EFFECT OF DEFECT WIDTH UPON BURST CAPACITY OF COMPOSITE REPAIRED PIPE

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ABSTRAK

Dalam tahun-tahun kebelakangan ini, penggunaan komposit polimer diperkuat gentian (FRP) dalam pembaikan saluran paip adalah salah satu sistem pemulihan saluran paip yang lebih digemari dalam industri saluran paip. Walau bagaimanapun, beberapa isu tentang kaedah pembaikan ini tidak difahami sepenuhnya oleh industri. Kesan geometri kecacatan mempengaruhi kecekapan paip yang dibaiki dengan komposit adalah salah satu isu yang menjadi perhatian industri. Kods dan piawaian untuk reka bentuk saluran paip telah dibangunkan dengan memberi tumpuan kepada kedalaman kecacatan dan mengabaikan geometri kecacatan lain seperti panjang kecacatan dan lebar kecacatan dalam memperbaiki saluran paip yang rosak. Kajian lepas menunjukkan bahawa kod dan piawaian ini dianggap konservatif dan terdapat ruang untuk pengoptimuman. Kajian terdahulu menyatakan bahawa geometri kecacatan terutamanya lebar kecacatan tidak boleh diabaikan dalam menilai dan merekabentuk sistem pembaikan paip. Ini juga terbukti dalam beberapa kod penilaian yang menggunakan geometri kecacatan sebagai salah satu parameter untuk menilai keadaan paip secara berkesan. Oleh itu, tekanan letus dari saluran paip yang rosak tertakluk kepada pelbagai lebar kecacatan ditentukan melalui kajian ini untuk menilai kesan lebar kecacatan kepada kapasiti letus paip diperbaiki komposit. Analisis unsur terhingga digunakan untuk menentukan kapasiti letus paip diperbaiki komposit dengan bentuk kecacatan segi empat tepat. Terdapat tiga lebar yang berlainan (*D*, *½D* dan *2D*, yang mana *D* ialah diameter paip) dipilih untuk dianalisa tanpa perubahan pada panjang dan kedalaman kecacatan. Model asas paip yang diperbaiki oleh komposit telah dibuat, disahkan dan diubahsuai dengan pelbagai lebar kecacatan yang disebut sebelum ini. Hasil kajian menunjukkan bahawa tekanan letus bagi tiga model berbeza-beza dengan peratusan 12.51% antara tekanan letus maksimum dan tekanan letus minimum. Gambar rajah plot kontur tekanan yang didapati daripada analisis unsur terhingga juga menunjukkan bahawa kawasan kepekatan tekanan tertinggi (557.7MPa) sekitar rantau kecacatan semakin besar apabila lebar kecacatan semakin luas dimana kawasan kecacatan juga semakin besar. Dengan ini, paip yang diperbaiki oleh komposit akan mengalami kegagalan dalm tekanan yang lebih rendah apabila kecacatan semakin meluas. Berdasarkan dapatan ini, lebar kecacatan terbuktikan akan mempengaruhi kepasiti letus paip yang diperbaiki oleh komposit.

ABSTRACT

In recent years, application of FRP composite in repairing steel pipeline is the most preferable pipeline rehabilitation system used in the pipeline industry. However, some issues about this repair method are not fully understood by the industry. Effect of defect geometry toward the efficiency of composite repair pipe is one of the issues that concerned by the industry. Design codes and standards of pipeline repair method have been developed mainly focus on defect depth and neglect other defect geometries such as defect length and defect width in repairing damaged pipeline. Past researches show that these codes and standard are considered conservative and there are rooms for optimization. Previous studies states that defect geometry especially defect width should not be ignored in evaluating and designing pipe repair system. This is also proven in some of the assessment codes that used defect geometry as one of the parameter to effectively assess the condition of pipe. Therefore, the burst pressure of the defective pipeline subjected to various defect widths is determined through this study in order to evaluate the effect of defect width upon the burst capacity of composite repaired pipeline. Finite element analysis was used to determine the burst capacity of the composite repaired pipe with rectangular shape of defect. There are three different widths (*D*, *½D* and *2D*, where *D* is the pipe diameter) were selected for analysis with no changes on defect length and depth. The base model of composite repaired pipe was created, validated and modified with the various defect widths that mentioned before. The result shows that burst pressure for three different models vary with a percentage of 12.51% between the maximum burst pressure and minimum burst pressure. The stress contour plot diagrams that extracted from the finite element analysis also shows that the area of highest stress (557.7MPa) concentration around defect region is getting bigger when the defect width is getting wider with the defect area getting larger. With this, the composite repaired pipe tends to fail at lower pressure when the defect is getting wider. Based on the results, the defect width is proven to affect the burst capacity of composite repaired pipe.

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LIST OF SYMBOLS

σ_{H}	Hoop stress of pipe at failure
$\overline{\sigma}$	Material flow stress
$\sigma_{m(YS)}$	Specified Minimum Yield Stress (SMYS) of the material
σ_A	Longitudinal compressive stress due longitudinal force
σ_B	Longitudinal compressive stress due to bending moment
σ_L	Combined nominal longitudinal stress
γ_d	Partial safety factor for corrosion depth.
γ_m	Partial safety factor for corrosion model prediction
ε_c	Allowable circumferential strain of the composite
ε_d	Factor for define fractile value of corrosion depth
ξ	Usage factor for longitudinal stress
θ	Ratio of circumferential length of corroded region to the nominal circumference of the pipe
A_r	Circumferential area reduction factor
c	Circumferential length of corroded region
d	Depth of defect
D	Outer diameter of pipe
E_c	Tensile modulus for the composite laminate in circumferential direction
E_s	Tensile modulus for substrate material
f_u	Tensile strength to be used in design
F	Safety factor
F_a	Total axial tensile loads due to pressure, bending and axial thrust
F_{eq}	Equivalent axial load
F_x	External longitudinal force
H_1	Factor to account for compressive longitudinal stresses
L	Maximum length of defect
M	Folias factor
M_y	External bending moment
P	Internal design pressure
P_{corr}	Maximum allowable operating pressure
$P_{coor,comp}$	Maximum allowable pressure in corroded pipe

P_{live}	Pipe internal pressure during repair
P_s	Maximum Allowable Operating Pressure (MAOP)
s	Specific Minimum Yield Strength (SMYS)
t	Remaining wall thickness of corroded pipe
t_{repair}	Design repair laminate thickness
t_s	Minimum remaining wall thickness of the composite

LIST OF ABBREVIATIONS

ASME	American Society of Mechanical Engineers
DGEBA	Diglycidyl Ether of Bisphenol-A
DNV	Det Norske Veritas
FE	Finite Element
FRP	Fibre Reinforced Polymer
MAOP	Maximum Allowable Operating Pressure
SMTS	Specified Minimum Tensile Strength

CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

Steel pipelines have been used as a basis element to transport oil and natural gas in large quantities over a long distance. This can be seen in the pipeline industry performance report, which launched by the Canadian Energy Pipeline Association (CEPA). CEPA stated that 2.9 billion dollars were spent in maintaining and monitoring pipeline systems over 2013 and 2014 (Canadian Energy Pipeline Association., 2015). Pipelines are considered as the most effective and economically reliable transportation mode for natural gas and oil as it can resist high pressure of fluid and gases (Ehsani, 2015). However, deterioration will happen on pipeline when oil and natural gas pipelines are exposed to the critical environment such as underground or fully submerged in seawater. Besides that, other factors such as material and construction defects, mechanical damage from construction, corrosion, creep and so on (Kishawy and Gabbar, 2010) will also cause deterioration on pipeline. Hence, reduction of bearing capacity of pipelines, wall thinning or cracks might happen and leakage of oil or gas might be the results of these deteriorations. This condition will become a threat to human health and pollution in the environment. Besides that, a corroded pipeline will lead to high expenses on repairing defective pipeline and cause inconvenience to the industry as the strength of pipeline will be reduced as well as service life of the pipeline.

The negative effects of deterioration on the pipeline can be seen in accidents such as explosion and pollution to environment that happened in recent years. This can be proven by the accident happened in Marshall, Michigan in 2010 when the ruptured pipeline released 4200m^3 of crude oil to the surrounding wetland and Kalamazoo River (National Transportation Safety Board, 2010). Besides the negative effect of oil spill towards the environment, clean-up efforts in this accident needed 767 million dollars to complete even though there were no fatalities reported. An explosion of the crude oil pipeline in Qingdao in eastern China killed 62 people and injured 136 people in 2013. This explosion caused 124.9 million dollars of direct economic loss and the oil spill had caused pollution to the about 3000 m^2 of sea water. Worker error on repairing the corrode pipeline as non-explosion proof hydraulic hammer was used and lighted sparks that caused blast in the pipeline (Aizhu, 2013). With all these accidents happened and pipeline that in service failed prematurely, the predominant techniques to rehabilitate the damaged pipeline due corrosion and metal loss is important to be available in the industry.

There are numerous repair methods available for the corroded pipeline of onshore or offshore. For instance, replacement of a new pipe for the entire damaged pipe or only for the particular section of the damaged area. Welding steel sleeve to the existing pipe also a technique to repair pipeline because the steel sleeve will act as a new pipe to the pipeline when defect fails and it will maintain the flow of resource in the pipe and thus the pipe system can operate as usual. Although these techniques are effective, but time-consuming, costly and dangerous if using welding work near the volatile substances inside the pipe (Melander and Österberg, 2016). In recent years, many pipeline operators prefer to use Fibre Reinforced Polymer (FRP) repair system to restore the strength of damaged pipes. The corroded defect area on the transmission pipeline will be strengthening by wrapping a composite sleeve bonded by epoxy grout to the pipe. Furthermore, the FRP composite offers many advantages such as corrosion resistance, lightweight, dimensional stability and high strength (Saeed, 2015). Besides the advantages offer by this method, there are some issue about the behaviour of FRP composite polymer occur and not fully study by the industry such as complexity of surface preparation for repairing, de-bonding between defective pipe with composite polymer, performance and contribution of the infill material, effect of defect geometry and conservativeness in existing design codes (Lim et al., 2015). Amongst the issues, FRP composite repair system that focused in this research aims to study the effect of defect width towards burst capacity of a composite repaired pipe.

1.2 Research Problem

Nowadays, deteriorations caused by corrosion towards pipelines have been the greatest concern of the oil and natural industry to maintain the pipeline integrity. This is stated by NACE International, where corrosion problem was estimated to cost 2.5 trillion dollars annually worldwide, which is 3 to 4% of Gross Domestic Product of industrialized countries (Gerhardus et al., 2016). Besides pipe wall thinning due to corrosion, other factors such as material degradation and cracks that cause a defect on the pipe are also the main concern of the pipeline operators. The condition of pipeline contains corrosion defect will have the negative impact of high stress concentration at the deepest point of flaw area, the pipeline may burst at that point if the operating pressure in the pipe has reached its maximum burst pressure (Fekete and Varga, 2011). However, it is not necessary to repair or replace the whole pipe when there are some minor defects occur on the pipe. Evaluation of the pipeline condition will be conducted with assessment codes and standard to determine whether the pipeline is still safe to operate. If repairs are necessary, pipeline operators can choose the most suitable repair system based on the condition of the pipeline (Lim et al., 2015).

Fibre reinforced polymer composite repair system is one of the repair technique that is widely used by oil and natural gas industry. It is used with the recent development of design codes and standards in recovering the damaged pipeline. Standards such as ASME PCC-2 and ISO 24817 were developed for the industry in designing the composite repair system to ensure the safety and effectiveness of the repaired pipeline (Alexander and Worth, 2010). These standards are known to be conservative as they implemented overdesign repairing method due to safety factory and premature replacement which is costly (Duell et al., 2008). Remaining pipe wall thickness and outer diameter of pipe are the parameters that considered in these codes standards but the defect geometry is neglected. In contrast, some of the assessment codes and standards considered defect geometry as one of the parameter to evaluate the condition of corrosion defects on the pipe by determining the remaining strength of the corroded area. Besides that, many modifications have applied on some of the original equations of assessment codes and standards to reduce conservativeness. For example, code ASME B31Gmod was modified from the code ASME B31G, which was developed by the American Society of Mechanical Engineers and was adopted as the US national standard (American Society of Mechanical Engineers, 1991). This assessment code only accounts the remaining pipe wall thickness, maximum defect length and outer diameter of pipe but neglect the defect width. In contrast, some of the assessment codes such as DNV-RP-F101 used defect width as one of the parameters to estimate the burst pressure of the damaged pipeline (DNV, 2010). The defect geometry especially defect width on the damaged pipe section should be considered in evaluating and designing pipeline repair system because it actually has influence on the burst strength of corroded pipe section. This statement can be seen from the study of Cunha and Netto (2012) where the authors stated that the prediction of the burst pressure of flaws not only depends on the material properties, but also on the defect geometry. By considering the influence of defect width, the composite repair system may be less conservative and more realistic in using the adequate amount of material to rehabilitee the damaged pipelines. The improved composite wrap repair system will result in reducing the cost of material and labours. Finite Element (FE) analysis have been developed to ensure the optimum repairing cost and the safe operation of a repaired pipeline. With the limited information about the behaviour of repairing material related to the dimension of a defect, the Finite Element Modelling (FEM) of the corroded pipeline is difficult to carry out. Detailed research and experiment need to be developed by focusing on the effect of defect width and material properties in sustaining the maximum pressure to support the development of maximum burst capacity of pipes (Chiodo and Ruggieri, 2009a).

1.3 Research Objectives

This research will be conducted according to the objectives below:

1. To determine the burst pressure of the externally corroded steel pipeline subjected to various defect widths.

2. To evaluate the effect of defect width towards burst capacity of a composite repaired pipe.

1.4 Research Scope

This research focuses on the prediction of failure of burst capacity of composite repaired pipe subjected to various defect widths. The effect of defect geometries such as length and depth of defect on the composite repaired pipe are not covered in this study. Besides that, the type of pipe damage for this study is limited to external corrosion defect. Finite element analysis was used to stimulate various defect widths on the pipe to investigate the maximum burst capacity of the repaired pipe by the composite wrap.

1.5 Significance of Research

Nowadays, the increasing number of accidents caused by the aging of pipelines are worried by the oil and natural gas industry. The pipeline operators cannot afford the economic consequences of reducing pipeline operating pressure and low production due to the stop operation of a pipeline for replacement or repair actions on the damaged or aging pipelines. Consequently, some of the pipelines were still in operation without repair them after ensuring the corroded pipeline can sustain the maximum pressure in transporting product and neglect the risk of accident might happen if situation get serious due to unknown factors. For the convenient of pipeline operator, a more accurate method to determine the residual strength of pipelines should be introduced by considering all necessary parameter of the defect of the pipe. The practice for assessing corroded pipelines has been carried out for many years and modification has been done to improve the performance of these standards. Despite the modification, current assessment codes still considered conservative as these codes included the safety factors that sometimes can be costly and a waste of material to repair. Most of the practices only consider defect length and defect depth as the only parameters to define defect but the defect width is hypnotically poses influence on the remaining strength of corroded pipelines. Therefore, the repair codes and standard that used to design composite repair method should also consider defect geometry as one of the parameters to determine the minimum repair thickness of composite wrap if it is proven influential. The defect geometry might influence the overall performance of the repair method as the corrosion happened on the pipe cannot be totally prevented and corrosion cannot be stopped to grow. When there are cracks on pipeline, failure of pipeline will eventually happens and this might lead to serious consequence such as explosion and pollution to environment. Therefore, more detailed information about the effect of defect geometry should be gained by conducting more detail study and experiment in order to determine whether there are necessary to include defect geometry to optimise the design codes and standards. This will be a good news to the pipeline operator to effectively estimate the useful life of pipelines depends on its residual strength. The accuracy on determining the repair thickness of composite wrap will also benefit the pipeline operators as the overdesign composite repair system might lead to the area out of the repair region failed first before the defect area do. With this result, not only the operation of the business will not be interrupted, but also the pipeline can be safer to be used by any party without any accidents happens that cause death and worry to the society in future.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter presents the types of defects occur over the pipelines and the consequences happen when the defect getting worse. The currently available corroded pipeline repair system by using composite material is explained in details. This is followed by a detailed review of the behaviour of infill material performance in composite repair system for a better understanding on steps of damaged pipeline rehabilitation techniques. Current codes and standards using by industry to evaluate the residual strength of pipelines and design the repair system also included and discussed in this chapter for better understanding of this topic.

2.1 Introduction of Pipeline

Steel pipe mostly used in transporting liquid and gas over other transportation modes such as truck and rail. The steel pipelines are considered more economical, less damage to the environment and more reliable (Liu, 2015). However, when the pipeline is aging, the pipeline will faces the risk of deterioration because most of the oil and natural gas pipelines are operated in a harsh environment such as underground and subsea. The deterioration can be in the form of corrosion, crack, wearing, dents, leaks and rupture (Shamsuddoha et al., 2013b).

Corrosion and metal loss of pipelines are the most common deterioration that happened on steel pipelines in oil and natural gas industry. Reduction of pressure bearing capacity and risk of failure in operation will occurs due to corrosion and these will leads to accidents which cause loss of money (Khan et al., 2017). However, not all the damages occurred on pipeline need to be repaired. The pipeline operator will assess the pipeline condition when defect is detected. Repair action will be confirmed if the pipelines are necessary to repair due to the safety factor. In order to maintain the operation of corroded pipelines, suitable repair system is the main concern of the pipeline operator in the oil and natural gas industry. Fibre reinforced polymer composites (FRPs) are recently widely used in strengthening, retrofitting and repairing of existing structures especially in repairing oil and natural gas steel pipelines (Saeed, 2015). FRPs are corrosion resistance, lightweight, poses high specific strength and easy to manufacture and install. However, there is uncertainty about the performance of the composite repair system as remaining wall thickness of pipes after corroded is the only the parameter being considered in current repair design codes. In order to improve the efficiency of composite repair system, further studies and investigation on the effect of defect geometry on the efficiency of repair design code on composite repaired steel pipeline should be carried out on evaluating the damaged pipeline condition to choose appropriate repair technique.

2.2 Type of Defect in Pipelines

Although steel pipeline is more preferable to be used in the transmission of oil and gases compared to other types of transportation due to its reliability and convenience, pipelines do fail sometimes like other engineering structure. According to Köpple et al. (2013), the failure may be caused by coating damage, erosion, corrosion or mechanical damage. The most common defect in oil and gas transmission pipelines is internal and external corrosion of the pipelines. The surface corrosion may lead to a risk to the structural integrity of pipe when the thickness of steel pipes getting thinner and also affect the burst bearing capacity of pipelines (Kumar et al., 2018). In addition to corrosion defect, mechanical damage defects such as dents and gouges will also affect the structural integrity of pipelines.

Corrosion occurs in steel pipelines is a natural process of metal material deteriorates through electrochemical reaction with its environment. This reaction begins with the presence of water which oxidizes the iron on steel pipeline and transfer electrons to the nearby oxygen atoms that act as an anode to precipitate and oxidize to produce rust. This reaction result with metal loss. There are external and internal factors that will influence the rate of corrosion of pipeline (Prabhu, 2016b). The external factors that affecting the rate of corrosion are the environment surrounding the pipeline, moisture condition of the underground pipes, and types of water for submerges pipes. Besides that, the presence of oxygen atoms or reactivity liquid and gases nearby the metal pipes is one of the internal factors that accelerate the rate of corrosion reaction. Another internal factor that affecting the rate of corrosion is the different types of metal used in the pipelines.

There are various common types of corrosion such as uniform corrosion, pitting corrosion, erosion corrosion and stay current corrosion (Vanaei et al., 2017). First of all, uniform corrosion is the most common type of pipeline corrosion. It has the condition of uniform loss of metal along the surface of the pipeline. Wall thinning will occurs on either external or internal surface of the pipes and it can cause leakage of pipeline once the condition of wall thinning continues to get severe. The rate of uniform corrosion is measured by the depth of penetration of corrosion from the surface of pipes with the units of mills per year (mpy) or millimetres (mm) per year. It can be prevented by selecting the appropriate methods such as cathodic protection, corrosion inhibitors, protective coating, and select the suitable piping material.

Pitting corrosion usually can be observed on the oil and natural gas transmission pipelines. It is a threat to the pipeline because it will attack a particular surface area of pipes and forms a hole that can penetrate through the pipe wall (Vanaei et al., 2017). Deterioration due to pipe material defect, damage on passive film around the pipe, or attack by aggressive chemicals will happen within that area. Stress corrosion crack will be the consequence of pitting corrosion experience the stresses from transmitting material. This types of corrosion can be controlled by using protective coating, selecting suitable pipe material depends on the service environment and controlling the chemical in material flow.

For the internal surface of the pipeline, the erosion corrosion is caused by the flowing of corrosive fluid against the internal surface of the pipe (Vanaei et al., 2017). It normally will attack the bends in pipelines and form holes in the direction of fluid flow. The pit formed on the inner surface of the pipeline will disturb the fluid flow and lead to fluid turbulence which will accelerate the rate of erosion (Prabhu, 2016b). As a result, the protection passive films on the pipeline will be damaged due to the vapour bubbles and the rate of local corrosion will be accelerated. Protection against erosion corrosion on the pipeline can be improved by cathodic protection and increase the internal diameter of the pipe to reduce the velocity of the fluid in promoting smooth fluid flow (Prabhu, 2016a).

Lastly, stray current corrosion is one of the types of corrosion that occurs at the outer surface of a pipe when there is a flow of stray currents through pipelines (Vanaei et al., 2017). This will lead to the formation of pinholes on the surface of pipes at the particular points where the stray current contacted with the surface. The stray current has the resources from high voltage overhead and buried electrical transmission line, railway with electrical train, and other electrical mechanics nearby. The reduction methods on this type of corrosion are controlling leakage of electricity and transmitting the stray current to an earthen station to earthen the source of current (Vanaei et al., 2017).

According to Øyvind Høie, dents can be defined as permanent plastic deformation at the outer surface of a pipe (Høie, 2015). It is also characterised as the gross distortion of a circular cross section of pipe. Dents induce local stress concentration at the corroded point with a result of the reduction of pipeline material properties. With this, the depth of the dent, which is the maximum reduction in diameter of a pipe compared to its original diameter, will be one of the factor influence the burst strength of plain dent. There are several types of dents such as smooth dent, kinked dent, plain dent, constrained, and unconstrained dent. Smooth dent is the dent that causes smooth changes in the curvature of the pipe wall. Kinked dent is a dent that change the curvature of the pipe wall with the value of the radius of curvature at the thinnest part of the dent less than five times the wall thickness. Kinked dents, which is not welded, have high stress and strain concentration factors due to severity local bend radii and this dents treated as severe defects that need to be noticed (Allouti et al., 2014). Moreover, plain dent is a smooth dent that has no reduction in wall thickness or other changes due to defect or imperfections such as weld seam. Constrained dent is a dent that cannot be freely rebound as the indenter cannot be removed. In contrast, an unstrained dent can be free to rebound elastically when indenter is removed and internal pressure changes.

Gouges occurs on pipes when the metal of pipe is removing from pipe surface (Allouti et al., 2014). It normally happens when external objects contact and slide across the pipeline surface. There will be some penetrations to the coating of pipe surface when gouges occur on the surface of pipes. With this, corrosion will happen to damage the pipes as this defect will have high stress concentration due to reduction of cross section thickness and lower capabilities of pipes to sustain the pressure applied on them (Høie, 2015).

2.3 Pipeline Repair System Using Composite

The traditional techniques to repair damaged pipeline are either remove and replace the whole or some pipes sections that have serious defects or insert steel clamp around the localized damage on the pipeline by welding or bolting. Fibre reinforced polymer (FRP) matrix composite overwrap systems recently have been an alternative choice for the pipeline repairing system. This method has a lot of advantages and it can eventually win over the conventional repair methods. The repairing process that does not involve hot work such as welding can avoid possible explosion. In the same time, the pipeline can be in operational while repairing and the duration of applying FRP composite wrap on the damaged pipe section is short (Duell et al., 2008). Another advantage of using FRP composite wrap is slowing down the further corrosion occurs on the pipe by covering up the damage from contacting with the environment that will worsen the corrosion (Duell et al., 2008). There are various types of repair systems that have been developed for industry to use FRP composites such as wet lay-up systems and pre-cured layered systems (Lim et al., 2015).

According to Ehsani (2015), wet lay-up method is the basic repair pipeline system. The damaged surface of pipes has to be cleaned to remove loose material particles before the process of wet lay-up. Infill material such as epoxy resin is applied at the defect section and resin matrix will also applied on the surface of pipe. The resin matrix applied to the corroded pipe surface is to create a stiff cover over the damage part after curing. This defect section will be wrapped by composite cloths which is fibre fabric to recover the load capacity of pipeline. Care must be taken while carry out the repair as proper bonding between FRP composite wrap and damaged pipes is required to withstand the stresses in pipeline as assumed by many design (Ehsani, 2015). Besides that, wet lay-up method can be applied to a complex geometries such as bends, tees and valves (Lim et al., 2015). This method also has its disadvantage when in the areas with high ground water table, the repair system will be difficult to install when the resin is curing. This will leads to improper curing which will affect the ability of resin matrix to transfer and the repaired pipeline cannot perform with fully strength. It also not the best choice to repair the damaged pipelines with narrow area surrounding them (Lim et al., 2015).

Pre-cured layered system is a pipeline repair method that bonding the pre-cured fibre composite layer to the outer surface of pipeline using adhesive in between them

(Lim et al., 2015). At first, the defect area on pipe will be filled with infill material that have high compressive strength and it is used for load transfer in the pipeline. Strong bonding adhesive will be applied on the pipe between the layer of composite wrap and infill material. The high strength FRP composite material will be wrapped in coil around the pipe on top of adhesive and infill material. This repair system is generally restricted for straight sections of pipe and this will be a disadvantage for pre-cured layered system compared to flexible wet lay-up method which is not limited on application to other components such as joints and bends. However, the pre-manufactured fibre composite, which has better quality control, will be able to perform with enhances mechanical properties while there are increasing of fibre volume fractions (Ehsani, 2015).

2.4 Infill Material

Some of the FRP repair systems such as flexible wet lay-up system and pre-cured layered system are using grout or putty as infill material to fill the corroded defect section in pipe (Duell et al., 2008). Infill grout fill the damaged section in pipe is to provide a smooth surface for the composite layer to lay on for the purpose of ensuring the load sustained by the pipe is successfully transfer to the outer composite layer. The load sustained by the pipe including the internal pressure towards pipe will be shared by the composite wrap as the composite sleeve act as a part of pipe. The infill grout will also support the defect on pipe by minimizing the outward deformation. Therefore, the performance of pipeline repair systems is largely influence by the properties of infill grout that act as a bridge to transfer load to the load carrying component, the composite sleeve (Shamsuddoha et al., 2013a).

The properties of epoxy grouts are the important elements that needed in designing an optimum pipeline repair system because the performance of repair system can be predicted with the behaviour of grouts. Shamsuddoha et al. (2013a) stated that the function of epoxy grouts to transfer load and effectiveness of FRP repair system are affected by the mechanical characteristics of the grouts, which are compressive strength and modulus elasticity (Shamsuddoha et al., 2013a). Besides that, in the research of Duell et al. (2008), a DGEBA (Diglycidyl Ether of Bisphenol-A) based epoxide cured with alphatic amine hardener with a silica additive act as putty to refill the defects in pipe with woven carbon fibre fabric act as composite wrap to provides structural reinforcement. The result suggested that the composite wrap is the first component that reached the failure criterion. This shows that the putty successfully transfers load from steel pipe to composite to share the load. Moreover, it was suggested by da Costa-Mattos et al. (2009) that epoxy resin should apply with composite sleeve to cover the defects on pipe to ensure the structural integrity of pipeline to a satisfactory level. There are two different epoxy resin used in the study of da Costa-Mattos et al. (2009), which are silicon steel alloy mixed with high molecular weight polymer and oligomer, and aluminium powder with epoxy resin. The properties of epoxy grout is one of the important parameter that required to conduct numerical stimulation or prediction of the performance of a composite repaired pipeline for an optimum design. Therefore, it is essential to select suitable epoxy grout to repair the defect pipe as epoxy grout is easily influence by compressive, tensile, shear and flexural loadings or combination of all the loadings that caused by the way of application.

2.5 Code and Standards

In the oil and natural gas industry, it is essential to accurately predict the residual strength of corroded pipeline to determine whether the pipeline system is still suitable to be operated. Chiodo and Ruggieri (2009b) states that the burst strength of pipe will be reduced when the steel pipes aging and experienced material degradation caused by corrosion. Under this condition, potential of pipeline failure will be increased and the economic consequences of pipeline stop functioning and accidents happen are unaffordable by the pipeline operators. Therefore, some codes and standards for defect assessment of corroded oil and gas pipelines have been developed to evaluate the remaining strength of corroded pipes based on the defect geometry, pipe dimensions, material properties and internal pressure, for example, ASME B31G criterion (American Society of Mechanical Engineers, 1991) and DNV RP-F101 equation (DNV, 2010). The ASME B31G is a criterion based on the material yield strength of highly ductile pipe material and it is considered to be conservative, meanwhile DNV-RP-F101 equation is a more recent failure criterion that been developed to calculate the burst strength of modern pipeline with more accurate geometry term of defect obtained from high resolution analysis (Dewanbabee, 2009). Besides assessment codes, there are also some remarkable development in design codes and standards, such as ASME PCC-2- Part 4 and ISO/TS 24817. These codes and standards are used to design the composite repair system, which became a better choice for the industry over the conventional methods.

2.5.1 ASME B31G

ASME B31G criterion is referred by the United States, Canada and Europe countries as corrosion assessment codes to evaluate the part-wall defects. In this criterion, a formula based on semi-empirical fracture mechanism is developed with "Folias" correction for pipe bulging to calculate the remaining burst strength of corroded pipes (Dewanbabee, 2009). Bulging of pipes is caused by the internal pressure acting along the longitudinal direction of crack occur in a pressurized pipe. The resistance of a material towards fracture occurs on material due to the presence of defect is the basic principle of fracture mechanism. This mechanism is related to the dimensions of defect as the increasing in defect size will decrease the pressure at the defect area, which may cause failure of pipe. This criterion also assumed that the hoop stress, that is the maximum principal stress in pipe, is controlling the failure of pipe. With these factors, the hoop stress of pipe at failure is related to the cross section of defect and flow stress, and estimated in ASME B31G with equation 2.1 (American Society of Mechanical Engineers, 1991).

$$\sigma_{\mathrm{H}} = \bar{\sigma}\left[\frac{1-\frac{2}{3}\left(\frac{d}{t}\right)}{1-\frac{2}{3}\left(\frac{d}{t\mathrm{M}}\right)}\right] \qquad 2.1$$

Material flow stress in pipe is taken as 1.1 times of the Specified Minimum Yield Stress (SMYS) of the pipe material and it is shown in equation 2.2. The value of Folias factor (M), which also known as bulging correction factor, can be obtained in equation 2.3.

$$\bar{\sigma} = 1.1\sigma_{m(YS)} \qquad 2.2$$

$$\mathrm{M} = \sqrt{1+\frac{0.8L^2}{Dt}} \qquad 2.3$$

where L is the maximum length of the defect, D is the outer diameter of the pipe, and t is the remaining wall thickness of corroded pipe. For long corrosion defect, the hoop stress will be calculated by assuming the corrosion defect is in rectangular shape without considering the length when $(L/\sqrt{Dt})^2 > 20$ and this shows in equation 2.4.

$$\sigma_H = \bar{\sigma}\left(1 - \frac{d}{t}\right) \tag{2.4}$$

The Maximum Allowable Operating Pressure (MAOP), P_s, with safety factor (F) of 0.72 is expressed in equation 2.5.

$$P_s = F\frac{2t}{D}\sigma_H \tag{2.5}$$

This assessment code is suitable to apply of the corrosion defect with the loss of wall thickness in smooth profile and less stress concentration such erosion corrosion and electrolytic corrosion (American Society of Mechanical Engineers, 1991). This criterion is considered as less accurate than the newly developed assessment codes and standards because of flow stress and geometry term that related to ASME B31G are determined according to the old steel pipes which have lower toughness compared to the modern pipes that using in industry now (Amaya-Gómez et al., 2019).

2.5.2 DNV RP-F101

DNV RP-F101 is a recommended practice to assess modern carbon steel pipeline that contains corrosion. Dewanbabee (2009) states that this criterion is developed based on the high quality pipelines that manufactured recently which have reasonable higher toughness and a more ductile properties. With this, it is obvious that the old assessment codes and standards such as ASME B31G, which validated the database contains burst test results based on low grade steel, are not suitable for the current pipelines. Besides that, DNV RP F101 can be a less conservative assessment codes as it considered more details in defect geometry by using finite element analysis to determine the accurate dimension of the corroded defect while the previous assessment methods has not been include the parameter of defect width because of the effect of defect width had been assumed to be negligible (Fekete and Varga, 2012). British Gas (BG) Technology has been cooperate with DNV to issue DNV Recommended Practice (RP) in assessing corroded pipeline in 1999 and updated in 2004. 70 burst tests on pipes that contain machined corrosion defects, wide range of pipeline material properties, and 3D finite element analyses on defects occur in pipeline were conducted by the BG Technology to predict the residual strength of corroded pipes. Meanwhile, DNV also generated a database that consists of analysis of finite element on pipes that containing defects and 12 burst tests on pipes that have machined corrosion defects including the failure pressure influenced by superimposed axial and bending loads (DNV, 2010) . With this, DNV-RP-F101 criterion was developed. DNV-RP-F101 is suitable in assessing the corrosion defect that experiencing only internal pressure loading or combination of internal pressure loading with longitudinal compressive stresses. It consists of two approaches with difference in their safety philosophy. DNV-RP-F101 (Part A) will be described in this study. Equations in this method are used to determine the allowable operating pressure of a corroded pipeline by considering the uncertainties related to the size of defect and the properties of material as partial safety factor. Assessment on pipeline that contains single defect, interacting defects and complex defect can be applied by this criteria.

The maximum allowable operating pressure equation in DNV-RP-F101 for pipe that contains a single rectangular shape of corrosion defect with internal pressure only is defines in equation 2.6.

$$P_{corr} = \gamma_m \frac{2tSMTS}{(D-t)} \left[\frac{1-\gamma_d (d/t)^*}{1-\frac{\gamma_d (d/t)^*}{Q}} \right] \tag{2.6}$$

$$Q = \sqrt{1+0.31\left(\frac{l}{\sqrt{Dt}}\right)^2} \tag{2.7}$$

$$(d/t)^* = (d/t)_{meas} + \varepsilon_d .StD[d/t] \tag{2.8}$$

where

D = Outer diameter (mm)

d = depth of corrosion defect (mm)

t = nominal pipe wall thickness (mm)

$(d/t)_{meas}$ = Measured defect depth and

ε_d = factor for define fractile value of corrosion depth.

γ_d = Partial safety factor for corrosion depth.

γ_m = Partial safety factor for corrosion model prediction.

$StD[d / t]$ = Standard deviation of the measured *(d/t)* ratio.

SMTS = Specified minimum tensile strength

The partial safety factors included in the equation can be determined by inspection accuracy and confidence level, inspection on the defect measurement of relative depth and absolute depth and safety class based on inspection methods. Determination of standard deviation from inspection accuracy and confidence level can also use to identify the γ_d, safety factor and ε_d, fractile value.

For a longitudinal corrosion defect under combination of internal pressure and compressive longitudinal loadings, the allowable corroded pipe pressure of a single defect can be calculated in the following procedure. Firstly, the combined nominal longitudinal stress based on nominal pipe thickness is expressed in equation 2.9.

$$\sigma_L = \sigma_A + \sigma_B \tag{2.9}$$

where σ_L is the combined nominal longitudinal stress, σ_A is the longitudinal compressive stress due longitudinal force with the formula expresses in equation 2.10 and σ_B is the longitudinal compressive stress due to bending moment with the formula expresses in equation 2.11.

$$\sigma_A = \frac{F_x}{\pi(D-t)t} \tag{2.10}$$

$$\sigma_B = \frac{4M_y}{\pi(D-t)^2 t} \tag{2.11}$$

where F_x is the external longitudinal force (N) and M_y is the external bending moment (Nmm). Secondly, the allowable pressure in corroded pipe $P_{coor,comp}$ is calculated in the following equation 2.12. $P_{coor,comp}$ is not allowed to exceed P_{corr} and it is shown in equation 2.6.

$$P_{corr,comp} = \gamma_m \frac{2tf_u\left(1-\gamma_d\left(d/t\right)^*\right)}{\left(D-t\right)\left(1-\frac{\gamma_d\left(d/t\right)^*}{Q}\right)} H_1 \quad 2.12$$

where

$$H_1 = \frac{1+\frac{\sigma_L}{\zeta f_u}\frac{1}{A_r}}{1-\frac{\gamma_m}{2\zeta A_r}\frac{\left(1-\gamma_d\left(d/t\right)^*\right)}{\left(1-\frac{\gamma_d\left(d/t\right)^*}{Q}\right)}} \quad 2.13$$

$$A_r = \left(1-\frac{d}{t}\theta\right) \quad 2.14$$

where

A_r = Circumferential area reduction factor.

c = Circumferential length of corroded region (mm).

f_u = Tensile strength to be used in design.

H_1 = Factor to account for compressive longitudinal stresses.

ξ = Usage factor for longitudinal stress. It is varied from 0.8 to 0.9

θ = Ratio of circumferential length of corroded region to the nominal circumference of the pipe, $(c/\pi D)$.

The fibre reinforced polymer wrap used to increase the structural integrity of corroded pipeline has been considered as a new repair technology and it attracts the interest of pipeline industry. With this, several new standards and revised standard have been published to assist the users in designing FRP polymer wrap repair system. The relevant standards for FRP composite repair system are ASME PCC-2-Part 4, Nonmetallic and Bonded Repairs (American Society of Mechanical Engineers, 2011) and ISO/TS 24817 – Composite repairs for piping (International Organization for Standardization, 2006). ASME PCC-2 was published in 2008 and revised in 2011 while there are no revisions on ISO/TS 24817 which was published in 2006. These standards are limited to apply on pipelines, tanks and nozzles with attachments, and pipework which including straight pipe, elbows, tees, flanges, reducers and valve. Besides that, they are also suitable in designing repairs for risers and structural strengthening applications. With sufficient input such as stiffness, strength and thickness as stated in ASME PCC-2 and ISO/TS 24817, the minimum thickness of the FRP wrap in restoring the capacity of corroded pipe is determined according to the design pressure that needed to be sustained by the pipe and this design pressure included other probable loads.

Both design standards identified defect type A (not leaking) and defect type B (leaking) with similar design approach depends on the extent of corrosion damage. Defect type A is the non-leaking defect that will happens on steel pipe and it is expected that it will not become through wall defect in repaired pipe so only structural reinforcement needed. It can be either external or internal. The depth of the defect type A is the only design parameter as the pipe is considered fully circumferential with constant remaining pipe wall thickness in both standards. In contrast, defect type B is through wall and it will cause leaking in steel pipe which will affect the structural integrity of the pipe. Structural strengthening and sealing the through wall defect is needed to be taken into consideration to repair this type of defect. For internal corrosion, the defect with remaining wall thickness that expected to be less than 1mm at the end of the service life of pipe will be assumed as defect type B. Furthermore, the shape of the defect type B will affect the repair system and thus shape such as circumferential, circular, and non-circular shapes with ratio smaller than 5 will be considered while designing the repair method.

2.5.3 ASME PCC-2

ASME PCC-2 is a standard that specifically developed for steel pipes repaired with composite overwrap. The information of the repair system provided in the standard cover methods involving metal deposits (welding or soldering), methods involving mechanical repairs (bolt clamps), and methods involving non-metallic composite repair systems. In this standard, the minimum thickness of FRP composite wrap to support hoop stress due to internal pressure in pipe system where no underlying substrate yield is calculated in equation 2.15.

$$t_{\min} = \frac{D}{2s} \bullet \left(\frac{E_s}{E_c} \right) \bullet (P - P_s) \qquad 2.15$$

where D is the component outside diameter (mm), E_s is tensile modulus for substrate material (N/m^2), E_c is the tensile modulus for the composite laminate in circumferential direction (N/m^2), P is the internal design pressure (N/m^2), P_s is the Maximum Allowable Operating Pressure (MAOP) and s is the Specific Minimum Yield Strength (SMYS) of the pipe.

The minimum thickness of composite wrap to support axial stresses due to bending or other axial loads in repair systems where no underlying substrate yield is determined by equation 2.16.

$$t_{\min} = \frac{D}{2s} \bullet \left(\frac{E_s}{E_c} \right) \bullet \left(\frac{2F_a}{\pi D^2} - P_s \right) \qquad 2.16$$

where F_a is the total axial tensile loads due to pressure, bending and axial thrust. The axial tensile load generated by bending moment with (*4M/D*) and it shall be determined by the repair system designer.

For pipe system with underlying substrate that does yield, the repair laminate thickness is designed according to allowable strain of the composite and would considered hoop loading only. The design repair laminate thickness, t_{repair} may be calculated:

$$\varepsilon_c = \frac{PD}{2E_c t_{repair}} - s\frac{t_s}{E_c t_{repair}} - \frac{P_{live} D}{s(E_c t_{repair} + E_s t_s)} \qquad 2.17$$

If the internal pressure during the repair system is zero, the equation would be rearranged in to equation below:

$$t_{repair} = \frac{1}{\varepsilon_c E_c}\left(\frac{PD}{2} - s\,t_s\right) \qquad 2.18$$

where ε_c is the allowable circumferential strain of the composite, t_s is the minimum remaining wall thickness of the component and P_{live} is the pipe internal pressure during repair. The substrate material for the equation 2.17 and 2.18 are assumed to be elastic and perfectly plastic where strain no hardening and no defect assessment needed to conducted.

Based on the equations above, the repair design standards mainly focus on the minimum remaining pipe wall thickness while defect geometry does not being considered in these equations. As stated by Cunha and Netto (2012), the remaining strength of the corroded pipeline not only depends on the material properties , but also the flaw geometry. For not taking this parameter into account, the design of the repair system may be conservative.

2.5.4 ISO/TS 24817

ISO/TS 24817 is the general standard for the pipes repair with different material from steel to FRP composite polymer. This standard is able to apply on the pipes that damaged by external corrosion, internal corrosion, pitting, circumferential cracks, and through wall penetration. The procedure for this standard is similar with the ASME PCC-2 standard and this can see from the equations to determine the repair thickness of the laminates are same in ASME PCC-2 standard. However, there are some differences between these standards such as ISO/TS 24817 will define repair class following the risk assessment while ASME PCC-2 does not. Besides that, ISO standard present an equation that will determine the equivalent axial load and this is not considered in the ASME PCC-2 and this shows in the equation 2.19:

$$F_{eq} = \frac{\pi}{4} p D^2 + \sqrt{F_{ax}^2 + 4F_{sh}^2} + \frac{4}{D}\sqrt{M_{ax}^2 + M_{to}^2} \qquad 2.19$$

2.6 Concluding Summary

As a conclusion, the literature review shows that the FRP composite polymer is an effective repair technology to restore the burst strength of the defective pipes of gas and oil industry. However, this repair method is considered conservative and needs to be optimised as there are several issues affecting the performance of the composite repair system that are not fully understand and solve. For example, the geometry of defect is one of the issue that highlighted in this study. As can see from the codes and standards mentioned in the previous section, the assessment code, DNV-RP-F101 (DNV, 2010), taking the circumferential length of defect, which also considered as defect width, into account to evaluate remaining strength of the corroded pipe so that the FRP composite wrap can be designed accurately according to the situation of pipe. For the design standards that mentioned before, ISO/TS 24817 and ASME PCC-2 only taking the remaining pipe wall thickness as parameter to design the FRP composite thickness to rehabilitate the strength of corroded pipe and the defect geometries such length and width are negligible. Although the standards used as guideline in designing the repair system is to ensure the quality of repaired of pipe, but the design of repair system was considered as conservative. Several researcher such as Cunha and Netto (2012) stated that the critical stress of the corroded pipe is depends on the material properties and also the flaw geometry. From this, we can see that if the effect of defect geometry especially defect width can be identified, then the defect width can be included in designing the FRP composite repair system to optimise the design if it is proven influential.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

The methodology of this study is divided into two stages and Finite Element Analysis (FEA) was conducted in this section. Stage 1 was designed to develop a base Finite Element (FE) model of the composite repaired pipe and validated via published experimental data. Modification of the defect geometry was done in stage 2. Stage 2 began with three different defect widths applied on the validated model. Results of the burst pressure of the model affected by the flaw width was obtained by Finite Element Analysis (FEA) on the composite repaired pipe models. This results mainly focus on the effect of defect width while keeping defect length and defect depth as constant. With the results obtained in stage 2, objective of determine the burst pressure of externally corroded steel pipe which affected by numerous defect width was achieved. Figure 3.1 summarised the overall methodology for this study.

3.1 Flowchart of Research Methodology

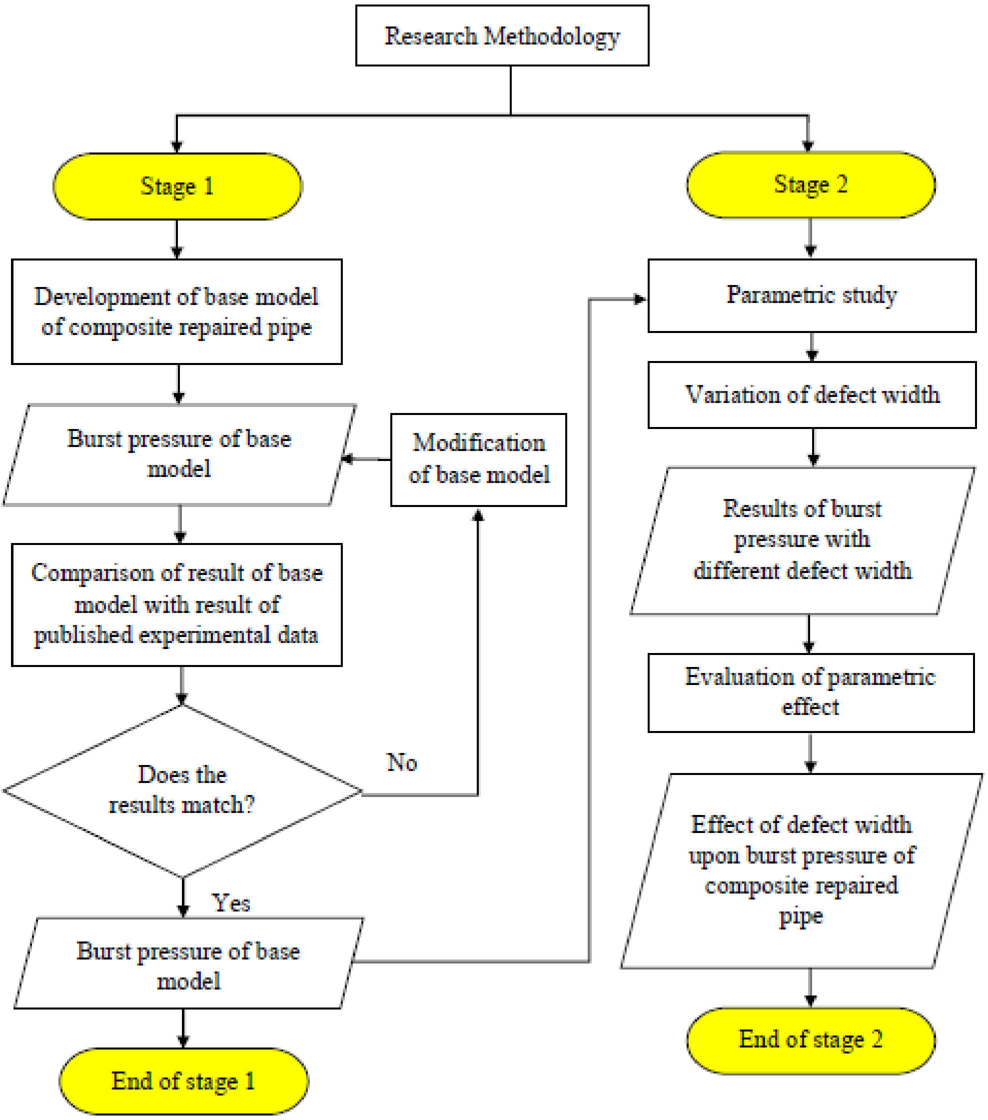


Figure 3.1 Flowchart of overall research methodology

3.2 Stage 1: Development of Composite Repaired Pipe Base Model

In this stage, ABAQUS$^{®}$ v6.12-1 (SIMULIA, 2012) FE modelling software was utilized to build models, create meshes and conduct FE calculations to stimulate the burst capacity of pipe. A FE model of composite repaired pipe was created as base model with components of corroded steel pipe, epoxy grout and FRP composite wrap. Validation of this model was done with comparison between the results of burst pressure of composite repaired pipe from the published experimental tests with the burst pressure of base model generated by finite element modelling. The properties of materials that used to develop the finite element models were taken from the same sources and were used to validate the base model which is needed later in stage 2.

It began by modelling the three components of base model with the dimension according to the dimension stated in the experiment test. All the parts were modelled individually and assigned with relevant material properties (Duell et al., 2008). Then, all the individual parts were assembled and interactions between different materials were created by applying boundary condition. Appropriate meshing size was applied on all parts of the finite element model after a mesh convergence study was conducted. When the model had completed, internal pressure was applied in the model. The analysis on determining the burst capacity of the models was carried out. The result of burst pressure of the FE base model was compared with the published experimental test data. As suggested by researcher, The error margin for the burst pressure between stimulated finite element model and experimental data is set at 10% (Chan et al., 2015). Modification of the base model will be conducted when the margin of error more than 10%. The modification will be continued until the base model has error margin less than 10% and thus the base model will be validated. The steps of development of composite repaired pipe as base model is presented in the following flowchart in Figure 3. 2.

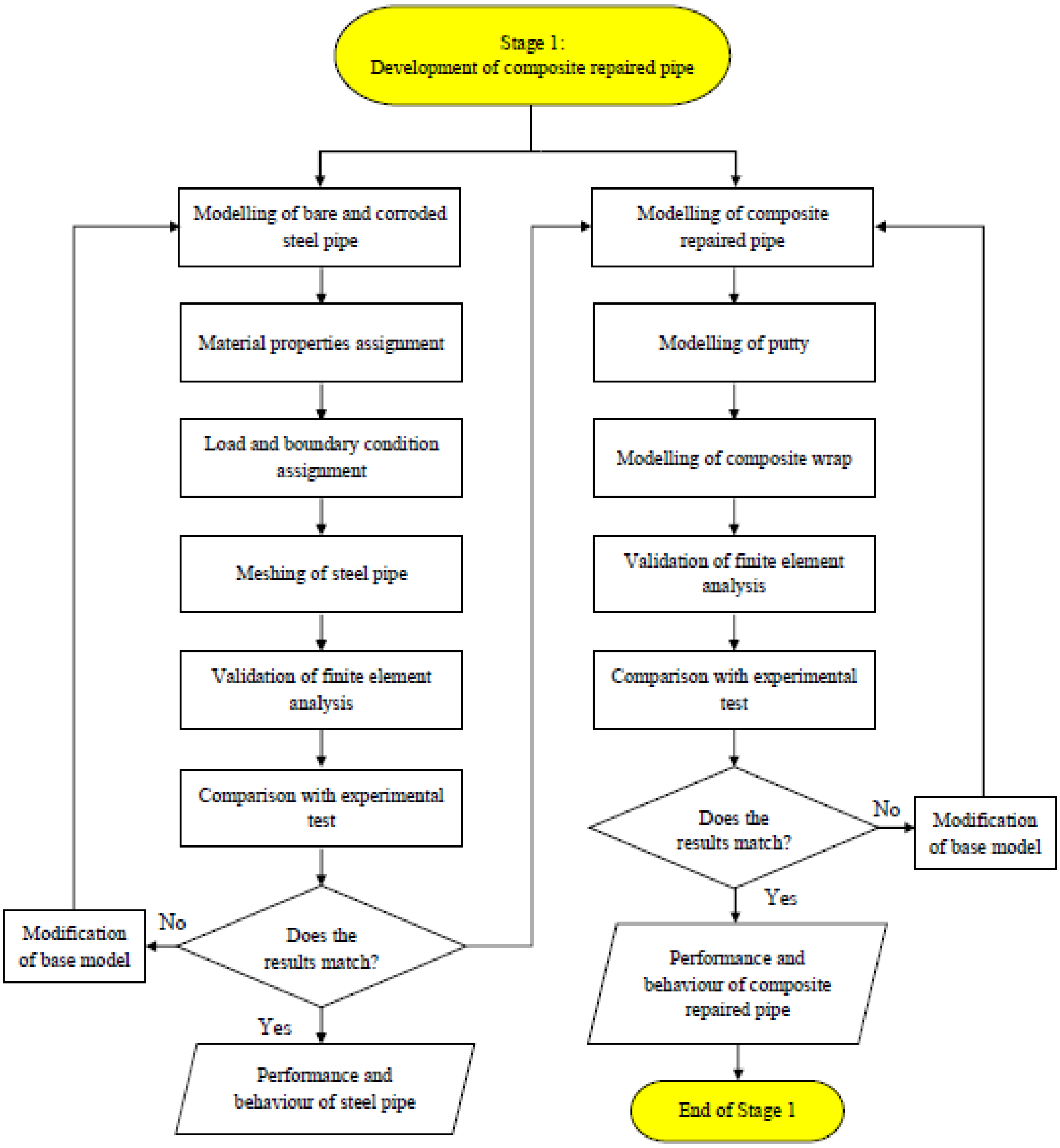


Figure 3. 2 Flowchart of Stage 1: Development of composite repaired pipe

3.2.1 Modelling Corroded Steel Pipe

Stage 1 was started by creating finite element model for defect pipe. This section was started by creating bare pipe then followed by applying defect at the centre of pipe to model corroded steel pipe which can refer to Figure 3. 3. Firstly, the bare pipe was created with three dimensional deformable solid structure by extrusion method. A solid part was constructed in dimensions of 168.3mm diameter and 1200mm length. It was followed by creating another model with 154.08mm diameter as the inner diameter of the pipe. The second model was inserted into the first model for it to cut through the whole length of first model. As a result, a hollow pipe with 168.3mm as outer diameter, 7.11mm as thickness of pipe wall and 1200mm as length of pipe was created. In order to model a defective pipe model, a two dimensional defect with geometry of 100mm arc length in the hoop direction and 3.555mm depth was sketched with 68 degree of angle located at the middle of pipe. The model of the defect on the pipe was completed by extruding the sketch with a 100mm length in axial direction and located the defect at the middle of pipe.

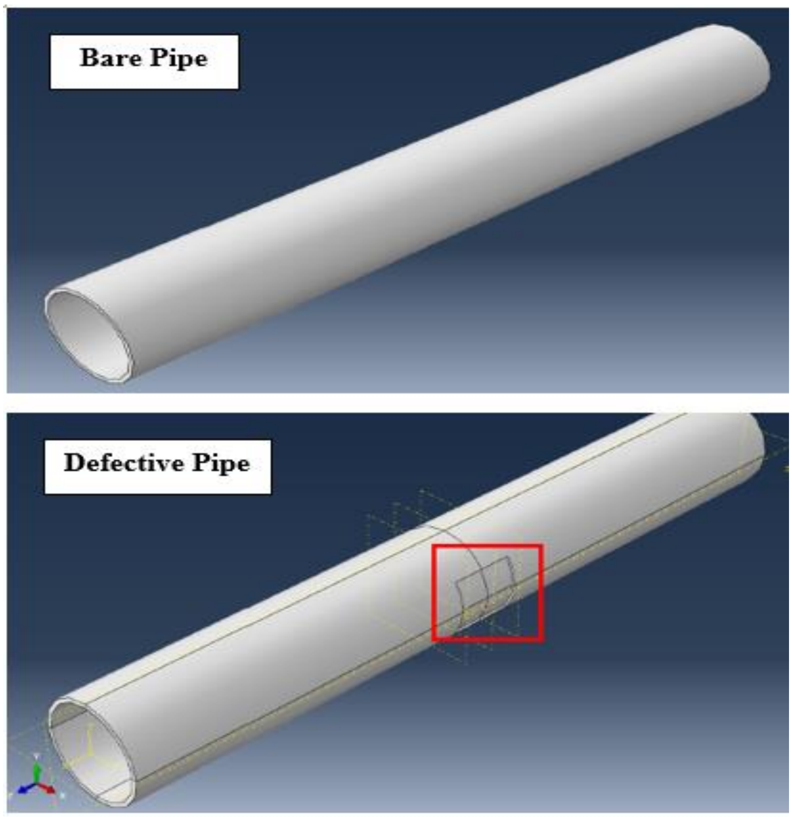


Figure 3. 3 Bare pipe model and defective pipe

3.2.2 Material Properties Assignment

After the modelling of defective pipe, material properties were assigned to the base model of steel pipe. The input of the material properties was the results of tensile test of steel pipe from the published experimental data, which included Young’s modulus, Poisson’s ratio and stress-strain curve. A multi-linear isotropic hardening plasticity model was suggested by several studies to model the material behaviour of steel pipe (Alang et al., 2013, Duell et al., 2008). Stress-strain curve obtained from tensile test, which also named as engineering stress-strain curve, was converted into true stress-strain curve in order to match the material model. The conversion process is conducted by using the equations as follow:

$$True_{stress} = Eng_{stress} * \left(1 + Eng_{strain}\right) \qquad 3.1$$

$$True_{stress} = ln * \left(1 + Eng_{strain}\right) \qquad 3.2$$

where $True_{stress}$ is the true stress, $True_{strain}$ is the true strain, Eng_{stress} is the engineering stress and Eng_{strain} is the engineering strain. The true stress-strain curve and engineering stress-strain curve that shown in Figure 3. 4 were drawn according to the result from the equations above. For this study, the material properties of the steel pipe was assigned according to Table 3. 1.

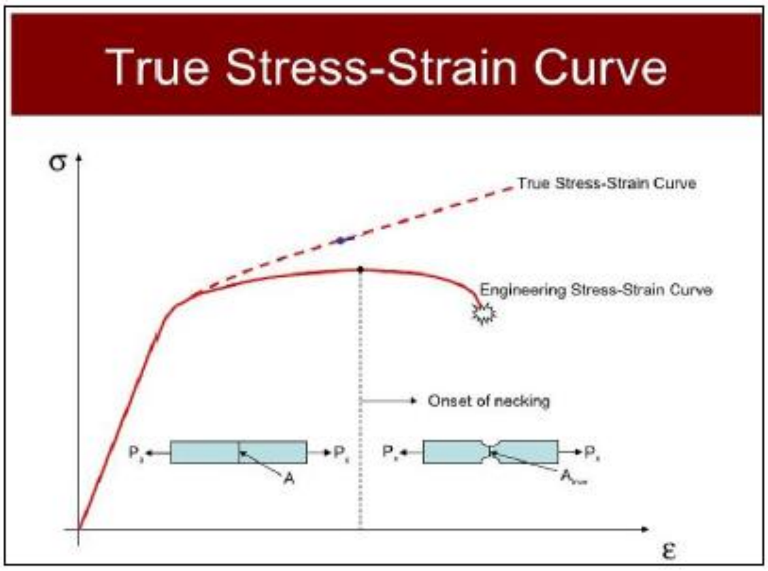


Figure 3. 4 Engineering and True Stress-Strain Curve

Table 3. 1 Material propeties of steel pipe

Properties	Value
Young's Modulus, E	222 GPa
Density	7850 kg/m^3
Ultimate Tensile Stress	557.7 MPa
Poisson's Ratio	0.3

Source:Lim (2017).

3.2.3 Load and Boundary Conditions Assignment

When the material properties were inserted into steel pipe models, the material model is ready to be assigned. The duration of stimulation was set by creating analysis step .A total 500 seconds of analysis time was assigned and the non-linear effect for large displacement was included in the analysis. The model was solved with automatic time stepping to save the results from every sub step. 50MPa of uniform pressure was applied to the internal wall of pipe by ramp amplitude to achieve 0.1MPa per second along the duration of analysis. The load and boundary condition that applied on the base model is shown in Figure 3. 5.

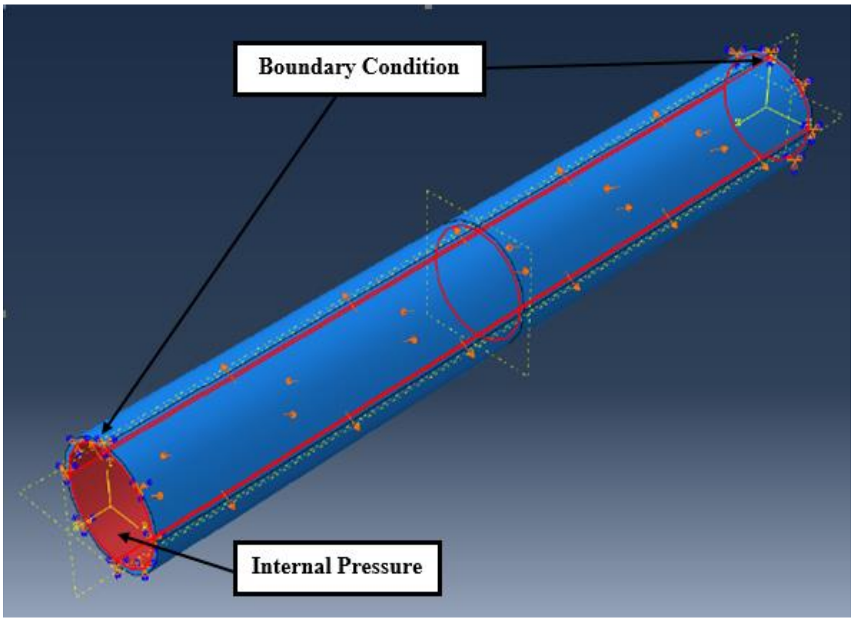


Figure 3. 5 Internal pressure and boundary condition

3.2.4 Meshing of Steel Pipe

In this study, eight-node linear solid element (C3D8R), which is the ABAQUS three-dimensional reduced integration, is selected to create mesh of steel pipe. A suitable mesh is needed to be chosen for the finite element analysis to achieve accurate result in a minimum analysis duration. However, a completed structural mesh cannot be created properly after the bare pipe model modified with odd geometries defect shape to create defective pipe. There are some parts of the model can be meshed and some cannot. As we can see in Figure 3. 6, the orange colour in the first diagram is indicated that the part cannot be meshed, yellow colour in the second and third diagrams are indicated that the parts need more partition in order to be meshed, and green colour in the following diagram represents the whole model can be structurally meshed. A structural mesh is needed to gain optimum results. Therefore, the odd geometries of the defect part on the pipe model can be eliminated to generate structural mesh. For this, the pipe model was sliced into multiple segments.

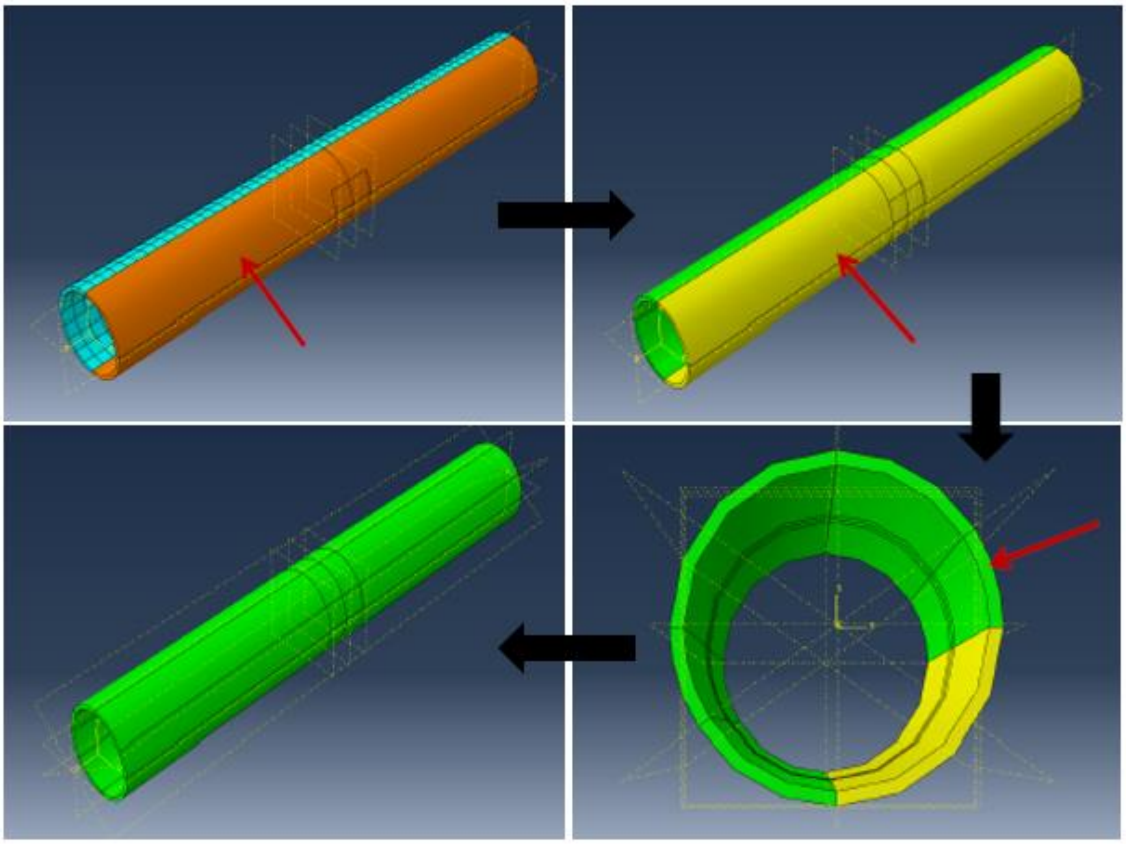


Figure 3. 6 Process of achieving structural mesh

3.2.5 Validation of Defective Pipe Model

A suitable mesh size to use on the pipe model needed to be determined by construct combination of mesh with several mesh size. For example, a denser mesh size is applied around the defect part of the pipe model as shown in Figure 3. 7. After an appropriate mesh size has been created on the pipe model, the development of the defective pipe with defect geometry of 100mm x 100mm as base model is completed and finite element analysis is carried out as followed. Once the result of stimulation which is the burst pressure of the pipe model are gained, comparison between the stimulation results and experimental results was conducted. The difference between the results of burst pressure is less than 10% so that the pipe model is acceptable and validated to stimulate the behaviour of the experiment work.

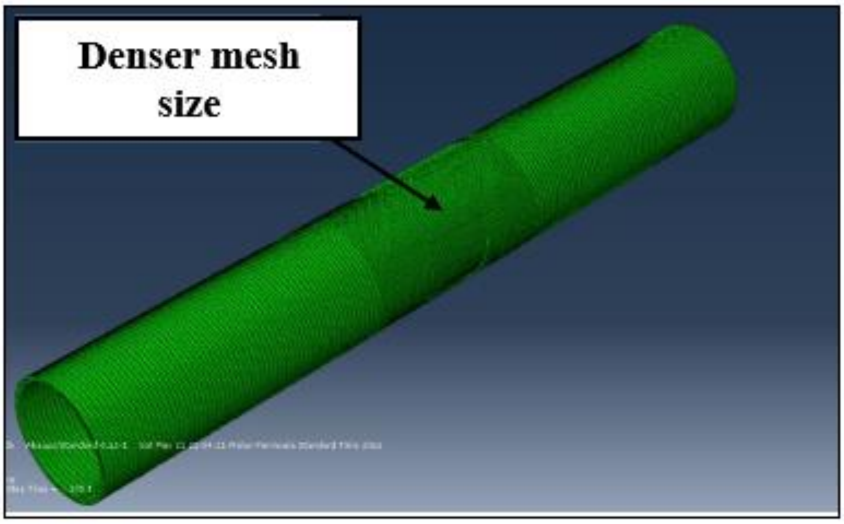


Figure 3. 7 Meshed defective pipe model

3.2.6 Modelling Composite Repaired Steel Pipe

For this section, epoxy grout and composite wrap are involved to investigate the behaviour of composite repaired pipe. The development of finite element for composite repaired steel pipe is more complicated than modelling a defective pipe because of more components and material properties involved. The location of all the components of composite repaired pipe model will not resemble the experimental test data due to all of them are created individually. Therefore, it is required to carry out translation of location/ coordinates of the components when assembling the whole model. Besides that, modelling of the contacts between the interfaces of steel pipe, epoxy grout and composite wrap are conducted.

The finite element modelling was done according to the size and features stated in the experiment test. However, certain characteristics in the experiment test were not considered in the modelling process due to the limited information about the features. For instances, it is a common practice to use the strain gauge to determine the strain of the composite repaired pipe. However, in this study, the effect of strain gauge is not applied on the defect area on the steel pipe and surface of the epoxy grout. The effect of the strain gauges around the small area of the repair region is negligible. With this, the strength of the strain gauge is small and hence any contribution of the strength of strain gauge was assumed to be insignificant. Furthermore, the primer presents as adhesive for the surface bonding between composite wrap and steel pipe, and between composite wrap and epoxy grout were neglected in the modelling too. The bonding test that need to determine the bond strength of composite wrap with steel pipe and composite wrap with epoxy grout was not conducted. Therefore, no information is gained as input for the bonding properties. The thickness of the primer was not considered in the modelling also as only a thin layer of primer was applied on the composite repaired pipe.

3.2.7 Modelling of Putty

For this section, a three-dimensional deformable solid part was created to stimulate the physical properties of the putty. The geometry of the putty was created according to the dimension of the defect area as the putty is designed to cover the defect region on the pipe. The structure of the putty can be refer in Figure 3. 8. The basic properties of the epoxy grout consist of Young’s modulus, Poisson’s ratio, ultimate strength and stress-strain curve were used to construct the material models and it is shown in Table 3. 2. All data are obtained from the laboratory test conducted by Lim (2017) as input of material models.

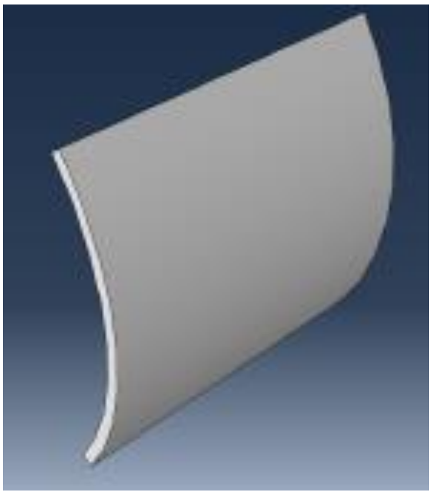


Figure 3. 8 Putty Model

Table 3. 2 Material propeties of putty

Properties	Value
Young’s Modulus, E	19 GPa
Ultimate Tensile Stress	20.01MPa
Poisson’s Ratio	0.35

Source:Lim (2017).

After the modelling of putty component, the component was assembled with the defective pipe and it is located at the defect region. In order to model the putty at the exact location, translation of the location of the putty was carried out as mentioned in previous section with “translate instances” which is a built-in feature. The process of using translate instances is illustrated in Figure 3. 9 and it is started by selecting one node of the putty. The node will be matched to another node, which known as reference node, at the edge of defect area as shown in the second diagram of Figure 3. 9. The following diagram shows that the putty was moved to the accurate location on the model to cover the defect part of the pipe as a result of the translation process. In the same time, the putty was modelled with eight-node linear solid element (C3D8R). Mesh size used on defect region was applied on the modelling of putty in order to determine a uniform result.

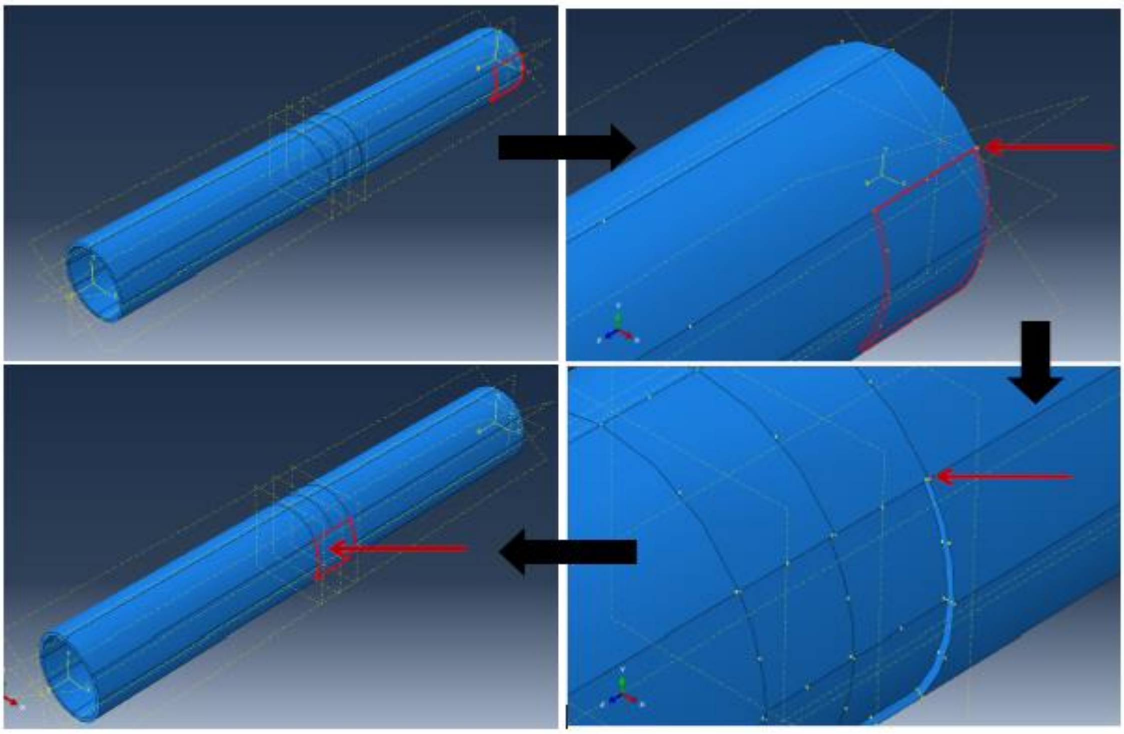


Figure 3. 9 Process of translate the location of putty

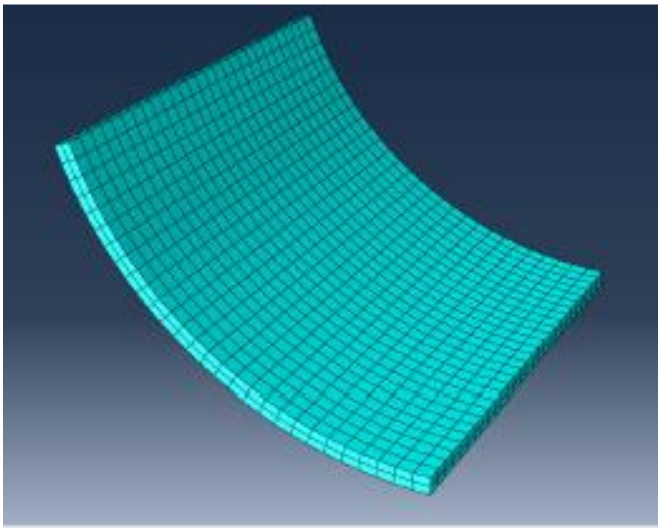


Figure 3. 10 Meshed putty model

3.2.8 Modelling of Composite Wrap

This section is started by creating a three-dimensional deformable shell part for the modelling of composite wrap. The basic part of the composite wrap was created with a thin shell layer contain dimension of 168.3mm as diameter and 300mm as length. The Engineering Constant Model from material model library in ABAQUS was utilised to create composite wrap model. Nine elastic properties of composite wrap such as E_1, E_2, E_3, v_{12}, v_{13}, v_{23}, G_{12}, G_{13} *and* G_{23} were included in the modelling. E is the tensile modulus of composite while G is the shear modulus of composite. Meanwhile, the v is known as the Poisson's ratio of composite wrap. The longitudinal and transverse directions of the FRP were presented by the number of 1 and 2, which also represent hoop and axial direction. The number of 3 was denoted the thickness direction, which also known as radial direction of the composite. In modelling the failure of composite wrap on the defect pipe, the Hashin Failure Criteria was applied to define the failure of composite wrap. These properties were selected from the Hashin Damage function. The tensile strength, compressive strength and shear strength in both longitudinal and transverse direction were inserted as the properties of composite wrap. All the material properties are shown in Table 3. 3.

The FRP composite shell thickness was modelled with a composite shell section. A composite wrap is presented by three layers of composite shells with 1mm as thickness for each layer. The composite model was needed to located at the defect region by using the same technique that applied while locating the putty, which is the "translate instances". This is because the composite shell was modelled individually. An integrated structure was formed after assembled defective steel pipe, FRP composite wrap and putty. Cylindrical coordinates system was created on composite wrap because it is the system that commonly used to analyse pressure vessel by accurately calculate the material properties in longitudinal and transverse direction. Figure 3. 11 is illustrated the cylindrical coordinate system. Besides that, it should be converted into cylindrical coordinates is due to the global Cartesian system as the default coordinate system that used in ABAQUS. The conversion was also applied on all components and used built-in coordinate conversion feature to assemble composite repaired pipe.

The interactions between all the components were created when all three parts assembled into one structure. There were four main surfaces that needed to be bond, which are inner surface of defect region, inner surface and outer surface of putty, and inner surface of composite wrap. The tie constraint feature was used to create bond between putty to steel pipe, putty to composite wrap and composite wrap to steel pipe. The tie constraint of putty-pipe, putty-composite and composite-pipe show in Figure 3. 12.

Table 3. 3 Material propeties of composite wrap

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

Source: Lim (2017).

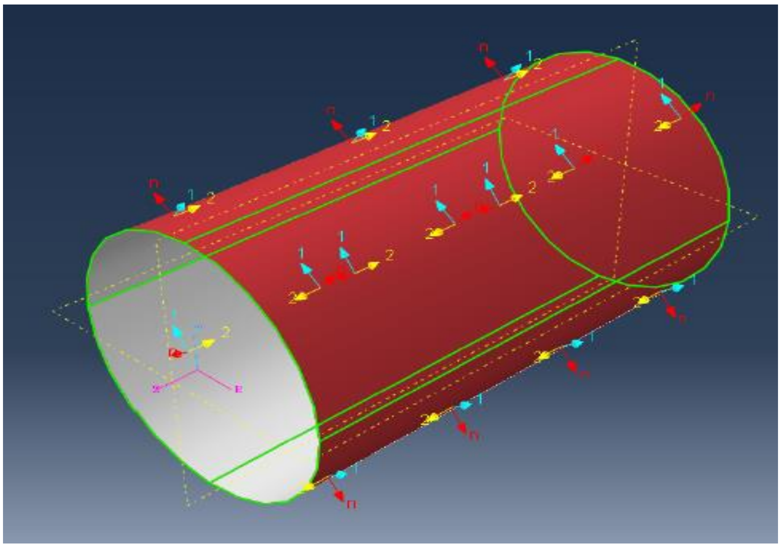


Figure 3. 11 Cylindrical coordinate system on composite wrap

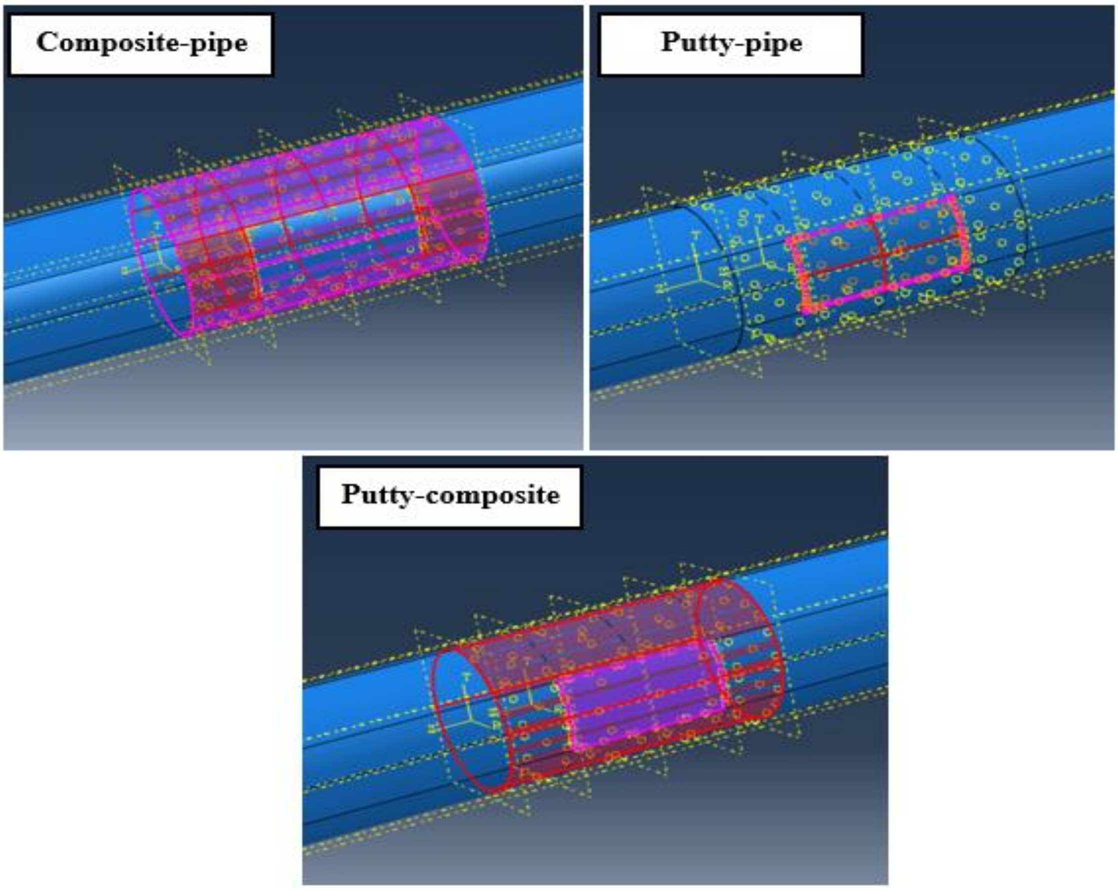


Figure 3. 12 Bonding beween steel pipe, putty and composite wrap

3.2.9 Execution and Validation of Composite Repaired Pipe Models

The steel pipe and putty components in the composite repaired pipe was meshed into reduced integration as 8 nodes linear brick elements of type C3D8R. In the same time, the composite shell was also meshed as reduced integration but in 4 nodes shell elements of type S4R. 500 seconds was set as analysis duration with 50MPa as pressure that linearly increasing to stimulate loading rate at 0.1MPa/s. Finite element analysis was then conducted with the applied boundary condition to determine the burst pressure of the pipe model for validation purpose. Modifications were no need after the margin of error gained is less than 10%.

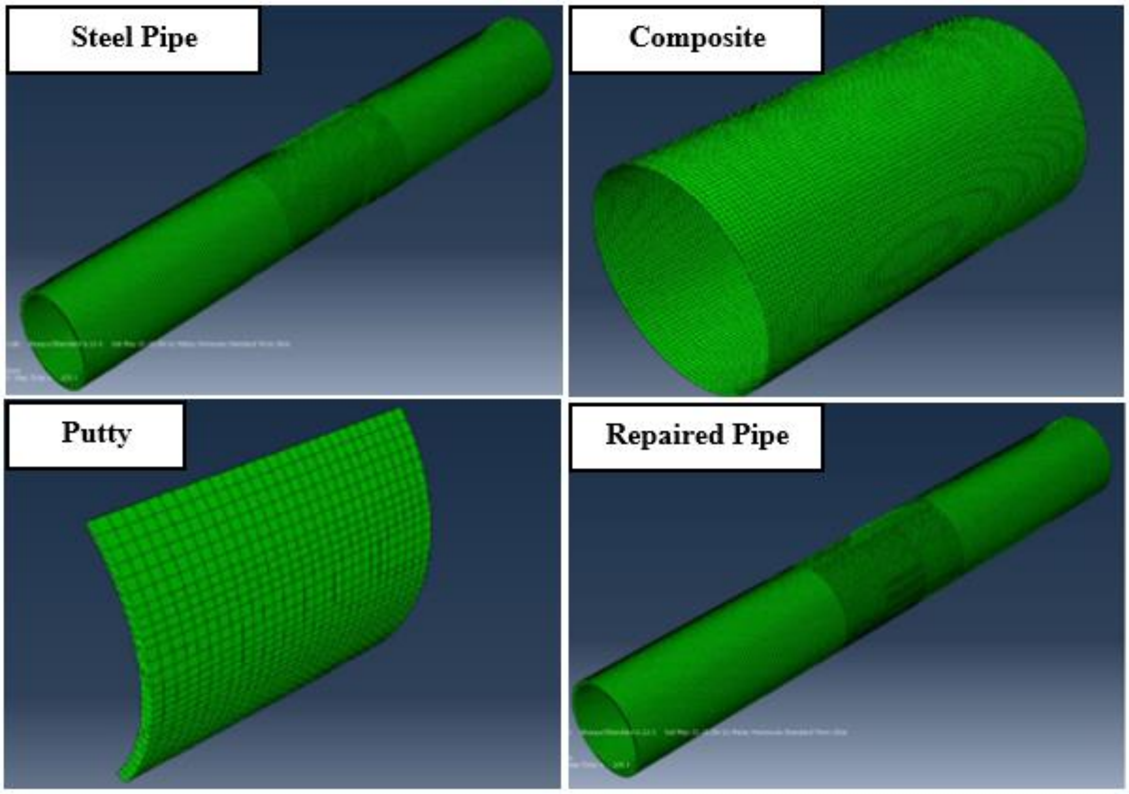


Figure 3. 13 Meshed model for steel pipe, composite wrap, putty and composite repaired pipe

3.3 Stage 2: Parametric Study

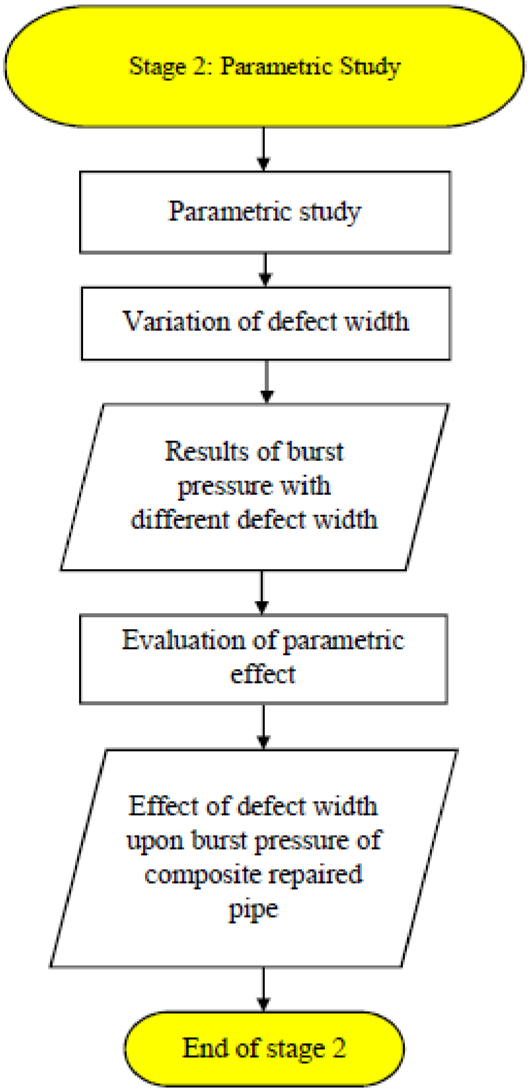


Figure 3. 14 Flow Chart of Stage 2: Parametric Study

3.3.1 Parametric Study

The validated composite repaired pipe model that developed in stage 1 was used in this section to perform parametric study. Only three different width of defect were used to in this study. In order to achieve the aim of this study is mainly focus on the influence of defect width on the burst capacity of a composite repaired pipe, three models with different defect widths of 168.3mm × 84.15mm (D × ½D), 168.3mm × 168.3mm (D × D) and 168.3mm x 336.6mm (D × 2D) were created by modifying the defect geometry in validated base model. Nevertheless, the defect length and defect depth were remains constant. Evaluation on the effect of defect width was conducted once the burst pressure of pipe model obtained as a result. If there are any significant influence observed, it will help in optimizing the repair design of using composite and epoxy grout.

3.4 Concluding Remark

This chapter explained the methodology that was conducted to determine the effect of defect width on the burst capacity of composite repaired pipe. The finite element analysis was conducted to build the base model and later used in stage 2 which serves as parametric study to investigate the effect of defect width upon burst capacity of composite repaired pipe. The properties and behaviour of steel pipe, epoxy grout and composite wrap were determined according to the published laboratory data. The properties of these material were then utilized in the finite element model of composite repaired pipe. Burst pressure of the composite repaired pipe model when it reached maximum value and failed is recorded. Analysis of the result of the data was carried out in order to evaluate the influence of defect width on the burst capacity of the finite element models.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

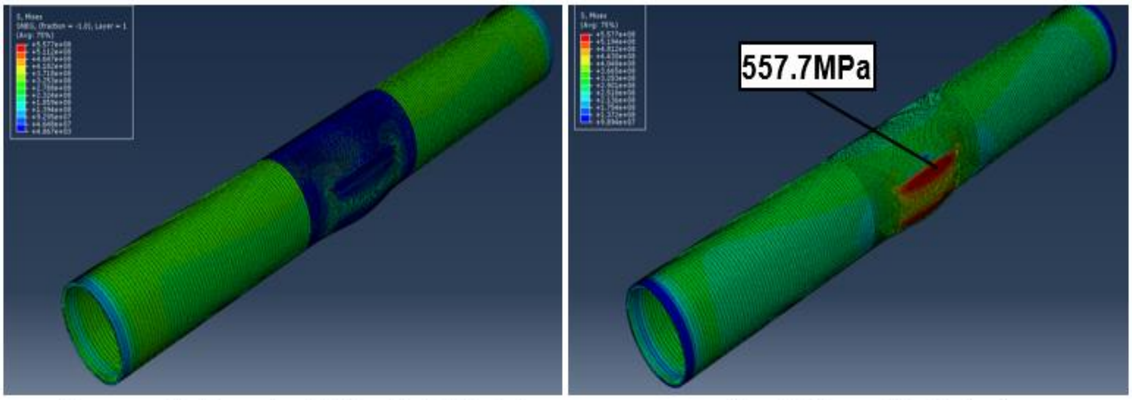
The base model with defect geometry of 100mm x 100mm generated in the finite element simulation have been validated by comparing the burst pressure obtained in finite element analysis (31.77MPa) with the burst pressure of experimental test (33MPa). The error margin between the burst pressures is 3.73% which means that the base model is considered validated because the value of the error margin is less than 10%. Therefore, the base model was modified with various defect width in order to determine the burst pressure of composite repaired pipe. The result of the finite element analysis is presented in this chapter. The result from the finite element simulation presented in stress contour plot diagrams and graph of the effect of the defect width upon the burst pressure of the composite repaired pipe. The stress contour plot diagram of the full model of defective pipe which contains steel pipe, epoxy grout and FRP composite wrap were used to present the stress concentration in the whole pipe with variation values of stress. The graph of burst pressure of composite repaired affected by defect width was generated from the finite element simulation with various defect width in order to determine the significance effect of defect width on the composite repaired pipe.

4.1 Result of Stress Contour Plot Diagram

4.1.1 Stress Contour Plot of D x ½D pipe model

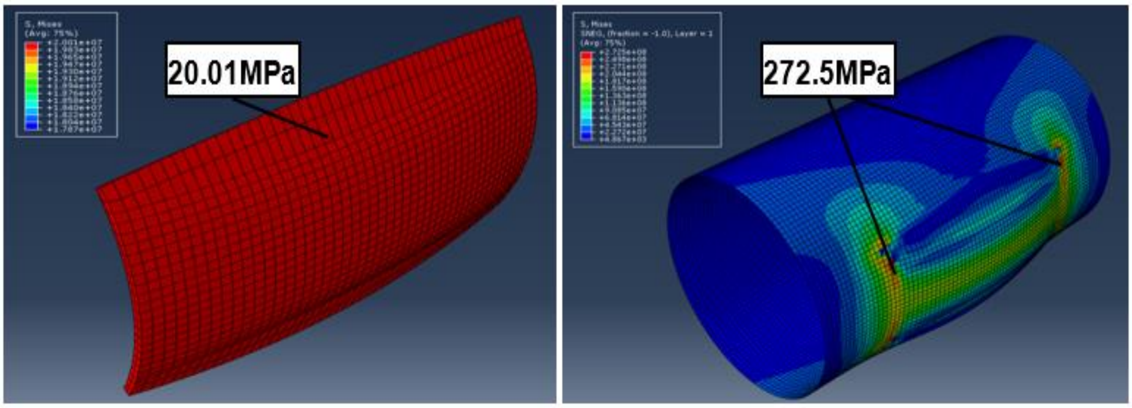
Figure 4. 1 illustrates the stress contour plot of completed defective pipe model (D x ½D model) with all individual components which are defective steel pipe, epoxy grout and composite wrap. It only shows hoop stress contour plot since hoop stress, which also known as circumferential stress, is the greatest stress experience by the pressurized pipe amongst the other stresses such as axial stress and radial stress where all of the stress occur at the same time. With the stress contour plot diagrams, the value of the stress that experienced by the pipe can be predicted. According to Lim et al. (2015), the highest stress concentration region can be recognised as pipeline failure location. This is because when the region sustained stress that reached ultimate tensile stress, the failure of pipeline will occur due to the decreasing of load bearing capacity of the pipe especially the corroded area (Liu et al., 2017) .

In Figure 4. 1, the whole structure of the putty is in red colour, which means the whole putty was experiencing the highest tensile stress (20.01MPa). It was illustrated that the putty has lower load bearing strength than other components and it may fail first before other components does. By comparing to the defective pipe model, the highest stress concentration with the value of 557.7MPa was observed at both edges of the defect region along the axial direction, not the whole structure. In contrast, the centre of the defect region was observed to have lower value of stress (443MPa) concentrated on it, which is in yellow colour. The composite component was found to have four red colour regions occur at the corners of the defect area underneath of the composite wrap. The highest tensile stress for composite wrap is 272.5MPa (red colour) which is higher than putty but lower that the steel defective pipe. There is also observed that high stress experienced at the both edges of the defect area underneath the composite wrap along the circumferential direction beside the four corners, which are the values of 227.1Mpa and 204.4MPa. As we can see, the defective pipe experienced the highest stress amongst the other components and this study is focusing on analysing whether the burst pressure of composite repaired pipe is significantly affected by the changes of defect width, thus, this section is more focus on the stress concentration in defective pipe.



Composite Repaired Pipe Full Model

Steel Pipe with Defect



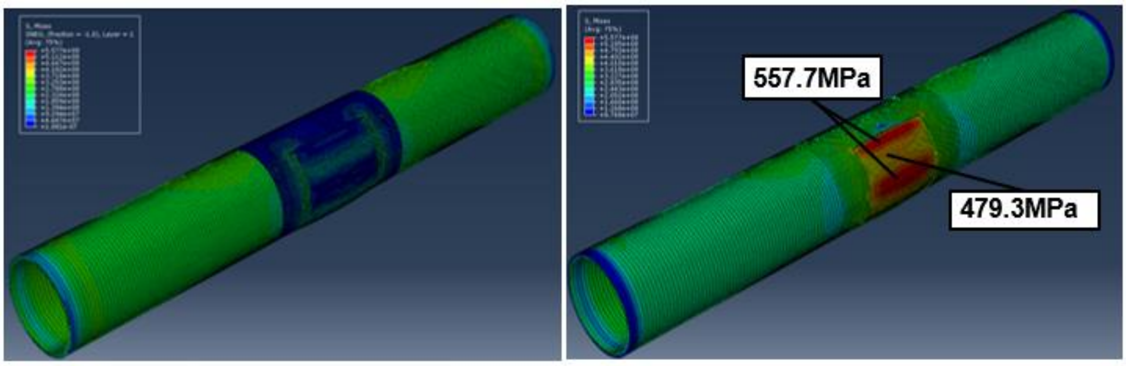
Epoxy Grout

Composite Wrap

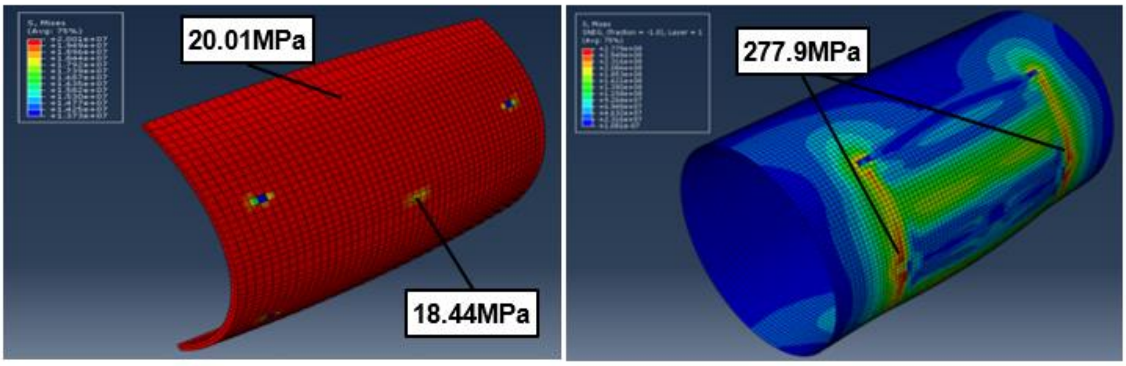
Figure 4. 1 Stress contour plot diagram of complete defective pipe model (D x ½D model) with all components

4.1.2 Stress Contour Plot of D x D Pipe Model

The stress contour plot diagram of completed composite repaired pipe model (D x D model) with all individual components is illustrated in Figure 4. 2. The condition of putty of D x D model is almost similar to D x ½D model where the whole structure of the putty also in red colour with the highest stress value of 20.01MPa. Besides that, the highest tensile stress with the value of 557.7MPa (red colour) was observed at the both edges of the defect region along the axial direction. This stress concentration area is located at the same location as D x ½D model but it is narrower than the area in D x ½D model. In D x D model, there is still a small area of highest stress concentration (557.7MPa) observed at the centre of the defect region in the defective pipe model. With this, the highest stress concentration area in this model is bigger than the highest stress concentration area in D x ½D model. Furthermore, it can be observed that there are yellow colour stress concentration area with the value of 469.3MPa located at the middle area between the edge and centre of defect region that experienced the highest stress concentration of 557.7MPa. The composite wrap of D x D model experienced bigger area of stress concentration with the value of 277.9MPa (red colour) when comparing to the composite wrap of D x ½D model that only had four corners of highest stress concentration (red colour). However, the highest stress sustained (272.5MPa) by the composite wrap of D x D model is lower than the stress of 277.9MPa that experienced by D x ½D model.



Composite Repaired Pipe Full Model **Steel Pipe with Defect**

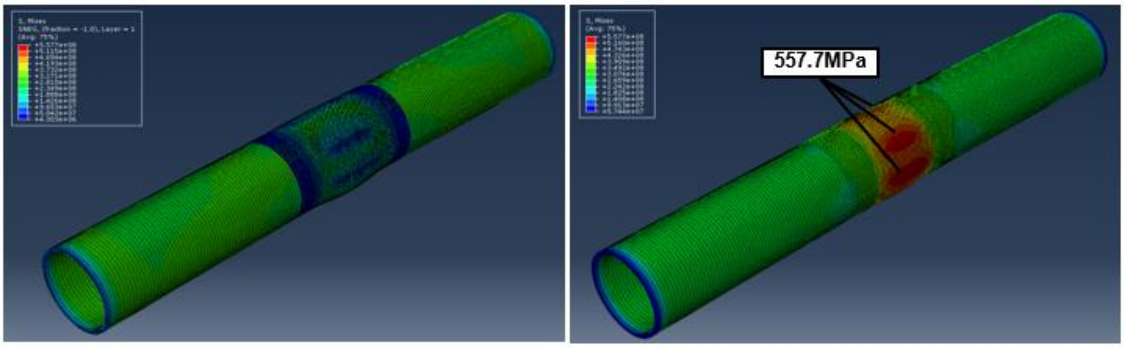


Epoxy Grout **Composite Wrap**

Figure 4. 2 Stress contour plot diagram of complete defective pipe model (D x D model) with all components

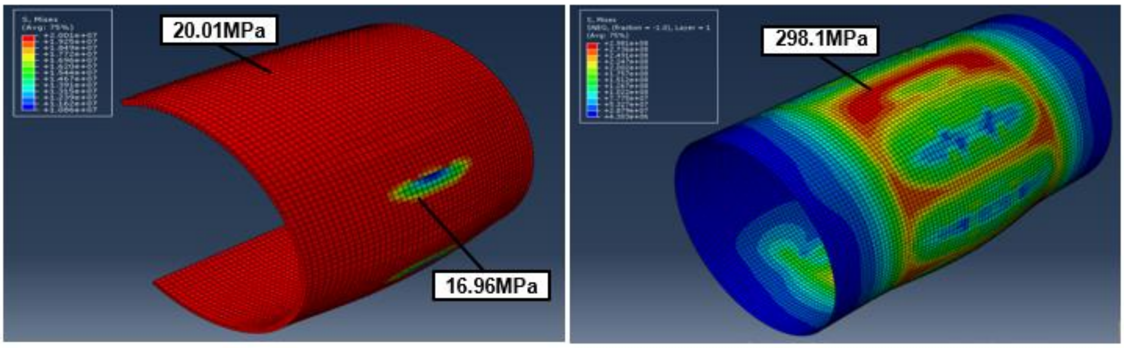
4.1.3 Stress Contour Plot of D x 2D Pipe Model

From Figure 4. 3 that shows below, it presents that the stress contour plot of composite repaired pipe model with the defect area of 168.3mm x 336.6mm (D × 2D model) and all of the individual components. The putty component in the below left corner of Figure 4. 3 also predicted to experience the same amount of highest stress (20.01MPa) in the whole putty structure but there were a small area of stress concentration with the colour of yellow, green and blue in the middle of the putty structure. These colour of stress are lower than the value of the highest tensile stress. The value of stress in yellow, green and blue colour are 17.72MPa, 16.20MPa and 10.86MPa respectively. In the stress contour plot diagram of steel pipe with defect, there were five areas in red colour which indicates that the areas in defect region were experienced 557.7MPa of stress, the highest tensile stress. The areas included both edges, middle and nearby the middle of the defect region along the axial direction. The area of highest stress concentration at the edges of the defect region is getting narrower compared to the other defective pipes. In contrast, the area of stress concentration in the middle of the defect region is getting wider as the defect width getting longer. There is another highest stress concentration area occur nearby the middle area of stress concentration. With these, it shows that the total area of the highest stress concentration in the defect region of D × 2D model is bigger than the previous two pipe model. From the diagram of composite wrap, the area of the highest stress (298.1MPa) concentration is much bigger as the red colour region was distributed around the edges of defect area underneath the composite wrap.



Composite Repaired Pipe Full Model

Steel Pipe with Defect



Epoxy Grout

Composite Wrap

Figure 4. 3 Stress contour plot diagram of complete defective pipe model (D x 2D model) with all components

By comparing the stress contour plot diagrams of three composite repaired pipes with different defect width, we can see that when the defect width increasing, the defect area of the pipe will experience more ultimate tensile stress as the stress concentration area getting bigger. The finite element analysis conducted by Liu et al. (2016) also shows that the stress concentration becomes more severe when the defect width increasing. With the defect width getting wider and more area of defect region experiences ultimate tensile stress, the load bearing capacity of the pipe will getting weaker and thus the failure of pipeline will occur (Chan, 2017) . Beside the defect region, the composite wrap also experienced the increasing of highest stress concentration area as the defect width increasing, the increasing tensile stress sustained in defective steel pipe will be transmitted to the composite wrap with the help of putty. As a result, the pipeline will fail at lower pressure. The pipeline failure occur when the pipe burst at high pressure round the highest stress concentration area which can be considered as the failure location according to the experiments conducted by Lim (2017).

4.2 Results of Effect of Defect Width on Burst Pressure of Composite Repaired Pipe

The bar graph of result of finite element analysis on burst pressure of composite repaired pipe subjected to various defect width is presented in Figure 4. 4. It shows that the burst pressure of the D x ½D pipe model that predicted by the finite element analysis is 29.33MPa, which is the highest burst pressure that sustained by a defective pipe model amongst three models. When the defect width increased and D x D pipe model created, the value of the burst pressure of the pipe model is 28.63MPa and it is lower than the burst pressure of D x ½D pipe model but higher than D x 2D pipe model that have 25.66MPa of burst pressure. The predicted burst pressures of all pipe model cases were found to be slightly different. By referring to Table 4. 1, the variation of burst pressure between D x ½D pipe and D x D pipe is 2.42%. When comparing the overall result of burst pressure, 12.51% is the value of the variation between the pipe having the highest burst pressure (D x ½D pipe) and the pipe having the lowest pressure (D x 2D pipe). All the variation between burst pressures of pipes refer to the Equation 4.1. The result of 12.51% of the variation between the results indicated that there is effect of defect width upon the burst pressure of the composite repaired pipe as the result is more than 10%. With results presents in Figure 4. 4 and Table 4. 1, it shows that the burst pressure of pipe is getting lower when the defect width of pipe model is getting wider. This condition is due to the load bearing capacity of pipe and composite is also getting lower when the defect getting longer. Previous studied such as ASME B31G also states that the bigger the defect area on the corroded pipe, the lower the pressure of a leak or rupture to occur (American Society of Mechanical Engineers, 1991). This condition can be linked to the stress experienced by the steel pipe, putty and composite in order to understand the effect of defect geometry upon the burst capacity of the composite repaired pipe. Besides that, the trend line in Figure 4. 5 also shows that the burst pressure is in decreasing trend when defect width increasing and the equation obtained from the trend line can be used to predicted the burst pressure of pipe with known defect width.

As we can see from the stress contour plot that discussed before this section, the area of stress concentration in defect region of pipe model is increasing while the defect geometry is increasing because the load bearing capacity of the pipe is decreasing due to the increasing of defect area. Therefore, the pipe fail and burst at the lowest pressure when the stress at the composite wrap reached ultimate tensile stress when the defect width is in 336.6mm length which is the longest defect width in this study. In contrast, with the short defect width and smaller defect area, the D x ½D pipe shows that it had the smallest area of stress concentration and thus the load bearing capacity of the pipe is still strong enough to sustain the stress. As a result, the pipe model failed at the lowest burst pressure as comparing to other composite repaired pipe with longer defect width and bigger defect area.

Table 4. 1 Parametric study of defect width

Defect	Geometry: L x W (mm x mm)	Burst Pressure (MPa)	Difference (%)
D x 1/2D	168.3mm x 84.15mm	29.33	-
D x D	168.3mm x 168.3mm	28.62	2.42
D x 2D	168.3mm x 336.6mm	25.66	12.51

$$Difference = \frac{(\mathrm{D}\times 1/2D) - other}{(D\times 1/2D)} \times 100\% \quad 4.1$$

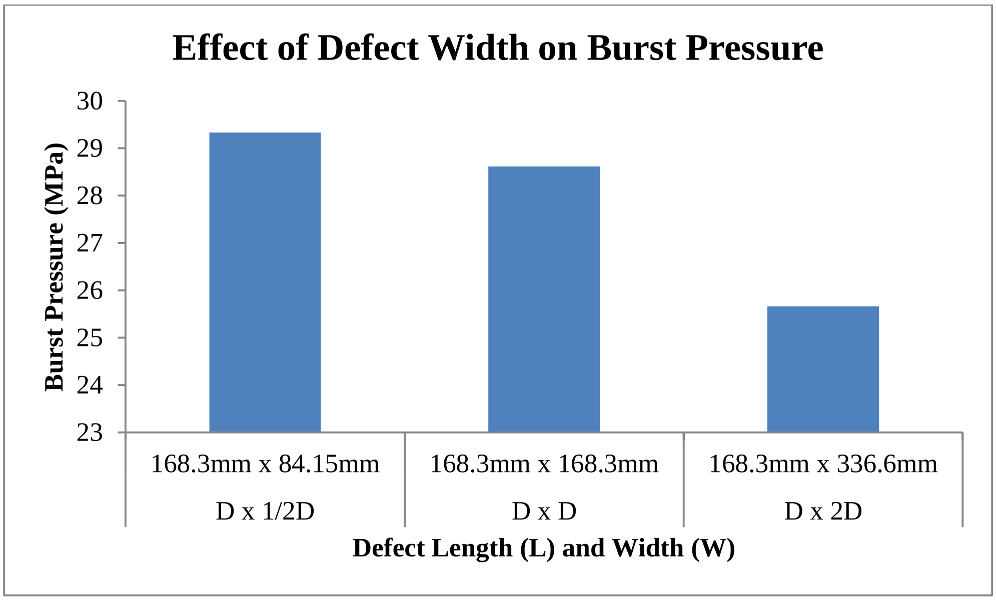


Figure 4. 4 Graph of effect of defect width on burst pressure of composite repaired pipe

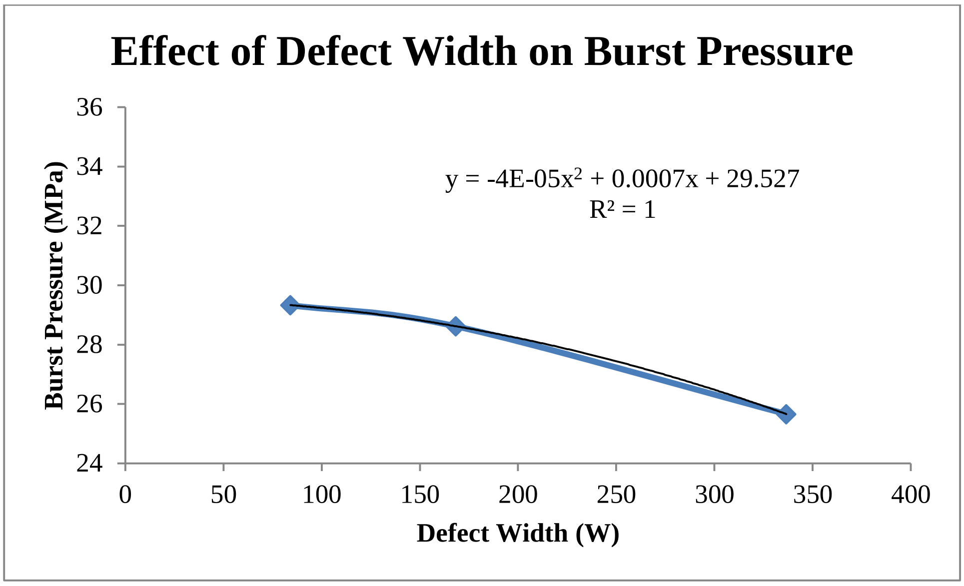


Figure 4. 5 The trend line of defect width with burst pressure of pipe

4.3 Concluding Remarks

The chapter has discussed all the results obtained through finite element analysis. The result of burst pressure of composite repaired pipe is discussed corresponding to the stress concentration that experienced by the pipe in order to understand more of the burst capacity of a composite repaired pipe influenced by the defect width. The stress contour plot diagram illustrated all the stress that experienced by the composite repaired pipe as all the individual components which are the defective pipe, putty and composite were also show in the chapter with respective values and colours. With the stress contour plot, we can see where the highest stress concentration area in the components are in order to predict the failure location on the pipe and the burst pressure of the pipe. The D x 2D pipe with the longest defect width which also having the biggest defect area, shows that it experienced big area of the highest stress concentration and caused it to fail at low burst pressure as the load bearing capacity of pipe model is the lowest. It is proven that the relationship of stress concentration experienced by the pipe and the changes of defect width will influence the burst capacity of the composite repaired pipe. The overall result of variation between the burst pressure of pipe models that simulated by finite element analysis with the longest and shortest defect width is 12.51%.

CHAPTER 5

CONCLUSION

5.0 Overview

This section summarise the findings of this study which achieved the objective of research. The results of burst pressure of externally corroded pipe are obtained from modifications of the defective pipe base model, which having defect geometry of 100mm x 100mm. The base model is validated with the published experimental data before modification conducted. The burst pressures of the defective pipe are successfully determined with the three modified pipe models with different defect widths, which the defect geometry of each pipes are 168.3mm x 84.15mm (D x ½D) pipe, 168.3mm x 168.3mm (D x D) pipe and 168.3mm x 336.6mm (D x 2D) pipe. The stress contour plot of the completed composite repaired pipe also extracted from the finite element analysis and considered as one of the results to evaluate the effect of defect width upon the burst capacity of the pipe. Significance of this study also presented in this chapter to remind us how important for us to carry out this study carefully with clear mind to obtain accurate results and able to contribute some ideas in optimization of the design codes and standards. In order to improve the accuracy and uses of the findings in this study, several recommendation is suggested and explained in this chapter so that simulated results that obtained will be more realistic and able to give more confident to the reviewers.

5.1 Conclusions

The following are the conclusions according the research objectives:

1. The burst pressure of the externally corroded pipe subjected to various defect width were determined with the modification of validated base model. In the results, the burst pressures for the D x ½D pipe, D x D pipe, and D x 2D pipe are 29.33MPa, 28.62MPa, and 25.66MPa respectively.

2. The defect width is proven influential on the burst pressure of composite repaired pipe. The stress contour plot diagrams and the bar graph show that when the defect width getting wider, the area of the highest stress concentration is getting larger and causing the load bearing capacity of the defective pipe getting lower. With this, the composite repaired pipe getting easier to fail at lower burst pressure. This can see from the result of the D x 2D pipe model with the longest defect width has the lowest burst pressure.

5.2 Significance of Research Contribution

The findings of this study indicates that the defect width has effect in assessing and designing composite repair pipe system in a more realistic and effective way. It should be included in the codes and standards when modification is carried out recently by the industry in order to optimize the current conservative design codes and standards in composite repair system. The effect of defect width might influence the design of thickness of the composite wrap and also influence the pipeline users in choosing the suitable epoxy grout based on its stiffness. The performance of the putty and composite wrap that are going to be design might be improved with a more optimized design method and it will extend the life time of the steel pipe. The steel pipe that can be repaired without stopping the operation of the pipeline will be favourable by the pipeline operators and the risk of explosion while repairing the steel pipe with welding will be reduced. The more effective way in using the amount of epoxy grout and composite wrap can save money of the users as well. Besides designing the composite repair methods, the findings of this study can also be improved in order to use to predict the burst pressure of the composite repaired pipe while externally corroded defect found to be occur on the surface of the pipe. If the condition of defect getting more severe, the pipeline operator can repair the pipe accurately based on the condition of the pipe. This can simplify the industry procedure in assessing condition of pipe in regular period and worrying about the pipe might burst at any time.

5.3 Recommendations

Recommendations on improving this study for further research is suggested at below:

1. Since this research only conducts finite element analysis, it is suggests to perform experiment test to further validate the result of this study for the research to have more confident on the simulation results.

2. The burst pressure obtained from the equation of design codes and standard and the findings of this study can be compared in order for this research to prove that the effect of defect width has significant effect on the burst pressure of composite repaired pipe.

3. More details on parametric study should be conducted by adding more defect width with smaller difference into the finite element analysis in order to get a detailed trend of the burst capacity of composite repaired pipe influence by various defect width.

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