer matrix, and the existing interface between the fibre and polymer matrix, in that particular environment (Sethi and Ray, 2015). When composite repair system exposed to environment, there are various factors which may affect the strength of FRP composite wrap over time include UV, temperature, acidity, alkalinity, humidity, fire and moisture. According to Keller et al. (2013), carbon fibre/epoxy matrix composites that exposed to water for over 18 months are conservative for 50 years design life with maximum loading of 16% and 65% ultimate tensile strength (UTS) for time-temperature superposition (TTS) high-crimp composite and tensile creep test, respectively.

From the past literature, there is limited information regarding the load bearing capacity of the FRP composite warp that can help in predict how long it can sustain steel pipe until failure. The lack of durability data of FRP composite wrap not only lead to use of high factors of safety in design such as 4-6 in marine industry and 8-12 in the area of tanks and pipe (Helbling et al., 2006), it also increase the cost of overall repair system. The environmental condition that the pipeline structure located is significant to the degradation of FRP composite wrap. However, the lifetime durability validated data and knowledge are limited that make the research difficult. In this study, collection, assessment and appropriate documentation of available data of degradation FRP composite wrap were reviewed from previous research that used in civil structure. The parameters investigated in this study are glass fibre-reinforced polymer in epoxy matrix composite and the effect of moisture environment condition towards the strength degradation of the FRP composite. All the degradation data of FRP composite strength collected from previous research were utilised in Finite element analysis to predict the burst pressure and service life of steel pipe that are repaired by FRP composite.

1.3 Objective of study

This study aims to investigate the durability of FRP composite warp under the effect of moisture content over time upon burst capacity of composite repaired pipeline by finite element analysis (FEA). The objectives of this study are:

1. To investigate of the strength degradation of FRP composite wrap under the effect of moisture variation.
2. To determine the burst pressure of composite repaired pipeline subjected to degradation of composite wrap under different moisture condition.
3. To determine the remaining service life of pipeline repaired by FRP composite wrap.

1.4 Scope of the study

This study focused on the loss of strength of steel pipeline repair system which is FRP composite wrap and not include of infill materials. The loss of strength of FRP composite wrap data were collected through previous research. The priority of data gathered from previous study is glass fibre reinforced polymer with epoxy matrix. The degradation strength of FRP composite is due to the various environment effects such as, UV, temperature, acidity, alkalinity, humidity, fire and moisture. In this study, the factor only focuses on moisture content in atmosphere that affect the performance of FRP composite wrap. Finite element analysis was used to investigate the degradation of strength of composite repaired steel pipeline and subsequently predicts its remaining life considering the effect of moisture content.

1.5 The importance of the study

In oil and gas industry, the cost of construction, operation and repairing works are high. The real-life investigation on the durability of steel pipeline composite repair system are short to be guaranteed which result to anxiety for pipeline industry. Due to lack of information on the long-term performance of FRP composite wrap, the factor of safety used is increase in repairing work to reduce the risk of failure. Determination of degradation strength of FRP composite wrap helps to identify the service life and durability of the steel pipeline. In order to improve the current design of the composite repair system, this study is significant as it might potentially optimise the factor of safety in design, reduce the cost and provide more confident to the long-term performance of composite repaired pipeline under various moisture environment.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There are many types of composite materials can be used for repair and rehabilitation of corrode, decay and leak pipeline. This chapter delivers the issue of the characteristic and behaviour of rehabilitation of pipeline with FRP composite wrap in long term service life. The tradition of rehabilitation methods and techniques are reviewed to give clearer picture of the improvement in repair technology and current issues that are associated with steel pipeline repair. The contribution of the composite repair in rehabilitation of damaged pipeline and the environmental effect on FRP composite are reviewed from previous research to provide better understanding in regards to this topic.

2.2 Overview

In early of 1850s, the exploitation of petroleum below the sea bed was initialized in California. The beginning of oil industry first exploration drilling was carried out from over a 21-meter-deep (Mustaffa, 2011). After the launch of oil industry in California, other early discoveries of oil were later observed in Pakistan (1886), Peru (1869), India (1890) and Dutch East Indies (1893) (Hassan, 2008). Offshore industry started to explore potential offshore area at North Sea to a more challenging technical in the early 1960s (Patel, 1995). The growth of offshore industry is proportionally to the development of pipelines system. The transport of crude oil through pipeline is in elevated temperature and high-pressure condition which up to 90°C and 17MPa, respectively (Mustaffa, 2011). Steel pipes have been considered as the optimal means of transport oil and gas under the requirements of temperature and pressure that had been mentioned.

2.3 Conventional Pipeline Repair Techniques

Ordinary corroded pipeline repair methods include shutdown of operation, cutting out the damaged part of pipe and replace with a whole new section (Melander and Österberg, 2016). Other than remove some or the entire damaged pipe sections, repairs also can be done by, install a full-encirclement steel sleeve and steel clamp. Full-encirclement steel sleeve and steel clamp are welded or bolted to the outside surface of pipe (Noor et al., 2015). Conventional repair methods are time consuming and pipe has to be off service and repair procedure decrease productivity (Melander and Österberg, 2016).

A method that has become increasingly popular during the last years is using a specially designed compound box that capsules the damaged part and is filled with compound sealing the repair. The epoxy compound is injected in valves located around the box, let the air trapped inside the box escape and make the compound cure. This repair method is expensive due to designed and produced specifically for each repair. The manufacturing time for each single application may also take a period of time. However, this method is seen as a safe way to repair pipeline temporary. It has a good compatibility with pipe since it designed specifically for each repair (Melander and Österberg, 2016). Figure 2.1 shows a repair flange joining two pipe sections, the valves on the box let the injected compound to cure.

Figure 2.1 Compound box

Source: SMC Sweden (2016)

Other than compound box, clamp is also a way to repair corroded pipeline. There are different types of clamps which are made of either plastic or metallic materials or fabrics. In advantage, this method is quick in applying procedure to damaged pipe. Fabric clamps, metal and plastic clamps are used for emergence leak stop and long-term repair respectively. Other repair methods can also be combined with clamp to prolong the repair period of pipeline. However, the low temperature and pressure working ranges of clamp cause not to use in many cases. Figure 2.2 shows a clamp made of fabric used for temporary repairs and can be combined with a compound box to increase lifetime.

Figure 2.2 Clamp made of fabric

Source: 3XEngineering (2016)

Another conventional repairing pipeline method is steel sleeves which is popular in the USA. This is a quick and reliable method; the damaged area of existing pipe is surrounding with an additional steel layer attached by welding. However, welding might build up stress concentrations and enable long term effects such as fatigue damages. Welding also cause in hydrogen embrittlement that lead to brittle cracking in the original pipe (Melander and Österberg, 2016). Figure 2.3 shows a steel sleeve used for long lasting repairs.

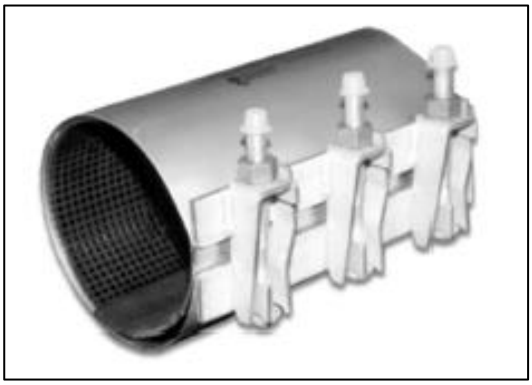


Figure 2.3 Steel sleeve repairs

Source: Romac Industries (2018)

2.4 Composite Repair System

Fibre composite repair provides many advantages over conventional repair methods in engineering practices (Shamsuddoha, 2014). Fibre composite repair system consists of 3 major layers which are infill material, interlayer adhesive and composite sleeve. Figure 2.4 shows the schematic illustration of fibre composite repair system. The role for infill, adhesive and composite layer are smooth bed, bond and load carrying, respectively. There are numerous researchers proposed the combination of infill materials and composite layer as structural repair of steel pipelines (Shamsuddoha et al., 2013). The corroded or gouged section of pipe are filled with suitable infill which is also call putty/grout between the pipe and the outer sleeve. Infill is not only a smooth bed for corrode pipe but also act as a bridge to transfer load from pipe to composite layer. Meanwhile the role for composite layer is the primary load-carrying component (Azraai et al., 2015). Fibre Reinforced Polymers (FRP) is usually made up of polymer/plastic matrix reinforced with fibres. Composite repair system supports defects and prevents defect failure through restraint and load transfer (Palmer-Jones and Paisley, 2000).

Fibre reinforced polymer is effective for construction and retrofit of filled and hollow in-air, underground cylindrical elements and marine structure (Lau and Zhou, 2001; Gibson, 2003; Patrick and Association, 2004; Cercone and Lockwood, 2005; Sen and Mullins, 2007; Geraghty et al., 2011). Fibre reinforced composite has been a successful application on the rehabilitation of corroded pipes using hybrid repair (Alexander, 2007); water depth up to 3000 m using high performance thermoplastic composite tubes (Picard et al. 2007); underwater application of steel tubular structure with carbon fibre reinforced polymer to assess the possibility of rehabilitation of steel tubular flexural members (Seica & Packer, 2007); and feasibility of infilled sleeved repair of pipeline (Palmer-Jones & Paisley, 2000). Based on the experiment and numerical investigation of Lukács et al. (2010), Lukács et al. recommended that fibre reinforced composite materials and the external reinforcing technology can be used for a wide difference of pipe lengths and diameters for both cyclically and quasi-static loaded pipeline sections of pipelines.

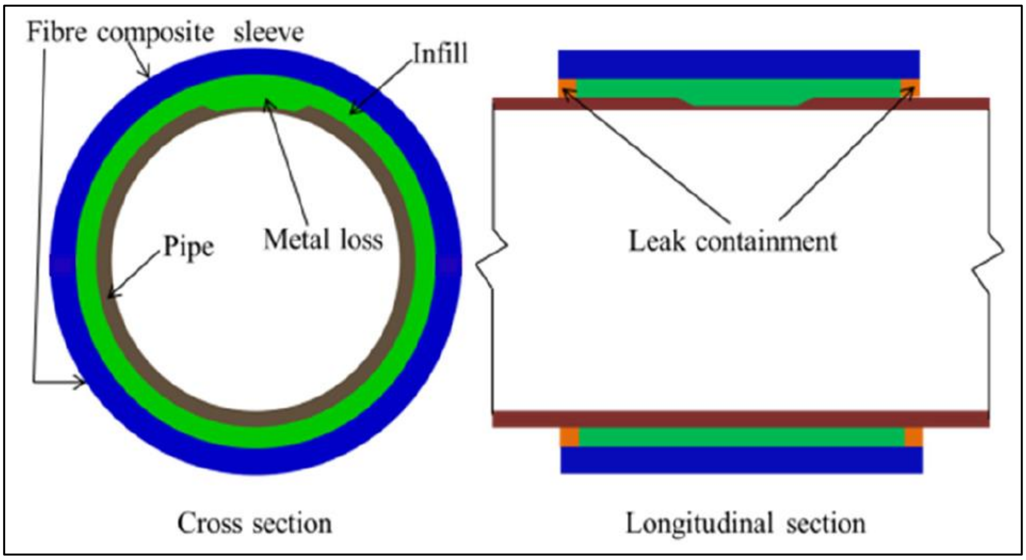


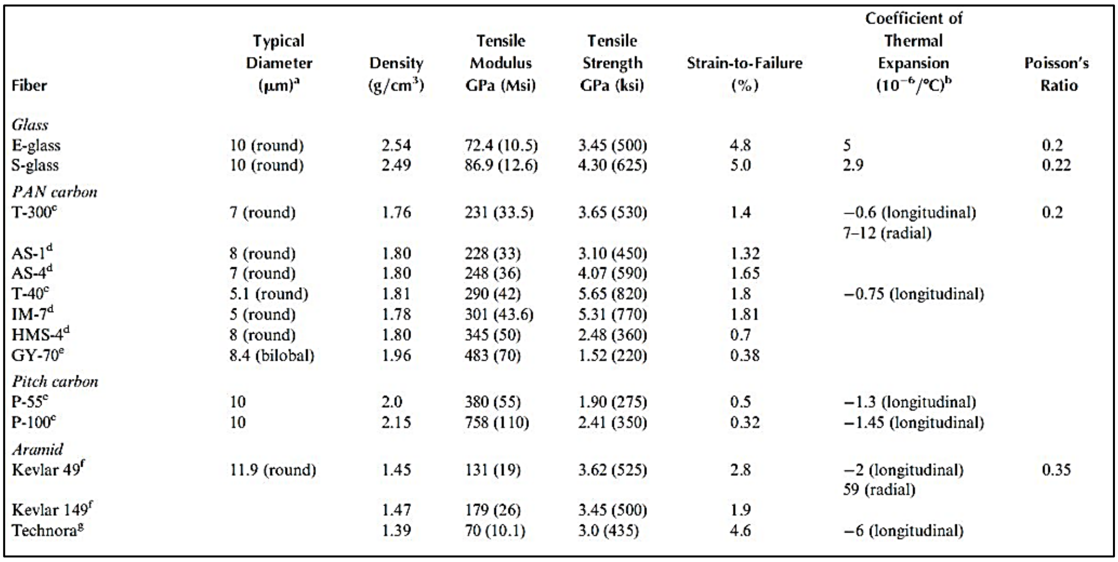
Figure 2.4 Infilled fibre composite repair system

Source: Shamsuddoha (2014)

Composite repair system has widely different performance compare to the production of different companies around the world. This system is mainly including three parts: (i) high compressed strength material for pipeline defect filling as load transfer medium.; (ii) adhesive materials with high curing speed and high performance; and (iii) high strength fibre reinforcing materials. Fibre reinforced composite repair system can be classify into 5 categories which are pre-cured layered, flexible wet lay-up, pre-impregnated split composite sleeve and flexible tape systems (Noor et al., 2015).

2.4.1 Fibre Reinforcement

Fibres are the principal constituents which primarily carrying load in a fibre reinforced composite material. Fibres are the largest volume fraction in a composite laminate and share the major portion of the load acting on a composite structure. Selection of fibre type, fibre volume fraction, fibre length, and fibre orientation are significant to the characteristic of composite laminate: (1) density; (2) tensile strength and modulus; (3) compressive strength and modulus; (4) fatigue strength as well as fatigue failure mechanism (5) electrical and thermal conductivities; and (6) cost (Mallick, 2007). Figure 2.5 shows a number of commercially available fibres and their properties. The commonly used of fibres for composites are glass, carbon, aramid, polyethylene, boron, polyester, nylon and natural fibres (Shamsuddoha, 2014). Glass fibres are low cost, high tensile strength, high chemical resistance, and excellent insulating properties; however, they have low tensile modulus and high density amongst the commercial fibres, and more susceptible to fatigue, creep and stress rapture (Mallick, 2007; Shamsuddoha, 2014). Carbon fibres are high tensile strength and stiffness, low density and superior fatigue performance than glass fibres (Ochola et al., 2004; Wonderly et al., 2005; Giancaspro et al., 2010). Nevertheless, the disadvantages of carbon fibres are their low strain-to-failure, low impact resistance, high electrical conductivity, and cost (Mallick, 2007; Shamsuddoha, 2014). For aramid fibres, they are the lowest density and highest tensile strength-to-weight ratio among the current reinforcing fibres however they absorb water and degrade in moisture rich condition (Sala, 2000; Tanaka et al. 2002). For some specific application, natural fibres are lower environmental impact compared to glass (Joshi et al. 2004). However, in consideration of strength and water absorption issues, natural fibres in an underwater condition are yet to be explored.



Fiber	Typical Diameter (μm)[a]	Density (g/cm³)	Tensile Modulus GPa (Msi)	Tensile Strength GPa (ksi)	Strain-to-Failure (%)	Coefficient of Thermal Expansion (10^{-6}/°C)[b]	Poisson's Ratio
Glass							
E-glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S-glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
PAN carbon							
T-300[c]	7 (round)	1.76	231 (33.5)	3.65 (530)	1.4	−0.6 (longitudinal) 7–12 (radial)	0.2
AS-1[d]	8 (round)	1.80	228 (33)	3.10 (450)	1.32		
AS-4[d]	7 (round)	1.80	248 (36)	4.07 (590)	1.65		
T-40[c]	5.1 (round)	1.81	290 (42)	5.65 (820)	1.8	−0.75 (longitudinal)	
IM-7[d]	5 (round)	1.78	301 (43.6)	5.31 (770)	1.81		
HMS-4[d]	8 (round)	1.80	345 (50)	2.48 (360)	0.7		
GY-70[e]	8.4 (bilobal)	1.96	483 (70)	1.52 (220)	0.38		
Pitch carbon							
P-55[c]	10	2.0	380 (55)	1.90 (275)	0.5	−1.3 (longitudinal)	
P-100[c]	10	2.15	758 (110)	2.41 (350)	0.32	−1.45 (longitudinal)	
Aramid							
Kevlar 49[f]	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	−2 (longitudinal) 59 (radial)	0.35
Kevlar 149[f]		1.47	179 (26)	3.45 (500)	1.9		
Technora[g]		1.39	70 (10.1)	3.0 (435)	4.6	−6 (longitudinal)	

Figure 2.5 Properties of selected commercial reinforcing fibres

Source: Mallick (2007)

2.4.2 Resin Matrix

A matrix in a fibre reinforced composite is responsible to transfer stresses between fibres, keep fibres in place, provide a barrier against an adverse environment, such as chemicals and moisture, and protect the surface of the fibres from mechanical degradation. There are two broad categories of resin matrix which are thermoplastics and thermosets depending on their behaviour when heated. Thermoplastic individual molecules are not chemically joined together, they held in place by weak secondary bonds or intermolecular forces (Figure 2.6a). Thermoplastic are more commonly with short fibre reinforced composites such as aromatic polyketones, polyarylene sulphides, polyamides, polyimides, etc. (Béland, 1990). In a thermoset resin matrix, the molecules are chemically joined together by cross-link, forming a rigid, three-dimensional network structure (Figure 2.6b). After polymerization, thermosets such as epoxy, vinyl ester, polyester and phenol formaldehyde resins are hardly to melt with application of heat. Nevertheless, there are still be possible to soften them when the cross-links are low at elevated temperature. The advantages of using thermosets are chemical resistance, thermal stability, less creep and stress relaxation than thermoplastics. However, thermosets are limited storage life at room temperature, long fabrication time in the mold and low strain-to-failure. The most significant benefit of thermoplastics over thermosets are high impact strength, fractur resistance and higher strain-to-failure which provide a better resistance to matrix microcracking in the composite laminate

(Mallick, 2007). Despite the advantages given by thermoplastics, they are also lower creep resistance and lower thermal stability than thermosets which cause in limited interest in structure applications (Mallick, 2007). For the consideration of pipeline repair, other than polyester and vinyl ester, the most suitable resin associate with high strength fibre which used for underground and underwater is epoxy resin. Moderately superior thermal stability of epoxies has excellent bonding properties and mechanical properties which enable them to use in most high performance fibre reinforced composite (Shamsuddoha, 2014). However, the long-term performance resin exposed to moisture and high-pressure repair conditions are yet to further investigate.

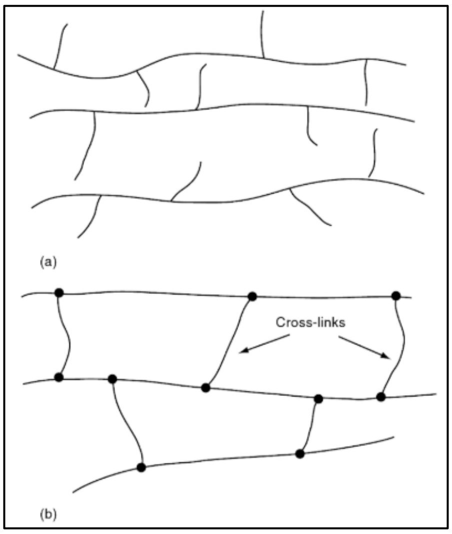


Figure 2.6 Schematic representation of (a) thermoplastic and (b) thermoset

Source: Mallick (2007)

2.5 Degradation of FRP composite

The ease of application of composite repair system makes them extremely attractive and increasingly use in civil infrastructure application. Composite repair is fairly successful record of use in pipelines, underground storage tanks, building facades and architectural components if appropriate designed and fabricated, these systems can provide longer lifetimes and lower maintenance than conventional materials (Karbhari, 2007). However, FRP composites can experience long-term degradation especially subjected to unfavourable environment for a long time. Environmental factors that are often considered more critical to the long-term performance of external strengthening systems include moisture/solution, thermal effects, fatigue, creep/relaxation, ultraviolet exposure, fire and synergistic effects. The durability of FRP composite can be altered by the response of its constituents such as fibre, polymer matrix, and the existing interface between the fibre ang polymer matrix.

2.5.1 Moisture

Exposure to moisture includes effect from direct exposure to rain, humidity, moisture or diffused solutions through other substrates, and immersion in aqueous solutions. All organic polymers will change in thermophysical, mechanical and chemical characteristics when moisture diffused into it. Resin is absorption primary effect through hydrolysis, saponification, plasticization and other mechanisms. This cause both irreversible and reversible changes in the polymer structure. The fibre-matrix interphase in some cases are wicked by moisture which cause loss of integrity of fibre-matrix bond. For the case of glass fibre, moisture extracting ions from the fibre cause structural changes and degradation. For aramid fibres, they absorb moisture and lead to accelerated fibrillation under specific conditions. In the presence of sodium hydroxide and hydrochloric acid with combination of temperature and stress will cause dramatic accelerate hydrolysis. However, it is possible to protect fibres from appropriate selection of resin system and processing conditions, and apply protective coatings to slow down the degradation (Karbhari, 2007). The application of FRP composite is increasing used in pipeline system which mean it will come in contact with moisture and various solutions, therefore, it is important to understand and documented the short- and long-term effects in moisture condition.

2.5.2 Thermal effect

Thermal effects include of response changes due to temperatures above the cure temperature, temperature variation and cycles, and freeze-thaw condition (Karbhari, 2007). FRP composites are anisotropic and heterogeneous which will form hygrothermoelastic stresses within their mesostructured. Resins and adhesives soften over a temperature range, which causes an increase in viscoelastic response, reduction in elastic mechanical performance levels, and increased susceptibility to moisture absorption. When moisture ingression of fibre and matrix occurred, a new-phase formed between fibre and matrix region. This phase has its own glass transition temperature different from its bulk matrix phase. The mobility of the polymer chain becomes restricted and behaves in ductile manner when below glass transition temperature, and it shows viscoelastic in nature when above glass transition temperature. From previous research, the effect of prior thermal conditioning on glass/epoxy composite in form of thermal shock and thermal spike (Sethi, 2014). The mechanical properties may undergo in two ways either in for of thermal stresses development in matrix and cause matrix damage through crack formation, or accelerate the moisture absorption by creating active sites that lead to differential hygroscopic stresses in composite.

2.6 Challenges of using composite repair system

Composite wrap is pre-manufactured in a controlled environment, so it provides better quality control. The available literature has shown fibre reinforced composite can effectively repair steel pipe. Nevertheless, different repair systems have its own limitations. For example, the preparation of current composite repair systems can be complicated. Resin are difficult in installation and curing for underwater condition and limited space. Pre-cured half shell metal repair sleeves have been effectively used in many repair projects, but difficult in heavy-weight installation. Considerable research by other researchers using fibres and infill to repair corroded and gouged pipes has been carried out (Shamsuddoha, 2014). Duell et al. (2008) and Freire et al. (2007) both studies the load transfer mechanism considered flexible wet lay-up method to regain burst pressure of original pipe. However, the geometries of corrosion and layer thicknesses affect the load transfer mechanism and burst failure patterns. So, to understand the system performance, the effect of defect geometry on the load transfer mechanism needs to be determined. Oil and gas pipelines are more affected to localised corrosions and need to be evaluated based on the orientation and severity to case basic (Shamsuddoha, 2014).

Composite repaired steel pipe will degrade over its service life. The effect of environment was found to affect the properties composite materials for pipeline repair such as heat and moisture (Ray, 2006; Carbas et al., 2013; Jiang et al., 2013). The moisture absorption damages the composite through diffusion of hydrogen molecule of water penetrate microcrack of matrix and cause debonding of interface between matrix and fibre (Chin et al., 1999; Ellyin and Maser, 2004). So, the limitation of long-term properties of composite repaired steel pipe demand a further investigation.

2.7 Concluding remarks

The benefit of using FRP composites to repair defected pipes are state in various available research. The benefit can be summarized into (i) shorter repair time compare to conventional method, (ii) weld and cut are not require in repair step, (iii) flexible in material and structure design and (iv) light weight and low cost. Despite of the advantage, FRP composites also have many issues regarding the performance. The issues are including (i) surface preparation complex, (ii) delamination of composite, (iii) limited information of infill contribution, (iv) conservative of code design, (v) lack of information of infill loading transfer and (vi) the defect geometry influence of steel pipe remaining strength. Figure 2.7 shows the summarization of current issues by using composite repaired system.

This study only involves for the performance of FRP composite warp. The properties of FRP composite is significant for numerical simulation parametric study and prediction of the durability of composite repaired pipe. Previous research on composite repaired system apply on steel pipe is limited, this make this study become more difficult. There are various of research study for the degradation of FRP composite on environmental condition which are glass/epoxy by Jeffrey et al. (2011), glass/epoxy by Kini et al. (2018), and etc. This study is to investigate the contribution of FRP composites warp towards the durability of the steel pipe and performance of composite due to moisture effect. This can predict the life span of repaired steel pipe and be prepared for further investigation.

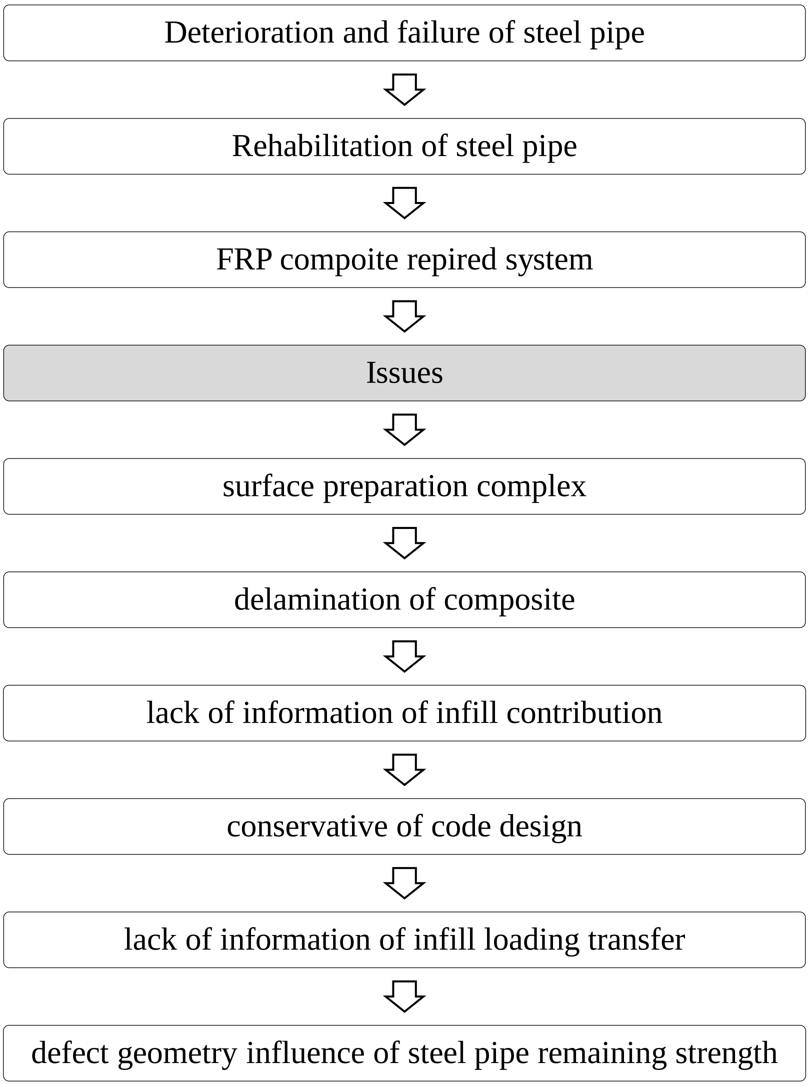


Figure 2.7 Summarization of current issues by using composite repaired system.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The research methodology consists of 2 stages which involve development of base model in stage 1 and parametric study in stage 2. All the stages of this research were carried out using finite element analysis method by ABAQUS® software. In stage 1, a finite element composite repaired pipe base model was developed by using published experimental data and validated against the burst test. After the base model was validated, it was then used in stage 2 for parametric study. In stage 2, parametric study of composite repaired steel pipe affected by moisture absorption and predict the lifetime of composite repaired steel pipe was conducted and evaluated.

3.2 Overview of overall research methodology

As mention before, there are two stages involved in this research to fulfil the objective of study. First stage involves input of mechanical properties of infill, composite wrap and steel pipe based on published experimental data by Lim (2017) into finite element model of composite repaired pipeline. The finite element model was then validated by comparing the predicted burst pressure against published experimental data. Next, in stage 2, previous studies on the performance of composite exerted in moisture environment were collected, analysed, and used as input of material properties into the validated base model. Finite element analysis was then conducted where the performance and life span of composite repaired pipeline was investigated. Figure 3.1 shows the summary of the overall research methodology.

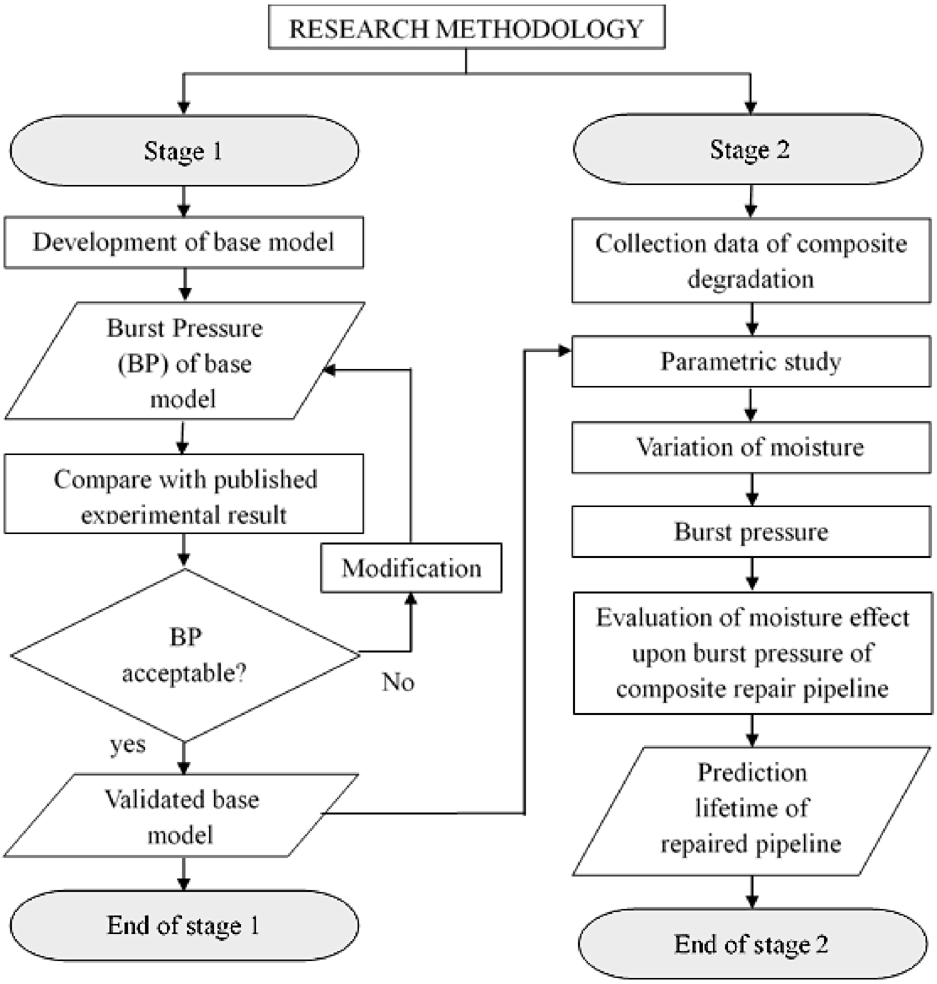


Figure 3.1 Flow chart of overall research methodology

3.3 Stage 1: Developed composite repaired pipe base model

The objectives of this research are achieved through numerical simulations. First stage of this research involved the development and validation of finite element composite repaired pipe models to simulate the experimental burst tests. The material properties of infill, composite wrap and steel pipe were determined by published experimental data and used as inputs for finite element analysis. Then, the burst pressure of numerical simulations was compared with experimental result for validation and referred as base model afterwards. After that, the validated base model was used for parametric study in stage 2.

Numerical simulation was generated using commercial finite-element modelling software, ABAQUS® v6.12-1 (SIMULIA, 2012). ABAQUS software was used to create model, generate meshes, and perform finite-element calculations. Modelling of finite element involve creating 2 models which were corroded steel pipe and composite repaired pipe. The geometries and material properties of individual components such as steel pipe, putty and composite were modelled using the results of previous experimental test by Lim (2017). After that, the individual parts were than assembled into an integrated structure. Then, the interaction of the structure appropriate boundary condition was assigned followed by inputting internal pressure and generate mesh for all components. These 2 models were ready to analyse and burst pressure was determined. The validated finite element model was determined by comparing predicted burst pressure with experimental tests. Burst pressure acceptable margin error was less than 10% between finite element simulations and experimental tests, otherwise the model needs to remodify until the result was acceptable (Freire et al., 2007; Shouman and Taheri, 2011; Chan et al., 2015). After the validated model was done, the composite repaired steel pipe model was used to conduct parametric study on moisture effect. The burst pressure of composite repaired pipeline affected by variation of moisture was later used for predict life span of repaired pipeline. Figure 3.2 shows the detail methodology of stage 1.

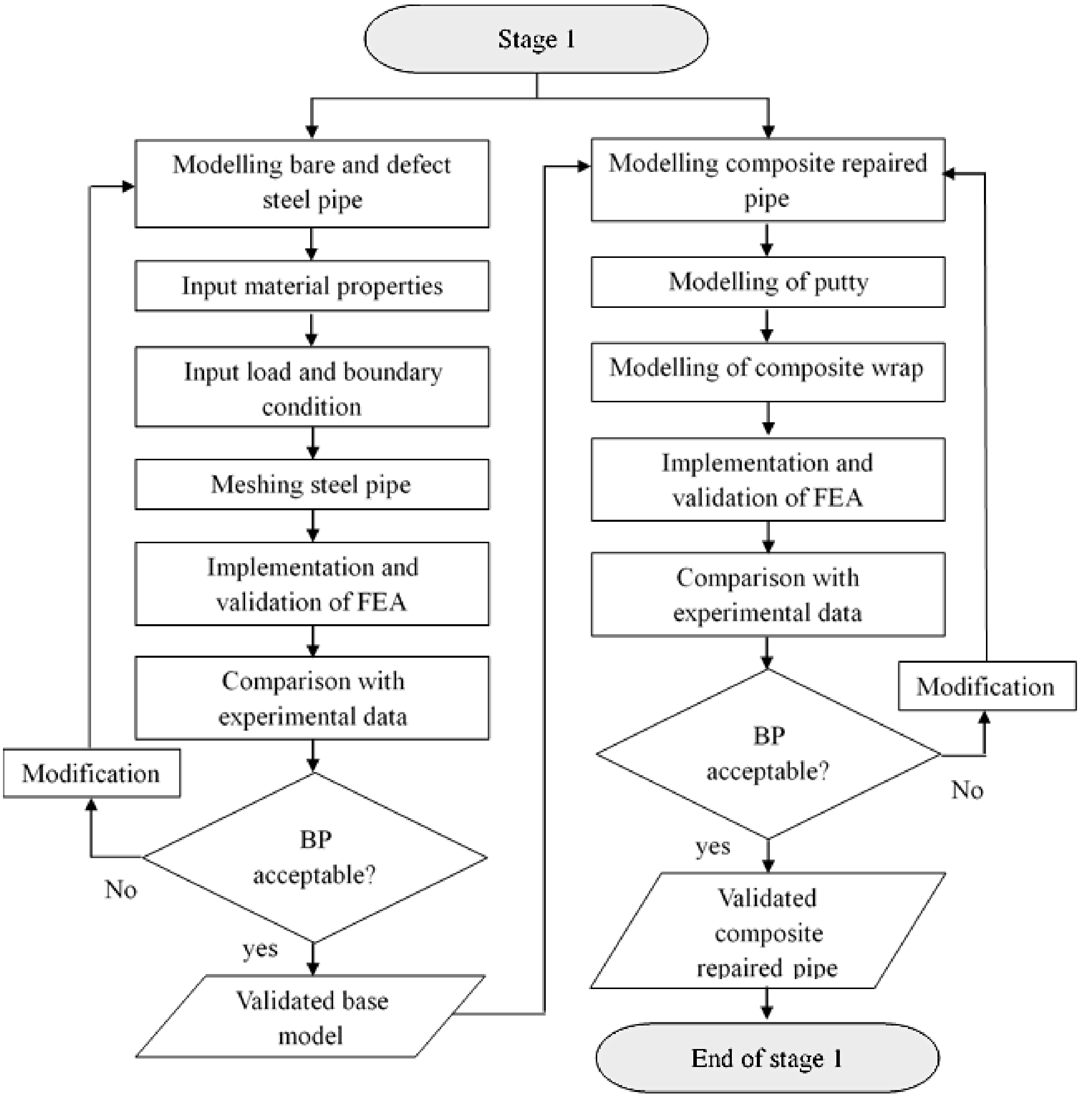


Figure 3.2 Flow chart of research methodology for stage 1.

3.3.1 Modelling defect steel pipe

First of all, a defective steel pipe finite element model was created by using ABAQUS software. A 3-dimensional deformable model was created similar to the physical properties material used in the provided experimental results. By using extrusion method, the solid model was created with 168.3mm diameter and length of 1200mm. Then, another solid was created with diameter of 154.08mm (pipe inner diameter). The latter was then cut through extrusion to the former and formed a hollow pipe with diameter of 168.3mm, length of 1200mm and thickness of 7.11mm. Then, the bare pipe was modified to create defective pipe. A 2-dimensional defect geometry located on the middle of pipe with 100mm arc length and 3.555mm depth was created in hoop direction. Meanwhile a length of 100mm was extruded in axial direction. Figure 3.3 shows the parts of bare pipe and defective pipe model.

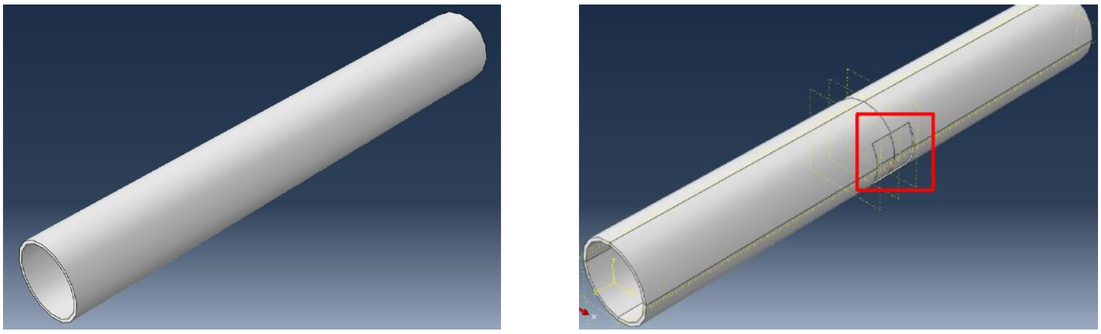


Figure 3.3 Geometry of bare pipe and defect pipe

3.3.2 Input material properties, load and boundary condition

Then, the material properties of steel pipe were assigned which include, Poisson's ratio, Young's modulus, and stress-strain curve from experimental tensile test results. The engineering stress-strain curve was based on the tensile test and it was converted into true stress-strain curve to suit the chosen material model. Figure 3.4 shows the calculated true stress-strain curve. Based on Lim (2017), the material properties of steel pipe were such as Young's Modulus, *E* (222GPa), density (7850kg/m^3), ultimate tensile stress (557.7MPa) and Poisson's ratio (0.3). After the material properties of model were assigned, the material model was allocated to steel pipe and assigned to simulation. The analysis time of 500s was assigned with activation of geometry nonlinearity which follow the experimental test loading rate of approximately 0.1MPa/s. Then the model's internal wall surface was assigned with a uniform pressure of 50MPa and the pressure ramp up with rate of 0.1MPa/s. Both ends of the test specimen was expanded and contracted axially, and rotated about the axial axis. Figure 3.5 shows the test specimen with boundary condition and internal pressure assignation. The modelling process did not include both welded end caps features because the results of few simulations with end caps and without end caps was similar. In the consideration of time saving, end caps were not modelled.

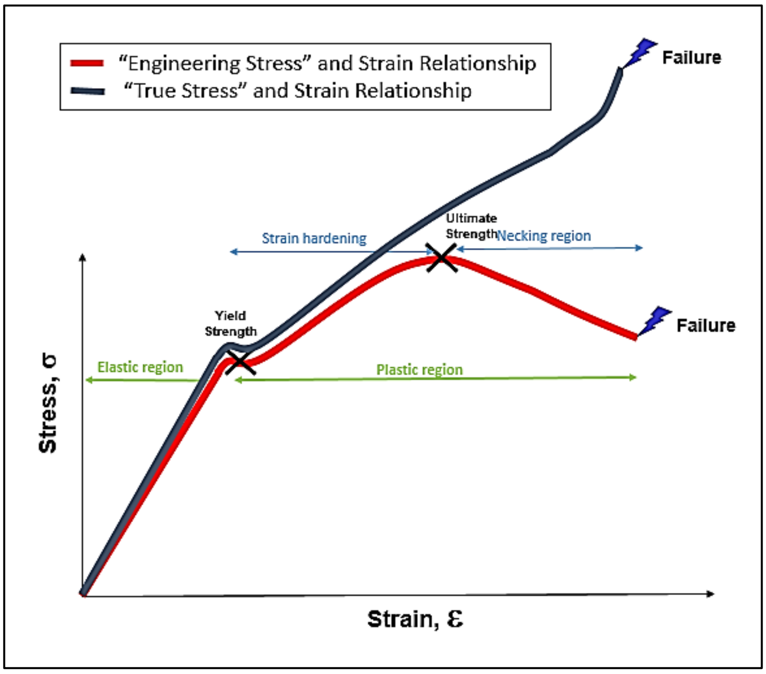


Figure 3.4 Engineering stress-strain and true stress-strain curve

Source: Jamal, (2017)

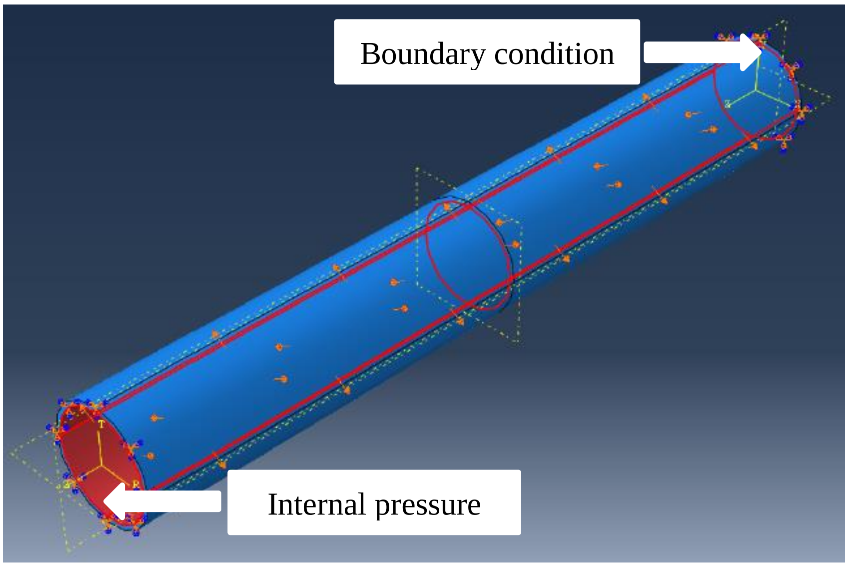


Figure 3.5 internal pressure and boundary condition of model.

3.3.3 Meshing steel pipe

C3D8R of ABAQUS 3-dimensional reduced integration, eight-node linear solid element was used for meshing model. A good finite element analysis can be obtained with a good mesh to get an accurate result and optimum analysis duration. ABAQUS contain colour code meshing control feature. Orange colour shows the structure cannot be meshed, yellow colour shows an unstructured mesh can be generated, green colour shows the part can be meshed. Defective pipe model has the nature of odd geometries that structural mesh cannot be generated by using original parts. The model was cut into several section in order to minimize or eliminate odd geometries. Figure 3.6 shows the model meshing process from orange to green colour which means the model is ready for meshing.

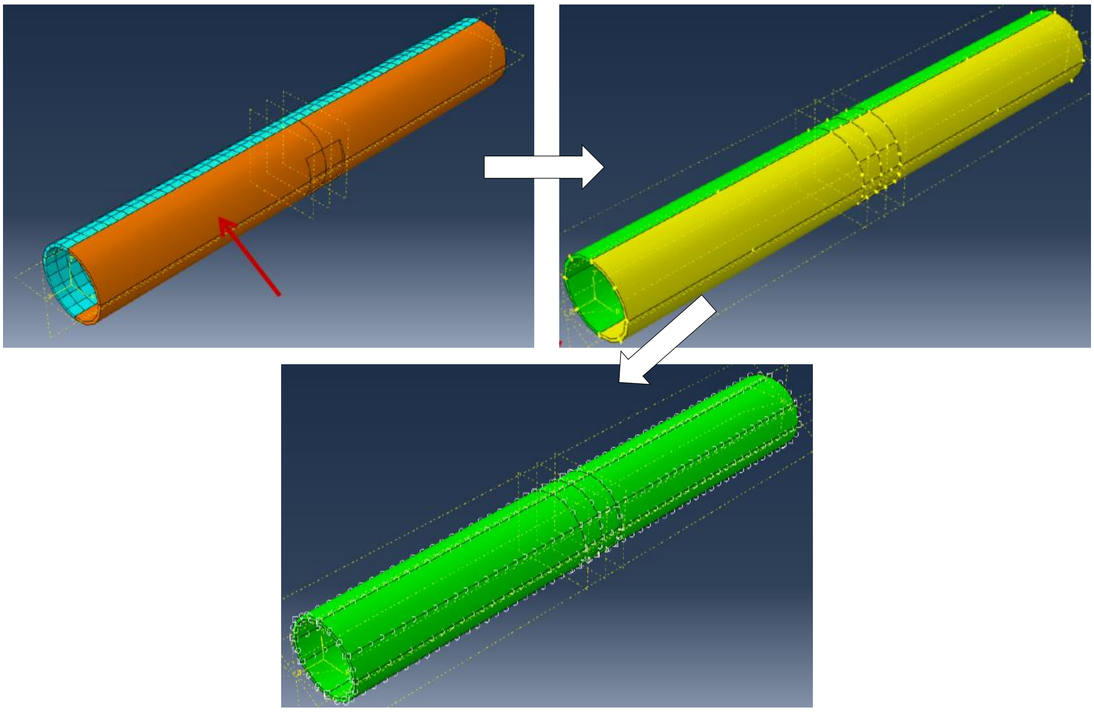


Figure 3.6 Meshing process of defect pipe until achieve structural mesh

3.3.4 Implementation and validation of defective pipe models

In order to determine the suitable mesh size of model, the combination of different mesh sizes was carried out. Figure 3.7 shows the meshed structure of bare pipe and defected pipe. After meshed process, finite element analysis was carried out. The burst pressure results were compared with the experimental results. The burst pressure of simulation and experimental result should be less than 10% of variation. Then, the defective model was completely generated and validated for further study on composite repair pipe.

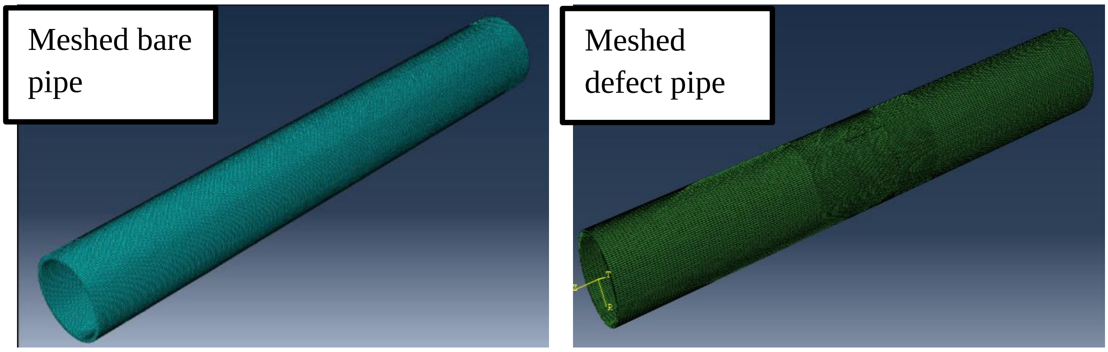


Figure 3.7 Meshed bare pipe and defect pipe

3.3.5 Modelling composite repaired steel pipe

The validated defective pipe was used to model composite repaired steel pipe. Composite repaired steel pipe model includes addition part of putty and composite warp which was more complicated then defected pipe modelling that include more materials properties input and parts. Composite repaired pipe model was to investigate the performance of repaired pipe. All the parts (pipe, composite and putty) were created individually which need to be assembled. All the parts interfaces were contact to each other. There are some features were neglected because of lack of information. The important common practice was studied the strain of composite repaired pipe which cannot be neglected. However, the strain gauges between the defect section and grout was neglected in this study because it only involves a small area of the repair area, thus, the contribution of strength was very small and insignificant. Other than strain gauge, adhesive strength was also neglected. This is because the adhesive apply for the composite repaired pipe was very thin and bonding test for the bond strength between composite with steel, and composite with putty was not determined. Therefore, no information of bonding properties input for adhesive and were neglected.

3.3.6 Modelling of Putty

Putty was used to cover the defective area of steel pipe, so the geometry of putty was modelled same as the defect geometry of steel pipe. The development of putty’s model was same as steel pipe which was a 3-dimensional deformable solid sample and input the physical properties for simulation. The model of putty created is shows in Figure 3.8. The information of material properties of putty used in simulation was limited. To model the putty, first was to determine the suitable material and properties.

This is because there were various material models used in previous studies which divided into (i) compressive-bilinear, (ii) elastic properties only and (iii) elastic perfectly plastic. This make the difficulty of selecting suitable material models (elastic, bilinear, plasticity, etc.) and suitable properties (tensile and compression).

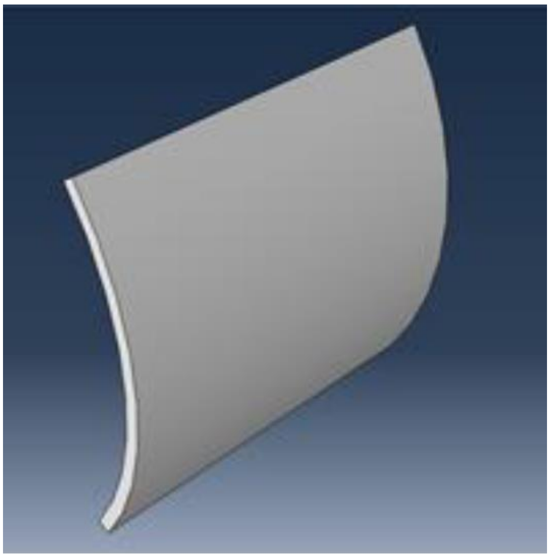


Figure 3.8 Model of putty

So, the properties of putty were based on the experimental test from previous study as input of numerical simulation Based on Lim (2017), the material properties of epoxy grout were such as Young's Modulus, *E* (19GPa), ultimate tensile stress (20.01MPa) and Poisson's ratio (0.35). There was also available material library of different models in ABAQUS. Then, various of material properties and material models were used for undergoes analyses. Then the result of analyses of burst pressure was compared with experimental result to find out the most suitable material model to simulate putty behaviour. Besides that, to locate the putty in exact location, translation of the location of putty was undergoes. This can be done by using "*translate instances*" which was a built-in feature of ABAQUS. Figure 3.9 shows the steps for translation process of putty location. Besides that, putty was modelled by using same element type with steel pipe which was eight-node linear solid element (C3D8R). Then the meshed size of putty was same as defeat region to obtain a uniform result. Figure 3.10 shows the meshed putty.

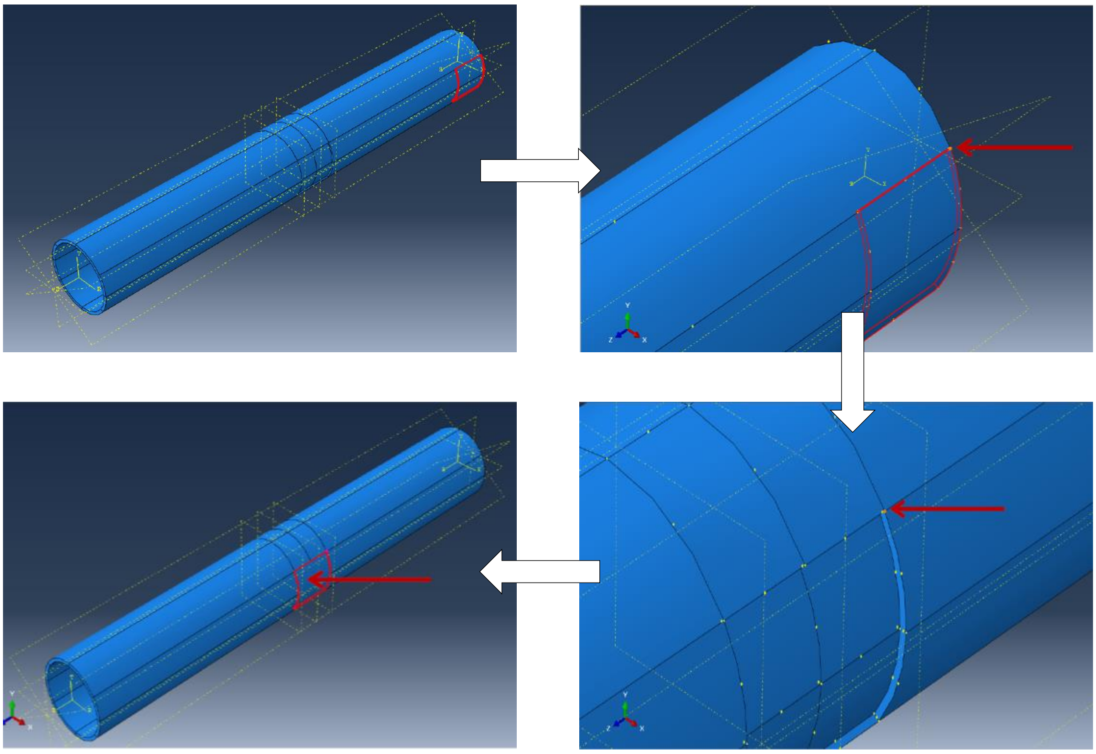


Figure 3.9 Steps for translation of putty location

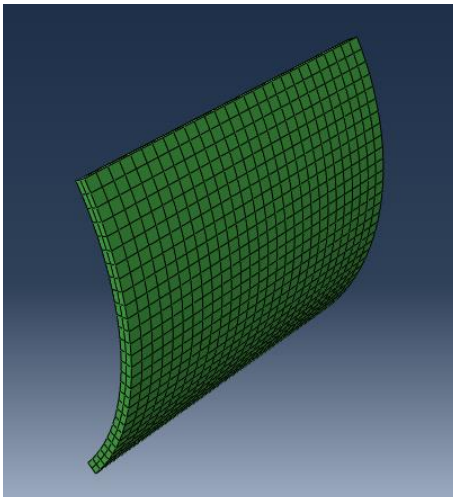


Figure 3.10 Meshed putty

3.3.7 Modelling of composite wrap

After model of putty has developed, composite wrap was modelled with a 3-dimensional deformable shell part by using the Engineering Constant Model from the material model library in ABAQUS. The composite wrap with diameter of 168.3mm, length of 300mm and thickness of 1mm of thin shell layer was formed. The composite wrap properties input includes *E*, tensile modulus, *G*, shear modulus and *v*, Poisson's ratio. The elasticity properties are *E1*, *E2*, *E3*, *v12*, *v13*, *v23*, *G12*, *G13,* and *G23*. The detailed properties of composite wrap were showed in Table 3.1. The subscripts 1 was represent the longitudinal directions of FRP which was also the hoop direction. Then 2 represents transverse directions which was axial direction and 3 s represents thickness which is at radial direction. Hashin Failure Criteria was used to model the failure of FRP composite. Strength in longitudinal and transverse direction of tensile, compression and shear were required to determine in modelling. After that, the material properties of the model used the experimental result from previous study which were tensile and compression test for hoop and axial directions. Because of the limitation of the other properties, secondary source was used for input some properties such as product technical datasheet and qualification testing certificates from the manufacturer. This step was considered acceptable because the most important properties were longitudinal and transverse tensile properties that obtain from experimental result.

To follow the experimental test of composite, three layers of composite shell with 1mm thickness was modelled. A composite shell section was formed and this option can allow us to input properties for each layer of composite wrap. After the input of properties, the translation technique of composite was conducted same as putty because it modelled out of the repair region. Then, defective steel pipe, putty and composite were assembled to form an integrated structure. ABAQUS was default in global Cartesian coordinate system which needed to be converted into cylindrical coordinates. This is because cylindrical coordinate can accurately calculate the pressure vessel in hoop, radial and axial direction, the material properties was also depending on the coordinate system. A built-in coordinate conversion feature was used for assemble all the parts after the conversion.

After the model assembly, the interactions of all bonded interfaces were modelled. The main bonded interfaces include (i) putty to composite, (ii) putty to steel pipe and (iii) composite to steel pipe. The tie constraint option as a perfect bond was used for bonding all interfaces.

Table 3.1 Material propeties of composite wrap

Properties	Value
E_1, (Hoop)	14.3GPa
E_2, (Axial)	10.1GPa
E_3, (Radial)	5.5GPa
v_{12}	0.11
v_{13}	0.43
v_{23}	0.43
G_{12}	0.3284GPa
G_{13}	0.1642GPa
G_{23}	0.1642GPa
Density	1659.2kg/m^3
Ultimate Tensile Strength (Hoop)	241.28MPa
Ultimate Tensile Strength (Axial)	169.43MPa
Ultimate Compression Strength (Hoop)	56.45MPa
Ultimate Compression Strength (Axial)	80.79MPa
Shear Strength (Hoop)	80.30MPa
Shear Strength (Axial)	80.30MPa

Source: Lim (2017)

3.3.8 Execution and validation of composite repaired pipe models

As mention previously, putty and steel pipe were modelled by eight-nodes linear brick elements of type C3D8R. Meanwhile, composite shell was modelled as a reduced integration, S4R type of four-nodes shell element. Then, the composite repaired steel pipe was undergoing analysis and boundary condition applied was same as the defective model. The duration for the analysis was five hundred seconds with ramping up of 0.1MPa/s of pressure rate until 50MPa throughout the simulation. Burst pressure was determined by finite element analysis for validation of modelling purpose. The parameters of the composite repaired model were modified if error margin was greater than 10%.

3.4 Stage 2: Parametric study

The objectives of this research were achieved through parametric study of composite repaired pipeline. For second stage of research methodology, this stage was involved the effect of variation of moisture to the composite repaired pipe models to simulate burst pressure. The prediction of long-term service life for composite repaired steel pipe was carried out. The validated composite repaired pipeline from stage 1 was used to evaluate the moisture effect. The finite element models were generated by using

ABAQUS same as stage 1. The validated model was modified based on the tensile strength of composite that affected by moisture condition. Few sets of models with the remaining strength of composite after exerted in moisture environment was undergoes finite-element simulation. The parameter of composite properties that have been changed includes elastic modulus, longitudinal tensile strength and transverse tensile strength. The model with different remaining strength was ready to analyse and determine the burst pressure. The burst pressure of composite repaired pipeline affected by variation of moisture was later used for predict life span of repaired pipeline. Figure 3.11 shows the detail research methodology undergoes in stage 2.

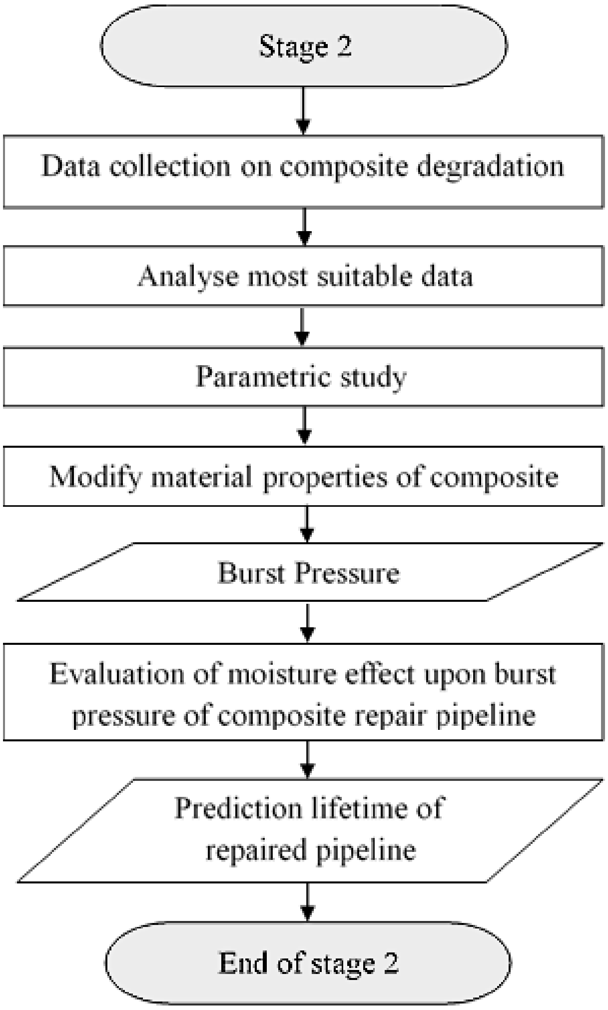


Figure 3.11 Flow chart of research methodology for stage 2.

The available of previous research that study the performance of composite exerted in moisture environment was used to determine the degradation of composite. The tensile strength of the composite immersed to moisture under specific temperature after some time provided in previous study were used to model the composite longitudinal (hoop) and transverse (axial) tensile strength. Transverse tensile strength was about 70 percent of the longitudinal tensile strength from the research. The elastic modulus (*E1, E2, E3*) of the composite was modified if provided by the same research. The composite material used in the experiment was the priority when data collection. The properties that close to the composite used in experimental test of Lim (2017) were glass/epoxy, carbon/epoxy, glass/vinyl-ester and carbon/vinyl-ester.

After collected data were used for parametric study. FE models were developed according to the period and moisture content that provided from the research data collected. The reduction of tensile strength provided was used for assignation of composite longitudinal and transverse tensile strength. Then, the FE model was undergoing simulation for getting burst pressure. The burst pressure was used for evaluation of moisture effect toward the strength of composite repaired steel pipe. The relationship of degradation of composite affected by moisture and burst pressure of pipeline helps in predict service life of repaired steel pipe. The prediction service life of composite repaired steel pipe was useful for giving industrial more confident in application and aware the durability of the composite repaired steel pipe.

3.5 Concluding remarks

This chapter shows the methodology used to study the durability of FRP composite wrap under the effect of moisture environment over period of time. Finite element base models of composite repaired steel pipe were developed and validated against published experimental burst test data. The difference between finite element and experimental result should be less than 10%. The validated base model was used for parametric study. Previous studies on the performance of composite exerted in moisture environment was collected and analysed in order to select the most suitable data. The selected material was used for parametric study by modifying the materials properties of composite into validated model. The hoop and axial tensile strength were replaced into composite material properties to carry out finite element analysis and determine burst pressure. Then the result of burst pressure over time was used for predict the service life of composite repaired steel pipe.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of finite element analysis of base model and parametric study of composite repaired steel pipe according to the proposed methodology (Stage 1 and Stage 2) in Chapter 3. Further discussion of the results was made for the aim of determining the performance of composite exerted in moisture condition in repaired steel pipe. Base model was validated by comparing the burst pressure of Pipe-C in experimental test conducted by Lim (2017). Then, parametric study of the validated base model was used to investigate the durability of chopped strand mat glass fibre/epoxy composite under the effect of moisture absorption. The moisture uptake by the composite in room temperature and its remaining strength was discussed. Besides that, stress sustainability of composite repaired defected steel pipe and each component were also discussed according to immerse duration. It was followed by the comparison of results and discussion of degraded tensile strength with moisture contents, burst pressure with moisture content and burst pressure with time. Prediction of service life of composite repaired steel pipe on moisture effect was also discussed.

4.1 Validation of base model

The development of composite repaired steel pipe model was developed based on the properties provided in experimental data of Lim (2017). The modelling process of composite repaired pipe was complex, some trials were carried out to accomplish acceptable result. The steel pipe was meshed as reduced integration, 8-nodes linear brick elements of type C3D8R generated a total of 121,968 elements with 153,953 nodes. The composite shell was modelled as a reduced integration, 4-nodes shell element of type S4R with 12,432 elements connected by 12,580 nodes. While the putty was meshed as a reduced integration, 8-nodes linear brick elements of type C3D8R with 2,268 elements and 3,248 nodes. The burst pressure of finite element analysis of Pipe-C was 31.77MPa which having error margin of 3.73% compare to experimental burst pressure of 33MPa.

4.2 Parametric study

4.2.1 Moisture absorption of chopped mat glass fibre/epoxy composite

The validated base model was used for parametric study by changing the properties of composite such as tensile strength and elastic modulus. Table 4.1 shows the selected data from previous studies on the performance of chopped mat glass fibre/epoxy composite exerted in moisture environment conducted by Jeffrey et al. (2011). The composite was immersed into water at room temperature for 28 days. The moisture absorption of composite for 1, 7, 14, 21 and 28 days were recorded. Moisture uptake for chopped strand mat glass fibre/epoxy in 1, 7, 14, 21 and 28 days were 1.078%, 2.758%, 3.693%, 4.100% and 4.121%, respectively. Figure 4.1 shows the moisture uptake for the composite for 28 days. The moisture content of composite was increased and about to keep constant when it immersed in water after day-21. This can be said that, it started to reached it saturation condition from day-21. The saturation time for glass fibre/epoxy has been estimated to be 30 days (Khalid et al., 2004). The reduction of moisture uptake may be due to irreversible degradation and/or leaching of low molecular weights (Chin et al., 1999).

Table 4.1 Properties of chopped strand mat glass fibre/epoxy when expose to moisture in duration of 1,7,14,21 and 28 days

Exposure Time (days)	Moisture Content (%)	Hoop Tensile Strength (MPa)	Axial Tensile Strength (MPa)
1	1.078	108.22	75.754
7	2.758	103.88	72.716
14	3.693	99.01	69.307
21	4.100	94.16	65.912
28	4.121	78.84	55.188

Source: Jeffrey et al. (2011)

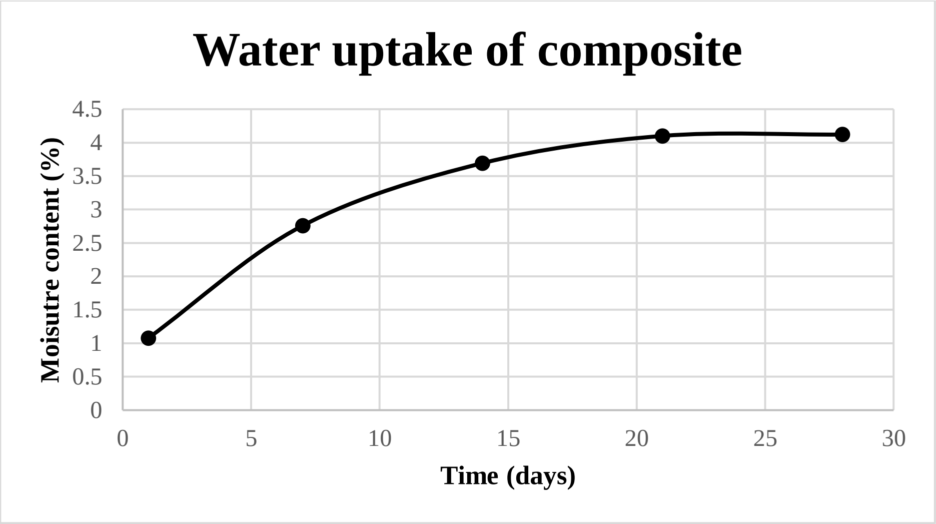


Figure 4.1 Water uptake of chopped strand mat glass fibre/epoxy immersed at room temperature

Source: Jeffrey et al. (2011)

4.2.2 Tensile strength of chopped mat glass fibre/epoxy composite

When a steel pipe is subjected to internal pressure, it will experience highest stress in hoop direction, followed by axial and radial direction. So, tensile properties of material are significant to be considered and understood in analysis (Antaki, 2003; Liu, 2003; Lim, 2017). The steel pipe will fail along longitudinal direction. Axial tensile strength was about 70% of hoop tensile strength. In order to determine more accurate result, axial tensile strength can be determined and modified in finite element model.

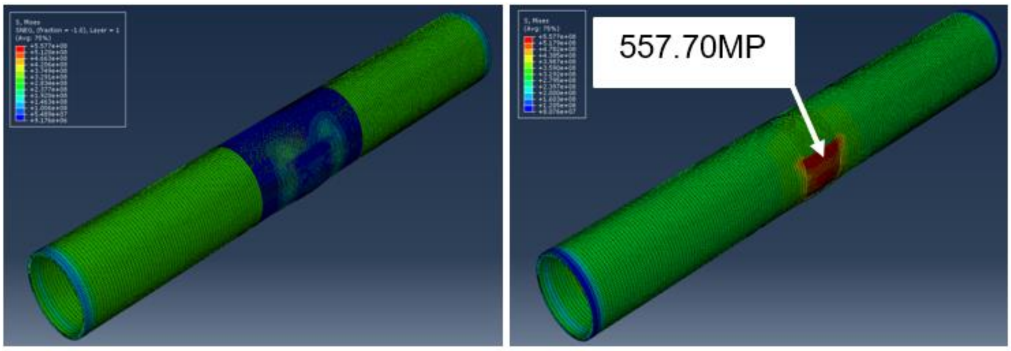
Tensile strength of composite is shown in Table 4.1 according to the exposure duration immersed in water. Tensile strength of composite was decreased with the increase of moisture content. Moisture content of 1.078%, 2.758%, 3.693%, 4.100% and 4.121% resulted hoop tensile strength of 108.22MPa (75.754 MPa for axial), 103.88MPa (72.716MPa for axial), 99.01MPa (69.307MPa for axial), 94.16MPa (65.912MPa for axial) and 78.84MPa (55.188MPa for axial), respectively. The reduction of tensile hoop strength for from day-1 to day-7 was 4.01%, from day-7 to day-14 was 4.69%, from day-14 to day-21 was 4.90% and from day-21 to day-28 was 16.27%. The tensile strength from day-1 to day-21 were decreasing in almost constant trend with about 4-5% while day-28 was rapidly decreasing.

Moisture penetration of composite was largely cause by diffusion and capillary or transport by micro-cracks. Moisture absorption affect the composite to changes in the mechanical, thermo-physical, and chemical characteristics of the matrix by plasticization and hydrolysis. It leads to fibre-matrix bond interface degradation and cause the loss of microstructural integrity. Matrix major properties such as impact resistance was affected significantly (Shilpa, 2010). Hence, the longer the specimen immersed in water, the higher the moisture content, and the weaker the strength of composite.

4.2.3 Stress contour plots

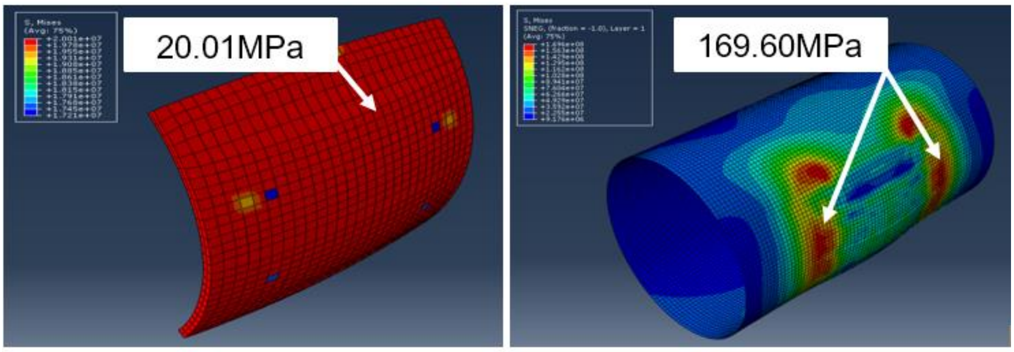
Figure 4.2 shows the stress contour plots result of repaired pipe for the composite immersed in water at room temperature for day-1. The stress contour plots include composite repaired steel pipe model, defective steel pipe, putty, and composite wrap. The highest stress concentration of defective steel pipe was 557.70MPa that located at the edges of defect region along the axial direction. While almost whole putty experiences the stress of 20.01MPa and composite wrap experienced highest stress of 169.60MPa at the corner and two edges of defected region along the hoop direction. Other than that, the finite element results for day-7, day-14 and day-21 were similar which having 167.9MPa of maximum stress concentration at composite. Figure 4.3 shows the stress contour plots of composite repaired steel pipe which composite immersed in water for day-7, day-14 and day-21. The stress sustained by the steel pipe (557.70MPa) and putty (20.01MPa) for day-7, day-14 and day-21 were the same as day-1, while composite was reduced by 1.00% for day-1 (169.60MPa) to day-7, day-14 and day-21 (167.90MPa). The composite sustained highest stress at the same region as composite in day-1.

On the other hand, the stress that can be sustained by composite was continue decreasing to day-28. The concentration of stress for steel pipe and putty in day-28 were also same as day-1, day-7, day-14 and day-21. Composite decrease its sustainability by 23.82% from day-1(169.6MPa) to day-28 (129.2MPa). The highest stress concentration for composite in day-28 was at the corner of defected region. While it also experienced 99.25MPa along both edges of defected region in hoop direction. Figure 4.4 shows the stress contour plot for composite repaired pipe at day-28. From the simulation result, the stress that can be sustained by the steel pipe is much larger than the putty and composite wrap.



Composite repaired steel pipe

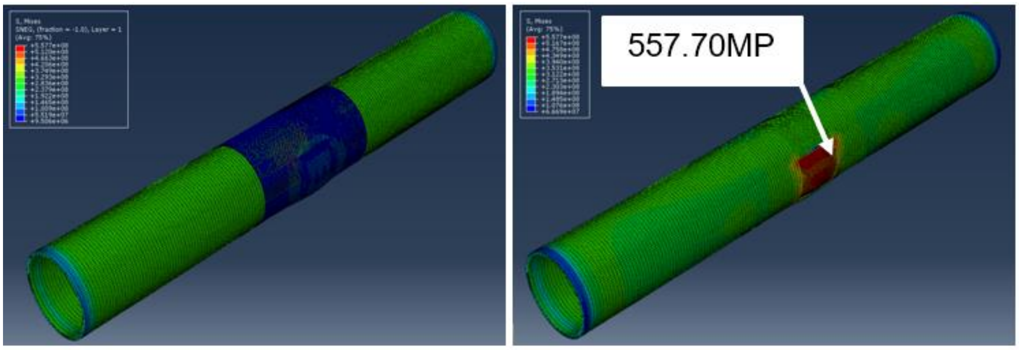
Steel pipe



Putty

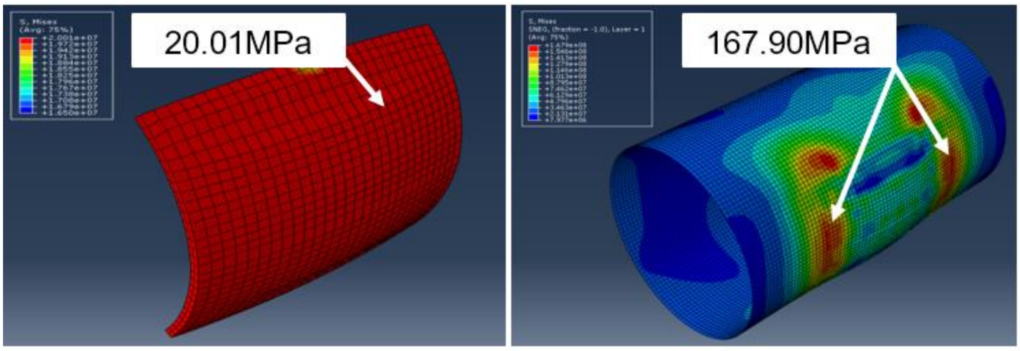
Composite wrap

Figure 4.2 Stress contour plot of composite repaired pipe and each component for day-1



Composite repaired steel pipe

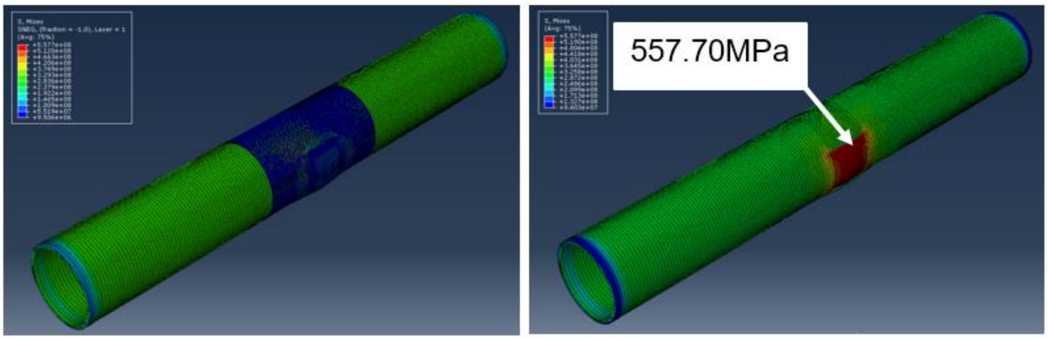
Steel pipe



Putty

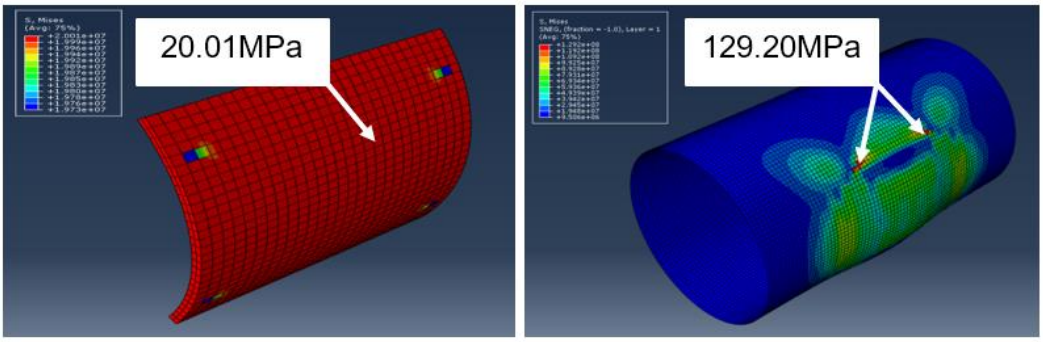
Composite wrap

Figure 4.3 Stress contour plot of composite repaired pipe and each component for day-7, day-14 and day-21.



Composite repaired steel pipe

Steel pipe

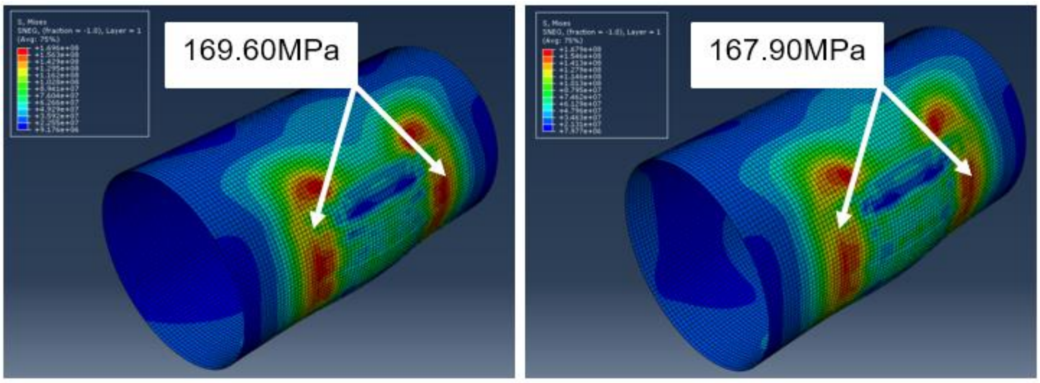


Putty

Composite wrap

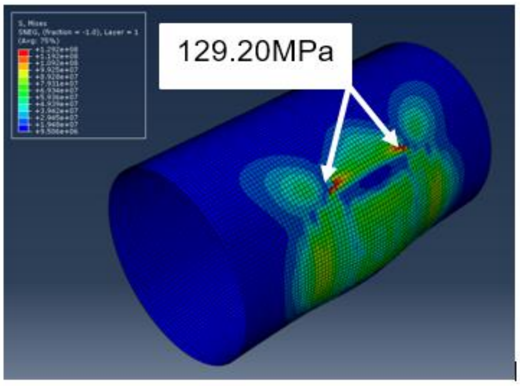
Figure 4.4 Stress contour plot of composite repaired pipe and each component for day-28.

The control composite model with the original strength can sustained the highest stress which was 169.60MPa in day-1 is shown in Figure 4.5. Then, the stress begins to reduce because of moisture uptake that cause the debonding of composite material. Moisture absorption damage the composite through the diffusion of hydrogen molecules of water to the polymer matrix which result in matrix cracks and debonding of fibre-matrix interface (Chin et al., 1999). In day-7, day-14 and day-21, the stress that composite can sustained are very similar which was about 167.90MPa with the percentage drop around 1.00% as compared to the control specimen. Then, the stress that the composite can sustained has continually reduce in day-28 with 129.20MPa and 23.82% drop as compared to control specimen. As mentioned before, the highest stress experienced by the composite for all the exposure time are hoop stress and at the edge of defected region, except for day-28, the corner of the defected region experiences highest stress.



Day 1

Day 7, 14, 21



Day 28

Figure 4.5 Stress contour plot of composite immersed in water at room temperature apply for composite repaired steel pipe for 28 days.

From the simulation result, the degradation of composite was less distinct from day-7, day-14 and day-21. However, after 28 days of exposure to moisture, there was a rapid strength reduction of the composite and the stress that can be sustained also dropped. When the matrix of composite expose to moisture in long term condition, it will result an irreversible damage (hydrolysis and microcracking). Microcracking lead to further mechanical properties degradation and more water absorption beyond the usual equilibrium level of undamaged matrix. The higher the equilibrium moisture content, the higher the swelling stress, thus, higher possibility that microcracking and hydrolysis will occur (Li, 2000). Hence, the longer the duration of composite immersed in water, the higher the moisture uptake, the lower the stress can be sustained.

4.2.4 Burst capacity of chopped mat glass fibre/epoxy composite repaired pipe

The tensile strength of the composite wrap shows a decreasing trend with the increase of moisture uptake as shown in Figure 4.6. The tensile strengths of composite were 108.22MPa, 103.88MPa, 99.01MPa, 94.16MPa and 78.84MPa for moisture content of 1.078%, 2.758%, 3.693%, 4.100% and 4.121%, respectively. Figure 4.7 shows the burst pressure over the moisture content and duration of composite repaired steel pipe immersed in water at room temperature. The burst pressure for control model was 31.981MPa with 1.078% moisture content in day-1. For day-7, the burst pressure had drop to 31.922MPa (0.184% drop) with moisture content of 2.758%. While for day-14, the model fails at burst pressure of 31.905MPa (0.238% drop) with moisture content of 3.693%. The burst pressure continually decreases at day-21 which having burst pressure of 31.901MPa (0.250% drop) with moisture content of 4.100%. For day-28, the burst pressure was 31.663MPa (0.994% drop) with moisture content of 4.121%. Burst pressure over moisture content had shown slightly decrease with non-linear trend from day-1 to day-21 and a rapid drop from day-21 to day-28. The rapid decreased in burst pressure may due to the irreversible damage long term exposure to moisture cause by hydrolysis and microcracking (Li, 2000).

The mechanical properties of composite affected by moisture condition and duration may result to reversible, partially reversible, irreversible, or combination effect. Reversible process involved plasticization and swelling of polymer matrix, the mechanical properties can usually be restored by drying (Antoon and Koenig, 1980). Irreversible process resulting in damage of fibres, matrix cracking, debonding of fibre/matrix interphase region, and delamination caused by swelling and/or internal stress generation (Antoon and Koenig, 1980; Apicella et al., 1982; Schutte, 1994). There were studies had proven that the fibre/matrix interphase region plays a significant role in long term performance of composites in moisture condition (Ishai, 1975a; Ishai, 1975b; Gaur et al., 1994; Wagner and Lustiger, 1994; Xu and Ashbee, 1994). The fibres may leave debonded from the matrix after attack by moisture. The longer the composite expose to moisture, the larger the decrease in strength and modulus of composite and this led to fibre/matrix debonding result to delamination and cracking combined with plasticization of the matrix. Therefore, chopped mat glass fibre/epoxy composite may undergoes combination effect along 21 days and irreversible effect after 28 days result in rapid drop of burst pressure.

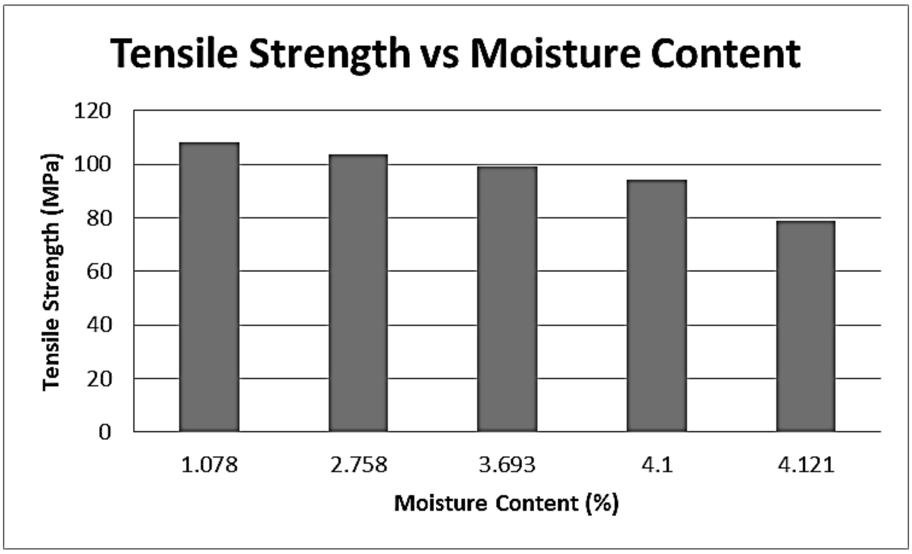


Figure 4.6 Effect of moisture content of composite wrap towards tensile strength.

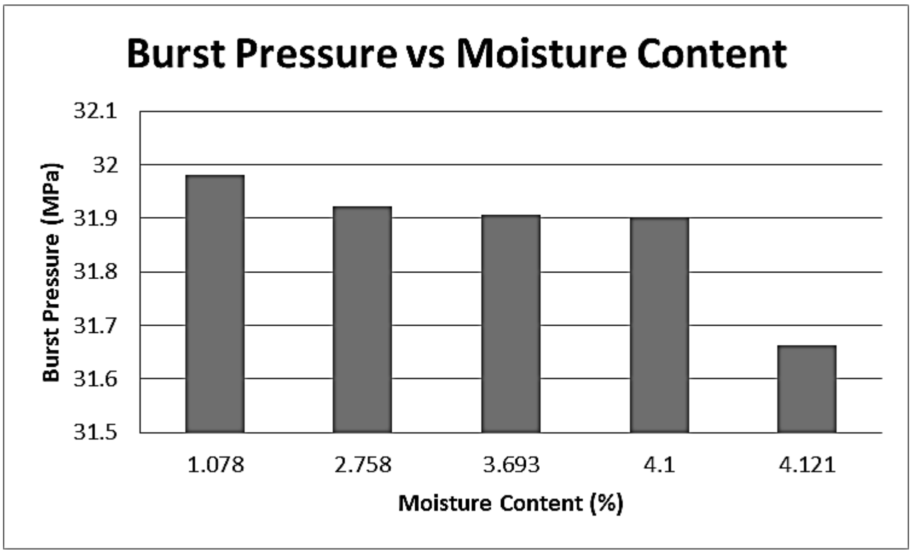


Figure 4.7 Effect of moisture content upon burst pressure of composite repaired steel pipe of day-1, day-7 day-14, day-21 and day-28.

Although there had shown decreasing in burst pressure over moisture content, however the dropping value were small. The contribution of composite wrap to burst pressure is depends on the properties of it such as tensile strength and tensile modulus. The chopped strand mat glass fibre-epoxy has low tensile strength which this tend to reduce the contribution of strength toward the repaired steel pipe.

Figure 4.8 shows the prediction of service life for composite repaired steel pipe using chopped strand mat glass fibre-epoxy composite wrap. Forward forecast was used to predict the service life of over 200 days service period of composite repaired steel pipe and its burst pressure. The composite repaired steel pipe can be used until 178 days if the operating pressure of pipeline is 15MPa. The burst pressure was predicted to reduce by 53.097% as compared to the control model which drop from 31.981MPa to 15MPa after 178 days.

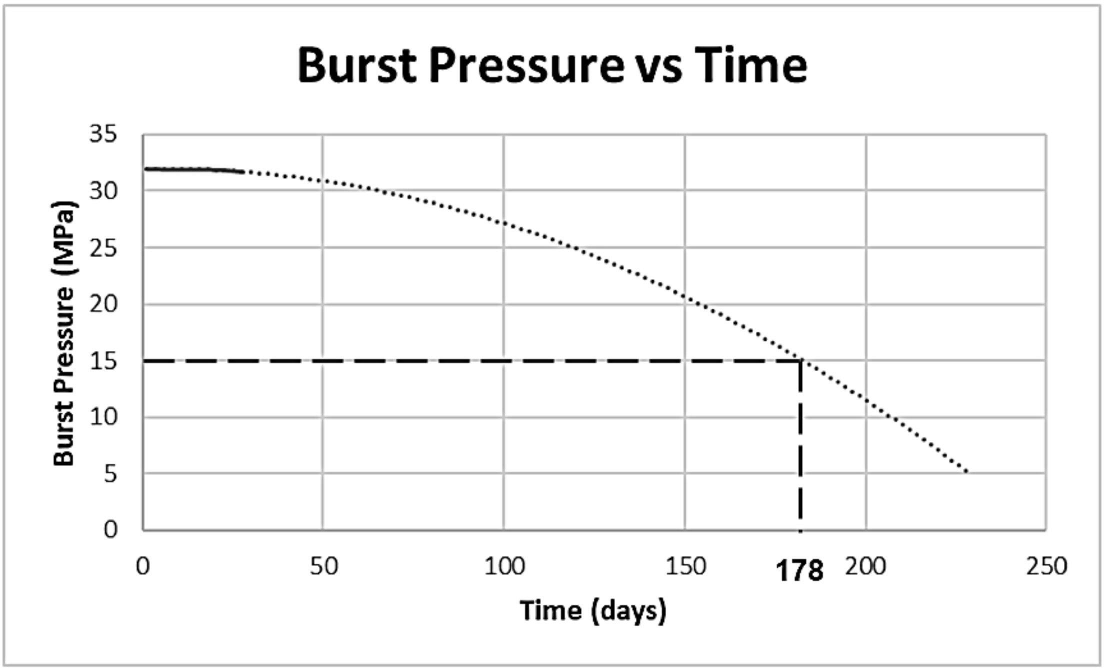


Figure 4.8 Predict service life of composite repaired steel pipe on moisture effect.

The low tensile strength of chopped strand mat glass fibre-epoxy lead to less contribution toward stress sustainability of repaired steel pipe. The condition of the immersed temperature also may affect the degradation of composite. From data collected in research done by Jeffrey et al. (2011), the composite was cure in room temperature result the composite having low glass transition temperature, Tg. The tested temperature of moisture which is room temperature was not significant to effects on mechanical behaviour of composite to become soften and lose of tensile strength (Epoxy Technology Inc, 2012; Sethi, 2014). Polymer matrix composite tends to increase moisture uptake and reduction of tensile strength of fibres if the temperature was above 30°C in long term duration (Gopalan et al., 1989).

On the other hands, the result shows not much effect also may due to short period of tested duration. There are few researches shows that the composite will be affected by high temperature and longer exposure time (Ray, 2006; Shilpa, 2010; Jeffrey et al., 2011; Sethi, 2014). Hence, the moisture effect on composite was not obviously showed by using chopped strand mat glass fibre-epoxy.

Epoxy resin can be confidently used in repair application on moist and underwater condition than other resins because of their anti-corrosive performance and durability. Epoxy resins is considered suitable for pipeline repair both underground and underwater conditions. Epoxy is good in moisture and chemical resistance; however, it also may possess corrosive content and degrade under UV. Therefore, the result of burst pressure shows not much effect on moisture effect may be due to the superior physical and mechanical properties of epoxy (Seica and Packer, 2007; Shamsuddoha, 2014). Although the result shows not much effect of moisture that cause the degradation of composite toward the burst pressure, but there was a trend shows the decreasing of burst pressure when moisture content was increasing. This can be proved that moisture can affect the strength and degradation of FRP composite (Herrera-Franco and Drzal, 1992; Zhou and Lucas, 1999; Ray, 2006; Carbas et al., 2013; Jiang et al., 2013; Sethi, 2014).

4.3 Concluding remarks

This chapter presents the results and discussion of the degradation of FRP composite repaired steel pipe under the effect of moisture over time. Chopped strand mat glass fibre-epoxy composite wrap had shown the reduction of tensile strength when moisture content increasing over time. From the finite element result, the stress that the composite can sustained until day-28 was 129.20MPa with 23.82% drop compare to day-1. The finite element burst pressure simulation result also shows reduction of burst pressure with increment of moisture content. The burst pressure result shows in day-28 was 31.663MPa (0.994% drop) with moisture content of 4.121%. The service life of composite repaired steel pipe can be predicted by using the result of burst pressure over service time. The burst pressure of composite repaired steel pipe decreases from 31.98MPa to 15MPa with reduction percentage of 53.097% after 200 days compare to control model. The contribution of composite is limited because of the low tensile strength of chopped strand mat glass fibre-epoxy which lead to small effect of reduction in burst pressure. Nevertheless, the result had shown a reduction of burst pressure which proved that moisture content increase will lead to degradation of composite.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Overview

The summarization of the findings of this research toward the aims of this study is explained in this chapter. Upon the completion of this study, there was a better understanding on the performance of composite repaired steel pipe that is affected by the moisture content. This study has successfully showed the performance of composite and degradation of the composite repaired steel pipe on the moisture effect. The data collection on tensile strength and elastic modulus of composite subjected to moisture effect was conducted with the aim to study the effect of moisture toward the strength of composite via finite element analysis. Validation of composite repaired steel pipe base model was successfully achieved and it is used for the purpose of further investigation on parametric study. Five (5) finite elements models of different tensile strength based on different moisture content of composite were successfully developed in order to simulate the burst pressure of composite repaired steel pipe. The stress contour plots showing the stress distribution of each elements in composite repaired pipe is also presented and discussed. Its purpose is to determine the highest stress sustained and location by each element. The stress contour plots also successfully show the longer the composite immersed in water at room temperature, the lower the sustainability stress of composite. Then, the burst pressure result was determined by finite element analysis. The degradation of modelling on moisture effect upon burst capacity of composite repaired steel pipe was successfully determined. Lastly, the significant of the findings was explained and helped in future research design the durability of composite repaired steel pipe on environmental effect and provide confident service life of composite repaired steel pipe for industrial.

5.2 Conclusion

The following are the conclusions based on three research objectives:

1. The degradation strength of FRP composite under various moisture effect was discovered. The degradation in tensile strength of composite was determined by collecting data from previous studies on the performance of composite exerted in moisture environment. The tensile strength of composite was decreased with increasing of moisture content. The moisture uptake on day-28 of composite was 4.121% with 78.84MPa hoop tensile strength. The reduction of tensile strength for hoop from day-1 (108.22MPa) to day-28 (78.84MPa) was 27.15%. The tensile strength from day-1 to day-21 were decreasing in almost constant trend with about 4-5% while day-28 was rapidly decreasing.

2. The burst pressure of composite repaired steel pipe subjected to moisture condition was studied by using finite element analysis. The burst pressure of composite repaired steel pipe exposed to moisture condition decreases when the tensile strength of composite decreased and at the same time increase in moisture content. At day-28, the burst pressure was 31.663MPa with 0.994% drop compare to burst pressure of day-1 which is 31.981MPa. The contribution of composite is limited because of its low tensile strength which lead to small effect of reduction in burst pressure. However, the result had shown a reduction of burst pressure which proved that increase of moisture content will lead to degradation of composite and subsequently the repaired pipe.

3. The service life of composite repaired steel pipe was determined by using burst pressure result. By using chopped strand mat glass fibre-epoxy as composite wrap of repair pipe, the service life of having an operating pressure of 15MPa was predicted can be last for 178 days which having the reduction of burst pressure from day-1 (31.981MPa) to day-28 (15MPa) with percentage drop of 53.097%.

5.3 Significant of research contribution

This research has significant impact towards the understanding of long-term performance of composite repaired steel pipe. It is important to identify the contribution of composite strength toward composite repaired steel pipe because steel pipes were operating under different environment that may lead to degradation of composite. The finding of composite tensile strength from previous studies on the performance of composite under moisture effect provide useful input for finite element composite repaired pipe model. The finite element model that includes the remaining tensile strength of composite under moisture effect can provides more accurate finding of degradation period of composite repaired steel pipe. This research shows the importance of environmental effect on material properties of FRP composite. The material properties of composite will further affect the burst pressure of composite repaired steel pipe. With the information of environmental effect, material properties of composite and burst pressure, long-term serviceability of composite repaired steel pipe can be determined. Prediction service life of composite repaired steel pipe was significant for industry to provide more confident and accurate information for the degradation of composite steel pipe. With the predicted service life of composite repaired steel pipe, the preparation of repairing degradation damage of composite steel pipe can be done before it fails.

5.4 Recommendations

Future research recommendations on improving the accuracy of long-term service life of composite repaired steel pipe is provided as follows:

1. Data collection of composite materials used for degradation study can be of higher tensile strength than chopped strand mat glass fibre-epoxy in order to get higher contribution strength to composite repaired pipe and result in more obvious degradation of burst pressure.
2. Data collection of composite materials tested duration can be longer in order to determine the larger degradation difference of tensile strength.
3. Experimental work can be done in order to validated the finite element analysis result.
4. Other environment condition such as temperature can be added to further study the degradation of composite repaired steel pipe. (i.e.: Room temperature, 60°C and 90°C)

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