EFFECT OF DEFECT LENGTH UPON BURST CAPACITY OF COMPOSITE REPAIRED PIPE

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ABSTRAK

Sistem saluran paip adalah salah satu infrastuktur yang amat penting dalam industri petrokimia kerana ia digunakan untuk mengangkut petroleum dan gas. Walaubagaimanapun, kerosakan dan kemerosotan paip akan berlaku beberapa tahun selepas ia digunakan, terutama berlakunya pengaratan pada saluran paip yang akan menipiskan ketebalan saluran paip dan kekuatan paip dan seterusnya menyebabkan kegagalan apabila baki kekuatan paip tidak mampu menahan tekanan operasi saluran paip tersebut. Oleh itu, kerja pembaikan paip amat diperlukan untuk menambahkan kekuatan paip, contohnya, dengan menggunakan komposit polimer diperkuat gentian (*FRP*). Kod pembaikan yang digunakan untuk menentukan baki kekuatan paip yang berkarat tidak memasukkan geometri kepanjangan dalam pengiraannya yang amat berbeza dengan kod penilaian. Dalam kajian ini, tekanan letus paip yang diperbaiki komposit akan dikaji dengan pelbagai kecacatan kepanjangan yang berlainan. Kajian ini dijalankan dengan mengunakan kaedah analisis unsur terhingga pada pelbagai paip yang mengalami kerosakkan dengan saiz panjang yang berlainan. Keputusan telah menunjukkan bahawa perbezaan tekanan paip ialah 15.59% dan ini telah menunjukkan bahawa geometri kepanjangan mempunyai kesan pada tekanan letus paip yang diperbaiki komposit. Penemuan ini sangat berguna untuk mengoptimumkan reka bentuk sistem pembaikan yang sedia ada.

ABSTRACT

Pipeline system is one of the infrastructures that are essential in petrochemical industries as it is uses to transport oil and gas. However, pipelines will start to damage and deteriorate after being used for some years, especially the happening of corrosion which will reduce the thickness of pipeline and the remaining strength of the pipe and consequently lead to failure once the remaining strength unable to withstand operating pressure of the pipeline. Hence, additional strength from repairing job needs to be provided, for instance, by using fibre-reinforced polymer (FRP) composites. Unlike the assessment codes, the repair code that use to determine the remaining strength of the corroded pipe does not include the defect geometries such as defect length. In this study, burst pressure of the composite repaired pipeline with different defect lengths and the effect of the defect length upon the burst capacity of composite repaired pipe is investigated. The study is carried out by a finite element analysis (FEA) on various defective pipe with different defect length size. The results show that the difference of the burst pressure subjected to various defect length is 15.59% and this had proved that there is an effect of defect length upon the burst capacity of composite repaired pipe. This finding can be very useful for optimizing the existing repair design.

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LIST OF SYMBOLS

D	*Outer Diameter of Pipe*
t	*Pipe Wall Thickness*
σ_y	*Material Yield Strength*
σ_u	*Ultimate Tensile Strength*
σ_a	*Axial Stress*
σ_r	*Radial Stress*
σ_h	*Hoop Stress*
L	*Defect Length*
d	*Defect Depth*
r	*Radius of Pipe*
w	*Defect Width*
P	*Burst Pressure*
M	*Bulging Stress Magnification Factor*
t_s	*Remaining Wall Thickness*
P_s	*Maximum Allowable Operating Pressure*
s	*Specific Minimum Yield Strength*
ε	*Maximum Strain*

LIST OF ABBREVIATIONS

FEA	*Finite Element Analysis*
FRP	*Fibre Reinforced Polymer*
CFRP	*Carbon Fibre Reinforced Polymer*

CHAPTER 1

INTRODUCTION

1.1 Overview

Pipelines act as a transport element in petrochemical industry which normally use in offshore and placed underground. This infrastructure is important in human life, it help in delivering oil and gas that has been produced into different products that we used. For instance, the heat supply for stoves, fuel supplies for transportation and run the machine to make the household product. The study of National Association of Manufacturers (NAM) had also estimated that the crude oil pipelines alone created over 200,000 jobs and over $21.8 billion in Gross Domestic Product in 2015 (National Association of Manufacturers, 2015). This had shown that pipeline infrastructure is also important in moving the country's economic (Lim et al., 2015).

There are a lot of pipeline accidents all around the world over the years including United States who has the longest network of pipeline in the world with 240,711km of the pipeline network is used to transport the petroleum products and 1,984,321 km in transporting the natural gas to make the total length of 2,225,032km (Central Intelligence Agency, 2013). After years in service, pipeline will experience deterioration and a deteriorated pipeline may subsequently fail if no proper action is taken. Hence, monitoring and inspecting of pipeline will be carried out to discover the failures or the deterioration of the pipeline system. One of the common ways for pipeline inspection is done by intelligent pigging to gather important data of the pipeline such as location and geometries of defects. Without carry out the inspection and repairing work of the pipe, the deterioration of the pipeline may cause pipe failures such as leaking and explosion.

1.2 Background of Study

The environment surrounding the pipelines will cause defect on the pipelines due to several factors and subsequently affect the service strength and its service life. There are several types of defect in the pipelines system which include the geometrical defect, defect in metal loss, planner discontinuities and change in metal, and all of these defects will bring effect to the pipelines system (Abdel-Alim, 2018). All of these defects will affect the remaining strength of the pipeline and its service life and performance.

There are a lot of method to repair the defect or the deterioration of the corroded pipeline. Fibre-Reinforced Polymer (FRP) composites is one of the effective repair methods in repairing defective pipeline system. FRP composites are lightweight, high performance, suitable to ocean environment, long-lasting and easily to be constructed and tailored to different requirements (Lee and Jain, 2009). However, the performance of this repair system is not fully understood due to several issues which include the complexity of surface preparation, delamination and de-bonding between steel pipe and composite, performance and contribution of the infill material, load transfer mechanism, effect of defect geometries and conservativeness in existing design codes (Lim, 2017). People will have better understanding on the behaviour on the composites by discovering up these issues and this could help to maximise the role and uses of the composite repair system.

1.3 Research Problem

Corrosions could occur at any places of the pipeline including internal and external surfaces of the pipelines and this will reduce the pipe thickness and reduce its strength due to the loss of metal. A low remaining strength may cause the failure of the pipeline and burst may be occurred.

Data such as the presence and the location of the corrosion happened in the pipe or other irregularities on the wall can be taken from the inspection by using the intelligent pig. From the data that are collected from inspection action, it can help in determining the remaining strength of the defective pipeline by referring to several engineering design codes. These include American Society of Mechanical Engineer (ASME) B31G, modified ASME B31G and DNV-RP-F101 codes. The input parameters that are used in these codes include outer diameter of the pipe, D, wall thickness, t, yield strength of the material, σ_y or ultimate tensile strength, σ_u, the length of the defect, L and the defect depth, d.

However, the repair codes include ISO/TS 24817 and ASME-PCC2 which are used to determine the repair material only include defect depth as the input parameter in determining the remaining strength of the defective pipe. Hence, investigation on other defect parameters such as defect length is needed to explore the potential effect of defect length towards the burst capacity of a composite repaired pipe.

1.4 Research Objectives

The aim of this study is to investigate the effect of defect length towards burst capacity of composite repaired pipeline. In order to achieve the aim, two objectives are established as follow:

1) To determine the burst pressure of the composite repaired pipeline according to different defect lengths.

2) To investigate the effect of defect length upon the burst capacity of composite repaired pipe.

1.5 Research Scope

The scope of this research concentrates about the effect of remaining strength and the burst capacity of the composite repaired pipe subjected to different lengths. Simulation method which is finite element analysis (FEA) was used where finite element (FE) models were developed to determine the burst capacity of composite repaired pipeline. Variation of other defect geometries such as width and depth are not included in this study.

1.6 Importance of Study

Repair cost can be reduced by reducing the usage of the composite wrap on the damage pipelines. One of the challenges in optimizing the composite repair design is the lack of information on the behaviour of the composite repaired damaged pipes. Base on the existing assessment codes and previous studies, the defect lengths has been proven to be influential on the remaining strength and the burst capacity of the damaged pipes.

Therefore, it is hypothesised that defect length will also affect the burst capacity of composite repaired pipe. Hence, it is important to discover and understand how the defect length will affect the burst pressure of the pipelines and hence optimizing the usage of the composite layer and also the whole repair systems.

CHAPTER 2

Literature Review

2.1 Introduction

This chapter starts with brief explanation about the pipelines defects which include the defect geometries and failure behaviour in the pipeline. Besides, the philosophy of the assessment codes and repair codes is also included in this chapter.

2.2 Overview

A pipeline is referring to a circular cross section structures that is mainly used to transport liquids and gases from one place to another. Different type of pipe has different purpose, for example API SPEC 5L is normally used for transport oil and gas while API SPEC 5CT is used for extracting the petroleum and natural gas casing pipe that serves as wall of the well. Pipeline system is always the reliable and safest way to transmit the product and produce into different product that used by human being in their daily life as this is due to a combination of good design, materials and operating practices. Hence, the major concern of the pipeline system is to maintain the integrity to ensure the safeness of the pipeline.

As mentioned in the previous chapter, the integrity of the pipeline will be reduced once the pipeline become thinner, especially the occurrence of corrosion which may lead to serious consequences such as leaking and burst. For instance, the gas explosion incident that occurred in Kaohsiung in 2014 that 32 people were being killed and 321 peoples were injured (Wingham, 2018). According to Saravanan et al. (2014), corrosion will deteriorate the pipes and cause the metal loss on the pipe’s surface. Corrosion may be occurred internally or externally at the pipeline and the mechanism includes electrochemical corrosion, chemical corrosion and stress-promoted corrosion (Khairul

Anwar, 2012). Hence, this will result the wall thinning of the pipes. After sometimes, the wall thinning of the surface will increases and the pipes will crack and leak at peak point and subsequently the pipe will fail. Hence, assessment and determination of the burst pressure before a total lost could occur is needed to ensure the integrity of the pipe.

2.3 Defect of Pipelines

As mentioned earlier in Chapter 1 that Abdel-Alim (2018) had stated that geometrical defects, defects resulting in metal loss, planner discontinuities and change in metal are the defect types in pipeline. Geometrical defect normally is the smaller change in wall thickness than the allowable wall thickness tolerance and this defect will result in stress accumulation and concentration. Regular buckle, sharp buckle, rolling imperfection, wrinkle, tube expansion, and joint imperfection are the example of geometrical defects. However, the defect resulting in metal loss is the define as the greater change in wall thickness than the allowable wall thickness tolerance and result in stress concentration. Corrosion is the most common defect which due to the metal loss. According to Abdel-Alim, general corrosion is the metal loss extending over a significant area of the pipe and resulting in reducing the wall thickness. The possible cause of origin is due to the effect of the transported medium, inappropriate material selection, imperfect coating, damaged coating and inadequate cathodic protection. Saravanan and his team also mentioned that the wall thinning on the pipeline usually results in localized pit with different depths and uneven shapes on its external and internal surfaces (Saravanan et al., 2014). After a certain period, the wall thinning on the surface will be increased and the pipes will crack and leak at the peak point and hence cause the operation of the pipelines to be shutdown. Corrosion in a pipeline may be difficult to characterize. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions. The simplest and perhaps most widely recognized definitions are as follows: pitting corrosion, defined as corrosion with a length and width less than or equal to three times the un-corroded wall thickness, and general corrosion, defined as corrosion with a length and width greater than three times the un-corroded wall thickness (Mohamad Zulfadli, 2012).

2.4 Repair Techniques

According to Lim et al. (2015), pipelines are subjected to deterioration due to several factors, including third party damage, material and construction defects, natural forces and corrosion. Corroded pipe defects can be divided into three main categories: (i) pipe subjected to external metal loss, (ii) pipe subjected to internal metal loss, and (iii) piping components that are leaking. Hence, monitoring and inspection of pipeline will be carried out to discover the defects or deterioration of the pipeline system to reduce the incidents of pipeline accidents. One of the common ways for pipeline inspection is by using intelligent pigging to gather important data such as location and geometries of defects. Geometrical defect is one of the types of defect in the pipeline systems. Geometrical defect includes the defect in different direction for example hoop and axial direction and the defect dimension has different parameters which including defect length, *l*, depth, *d*, and width, *w*. Figure 2.1 illustrates the geometrical defect of pipeline.

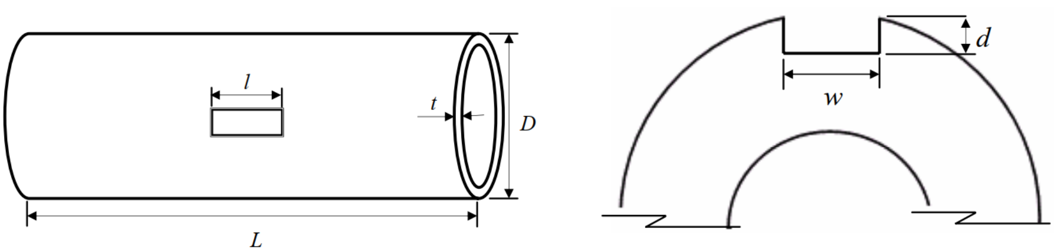

Figure 2.1 Defect Geometries in Schematic Defective Pipelines

Source: Alang et al. (2013).

There are two repair methods for the corroded pipe which are the steel repair techniques and the composite repair systems. Conventional steel repair techniques are the most common solution for the repairing work as it is only removing the pipe entirely or only the localized section and replace with a new steel part. This repair method can also be done by installing a full-encirclement steel sleeve or steel clamp which are either welded or bolted to the external of the pipe as shown in Figure 2.2. The sleeves can be also joined by mechanical fastening. However, this repair method is generally suitable for straight pipe section and very limited for joints or bends due to the very limited workspace especially the underground condition. Therefore, the fibre reinforced polymer (FRP) composite had been invented.

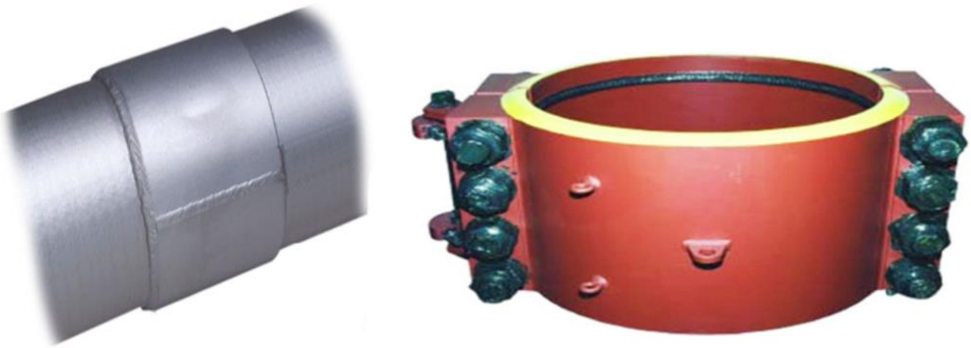

Figure 2.2 Full-encirclement steel sleeve and repair clamp
Source: Lim et al. (2015).

FRP composite material has been used in the late 1980s and after some efforts and development it finally offer numerous advantages over the traditional steel sleeve and clamp repairs and have lower repair costs (Lim, 2017). FRP composite is lightweight, high performance, suitable to ocean environment, long lasting and easily to be constructed and tailored to different requirement. Carbon Fibre-Reinforced Polymer (CFRP) composite is one of the examples of FRP composite that having similar strength and stiffness to steel but with a density three times lower than steel (Lim, 2017). FRP composite is also a repair material that indicated through the development of the pipeline repair codes, such as ASME PCC-2 and ISO/TS 24817 (Lim et al., 2015). Generally, FRP composite repair system consists of three parts: (i) FRP composite, (ii) interlayer adhesive, and (iii) infill material as load transfer medium. Figure 2.3 shows one of the examples of the FRP composite repair system which named Clock Spring® Repair System. The repair system from The Clock Spring Company are made of fibreglass as reinforcement and claim that it can repair defects up to 80% metal loss (The Clock Spring Company, 2012). The defect area is filled with high compressive strength infill material to assist the load transfer prior to their installation while the layers of wrap are sealed together with a strong interlayer bonding adhesive. This repair method can support the defects and prevent defects failure through load transfer and restraint.

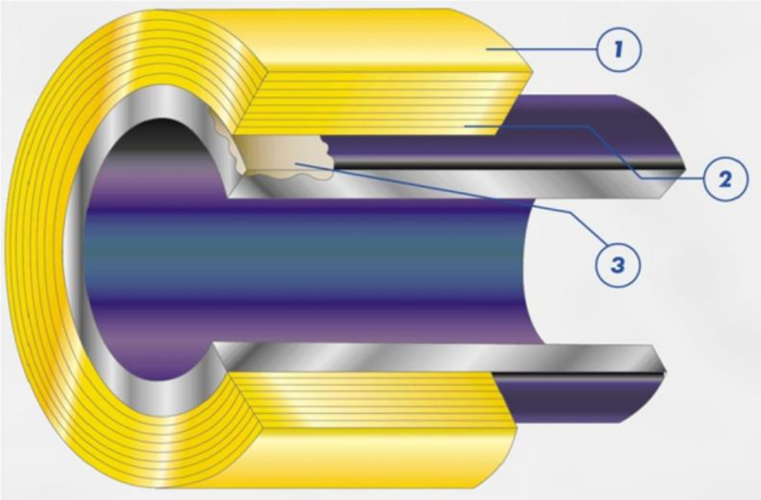

Figure 2.3 Clock Spring ® FRP composite repair system with FRP composite (1), Interlayer adhesive (2), and Infill material (3)

Source: The Clock Spring Company, 2012).

2.5 Stresses Acted on Steel Pipes

Pipelines system is assumed to be failed when the von Mises stress which is the combination of three principal stresses is exceeding the yield strength of the material (Mohamad Zulfadli, 2012). The three principal stresses are axial stress, σ_a, radial stress, σ_r and hoop stress, σ_h. Figure 2.4 illustrates the direction of hoop and longitudinal stress on the pipe. Thin-walled pressure vessel and thick-walled pressure vessels are the assumptions that take into the analysis for the stresses. Thin-walled pressure vessel can be assumed when the ratio of $\frac{r}{t} \geq 10$ where *r* is representing the radius of the pipe and *t* is the wall thickness while it was assumed for thick-walled pressure vessel when the ration of $\frac{r}{t} \leq 10$.

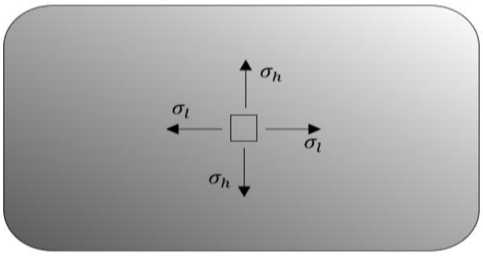

Figure 2.4 Direction of hoop and longitudianl stress

Source: Mohamad Zulfadli (2012).

Hoop stress is the force that resisted by the tangential stress and it is acting uniformly over the stressed area for thin-walled pressure vessel. However, the hoop stress of the pipeline is equal to the tangential stress when the pipe is considered as a thick-walled pressure vessel. When the assumption for thin wall states that the ratio of the internal radius of the pipe and the thickness is less than 10, the stress acted in the z axis, σ_z is also equal to zero, hence the radial stress, σ_r will be also equal to zero since the radial stress acted on the pipe is rotated along the z-axis (Mohammad Zulfadli, 2012). Axial stress where also known as longitudinal stress is the tension or compression stress created by the application of a lengthwise axial load in the cylindrical member.

2.6 Current Codes and Practices

According to Saravanan et al. (2014), burst pressure is defined as the maximum pressure that the pipes can sustain before they burst or as the point right before failure occurs. Material quality, thickness of the pipes, heat are the factors that can bring effect to the burst pressure. To be general, a defective pipe would have a lower burst pressure rather than a non-defective pipe. According to Alang et al. (2013), there are several design codes used in practice to evaluate the remaining strength of corroded pipelines such as America Society of Mechanical Engineer (ASME) B31G (ASME International, 1991), modified ASME B31G and DNV-RP-F101 codes (DNV, 2010) and these codes were developed many years ago and have been used throughout the industry.

ASME B31G is a manual for evaluating the remaining strength of corroded pipelines and this code is referred as guidance in the evaluation of metal loss in pressurized pipelines and piping systems. On the other hand, DNV-RP-F101 code is capable to evaluate single defect, interacting defects and complex shaped defects (Saravanan et al., 2014). ASME B31G and modified ASME B31G had simplify a short longitudinal corrosion defect as a parabolic curve whereas long corrosion defect can be simplified to a rectangular shape. In the codes, it had mentioned that the failure of the corroded pipelines is also controlled by the defect size as well as the flow stress of the material. Alang and his team had mentioned that the DNV-RP-F101 code can be applied for both defects subjected to internal pressure loading only or internal pressure loading combined with longitudinal compressive stresses. However, the ASME B31G is limited to defect subjected to internal pressure only.

ASME B31G and DNV-RP-F101 codes also mentioned that the failure of corroded pipelines is manipulated by the defect size and the flow stress of the material.

The input parameters of these codes include the outer diameter of the pipe, *D*, wall thickness, *t*, yield strength of the material, σ_y, or ultimate tensile strength, σ_u , length of defect, *L*, and defect depth, *d*. The equations used to calculate the burst pressure, *P*, based on these codes are expressed as:

For ASME B31G:

$$P = \frac{\sigma_{flow} \cdot 2 \cdot t}{D} [\frac{1 - \frac{d}{t}}{1 - \frac{d}{t} \cdot \frac{1}{M}}] \quad 2.1$$

$$M = \sqrt{1} + 06.275 \frac{L^2}{Dt} - 0.003375 (\frac{L^2}{Dt})^2 \quad 2.2$$

For DNV-RP-F101:

$$P = \gamma_m \frac{2t\, SMTS}{(D - t)} \frac{(1 - \gamma_d \left(\frac{d}{t}\right)^*)}{(1 - \frac{\gamma_d \left(\frac{d}{t}\right)^*}{Q})} \quad 2.3$$

where *M* represents as bulging stress magnification factor.

As mentioned earlier, the FRP composite is a repair material that indicated through the development of the repair codes which including ASME PCC-2 (ASME, 2011) and ISO/TS 24817 (ISO, 2006). ASME PCC-2 is the codes that specifically focuses on steel pipes while ISO/TS 24817 is recognized as a general code that covers pipe with different materials from steel to FRP. Both codes are used to determine the minimum thickness for the FRP wrap that could restores the capacity in the damaged pipe to resist the design pressure in the presence of other probable loads such as bending and compression (Lim, 2017). Lim had also mentioned that these codes design the repair system in the most critical direction which is hoop and axial direction so that the original design pressure can be reinstated.

The yield strength of the substrate is the criterion for determining the thickness of the composite repair, the minimum remaining wall thickness, t_s in hoop direction of the steel substrate when un-reinforced is defined as:

$$t_s = \frac{P_s D}{2s} \quad 2.4$$

where P_s is the Maximum Allowable Operating Pressure (MAOP), D is the pipe diameter and s is the Specific Minimum Yield Strength (SMYS) of the pipe. By substitute in the maximum strain, ε of the substrate and composite combination, minimum repair thickness equation will be formed as:

For ASME PCC-2:

$$t_{min} = \frac{D}{2s}\left(\frac{E_s}{E_c}\right) \cdot (P - P_s) \qquad 2.5$$

For ISO/TS 24817:

$$t_{min} = \frac{1}{E_c \varepsilon_c}\left(\frac{PD}{2} - st_s\right) \qquad 2.6$$

From both repair codes the input parameter only includes the pipe diameter, D, minimum yield strength, s, tensile modulus of pipe material, E_s, tensile modulus of composite laminate, E_c, internal design pressure, P, maximum allowable operating pressure, P_S, allowable strain of the composite, ε_c and minimum remaining wall thickness, t_s. As can be seen, the repair codes does not consider for the defect length and defect width unlike the assessment code. Hence, it is important to discover and understand how the defect length will affect the burst pressure of the pipelines and as this may potentially optimize the usage of the composite layer as well as the whole repair system since this could reduce the overall repair cost by reducing the usage of the composite wrap on the damage pipelines.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The research methodology of this study is briefly divided into two stages which the first stage is the development of base model and the second stage is parametric study of the model. The input for material properties of epoxy grouts, steel pipe and composite for the base model were obtained from a published hydrostatic burst test study. The burst pressure for the numerical simulations was compared with the published data for validation purposes.

ABAQUS® v6.12.-1 commercial finite element modelling software was used to create the model, generate meshed, and perform finite element (FE) calculations. In stage 1, geometries of the steel pipe, putty and composite were modelled which similar to the published data and the material properties is then modelled and assigned. The load and boundary condition are then assigned and applied. The meshed defective pipe, putty, composite and repaired pipe is modelled in this study to achieve the idealisation of the repair process with perfect bonding between the two interface which are (i) putty filling the defect area and the steel pipe and (ii) composite wrap, which encloses the steel pipe and putty (Lim et al., 2019). The FEA results of the base model were then compared with the published experimental result for validation purposes. The margin of error should be less or equal to 10% (Lim, 2017). The model needed to be modified if the percentage of error is more than 10% until it was validated. The validated model is then used to carried out the parametric study in stage 2. The flow chart for the methodology is presented in Figure 3.1.

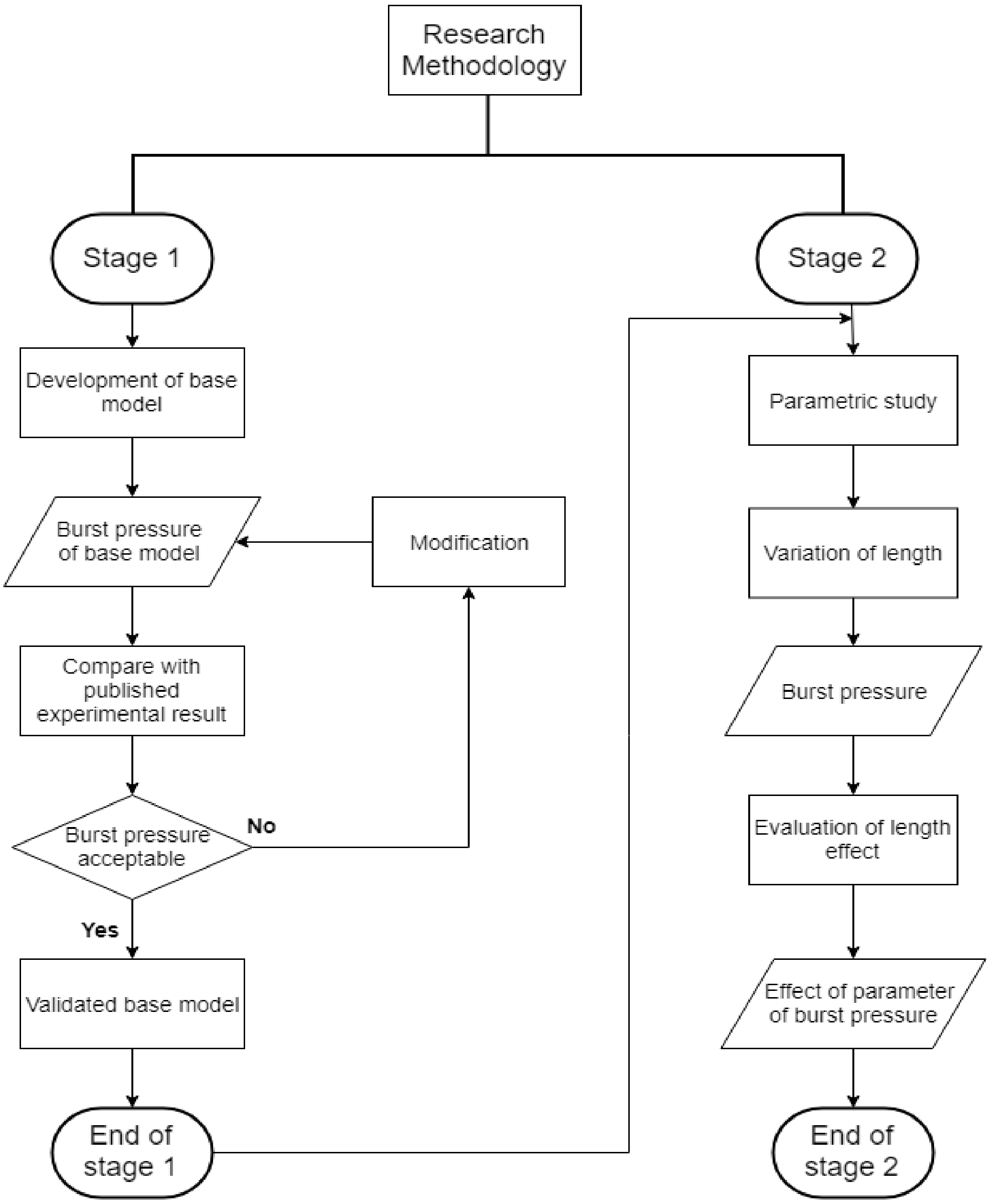

Figure 3.1 Flow chart of research methodology

3.2 Modelling Bare and Corroded Steel Pipes

In this stage, a bare pipe and a defect pipe is modelled. Firstly, a three-dimensional deformable solid part was created to simulate the physical properties of the bare pipe. A pipe with 1200mm in length, 168.3mm outer diameter, 7.11mm thick is modelled. Then another solid part with 154.08mm which equal to the inner diameter to the bare pipe is cut through the whole length of the bare part. Once the second part had been cut through, a hollow bare pipe was successfully created as shown in the Figure 3.2.

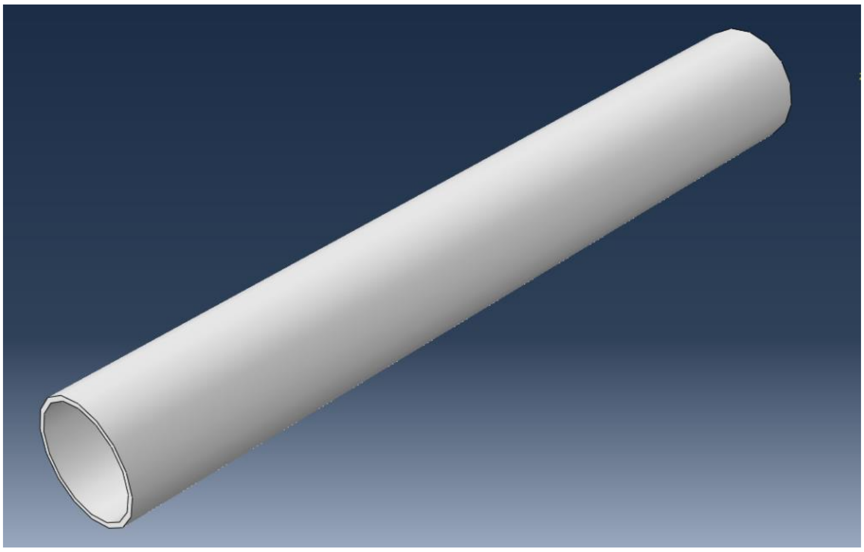

Figure 3.2 Geometry of bare pipe

A two-dimensional defect geometry with arc length of 100mm both in hoop and axial direction and depth of 3.555mm was then sketched onto the middle of the pipe and then extruded to completely model the defective pipe as shown in Figure 3.3.

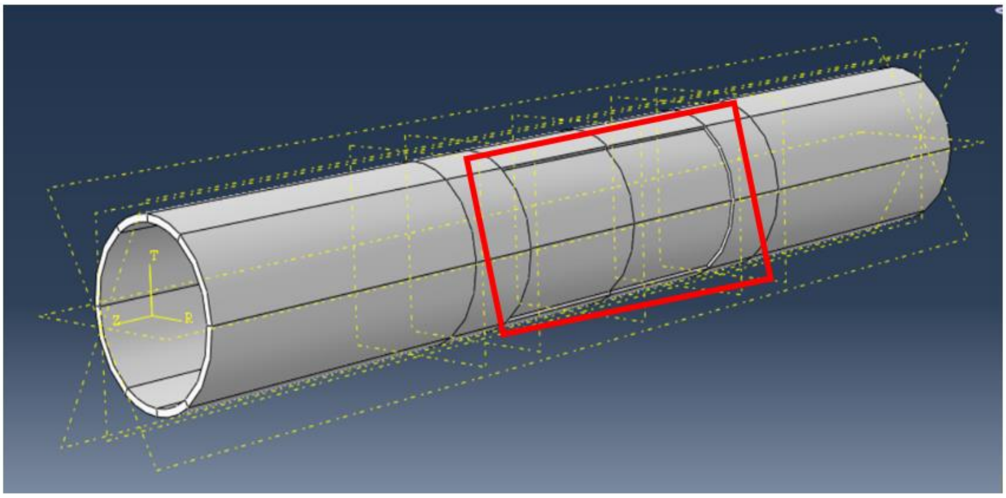

Figure 3.3 Geometry of defective pipe

3.3 Material Properties Assignment

Once the geometry of the pipe had been modelled, the material properties were then assigned to the steel pipe. Young's modulus, Poisson's ratio, and stress-strain curve that obtained from the published hydrostatic burst test result was used as input information for the material properties. The true stress and true strain value were used in this stage to suit the chosen material model (Lim, 2017). The material model was then assigned to the steel pipe.

3.4 Load and Boundary Conditions Assignment

Analysis step was created after the material model was assigned to the steel pipe by assigning the simulation duration. The analysis duration was set to 500s with a linear increase in pressure to 50MPa which simulates a loading rate of 0.1MPa/s. The test specimen was capped with two end caps at both ends so that both ends could expand and contract axially and rotate about the axial axis. Figure 3.4 illustrates the internal pressure and boundary condition of the steel pipe.

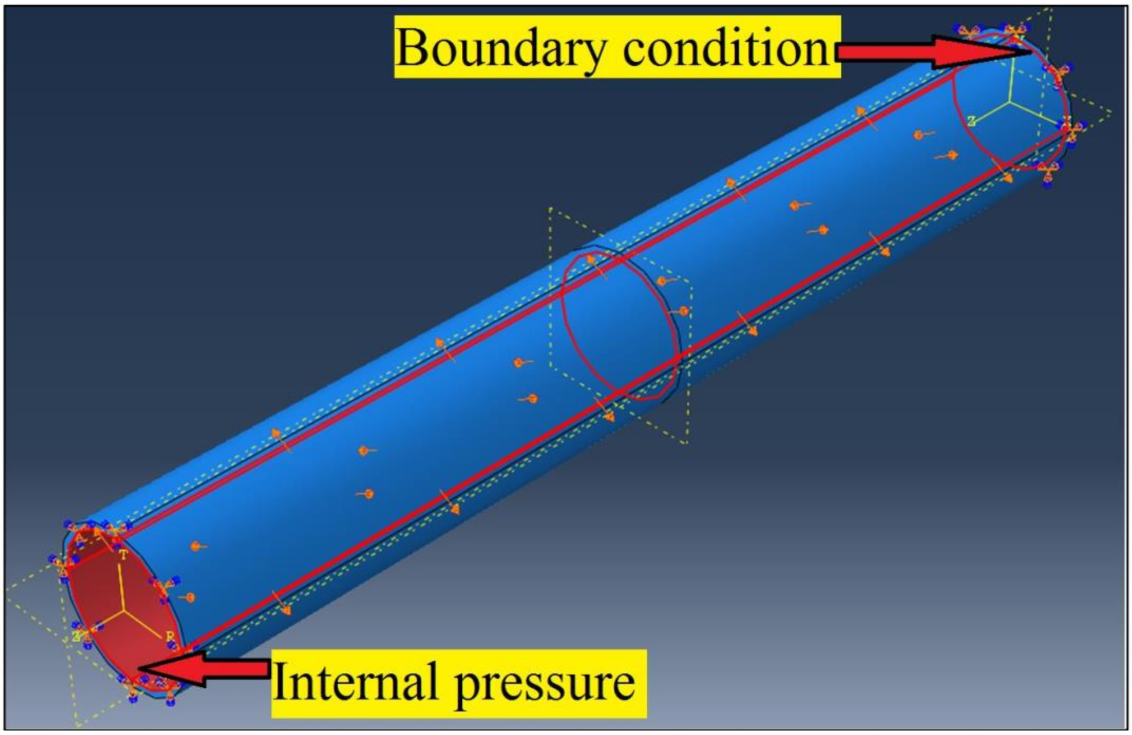

Figure 3.4 Internal pressure and boundary condition

3.5 Meshing of Steel Pipe

In this study, eight-node linear solid element (C3D8R) in the ABAQUS® was selected to produce the mesh of the steel pipe. Good meshing is needed during finite element analysis to obtain the most accurate results and minimize the analysis duration. A structural mesh cannot be created using the original parts in the defect region of the defective pipe due to the nature of odd geometries. Hence, the odd geometries need to be eliminated. The defective pipe was sliced into multiple segments so that the parts with odd geometries were eliminated. In ABAQUS®, different colours in meshing stage is represented by the colour control feature. For example, orange represents that the part cannot be meshed, yellow represents an unstructured mesh can be generated, and green represents a structural mesh is can be achieved (Lim, 2017). Figure 3.5 shows the process of the whole model to be achieved in the meshing process while Figure 3.6 shows the example of the meshed defective pipe used in this study.

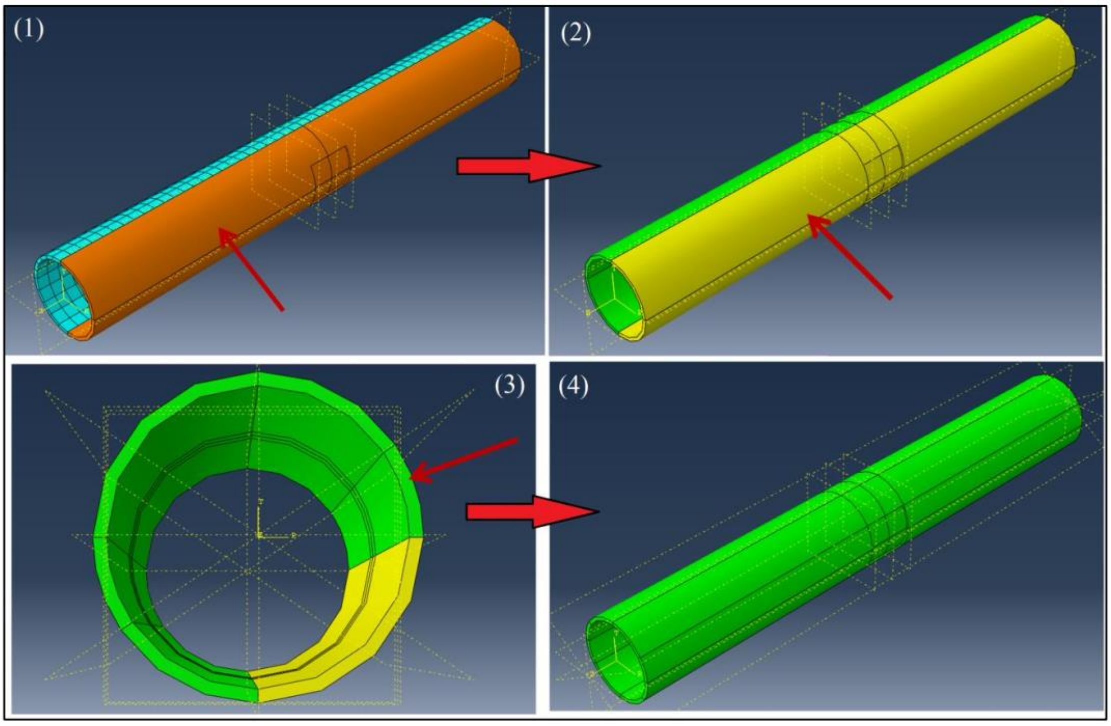

Figure 3.5 Process in achieving structural mesh

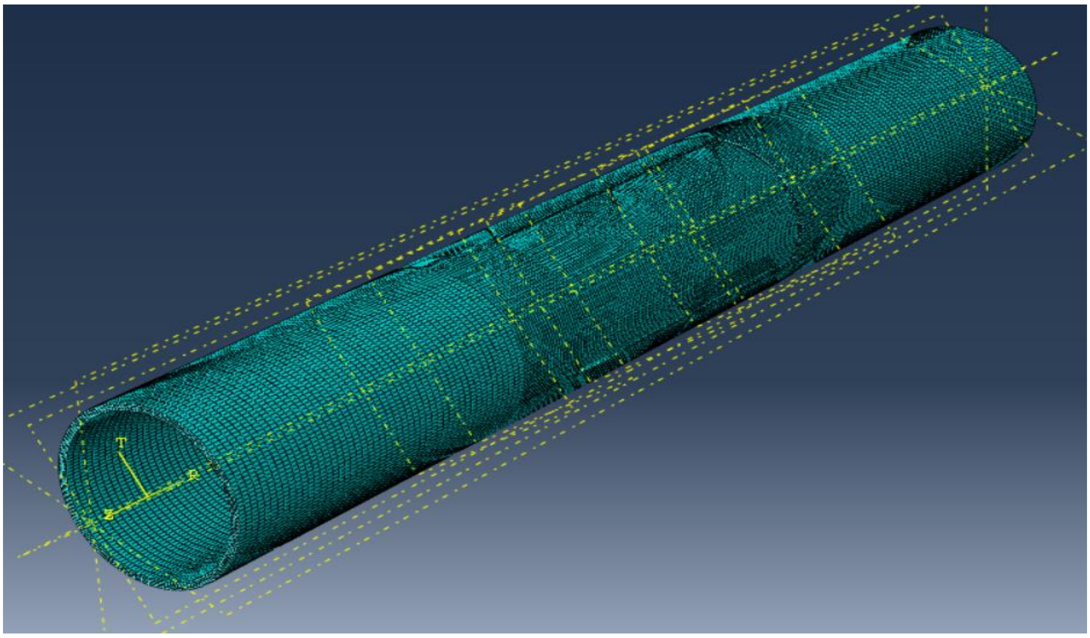

Figure 3.6 Example of a meshed defective pipe

3.6 Execution and Validation of Bare Pipe Models

Once the mesh was generated, the model was completely developed, and finite element analysis was carried out to get the burst pressure of the pipe. According to Lim (2017), the acceptable percentage of error should be less or equal to 10%. The published experimental burst pressure is 33MPa while the FEA burst pressure of the validated base model was 31.77MPa, so the percentage of the error is 3.73% which less than the margin of error mentioned earlier based on the equation:

$$Percentage\ of\ Error = \frac{|P_m - P_d|}{P_d} x\ 100\% \leq 10\% \qquad 3.1$$

where P_m represent the burst pressure of the base model while P_d represent the burst pressure of the published data.

3.7 Modelling Composite Repaired Steel Pipes

The modelling of composite repaired steel pipes consists of three parts which is the corroded pipes, putty and the composite wrap which is more complicated as compared to the modelling of the bare pipe or the corroded pipe due to the additional materials. Three of these parts were created individually and the location of all the parts might not resemble to the experimental tests, hence translation of the coordination of the parts needed to be carried out. Certain features were neglected in the modelling process due to limited information. This includes the bond strength of composite-steel and composite-putty since bonding test was not carried out to determine for the input bonding properties.

3.8 Modelling of Putty

The validated defect pipe model was modified for the development of composite repair pipe model. A three-dimensional deformable solid part was created to simulate the physical properties of the putty. The geometry of the putty was created as same as the geometry of the defect since the putty was designed to cover the whole defect region. The information of the material properties of the putty such as Young’s modulus, Poisson’s ratio, ultimate strength and stress-strain curve were also obtained from the published data as the input. Translation of the location of the putty was needed to carry out to make sure the putty can be modelled at the exact location on the defect region on the defect pipe. By using the “*translate instances*” feature in the ABAQUS®, one node of the putty was selected and then matched with another node at the edge of defect region. The putty was then successfully moved to the accurate location to cover the defect region. Figure 3.7 shows the sequence for the putty location translation.

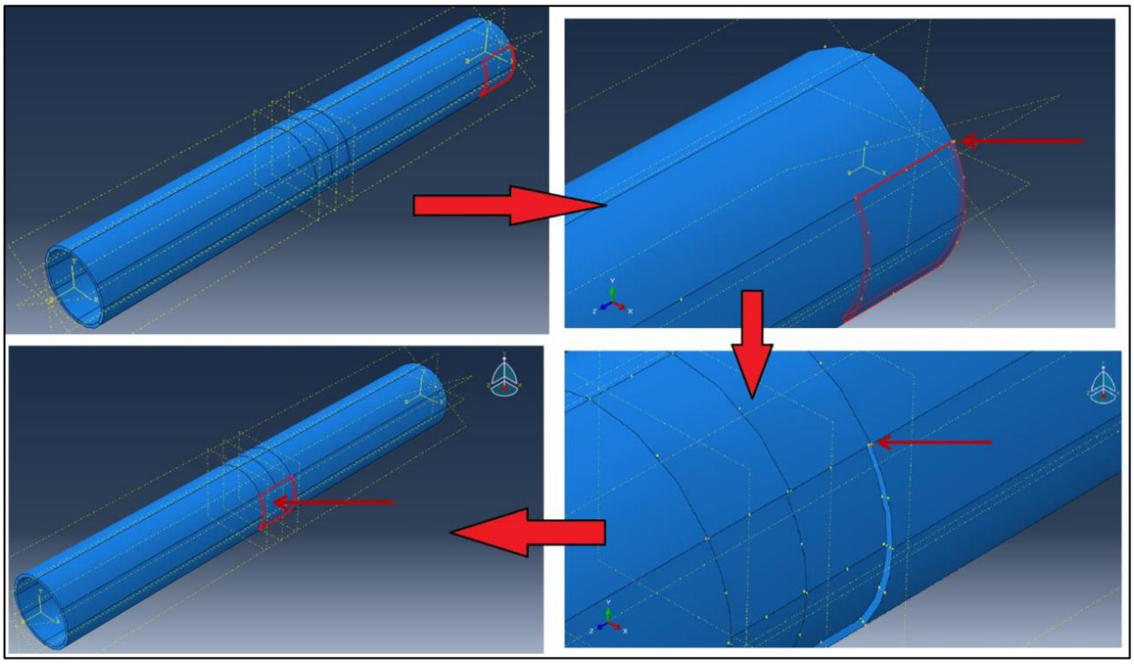

Figure 3.7 Sequence for putty location translation

The putty was also meshed by using the eight-node liner solid element (C3D8R) with a similar mesh size as the defect region to obtain a uniform result. Figure 3.8 shows the meshed putty.

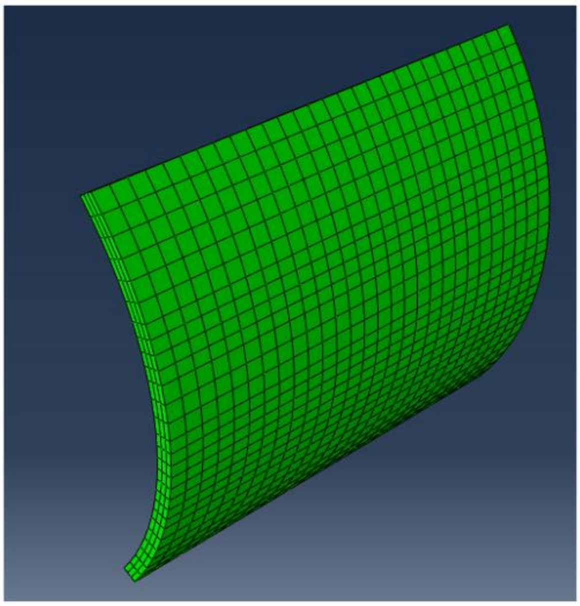

Figure 3.8 Example of a meshed putty

3.9 Modelling Composite Wrap

After modelling the putty, a three-dimensional deformable shell part was chosen to model the composite wrap for the composite repaired pipe model. A 168.3mm diameter with length of 300mm thin shell layer was created as the basic part of composite wrap. Hashin Failure Criteria was employed in order to model the failure of the FRP composite (Lim, 2017). The material properties for the modelling of the composite wrap which is the tensile and shear modulus both in hoop and axial directions were also obtained from the published data as the input. After input all the material properties, the thickness of the composite shell was then modelled by creating a composite shell section and this option allows users to create different properties for each layer of the composite wrap. Three layers of composite shell with a thickness of 1mm each were modelled in this stage and followed by the location translation technique similar to the modelling of putty to place the composite wrap at the exact location. The corroded steel pipe, putty and composite wrap were then assembled together to form a completed composite repaired pipe model. Lastly, the default coordinate system used in ABAQUS® which is global Cartesian system was converted to cylindrical coordinates for analysis in pressure vessel as such the information in hoop and axial direction can be accurately calculated.

3.10 Parametric Study

In this study, three defective pipes with different defect length were modelled and the burst pressure was obtained by using finite element analysis. The modelling process is same as the base model as mentioned in stage 1 where only the defect length in axial direction was modified. Table 3.1 summarised the value of the defect geometries that are used in this study.

Table 3.1 Defect geometry of defective pipe

Defect Size	***Defect Geometry: L x W***
Half D x D	*84.15mm x 168.3mm*
D x D	*168.3mm x 168.3mm*
2D x D	*336.6mm x 168.3mm*

where *D* implies size of outer diameter, *L* implies length of defect region and *W* implies width of defect region.

The size of the putty and composite wrap was also changed due to the different size of the defect region to cover the defect region. The following table show the sizes of the putty and composite wrap modelled according to different defect sizes of the corroded steel pipe.

Table 3.2 Geometry of putty and composite wrap

Defect Size	***Putty Geometry: L x W***	***Composite Wrap Geometry: L x D***
Half D x D	*84.15mm x 168.3mm*	*300mm x 168.3mm*
D x D	*168.3mm x 168.3mm*	*300mm x 168.3mm*
2D x D	*336.6mm x 168.3mm*	*500mm x 168.3mm*

where *D* implies size of outer diameter, *L* implies length of defect region and *W* implies width of defect region.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The result from the finite element analysis is presented in this chapter. Three composite repaired pipes had been modelled with different defect sizes and each pipe had been simulated to investigate the expected burst pressure on the pipe. The stress concentration of the composite repaired pipes was also being investigated. The behaviour of the composite repaired pipes was analysed focusing on the defective steel pipe only.

4.2 Finite Element Analysis

The finite analysis was carried out to numerically investigate the expected burst pressure of the composite repaired pipe. In this study, three composite repaired pipes with different defect lengths were modelled and identified as *Half D*, *D*, and *2D* models where *D* is representing the outer diameter of the defective pipe. The base model of the study had been validated by comparing the simulated burst pressure with the published hydrostatic burst test study and the percentage of error is 3.73% and hence it was validated and used in the parametric study.

4.2.1 Finite Element Analysis of Half-D Model

The defect geometry of this model is 84.15mm x 168.3mm (Length x Width) which 84.15mm is the half dimension of the outer diameter of the steel pipe, hence it was named as *Half D Model* in this entire study. Figure 4.1 shows the stress contour plot for the whole composite repaired pipe model of the *Half D Model.* The first image represents the full model and followed by the steel pipe (top right), putty (bottom left), and composite wrap (bottom right). Generally, a pressurized pipe will generate three principal stresses which are hoop stress, axial stress, and radial stress. According to Lim et al.

(2019), it is known that hoop stress is the greatest stress when the pipe was pressurized hence there is only one stress contour plot is presented for the steel pipe. As mentioned earlier in the Chapter 2, when the ratio of the pipe radius to thickness is greater or equal to 10 ($\frac{r}{t} \geq 10$), the pipe can be considered as a thin-wall structure (Mohamad Zulfadli, 2012). The pipe used in this study has a radius of 84.15mm and thickness of 7.11mm, so the calculated $\frac{r}{t}$ ratio is 11.84mm, hence, the thin-wall assumption was adopted to determine the stresses. From the observation, the highest stress concentration (red colour) was observed at the edge of the defect region along the axial direction. The red colour region is representing the location of where the failure of the pipe occurred where the stress at centre part of defect region is lower. The predicted maximum stress of the defective steel pipe is 557.7MPa while there is only 20.01MPa for the putty and there is 272.9MPa for the composite wrap.

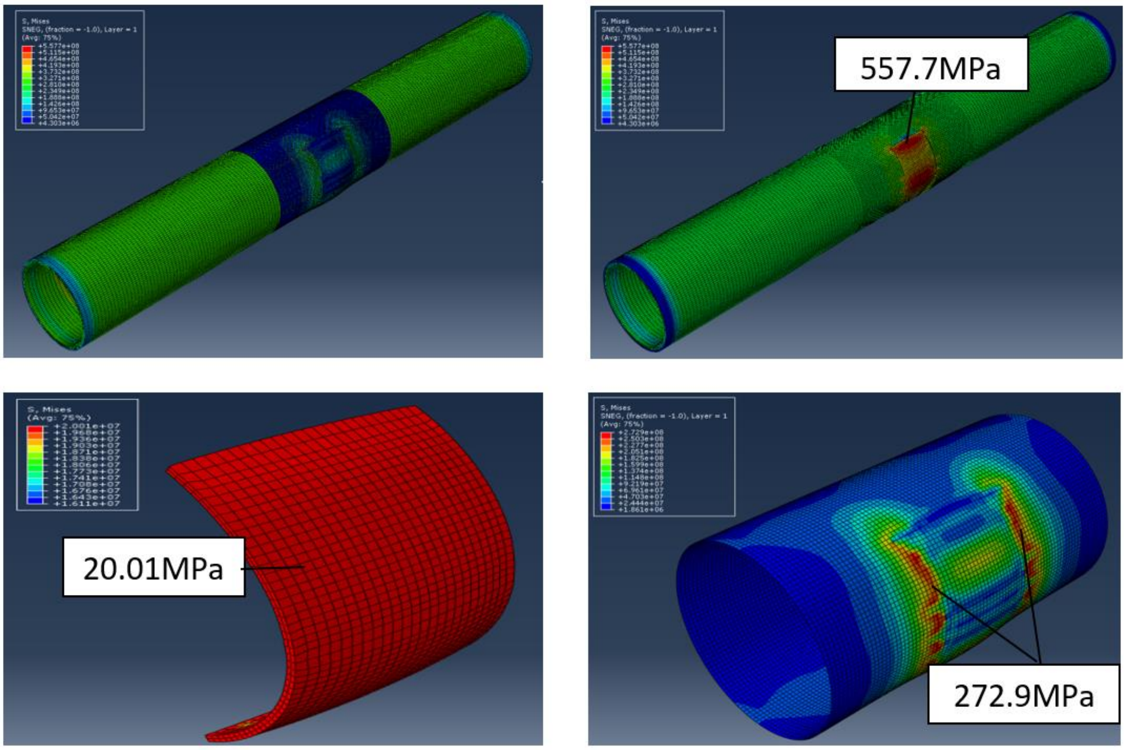

Figure 4.1 Stress Contour Plot for the *Half D* composite repaired-pipe model

4.2.2 Finite Element Analysis of D Model

The defect geometry of this model is 168.3mm x 168.3mm (Length x Width) which had the same size with the outer diameter of the steel pipe, hence it was named as *D Model* in this entire study. Figure 4.2 shows the stress contour plot for the whole composite repaired pipe model of the *D Model*. The first image represents the full model of the composite repaired pipe and followed by the steel pipe, putty, and composite wrap. This composite repaired pipe was also considered as thin-wall structure since it had the similar geometry with the *Half D Model*, hence the thin-wall assumption was also adopted to determine the stresses in this case. The observation had showed that the highest stress concentration (red colour) of the defected steel pipe was concentrated at the edge of the defect region along the axial direction which similar to the *Half D Model* with the predicted stress value which is 557.7MPa. In this case, the stress concentration at the centre of the defect region was also observed to be lower compared to the edge of the defect region. The predicted maximum stress of the putty is 20.01MPa and there is 277.9MPa for the composite wrap.

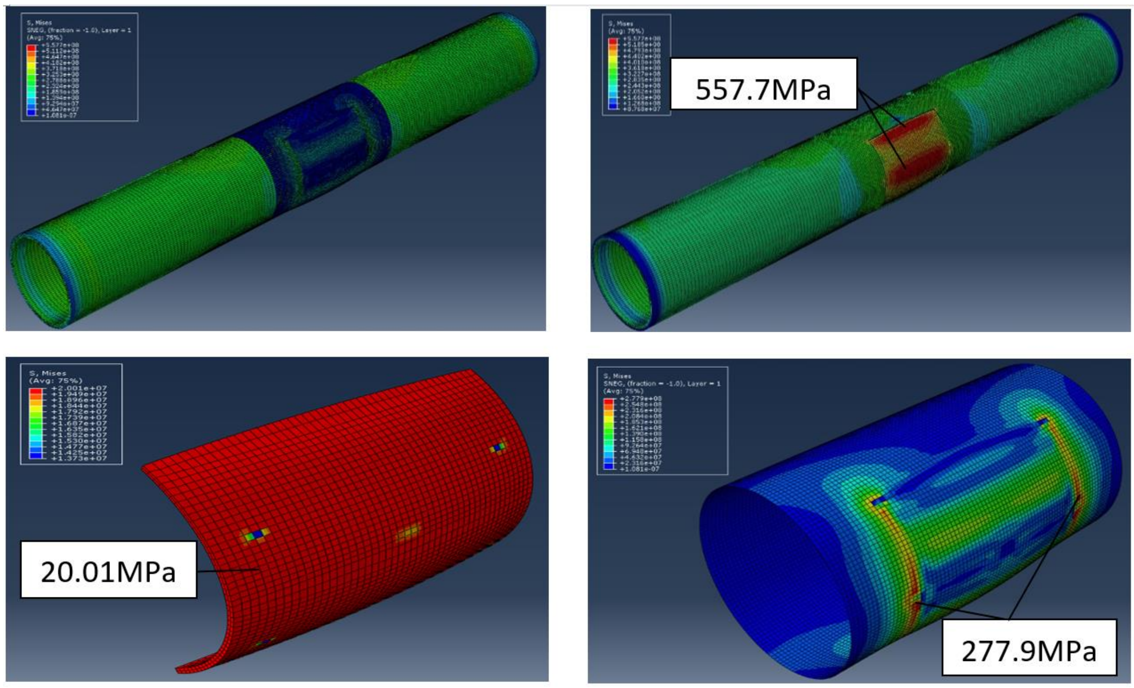

Figure 4.2 Stress Contour Plot for the *D* composite repaired-pipe model

4.2.3 Finite Element Analysis of 2D Model

The defect geometry of this model is 336.6mm x 168.3mm (Length x Width) which 336.6mm is double dimension of the outer diameter of the steel pipe, hence this model was named as *2D Model* in this study. Figure 4.3 shows the stress contour plot for the whole composite repaired pipe model of the *2D Model* and the first image is the full composite repaired pipe model and followed by the steel pipe, putty, and composite wrap. Similar to the *Half D Model* and *D Model*, the *2D Model* is also considered as a thin-wall structure since these three models is modified from the same base model with the same material properties. This case also show that the highest stress of the repaired pipe is concentrated at the edge of the defect area along in axial direction and the predicted maximum stress of the defective steel pipe is 557.7MPa and 20.01MPa which is similar to the previous cases. However, the predicted maximum stress of the composite wrap had slightly drop to 216.7MPa in this case compared to the previous two cases.

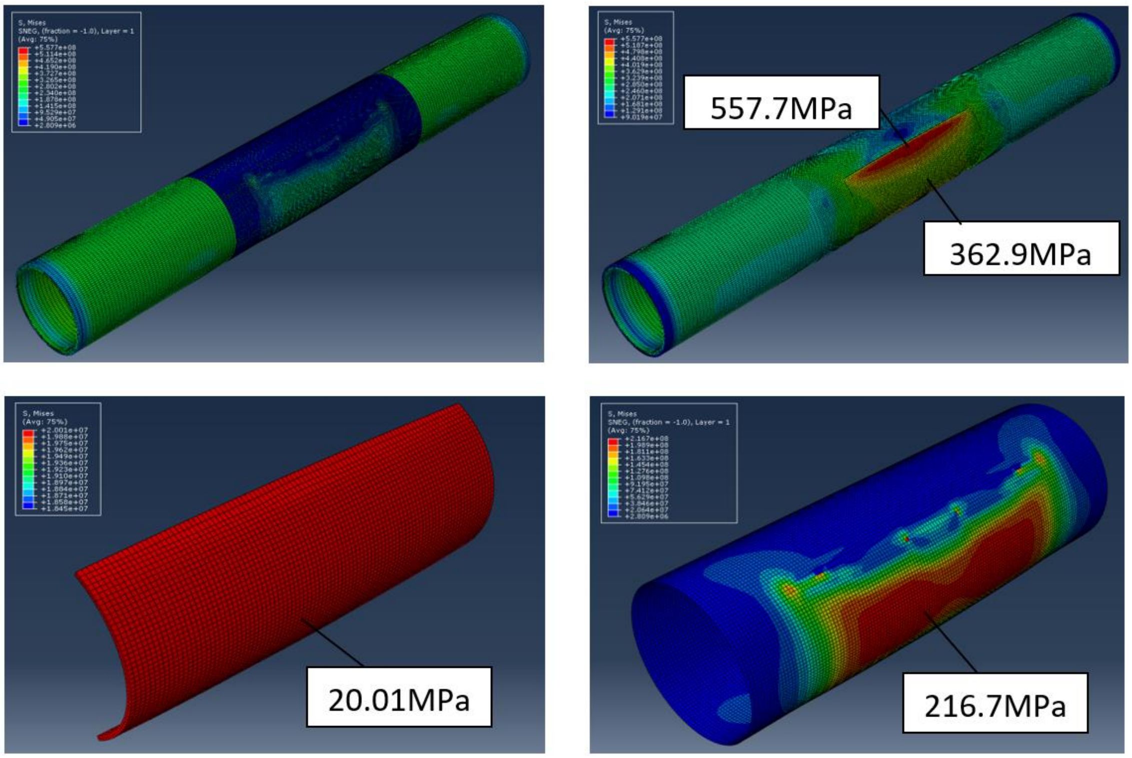

Figure 4.3 Stress Contour Plot for the *2D* composite repaired-pipe model

The stress contour plots for the 3 cases show the similar result which the highest stress concentration is concentrated in the axial direction at the edge of the defect region which is in line with the theory stated that the hoop stress is always the greatest stress, hence the failure of the pipe will always occurred in axial direction. The stress contour plans also show that the stress concentration area is reducing, and its size increasing in axial direction and decrease in width direction as the defect length increase as well as strength reduction.

4.3 Burst Pressure Test

Figure 4.4 shows the burst pressure test results corresponding to the composite repaired pipe of three different sizes of defect lengths. The failure of the pipeline is assuming to occur when the stress developed in the pipes has exceeded the ultimate tensile strength of the pipelines according to the assessment code (Alang et al., 2013).

Referring to the finite element result from Figure 4.4; we can see that the burst pressure for the *Half D Model* is 31.95MPa while there is 28.62MPa for the *D Model* and 26.97MPa for the *2D Model*. The burst pressure drops higher than 13% which is 15.59% as the length of defect change. As expected, the results had also showed that the higher the defect length, the lower the value burst pressure due to the remaining strength is decreasing when the defect area increasing. This result had also in line with the result that obtained in the study of Alang and his team in 2013 which mentioned that the burst pressure of the defective pipelines is affected by the length of the defects and also the assessment code which include the defect length as the parameter to obtain the burst pressure of the defective pipe. Hence, the hypothesis of this research has been confirmed by the finite results which the defect length will affect the burst pressure.

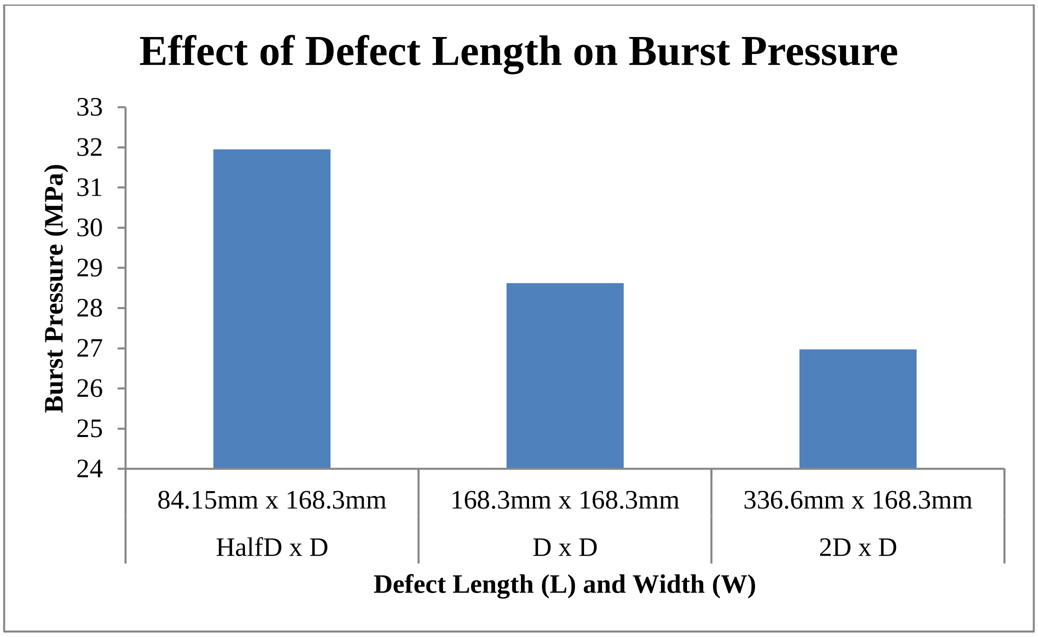

Figure 4.4 Result of defect length on burst pressure

Figure 4.5 shows the effect of defect length on burst pressure of the composite repaired pipe. The blue colour dots show the burst pressure result of the three models (*Half-D, D and 2D Models*) while the blue colour line indicates the changing of burst pressure results getting from the finite element analysis. The figure clearly shows that the effect of defect length upon burst capacity of composite repaired pipe is non-proportionate due to the irregular increased in difference of burst pressure between the models. The difference of burst pressure of the *Half-D Model* (31.95MPa) and *D Model* (28.62MPa) is 3.33MPa and the defect length of this two model is half-D. The hypothesised burst pressure of the *2D Model* should be at around 21.96MPa by reducing the burst pressure of the *D-Model* with 6.66MPa (double of 3.33MPa) due to the difference of the *D-Model* and *2D Model* is another D. However, the simulated burst pressure from the finite element burst test for *2D Model* is expected at 26.97MPa which is 18.58% different with the hypothesised. Hence, the polynomial trendline (red dotted line) is created to estimate the expected burst pressure responding to different defect lengths.

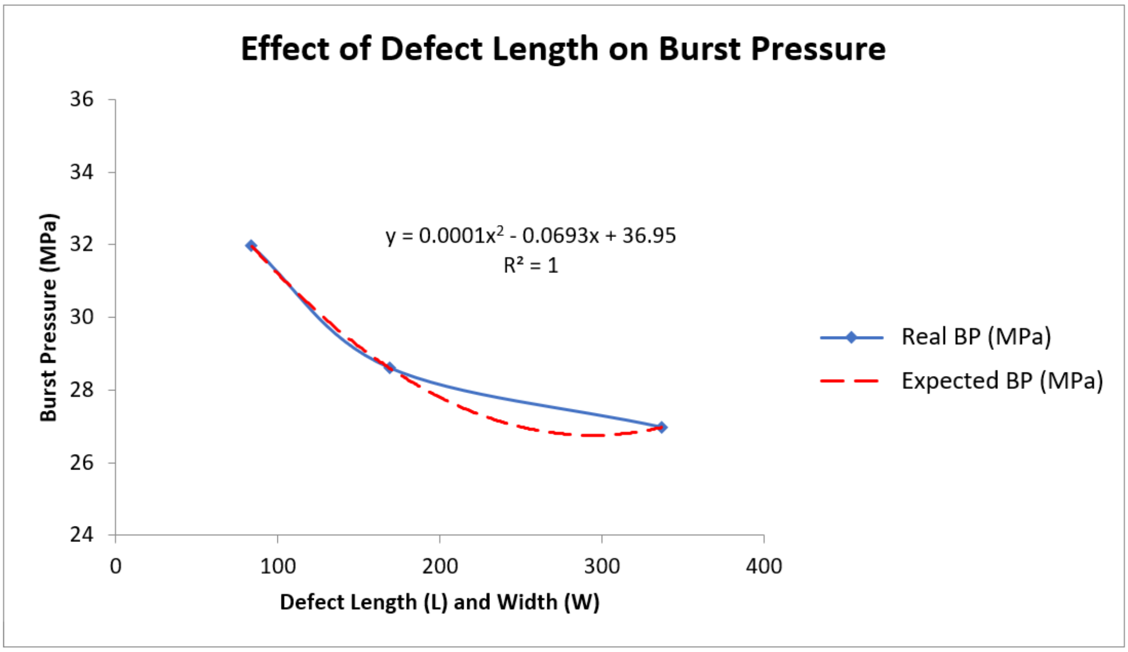

Figure 4.5 Effect of defect length on burst pressure

CHAPTER 5

CONCLUSION

5.1 Overview

This chapter summarized the finding of this study in accomplishing the research aim and objectives. This study has successfully investigates the effect of defect length upon the burst capacity of composite repaired pipe. Finite element analysis of composite repaired pipe had been carried out by varying the defect length to predict the burst pressure on composite repaired pipe. Three repaired pipes which having defect length of Half-D, D, and 2D is investigated in this study. The purpose to carried out this study is to investigate the relationship of the defect length upon the burst capacity to explore the potential in optimizing the whole repair system.

5.2 Conclusions

The following are the conclusions based on two research objectives:

1) The burst pressure of the composite pipeline according to different defect lengths were investigated. Stress contour plot *2D Model* had showed that the pipe is having the smallest stress concentration area and the longest size of stress concentration in axial direction but shortest in width direction. This also indicates that the steel pipe is having the lowest remaining strength in the pipe. Stress contour plot of composite repaired pipe model with defect length of Half-D of outer diameter showed that the pipe has the largest stress concentration area and the highest remaining strength followed by the steel pipe model with defect length of the dimension of outer diameter.

2) The effect of defect length upon the burst capacity of composite repaired pipe was discovered. The result of finite element shows that the lower the defect length, the higher the value burst pressure. The burst pressure for half of the outer diameter of the composite repaired pipe is 31.95MPa which having the highest burst pressure among the three models. The burst pressure drops 15.59% as the defect length change and this result showed that there is effect of defect length upon the burst capacity of composite repaired pipe.

5.3 Significant of Research Contribution

The finding in this study has significant impact towards the repair code by considering the inclusion of defect length into the codes when determining the minimum thickness of the composite repaired pipe as the results had showed that the lower the defect length, the higher the value burst pressure. This could also optimize the whole repair system.

5.4 Recommendations

Recommendations for future research on improving the whole composite repair system is provided as follows:

1) Investigation of the burst pressure of the repaired pipe with more variation of sizes of defect length should be carried out to get the best fit trend line of the relationship of the defect lengths and the burst pressure.

2) Experimental work should also be done as validation of simulation work to justified and support the finding of simulation work.

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