Revised Burst Model for Pipeline Integrity Assessment

By

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A thesis submitted to the

School of Graduate Studies

in partial fulfilment of the

requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

May 2017

St. John's Newfoundland

Abstract

The failure of pipelines，often caused by corrosion affects the environment and economy considerably. To prevent this, it is necessary to focus on the corrosion of the pipelines. Burst pressure is a key factor to assess the integrity of a pipeline. There are three ways to determine burst pressure, lab testing, evaluation criteria (based on deterministic approach), and the Finite Element Method (FEM). The results of burst pressure assessment using evaluation criteria are too conservative compared to the results of an actual pipe burst experiment and FEM (Alves J L, 2003).

The objectives of this thesis are to analyze the changing trend of burst pressure of pipelines with different defect dimensions; to compare the FEM results with those of the evaluated criteria to indicate the conservative property; and to revise the DNV burst model and verify its validity with actual burst experiments. The revised DNV model predicts burst pressure more reliably that could result in better engineering design of pipelines.

Keywords：Burst pressure, Finite Element Analysis, Corrosion defect, DNV burst model

Acknowledgements

First and foremost, I would sincerely thank Dr. Faisal Khan for his unconditional guidance and wisdom as I made my research. Without him, I could not get the precious opportunity to learn and live in Canada.

Second, I would like to thank Dr. Premkumar Thodi, Dr. Susan Caines and the others in CUI group for their most support and encouragement for giving me in my study.

Finally, I would like to thank to my parents, friends, who provide the advice and financial support for over two years.

This project would have been impossible without the financial support provided by Natural Science and Engineering Research Council (NSERC), Research and Development Cooperation (RDC).

Contents

Abstract i

Acknowledgements ii

List of Tables vii

List of Figures viii

List of Symbols and Abbreviations x

Chapter 1 Introduction 1

1.1 Background Information 1

1.2 The Evaluation of Defects in Corroded Pipelines 3

1.3 Evaluation Criteria of Corroded Pipeline 5

1.4 The Objectives of Current Research Project 9

1.4.1 Overview of the relevant materials and standards 9

1.4.2 Simulation of the burst pressure of pipelines using FEM 10

1.4.3 Compare the results of the DNV model and FEM 10

1.4.4 The amendment of the DNV model 10

1.4.5 Parameter sensitivity analysis 11

Chapter 2 Pipeline Corrosion Reason and Category 13

2.1 Analysis and Category of Reasons for Pipeline Corrosion 13

2.1.1 The Analysis of the Reasons for Pipeline Corrosion 14

2.1.2 The Category of Pipeline Corrosion 17

2.2 Two Evaluation Methods of Residual Strength used by the paper 19

2.2.1 DNV Model...20

2.2.1.1 Calibrated Safety Factor Approach of DNV-RP-F101 21

2.2.1.2 Allowable Pressure Approach for DNV-RP-F101 23

2.2.2 Finite Element Analysis 25

Chapter 3 Finite Element Analysis 27

3.1 Introduction of the Finite Element Analysis Software Evaluation Process 28

3.2 Finite Element Analysis of Pipeline Corrosion...29

3.2.1 The Model Establishment 29

3.2.2 Element Selection 32

3.2.3 Boundary Condition..34

3.2.4 Loading Analysis..34

3.2.5 Mesh Division..35

3.2.6 Failure Criterion...37

3.3 Methodology for Establishing the Burst Pressure...41

3.4 Results and Discussion 46

Chapter 4 Evaluation Criteria for Defects in Corroded Pipelines........................48

4.1 Introduction of the Evaluation Criteria 48

4.2 Comparison of the DNV Model and FEM..55

4.3 Results and Discussion 56

Chapter 5 Revising the DNV Model 58

5.1 Concept of Revising the Model 59

5.2 Methodology 60

5.3 Regression Analysis 62

5.3.1 Introduction of Regression Analysis 62

5.3.2 Establishing Regression Equation and Testing 64

5.4 Results and Discussion 67

Chapter 6 Sensitivity Analysis 69

6.1 Orthogonal Experiment..70

6.1.1 The Aim of the Orthogonal Experiment 70

6.1.2 Design of the Experiment 70

6.1.3 Variance Analysis 72

6.2 Single Parameter Sensitivity Analysis 76

6.3 Results and Discussion 77

Chapter 7 Summary and Conclusion 78

7.1 Summary of the Paper 78

7.2 Conclusion 79

7.3 Future Work 80

Bibliography 81

List of Tables

Table 1: Representative corrosion evaluation criterion for corroded pipelines 6

Table 2: Value of burst pressure by DNV and FEM 56

Table 3: The value of d_{new} under different parameters 62

Table 4: Results of linear regression 65

Table 5: Comparison of the value of burst pressure using DNV and Test 67

Table 6: Comparison of the Result using the Revised model and test 68

Table 7: Level of factors for the orthogonal experiment 71

Table 8: Experimental scheme for the orthogonal experiment 72

Table 9: Variance Analysis Calculation Table 75

Table 10: Result of Variance Analysis 76

List of Figures

Figure 1: Flow chart of the paper work 12

Figure 2: Plots of volume corrosion for marine pipelines... 17

Figure 3: Dimension of the isolated defect 23

Figure 4: Dimensions of interacting defects 24

Figure 5: Geometric model of the defect 32

Figure 6: Finite Element Model of the defect 32

Figure 7: Element models for C3D8, C3D20, CPS8 33

Figure 8: The Loading status by FEM 35

Figure 9: Distant view of mesh division 36

Figure 10: Detail view of hexahedral grid 37

Figure 11: The von Mises Stress Contour of a pipeline under a pressure of 17MPa... 39

Figure 12: The von Mises Stress Contour of pipeline under pressure of 17.5MPa 39

Figure 13: The von Mises Stress Contour of a pipeline under pressure of 18MPa 39

Figure 14: The von Mises Stress Contour of a pipeline under pressure of 18.5MPa .. 40

Figure 15: The zooming view of von Mises stress for the sample 40

Figure 16: The global view of von Mises stress for the sample 40

Figure 17: Flow chart of steps for FEM simulation.. 41

Figure 18: Length, width, and spacing of the defects of the sample............................ 42

Figure 19: The plot of burst pressure among varied widths 43

Figure 20: The plot of burst pressure among varied lengths....................................44

Figure 21: The plot of burst pressure among varied depths....................................44

Figure 22: The location of different number of defects of the samples 45

Figure 23: The plot of burst pressure among different numbers of defects 46

Figure 24: Projection of circumferentially interacting defects 50

Figure 25: Projection of overlapping sites and the formation of a composite defect ..51

Figure 26: Combining interacting defects...52

Figure 27: Example of the grouping of adjacent defects 53

Figure 28: Flow chart of DNV model calculation 55

Figure 29: Comparison of burst pressure between DNV and FEM 57

Figure 30: Concept of Revising Model..60

Figure 31: Flow chart of variance analysis 73

Figure 32: Plot of the partial derivative among different lengths of defects 77

List of Symbols and Abbreviations

FEM	Finite Element Method
DNV	Det Norske Veritas
D	Nominal outside diameter (mm)
p_f	Failure pressure of the corroded pipeline (N/mm^2)
w	Circumferential length of corroded defect (mm)
d	Depth of corroded defect (mm)
l	Longitudinal length of corroded defect (mm)
t	Thickness of corroded defect (mm)
n	The number of corroded defects
σ_u	Ultimate tensile strength (N/mm^2)
d_{new}	Equivalent depth of corroded region (mm)

Chapter 1 Introduction

1.1 Background Information

Development of every resource has been further extended towards offshore fields over the last decade, and pipelines are necessary elements of offshore developments.

85% of crude oil transportation and 100% of natural gas transportation throughout the world are done using pipelines (Kennedy, 2993). The gathering and transportation of offshore oil and gas products is also based on pipelines. Thus, pipelines are important and necessary components of offshore oil and gas field development. A very common issue in pipeline is corrosion, which has the highest contribute to OPEX. Failure of pipelines can be catastrophic, which will influence people's life. This also caused environmental pollution in the ocean, even damaging the balance of the ocean's ecology. These effects can cause serious losses to the environment and to economy (Dayton, 1995). Therefore, ensuring the safe and reliable operation of pipelines is a key element in ocean engineering.

Pipeline corrosion is defined as a chemical or electrochemical reaction that occurs between the material of the pipeline and its surrounding ocean environments, which causes crystal failure or damage on the surface of the pipeline (Popoola, 2013). Several methods are used in pipeline designs to prevent pipeline corrosion. However, the failures because of corrosion cannot be completely eliminated because of the influential combination of the complex external ocean environment and the corrosive substances inside of the pipeline. Meanwhile, according to the statistics from the literature in recent years, corrosion is the most significant factor in the failure of pipelines (T.A.Netto, 2005).

The corrosive phenomenon becomes more serious when the longer amount of time the pipelines are being used. This leads to the wall thickness of the pipeline reducing gradually, and the capability for withstanding pressure also reduces. Accidental corrosive perforation, leakage or rupture are other modes of failure, which can influence the service life of pipelines (Wang, 2010).

Finally, corrosion not only forces the operation of a pipeline to shut down, but also causes harmful substances to leak from the pipeline to pollute the ocean environment, which negatively influences the health of human and animal life, perhaps even destroying the ecological system. The serious issues related to oil spillage which have occurred around the world in recent years have led pipeline operators and relevant administrational government agencies to pay more attention to the safety and reliability of the facilities being used in the procedures of exploiting the ocean's offshore oil.

Hence, in cases of accidental oil leakage, it is necessary to predict the status of the corrosion of the pipelines and analyze the different factors that could influence the corrosion, to consider the harmful degree of damage of the pipeline caused by corrosion and evaluate the remaining strength of the corroded pipeline, to further ensure that the pipeline could be used in a safe way (Taylor, 1994) (Bayly, 1994)

These considerations are important and meaningful for design and manufacturing in the pipeline industry.

1.2 The Evaluation of Defects in Corroded Pipelines

The research on failure assessments of corroded pipelines includes many aspects, such as the mechanism of formation of corrosion, the failure mechanism of corroded pipelines, the calculation of the residual strength of corroded pipelines and the quantitative standardization evaluation of defect safety. However, the most important aspect is the research based on the calculation of the residual strength of corroded pipelines.

The evaluation of the residual strength of pipelines is the basis for predicting the residual life of pipelines, conducting reliability analysis and for risk evaluation. The evaluation of residual strength aims to analyze whether a pipeline which already has defects could continue safely operating or not, under a working pressure, and furthermore, to provide a scientific basis for formulating the regulations for maintenance and safety management appropriately. This can not only maximize cost effectiveness, but also ensure the economic efficiency of the operation. Any corroded defect that occurs during the operation of a pipeline can reduce its ability to bear pressure. It can also make the period for pipeline inspection, maintenance, and replacement shorter and increases the investment and operation cost, all of which would influence the operation of the pipeline system. Hence, it is necessary to conduct an evaluation of the residual strength of corroded pipelines. Based on the different damage mechanisms, the evaluation of the residual strength of pipelines includes the following four types (Bjornoy OH S. G., 2001):

(1) The semi-empirical formula obtained based on the statistics for blasting experiments on corroded pipelines;

(2) Analytical methods based on the theory of continue and fracture mechanics;

(3) The numerical methods based on Finite Element Analysis;

(4) The probability methods based on the failure criterion of corroded pipelines combined with the theory of probability and reliability.

Various studies have been conducted on the residual strength of corroded pipelines with different shapes of defects by using different theories, experiments, and FEM modeling.

Alves J L (Alves J L, 2003) conducted the finite element analysis of pipelines which were under the combined load effect, and compared the results with those gathered from experiments and criteria and found that DNV-RP-F101 is more reasonable in the analysis of the integrity of pipelines.

Choi (Choi J B, 2003) conducted research on the results of pipeline burst pressure testing and FEM analysis. They suggested the failure criterion suited to the X65 pipeline with rectangular-shaped corrosion. Moreover, they analyzed the influences of the length and depth of defects on the residual strength.

Netto TA (Netto TA, 2005) conducted research on the effects of burst pressure of pipelines caused by different geometric parameters of defects (mainly on the depth and length of defects) and material parameters (mainly on the yield strength of materials). The research was conducted by indoor small-size burst pressure testing and FEM analysis. The burst pressure testing and FEM analysis showed that the depth of defects of pipelines has a significant influence on burst pressure, and the influence of the length of defects is less than that of depth. Moreover, when the ratio of the length of defects and outside diameter of pipelines is over 1.5, the length of defects has a minor effect on the burst pressure of pipelines, and the influence of the length of defects could be ignored during the processing of safety evaluations.

De Souza (RD, 2007) conducted bursting tests on corroded pipelines with complex-shaped defects and compared the experimental results with the ones calculated by the two evaluation criteria of the corroded pipelines. It turns out that the results from the DNV-RP-F101 model are closer to the test results and the ones from the ASME B31G model show a relatively larger error margin compared with the test results.

1.3 Evaluation Criteria of Corroded Pipeline

Since the 1960s, many tests and simulation methods have been used to analyze the residual strength of corroded pipelines and some evaluation criteria on residual strength were defined based on the results of this research. The technology of evaluation of pipelines has developed from the old qualitative analysis into the current quantitative evaluation analysis of the failure of pipelines. Moreover, the technical criteria of the evaluation have been normalized as well. Here, some of them are representative, for example, DNV-RP-F101 model (Coflexip Stena Offshore, 2001) ，AP1579 model (Osage, 2004), BS7910 model (Moan, 2009), the ASME B31G model (Liolios, 2011), and CAS-Z184-M86 model (Canada, 2016). The details about the criteria above are shown in the Table 1:

Table 1: Representative corrosion evaluation criterion for corroded pipelines

No.	Criterion	Issued Organization	Time	Country	Type of defects
1	ASME B31G	American Engineering Academy	1984	USA	Volume
2	CAS-Z184-M86	Canada Criterion Organization	1999	Canada	Volume
3	BS 7910	UK Criterion Organization	1999	UK	Plane
4	API RP 579	American Oil Organization	2000	USA	Plane Volume
5	DNV RP-F101	Det Norske Veritas	2000	Norway	Volume

In the beginning, the pipeline corrosion was co-studied by the American Gas Association (AGA) and the pipeline committee of Texas in the eastern United States. The studies mainly used the fracture mechanics theory to research the cracking extension mechanism, failure model and defect evaluation method. On the basis of these studies, the evaluation formula for surface defects was suggested for calculating the residual strength of pipeline corrosion. Through testing the formula by experiments, the evaluation criterion of B31G was proposed. In 1984, the B31G criterion was embodied into pipeline design specifications by the Association of American Mechanical Engineering, which was called ANSI/ASME B31G (Liolios, 2011). The theoretical basis of B31G was the evaluation formula of fracture mechanics for surface defects, so that this formula has the characteristics of assumption and simplification. Hence, the results of residual strength calculated by B31G have many limitations, which causes some pipelines to be removed or exchanged unnecessarily and leads to a large amount of waste.

Aimed at the conservatism of the B31G model, the Natural Gas Association in the United States analyzed the reasons for this conservatism in 1989, and revised the B31G model based on the research they have conducted into ASMEB31G. After this, some other scholars further researched the conservatism of the ASMEB31G model through considering additional load and the influence of interactive defects to build a new evaluation criterion－API579 (Osage, 2004). This new model takes into consideration the relationship between the residual strength of corroded pipelines, the parameters of material strength and the dimensional size of defects. The main difference between the API579 model and ASMEB31G model is that the API579 model takes into consideration extra influences such as the shape of defects, interactions between defects and the additional load on the burst pressure of pipelines.

The British Gas (BG) Company conducted burst testing on pipelines with a single defect, multiple defects and complex shaped defects separately, and the results of this research were adopted by the BS7910 criterion (Moan, 2009). At the same time, Det Norske Veritas (DNV) and BG jointly promulgated a new evaluation criterion for corroded pipelines－DNV-RP-F101, according to the material characteristics of modern high-strength pipelines. This criterion not only considers the internal pressure, but also the influence of the axial and bending load of pipelines on residual strength.

The DNV-RP-F101 model (Coflexip Stena Offshore, 2001) could offer different evaluation methods based on different types of defects. It could be used to evaluate the corrosion of pipelines with a single defect, with interactive defects and complex-shaped defects. The DNV-RP-F101 model can also assess the corrosion of pipelines with longitudinal defects, which is affected only by the internal pressure and the ones with longitudinal or circumferential defects which are both superposed, and loaded by internal pressure and longitudinal pressure. DNV-RP-F101 has a wide range of applications and it has become the criterion which is widely used in the most general range for evaluating the corrosion of pipelines.

All these criteria were established at different periods. Since the strengths of different pipelines are not the same, choosing the according criteria based on various types of pipelines is required for analysis. However, most of evaluation equations for assessing pipeline corrosion are all conservative to some degree. For example, B31G is built according to the dimensional size of the defects and it could only be used for evaluating the integrity of pipelines with lengthwise defects. However, the integrity of the corroded pipeline is influenced by many factors, such as internal pressure, material properties, etc. These factors are not considered in the B31G model (Liolios, 2011). In 1989, the American Gas Association (AGA), analyzed the reasons for this conservatism by studying 86 sets of corroded pipelines with different shape defects, and revised the B31G model by considering the residual strength and accordingly the material coefficient (R_s), to lower the conservatism of the B31G model.

1.4 The Objectives of Current Research Project

The paper focuses on research on pipeline corrosion by using the Finite Element Analysis Method (FEM). Through building the nonlinear finite element model using ABAQUS to analyze the different influences on burst pressure by different parameters of defects of corroded pipelines, the paper aims to discover the corresponding variation trend of burst pressure with the changing of the defect size. Meanwhile, through comparing the values of burst pressure by using the DNV model and finite element model, it was found that the results obtained by the DNV model were conservative, and then used the regression analysis method to optimize the DNV model. This work offers a practical evaluation tool for professional personnel in the industry, and enables staff who have a lack of knowledge of pipeline corrosion to predict the burst pressure and the residual life of pipelines.

1.4.1 Overview of the relevant materials and standards

Based on the literature, the research data and the on-site survey, the work analyzes the reasons for and types of pipeline corrosion. They are then compared with the current methods being used in research and the engineering industry for predicting the residual strength of corroded pipelines.

1.4.2 Simulation of the burst pressure of pipelines using FEM

After building a three-dimensional physical model of pipelines using FEM, the simulation results are used to impose the equivalent stress on corroded pipelines with defects of different dimensional sizes. The burst pressure of pipelines is evaluated using plastic failure criteria, while examining the degrees of influence on burst pressure by considering the different lengths, widths, depths, and number of defects.

1.4.3 Compare the results of the DNV model and FEM

Through comparing the results using the criteria for assessing the integrity of pipelines (DNV) with FEM, the work identified differences in the results under DNV RF-101 and FEM. Also, conservative properties of the DNV model and the reasons for making this happen were obtained.

1.4.4 The amendment of the DNV model

After finding the reasons why the results established by the DNV model were different from FEM, the work used the results from FEM and regression analysis to revise the DNV model. The work also used the revised model to evaluate the burst pressure for both single defect and interacting defects and used the results obtained by experiments to verify the feasibility and reliability of the revised model.

1.4.5 Parameter sensitivity analysis

The indicators of sensitivity are defined by the parameters of defects, which would influence the failure of pipelines. The work conducted studies on the sensitivity analysis of the length of defects, the depth of defects and the number of defects, so that the revised model may recognize the different effects on burst pressure of pipelines by the changing of parameters. The conclusion of the sensitivity analysis is in accordance with the results obtained by FEM. This not only proves the reliability and accuracy of the revised model, but also provides a good reference for the parameter-sensitive analysis of defects of corroded pipelines in the engineering industry (The flow chart of all the work is in Figure 1.)

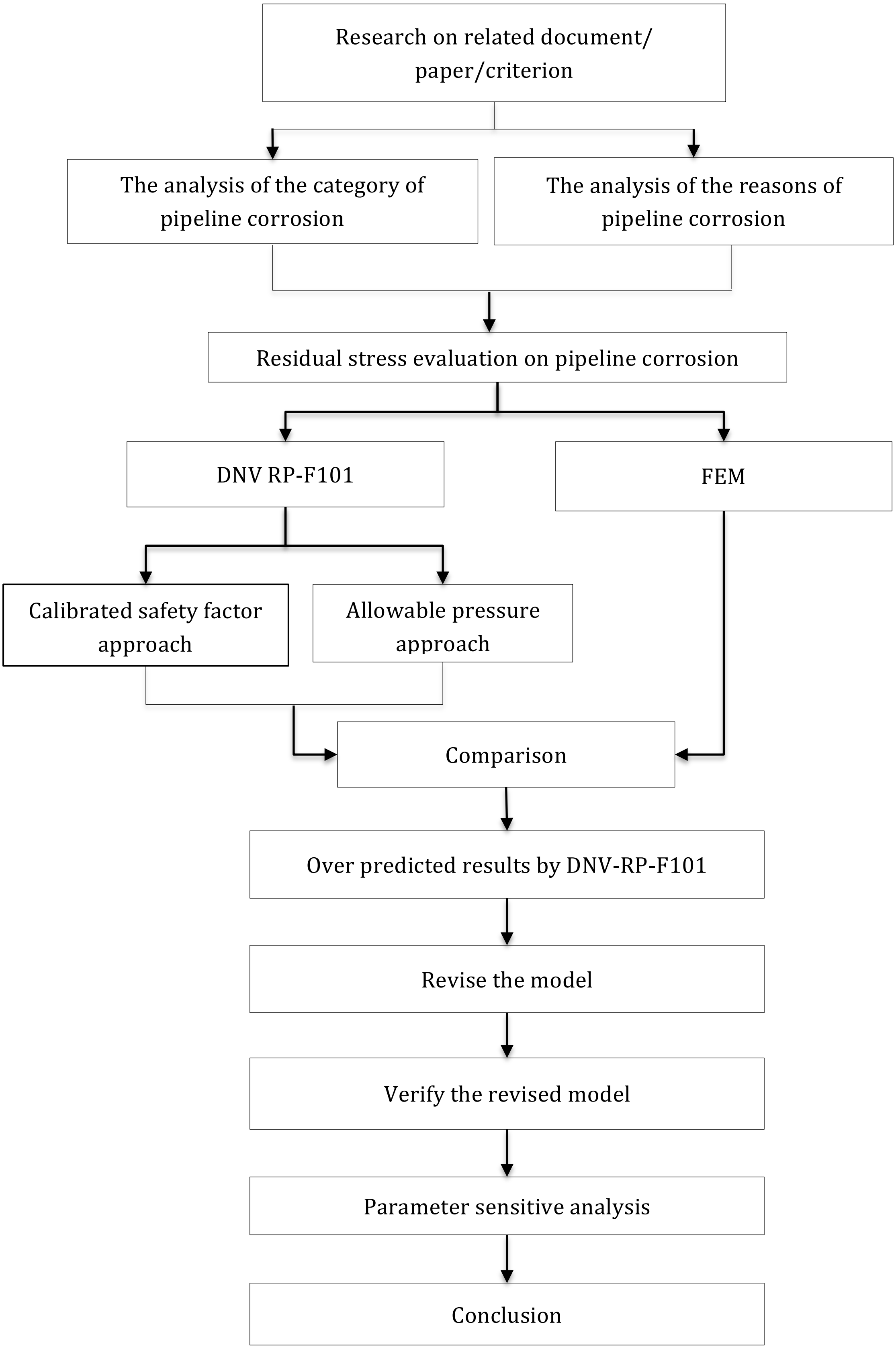


Figure 1: Flow chart of the paper work

Chapter 2 Pipeline Corrosion Reason and Category

The analysis of the reasons for and the types of pipeline corrosion will be introduced in this chapter. Moreover, two methods for evaluating the residual strength of corroded pipelines (Finite Element Analysis and DNV RP-F101 criteria) will be briefly discussed and analyzed as well.

2.1 Analysis and Category of Reasons for Pipeline Corrosion

Corrosion is defined as a material damage phenomenon resulting from chemical or electrochemical action between engineering materials and their surroundings. Steel pipelines are generally used in the chemical industry, such as for oil and gas transportation, petroleum refining, the coal chemical industry, etc. Also, corrosion is the most common model of failure in the operation of steel pipelines. Corrosion occurs on the internal and external surfaces of pipelines and is the main cause of pipeline failure (Hopkins, 2007). Chemical corrosion and electrochemical corrosion are the two main mechanisms for corrosion (Song, 1999).

Chemical corrosion means that the damage between the metal surface and the non-electrolyte is directly caused by a purely chemical action. This can be categorized into gaseous corrosion and non-electrolyte solution corrosion (Song, 1999). Chemical corrosion occurs in a specific environment in which the oxidants in the non-electrolyte can directly interact with the atoms on the metal surface. In the process of chemical corrosion, electron transfer occurs between the metal and the oxidizing agent directly; hence there is no electric current happening.

Electrochemical corrosion is defined as destruction caused by the electrochemical reaction between metal and electrolyte (Song, 1999). Any kind of corrosive reaction which is carried out by an electrochemical mechanism includes at least one anodic reaction and one cathode reaction. The anodic reaction is the process by which the metal atoms are transferred from the metal to the medium and emit electrons, namely in the oxidation process; the cathode reaction is the process by which the antioxidants in the medium capture the electrons, namely the reduction process.

However, pipeline devices in different industries have their own special corrosion characters. Hence, the following will introduce the reasons for corrosion in marine pipelines.

2.1.1 The Analysis of the Reasons for Pipeline Corrosion

The internal side of oil and gas pipelines generally contains mediums, such as natural gas (or less atmosphere), water and oil. Corrosion is caused by the process of electrochemical and chemical reactions. The reactions of the electrochemical corrosion is very strong around the area of pipeline bends, the gas-liquid interface, and the low-lying water department, causing the serious corrosion of pipelines, shown by a large area of thinning or a formation of a series of corrosion pits and trenches.

The internal corrosion of submarine pipelines is mainly influenced by pipeline materials and the medium transportation environment.

The factors of the medium transport environment mainly include: transport temperature, the partial pressure of CO_2 and H_2S, the total pressure of the system, pH value, concentration of Cl^- and HCO_3^-, the total mineralization degree of the medium, gas-oil ratio, water-gas ratio, and the fluid velocity, etc. Here, the partial pressure/concentration of CO_2 and H_2S are the main effect factors for internal corrosion in submarine pipelines (Kim, 2012).

The conditions of external corrosion of a pipeline are complicated; hence, research should be conducted in the environment in which the pipelines are located. Moreover, electro-chemical corrosion is the main cause of the external corrosion of pipelines (Song, 1999). The reaction of electrochemical corrosion is caused by the moisture on the metal surface; even if only a small amount of water exists, the reaction would still happen. This moisture cannot be totally eliminated in the process of oil and gas manufacturing, hence, the corrosion medium of the submarine pipeline can be classified as follows: 1) corrosion agents, such as CO_2, H_2S and O_2; 2) catalytic agents, such as Cl^-; and 3) reaction carriers, such as water (Kim, 2012).

H_2S and CO_2 corrosion is hydrogen depolarization corrosion. The cathodal procedure of H_2S hydrogen depolarization corrosion is as follows:

$$H_2S = HS^- + H^+ \qquad (2\text{-}1)$$

$$HS^- = S^{2-} + H^+$$

$$2H^{+} + 2e \rightarrow H_2 \uparrow \text{ (into the metal)}$$

The cathodal procedure of CO_2 hydrogen depolarization corrosion is:

$$CO_2 + H_2O = H_2CO_3 = HCO_3^{-} + H^{+}$$

$$2H^{+} + 2e \rightarrow H_2$$

O_2 corrosion is oxygen depolarization corrosion. The cathodal procedure is:

Acid liquid: $O_2 + 4H^{+} + 4e \rightarrow 2H_2O$

Alkaline liquid: $O_2 + 2H_2O + 4e \rightarrow 4OH^{-}$

From the analysis above, the features of electrochemical corrosion are as follows:

(1) The medium is the ion-conductive electrolytes.

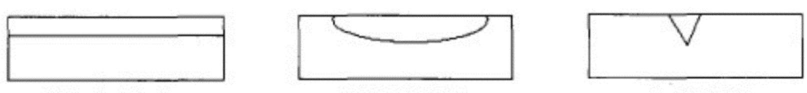
(2) The process of the metal/electrolyte interface reaction is caused by the charge transfer. It has to include the transfer of electrons and ions at the interface.

(3) The process of the electrochemical reaction on the interface concludes two mutually independent aspects of the oxidation process and reduction process. The chemical reactions that occur at the metal/electrolyte interface with the charge transfer are called electrode reactions.

(4) The process of the electrochemical reaction accompanies the flow of electrons, which is the electric current.

2.1.2 The Category of Pipeline Corrosion

Chemical corrosion and electrochemical corrosion have combined actions that can cause corrosion damage to form corrosion grooves, pits and large areas of corrosion thinning in submarine pipelines. According to the features of corrosion defects of submarine pipelines and failure characteristics, the corrosion defects could be categorized into volume-type defects and planar-type defects (Cosham, 2004). The planar-type defects are typically weld cracks, incomplete fusion, stress corrosion cracks and so on. The volume-type defects include uniform corrosion defects, partial thinning corrosion defects, groove-shaped pitting corrosion defects and so on. The figures of defects are shown in Figure 2. This paper mainly focuses on research on the influence of volume-type defects on the safe operation of submarine pipelines.



Uniform corrosion   Partial corrosion   Pitting corrosion

Figure 2: Plots of volume corrosion for marine pipelines

(1) Uniform corrosion

The uniform corrosion of submarine pipelines is defined as the same degree of corrosion that happens along the surface of the pipelines, which holds little risk (Cosham, 2004). It is a common type of corrosion. The character of uniform corrosion is that the corrosion is distributed over the whole surface of the metal, which results in the decrease of the sectional dimension of the metal pipeline and also its bearing capacity. The size of areas for both the anode and cathode of the corrosion cell formed along the metal surface are small and closely linked with each other. Due to the whole metal surface being in a status of excitation, and some points having energy fluctuation at different moments, with the area with high energy being the anode, and the area with low energy being the cathode, this results in corrosion occurring over the whole metal surface.

Uniform corrosion causes a large amount of metal loss from every point of view; however, technically, this type of corrosion can easily be measured and found, and severe degrees of corrosion can also be easily predicted. Hence, it will not make the failure/crack of pipelines occur suddenly.

(2) Partial corrosion

Partial corrosion means that the corrosion happens on specific parts of the surface of the pipelines (Cosham, 2004). This means that the corrosion occurred only on a partial area of the metal surface, and the rest of it was not affected. However, partial corrosion is one of the most important causes of damage to equipment. Many unexpected corrosion accidents in engineering are caused by local corrosion.

Local corrosion is mainly due to considerable electrochemical inhomogeneity for the metal aspect or solution aspect. The relatively fixed macro and micro cathode and anode regions of corrosion cells can be clearly recognized on the pipeline’s surface. Generally, the corrosion cell of local corrosion appears smaller in the anode region, while in the regions of the cathode they are larger. Although the amount of corrosion of material is small, the local corrosion is very serious. The electrochemical reactions in the region of local corrosion have autocatalytic properties, which usually further creates the conditions that cause corrosive reactions to occur. These reactions can continuously reduce the local thickness of pipelines.

The occurrence of local corrosion has strong concealment characteristics. It is generally difficult to be found or predicted by detection; hence the destruction caused by local corrosion often occurs suddenly and without any obvious signs. Meanwhile, in corrosion damage accidents, the amount of local corrosion is much more than that of overall corrosion and this can have a more serious harmful effect on pipelines. Local corrosion includes pitting corrosion and stress corrosion cracking (SCC). Pitting corrosion means that a small but deep pitting is formed in a corroded region. Where the corrosion is serious, pitting will perforate the pipeline.

2.2 Two Evaluation Methods of Residual Strength used by the paper

Technically, a calculation of the residual strength of pipelines is a study of the calculation of mechanical failure. Currently, experimental criteria and computer simulation are two of the main methods used to evaluate the residual strength of pipelines. In this paper, the work conducted research by using the DNV-RP-F101 (Veritas, 2004) and Finite Element Analysis (Chouchaoui, 1992).

2.2.1 DNV Model

In 1999, British Gas Co (BG) and Det Norske Veritas (DNV) cooperated to develop evaluation criteria for assessing the integrity of pipelines, which is DNV-RP-F101 (Veritas, 2004), and the newest revised version of DNV-RP-F101 was published in 2010 (Vertas, 2010). The DNV-RP-F101 criteria mainly include a calibrated safety factor approach and an allowable stress approach (Veritas, 2004). It has different evaluation methods for different types of defects, to be able to evaluate independent defects, interactive defects and also defects with intricate shapes. Moreover, it could be used to evaluate the integrity of pipelines with longitudinal defects loaded only by internal pressure, pipelines with longitudinal defects overlap loaded by internal pressure and longitudinal stress. And also pipelines with circumferential defects overlap loaded by internal pressure and longitudinal stress. However, when applying the calibrated safety factor approach to evaluate the integrity of pipelines, more detailed parameters of pipelines and defects are necessary, which made it of limited use to evaluate some old pipelines where this information is missing.

The difference between the calibrated safety factor approach and the allowable stress approach is mainly due to applying various safety criteria. The calibrated safety factor approach provides a probability calibration equation, which is used to determine the allowable stress of corroded pipelines, and its process of calculation is complex. However, the allowable stress approach is a safety criterion based on allowable stress design (ASD), without considering any uncertain elements, to calculate the burst pressure of pipelines. This pressure is multiplied by a total used coefficient, which is based on an initial designed coefficient to determine a safe working pressure for the corroded pipeline. This approach is concise and easy to operate.

Even though the calibrated safety factor approach and allowable stress approach use different safety criteria, the processes for evaluation are basically the same. The DNV-RP-F101 criteria classify defects into single defects and interactive defects to calculate the burst pressure of pipelines. The process of evaluation is generally as follows:

(1) Determine an evaluation approach via the condition of the field and the degree of details of the data;

(2) Determine the type of load of pipelines, and the model of defects based on their locations and shapes. The measurement methods for the size of defects should also be determined when applying the calibrated safety factor approach (absolute measurement method or relative measurement method);

(3) Determine the allowable pressure or operating pressure of defects;

2.2.1.1 Calibrated Safety Factor Approach of DNV-RP-F101

The calibrated safety factor approach considers the measurement of depth of defects and the uncertainty factors of characters of materials, and by using the calibrated safety coefficient to reduce the conservatism of evaluation results (Veritas, 2004). It is determined by the measurement approach, the accuracy of measurement, confidence coefficient and pipeline safety level. For example, the formula for calculating the allowable stress of a pipeline with a single longitudinal defect, which is only loaded by the internal pressure is as Eq(1):

$$P_{corr} = \gamma_m \frac{2t\text{SMTS}(1-\gamma_d (d/t)^*)}{(D-t)(1-\frac{\gamma_d (d/t)^*}{Q})} \qquad \gamma_d (d/t)^* < 1$$

$$P_{corr} = 0 \qquad \gamma_d (d/t)^* \geq 1$$

where, $$Q = \sqrt{1 + 0.31(\frac{l}{\sqrt{Dt}})^2} \qquad \text{Eq(1)}$$

$$(d/t)^* = (d/t)_{meas} + \varepsilon_d \text{StD}\,[d/t]$$

Here,

P_{corr}—Allowable corroded pipe pressure of a single longitudinal corrosion defect under internal pressure loading, MPa

d—depth of defect, mm

l—length of defect, mm

D—diameter of pipe, mm

t—thickness of defect, mm

Q—length correction factor

SMTS—Specified minimum tensile strength, Mpa

γ_m—Partial safety factor for the longitudinal corrosion model prediction

γ_d—Partial safety factor for the corrosion depth

ε_d—Factor for defining a fractile value for the corrosion depth

StD [d/t]—Standard deviation of random variable d/t

2.2.1.2 Allowable Pressure Approach for DNV-RP-F101

The formula of the burst pressure of a pipeline with a single defect only under internal pressure was shown as Eq (2), and the dimensional figure of the isolated defect is shown in Figure (3).

$$P_f = \frac{2t\sigma_u(1-\frac{d}{t})}{(D-t)(1-\frac{\frac{d}{t}}{Q})} \qquad \text{Eq (2)}$$

where, $Q = \sqrt{1 + 0.31(\frac{l}{\sqrt{Dt}})^2}$

P_f— burst pressure, MPa

d— depth of defect, mm

l— length of defect, mm

D— diameter of pipe, mm

t —thickness of defect, mm

σ_u—ultimate tensile stress, MPa

Q— length correction factor

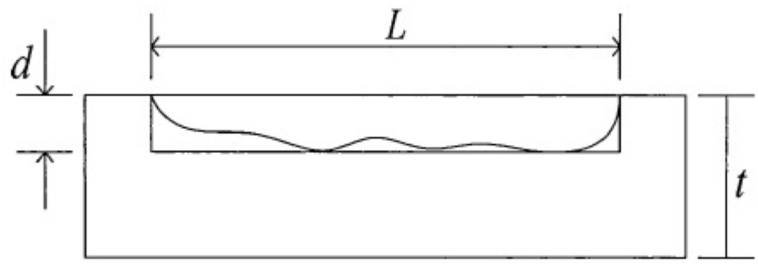


Figure 3: Dimension of the isolated defect

In addition to the single defect, when calculating the burst pressure of pipelines with interacted defects, the pressure cannot be simply calculated by the approach of calculation for a single defect (Bjornoy OH S. G., 2001). This is because the pressure can be influenced when the distance between adjacent defects is close enough.

However, when the distance between two adjacent defects satisfies one of the following conditions, Eq(3), Eq (4), the defect could still be regarded as a single defect. The dimensions of interacting defects are shown in Figure (4),

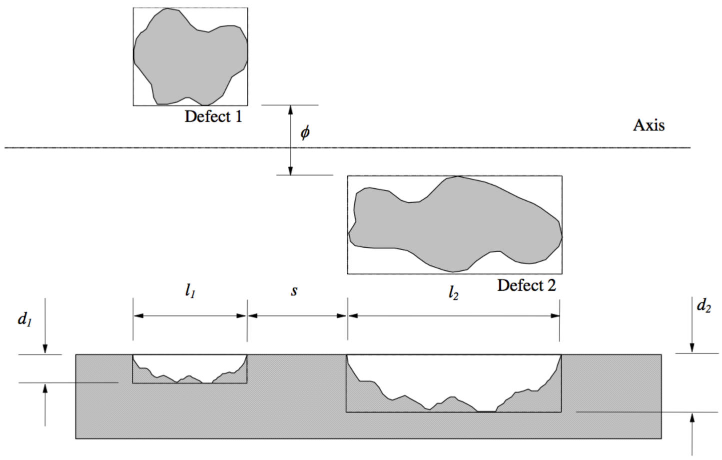


Figure 4: Dimensions of interacting defects

The circumferential angle ∅ of adjacent defects should be satisfied:

$$\emptyset > 360\sqrt{\frac{t}{D}} \qquad \text{Eq(3)}$$

The longitudinal spacing of adjacent defects should be met:

$$S > 2\sqrt{Dt} \qquad \text{Eq(4)}$$

The burst pressure of a pipeline should be evaluated based on the approach for interacted defects, which cannot satisfy the dimensional conditions above. The minimum data, which is required in the process of evaluation for interacting defects, are: the angle position of the circumferential direction of each defect around the pipe; the longitudinal spacing between adjacent defects; the length, depth and width of each defect.

The evaluation process for interacted defects is different. A vertical projection line with a circumferential angle is needed first, and then all the defects need to be projected onto the projection line. After the projection, if the defects are overlapped, these defects will be regarded as a composite defect. Then, Eq(2) will be used to calculate the burst pressure of each defect or each composite defect. Finally, the minimum burst pressure between all individual defects（P_1 to P_N）and all the combinations of individual defects (P_{nm}) on the current projection line is the burst pressure of the pipeline.

2.2.2 Finite Element Analysis

The evaluation approaches for residual strength introduced in chapter one are all based on empirical formulas. These approaches all have their own limited applicability and accuracy. Moreover, the corrosion condition of pipelines cannot be completely addressed during the assessments. The work will use Finite Element Analysis to evaluate the residual strength of pipelines.

The finite element method is categorized into linear finite element analysis and nonlinear finite element analysis. This could be used to analyze the corrosion situations for both a single defect and interacted defects, mainly based on the theory of elastic ultimate criterion and plastic failure criterion (Rita C. C. Silva, 2008). It uses software such as ANSYS, ABAQUS, etc. to establish the entity model of corroded pipelines. Compared with the other approaches, the FEM can more accurately simulate the actual operating and corrosion conditions of pipelines and the results have been proved to be more accurate as well (Friswell, 2007).

Chapter 3 Finite Element Analysis

Finite element analysis is a strong approach for evaluating the residual strength of corroded pipelines. Finite element analysis can effectively model the failure process of corroded pipelines under internal pressure. Regarding pipelines with defects, the influencing factors are the length, width, depth and number of defects. This chapter will use finite element analysis to conduct simulations on pipelines with different lengths, widths, depths, and numbers of defects to see the influence of the change of each parameter on the burst pressure.

The basic idea of the theory of finite element analysis is the “Ritz method”, which uses the approximate function of mathematics to simulate the actual physical system (geometry and load-up conditions) (Junior, 2015). Then, dividing the solid model built by FEM into many small units for further calculations. By using FEM can get rid of some constraints in the field, thereby simplifying the complexity of the problems. Meanwhile, the characteristics of good versatility, adaptability and flexibility are also reasons for using FEM in a more general way to solve engineering problems. The greatest advantage of finite element analysis is that it is not restricted by the condition of the experiments, and the simulation process can be closer to the actual conditions. Regarding the research on pipeline corrosion, FEM can not only be used to evaluate the effect on one defect caused by various stresses, but also the effect on multiple defects.

Based on the circumstances of the defects and the characteristics of the pipelines, the finite element model is built using the following assumptions:

The impact caused by the liquid in the pipeline while it is in operation is not considered. When transporting a high-temperature or low medium, thermal stress is produced. The impact of thermal stress on the pipeline is not considered. In practice, the pipeline is influenced by the working load and the internal pressure has the greatest effect on the pipeline. Therefore, when analyzing the burst pressure of the pipeline by FEM, this work assumes the pipeline is only influenced by internal pressure (A. Limam, 2012).

3.1 Introduction of the Finite Element Analysis Software Evaluation Process

ABAQUS is a set of advanced finite element program systems. The purpose of this software is to conduct a numerical analysis of mechanic's problems in structures. It is generally regarded as one of the most powerful finite element software and can be used to analyze complex solid mechanics and structural mechanics systems, especially for nonlinear problems (Felippa, 2001).

Normally, the FEM would use the follow steps to conduction the simulation. First, ABAQUS uses a 〈Pre〉 module to provide a pre-processing function including cell generation. This function is mainly used for model building and grid division, and guarantees unit form and solution accuracy. Then, it uses two main analysis modules， ABAQUS/Standard or ABAQUS/Explicit, to analyze the stress and deformation by loading up and constraining the boundary conditions to the model by FEM; at the end, using the ABAQUS〈Post〉module also provides the post-processing function of the mechanical model and calculation results, which includes the plot, animation, X-Y graphic plot, time-history plot, etc.

3.2 Finite Element Analysis of Pipeline Corrosion

Pre-processing takes a long time in finite element analysis, and it should be conducted with the utmost care. Even slight inattention can cause a calculation error from the establishment of the solid model to the grid division, and this error would affect the analysis results. In addition, the load and boundary conditions applied on the FEM model must be correct; otherwise it would cause non-convergence in the calculation, and the result would fail. After simulation by FEM, the FEM results were needed to combine the failure criterion to evaluate the integrity of the pipelines.

3.2.1 The Model Establishment

1) The determination of material parameters

With the increase in transporting pressure, the steel-grade used for pipelines is improving all the time, achieving high-strength and ultra-high-strength steel-grades (Graf, 2003). Currently, X80 is recognized internationally as the ideal steel to be used for pipelines with a large diameter (Arafin, 2011). Hence, in this paper, the X80 is chosen as the model material for pipeline analysis.

According to the specific situations of research objects, after selecting the type of materials, the parameter of the material needs to be set up. Pressure pipelines with corrosion defects are the focus of this paper， and in order to simulate the elastic and plastic behaviors of pipelines under the load effectively, the linear and nonlinear parameters of the material need to be established in the pre-process stage. The linear parameters of the pipeline material include the elastic modulus and Poisson's ratio; the nonlinear parameters contain the stress-strain relationship of materials (reflecting the hardening properties of materials after yielding), which is obtained according to the measurement by tensile experiments, and different materials have different stress-strain curves. The related parameters of materials used in the paper are as follows: the elastic modulus E: 200, 000MPa, Poisson ratio γ : 0.3, yield strength s:534.1Mpa, and tensile strength b:718.2MPa (Benjamin, 2005).

It should be noted that to avoid the influence of constraint at both ends on the stress of the corroded area, the length of the pipeline is defined as 20 times larger than the corresponding length of the defect.

2) Uniform corrosion defect

The shape of pipeline defects can be simplified as a uniform and regular shape. To make it easier when conducting the simulation, the work used uniform corrosion defects with a rectangular shape. The three factors for the construction of a rectangular-shaped defect are the length, width, and depth of the defect. The residual wall thickness in the corroded area is basically the same due to the uniformity of the corrosion defects, and the shape under the corrosion is a cylindrical surface.

In the process of finite element analysis, the simplified model of the defect is regular. Hence, the pipeline with the defect is symmetrical to the plane running through the axis of the pipeline and the center of the defect, and is also symmetrical to the plane that is perpendicular to the axis of the pipeline and running through the center of the defect. Based on the above, only a quarter of the pipeline is modeled in the process of analysis.

The geometric dimensions related to the defect are: a depth of 5.39 mm, a length of 39.6 mm and a width of 32.2 mm, longitudinal spacing of 20.5 mm and circumferential spacing of 9.6 mm; the dimensions of the pipeline were: an outside diameter of 458.8 mm, and a wall thickness of 8.1 mm (Chouchaoui, 1992).

The geometric model of the defect is shown in Figure (5), and its finite element model is shown in Figure (6).

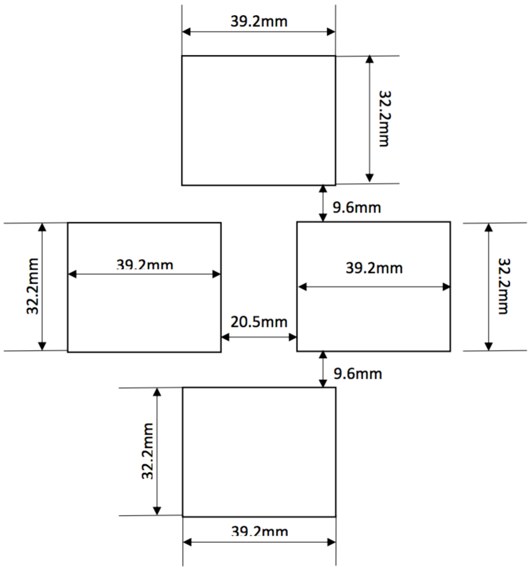


Figure 5: Geometric model of the defect

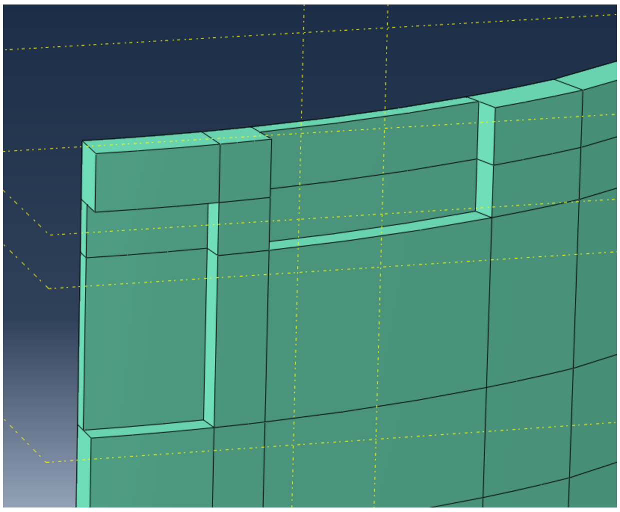


Figure 6: Finite Element Model of the defect

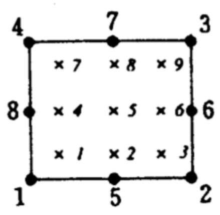
3.2.2 Element Selection

Each finite element of the model represents a discrete part of the structure and the elements are connected to each other through common codes, which determine the basic geometrical form of the structure for simulation. Both the type and number of elements being used in the model would affect the results of the simulation.

The model being used in the paper is a three-dimensional model; hence, the 3D solid element is used in the selection of the elements. There are some options for 3D solid elements in the ABAQUS unit storehouse, such as the 8-node linear unit C3D8, 20-node secondary unit C3D20, 8-node secondary unit CPS8, etc. The secondary unit is suitable for mesh generation for the model with an irregular-shaped boundary, but the boundary conditions of the model used in this paper are regular. Therefore, the 8-node solid element C3D8 would be used in the simulation, and the model of the element is shown in Figure (7)

(a) Linear Element (8-node cube, C3D8)

(b) Quadratic Element (20-node cube, C3D20)



(c) Quadratic Element

(CPS8)

Figure 7: Element models for C3D8, C3D20, CPS8

3.2.3 Boundary Condition

In fact, the pipeline is very long, and when corrosion occurs it only influences the strength of the part around the corrosion; hence, only the part of pipeline which is corroded is considered when conducting the simulation, which also means the pipeline has no displacement in the axial direction. Hence, in the process of simulation, the axial displacement for one end of the pipeline model would be fully restrained. In addition, the pipeline model is a symmetrical structure, and the defects have symmetrical characteristics as well, so the vertical displacement for the wall section of pipelines with it being lengthways cut should also be zero, and this end of the pipeline should be imposed with symmetrical constraints.

3.2.4 Loading Analysis

In the actual operation of the pipeline, the loading is complicated, needing to consider the weight of the pipeline, concentrated load, and the other loads. Internal pressure is the main type of load for pipelines and also the main factor that influences the stress of pipelines; therefore, the effects of internal pressure on pipelines with defects are the main consideration in this work (A. Limam, 2012). Meanwhile, it is assumed that this internal medium pressure will stay constant in the process of simulation. Hence, the load applied in the FEM is "pressure", which is on the inner surface of the three-dimensional finite element model, see Figure (8).

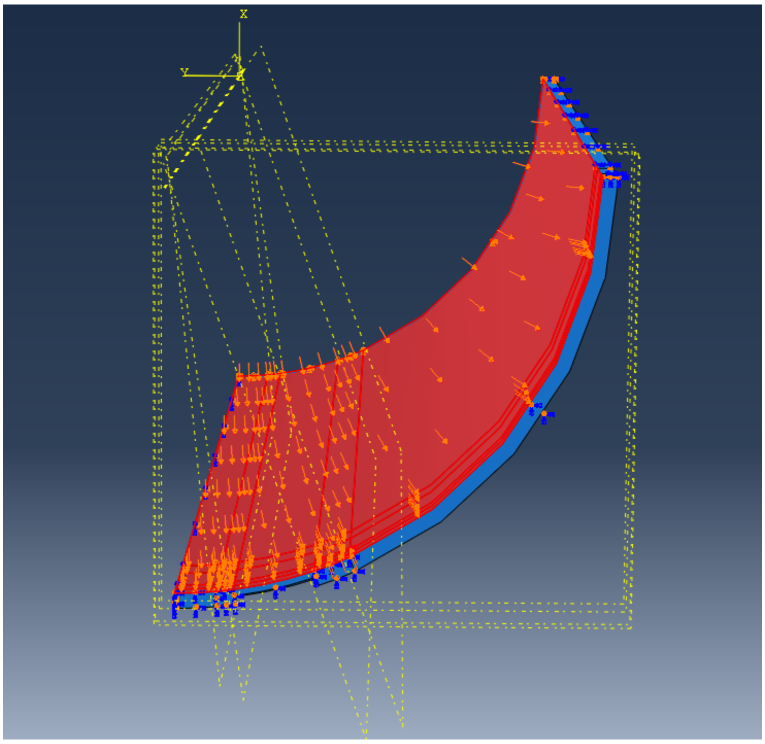


Figure 8: The Loading status by FEM

3.2.5 Mesh Division

The accuracy of the results calculated by FEM is directly determined by how the mesh of the 3D entity model is divided. Normally, the more refined the mesh division, the more accurate the results of the calculation will be, but this also necessitates higher performance requirements for computers, and more time would be needed for the calculation. Therefore, the mesh division should be set up appropriately according to the size of the model and the requirements for the accuracy of the calculation. When meshing the pipeline with defects, a larger grid size should be chosen for the body part to save on the calculation amount; however, the corrosion parts are an important area of research due to their big changing gradient for stress and strain and hence a smaller grid size is needed to be set up in the area around the defects to ensure the accuracy and convergence of the calculation. The grid form being used in this paper is hexahedral in order to reduce the probability of the occurrence of grid singularity. A hexahedral grid can only be used for dividing a regular entity. Hence, according to the complex model structure in the corrosion area, dividing the model body to form a number of small rule bodies is needed at first, and then a hexahedral grid should be used to conduct the mesh division for these parts.

Based on the theory above, in the corroded area more meshes were used (seeds were chosen by the number, with the value of 10); for the area, far from the corrosion, fewer meshes were used (seeds were chosen by the size, bias on single, from 0.015 to 0.03). The failure would occur in the corroded area, which also explains why more meshes were used in the corroded area. This not only improves the accuracy of the simulation, but also saves on simulation time. The details could be seen in Figure 9 and 10.

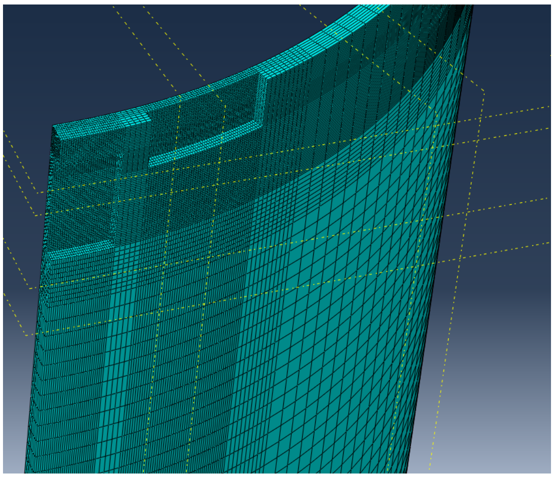


Figure 9: Distant view of mesh division

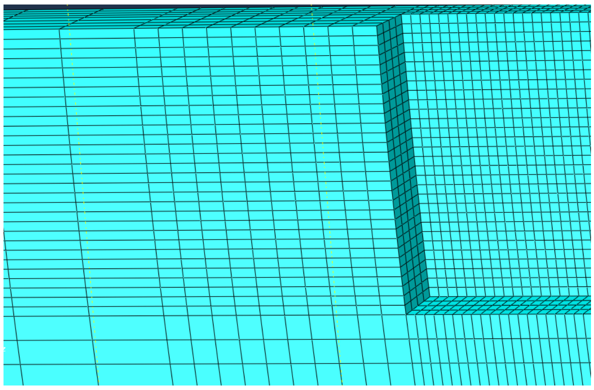


Figure 10: Detail view of hexahedral grid

3.2.6 Failure Criterion

The characteristics of loading force on the pipelines are complicated, with circumferential stress, axial stress and radial stress occurring at the same time, which are called the triaxial state of stress. The yield condition used in this paper is the von Mises yield condition. The von Mises yield condition considers that the yield occurred when the ratio of the maximum shape change reaches a certain value, and the expression for it is shown in Eq (5):

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma^2 \qquad \text{Eq (5)}$$

In the post-processing of FEM by ABAQUS, von Mises is generally called Mises equivalent stress. The stress distribution for the model can be represented by the stress contour, which can make a clear description of the variation of the result for the whole simulation, to determine the failure zone for the model and the value of stress for that area. In this work, whether the corrosion pipeline failed or not is evaluated based on the value of von Mises equivalent stress in the corroded area by adopting the plastic failure criterion (Fu, Nov, 1996).

The plastic failure criterion suggests that when the von Mises equivalent stress of the corroded area reaches the post-yield point of the material, when the minimum stress along the wall thickness in the corroded area reaches the ultimate tensile stress that will cause pipeline failure to occur, and the pressure to make this happen is called burst pressure.

For example, the changing status for the equivalent stress for a corroded pipeline (with a defect having a length of 39.6 mm, depth of 5.39 mm and width of 19.3 mm) under different pressures is determined in Figures (11-14). The pressure was applied using 0.5MPa as an interval, resulting in 17MPa, 17.5MPa, 18MPa, and 18.5MPa. A comparison of the four Figures (11-14) (partially magnified) shows that the distribution of the value of stress in the corroded area is in different scales. Stress on the external side of the pipeline is the largest, while stress on the internal side is the smallest. By gradually increasing the pressure, the external stress on the corroded area reached the ultimate tensile stress (718.2MPa) first. This gradually extended from the external side to the internal side of the corroded area along the wall thickness. When the pressure reached a certain point (18.5MPa), the innermost point of the corroded area reached ultimate tensile stress as well. According to the plastic failure criterion above, when the equivalent stress of the corroded area reaches the post-yield point of the material the failure occurred, since the failure of the pipeline happened under this pressure, and is called the burst pressure (18.5MPa). The global view and zooming view of von Mises stress for the sample at this moment can be seen in Figures (15, 16).

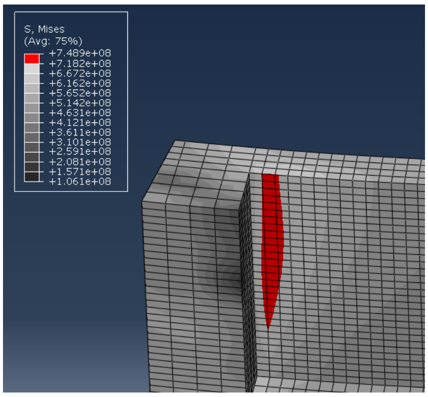


Figure 11: The von Mises Stress Contour of a pipeline under a pressure of 17MPa

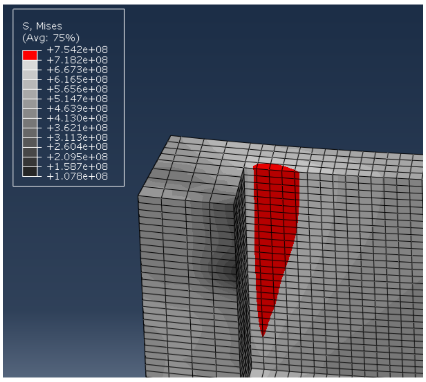


Figure 12: The von Mises Stress Contour of pipeline under pressure of 17.5MPa

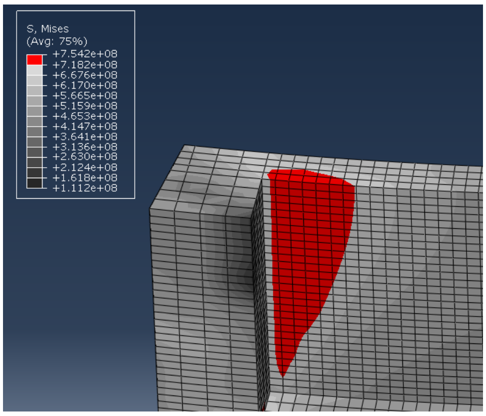


Figure 13: The von Mises Stress Contour of a pipeline under pressure of 18MPa

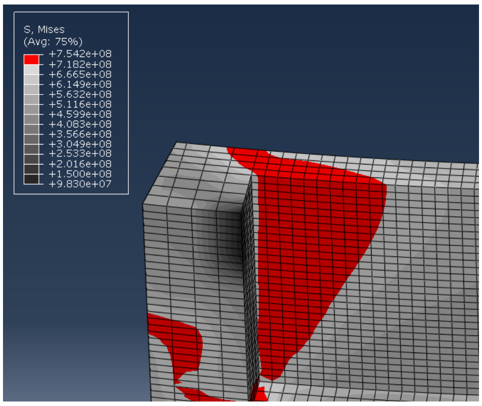


Figure 14: The von Mises Stress Contour of a pipeline under pressure of 18.5MPa

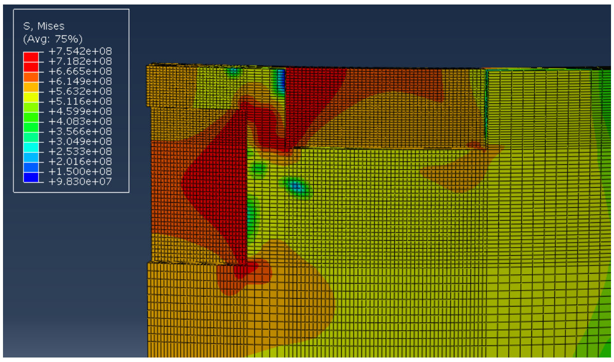


Figure 15: The zooming view of von Mises stress for the sample

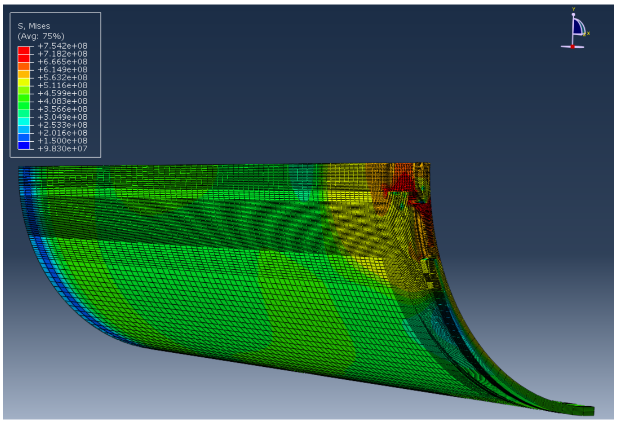


Figure 16: The global view of von Mises stress for the sample

Base on the FEM steps analyzed above, the flow chart is shown in Figure (17).

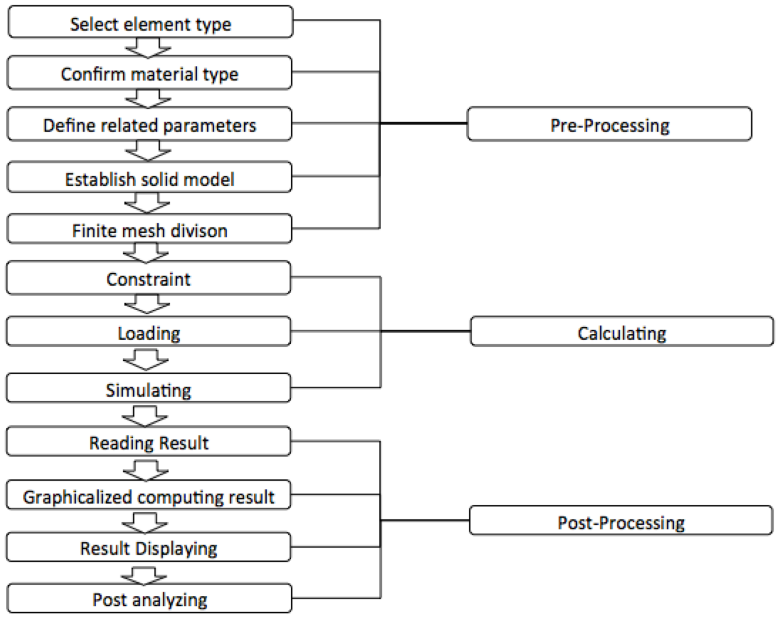


Figure 17: Flow chart of steps for FEM simulation

3.3 Methodology for Establishing the Burst Pressure

The distribution state of the stress of the pipeline can be directly presented from the results by FEM through building the model, meshing, etc. In the process of non-linear analysis, the load will be increased by incremental change, and the stress will be changed as well through this incremental process for each step. The results could be learnt from the results in the Equivalent Stress Chart by reviewing the distribution of value of stress and combining the failure criteria for the pipeline to evaluate whether the pipeline has failed as well as the burst pressure when the failure happened.

To calculate the changing relationship of the burst pressure and different parameters (depth, length, number, and width of defects), the work changed one variable by increasing the size gradually each time to determine how the burst pressure changed. For example, to learn the relationship of the burst pressure and the width of the defects using FEM, the values of widths were changed as follows: 25.8 mm ($0.8w_0$), 32.2 mm (w_0), 38.6 mm ($1.2w_0$), 45.1 mm ($1.4w_0$), and 51.52 mm ($1.6w_0$). The other geometric dimensions related to the defects remained the same, which were a depth of 5.39 mm and length of 39.6 mm, using 4 defects. The dimensions of the pipeline were: an outside diameter of 458.8 mm, wall thickness of 8.1 mm, longitudinal spacing of 20.5 mm and circumferential spacing of 9.6 mm.

Note that all the defects are assessed as being equal and are artificially quadrilateral arranged on the outside surface of the pipelines. The location is illustrated in Figure (18).

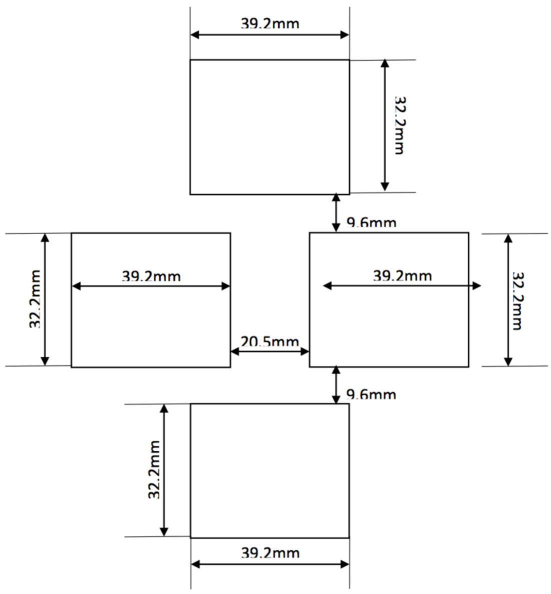


Figure 18: Length, width, and spacing of the defects of the sample

From the steps above using FEM, the 5 sets of simulations were conducted for pipelines with different widths, and the results are shown in Figure (19). From the figure, the relationship between the burst pressure and the change of the circumferential length of defects is presented.

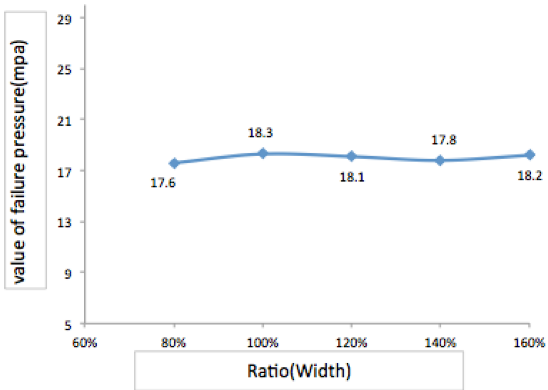


Figure 19: The plot of burst pressure among varied widths

The value of the burst pressure with different axial lengths of defects is also calculated according to the above. During the simulation, the values of the length of defects were changed from 60% to 180% of the original length of defects, and the values of length were shown as follows: 23.76 mm ($0.6l_0$), 31.68 mm ($0.8l_0$), 39.6 mm (l_0), 47.52 mm (1.2 l_0), 55.44 mm (1.4 l_0), 63.36 mm (1.6 l_0) and 71.28 mm (1.8 l_0). The other parameters of the defects and pipelines were considered to be identical. The results of the changing trend of burst pressure for different axial lengths of defects are shown in Figure (20).

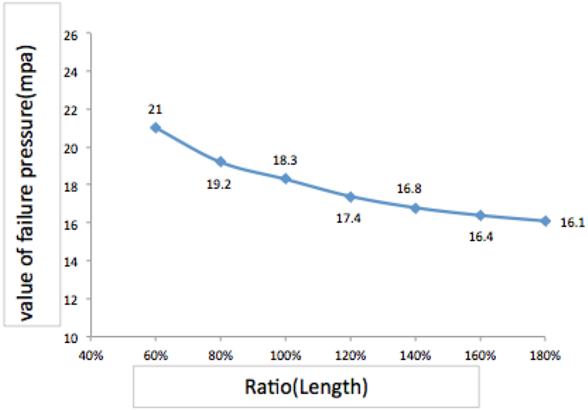


Figure 20: The plot of burst pressure among varied lengths

When defining the depth of the defects being used by FEM to find the relationship between burst pressure and defect depth, the changing ratio was arranged from 60% to 140% of the original depth to prevent the maximum depth of defect exceeding the thickness of the pipe (8.1 mm). The values of the depth are: 3.234 mm ($0.6d_0$), 4.312 mm ($0.8d_0$), 5.39 mm (d_0), 6.46 mm ($1.2d_0$) and 7.54 mm ($1.4d_0$). The other parameters of the defects and pipelines were the same as those used for the width analysis. The FEM simulation results of burst pressure for different depths of defects are illustrated in Figure (21).

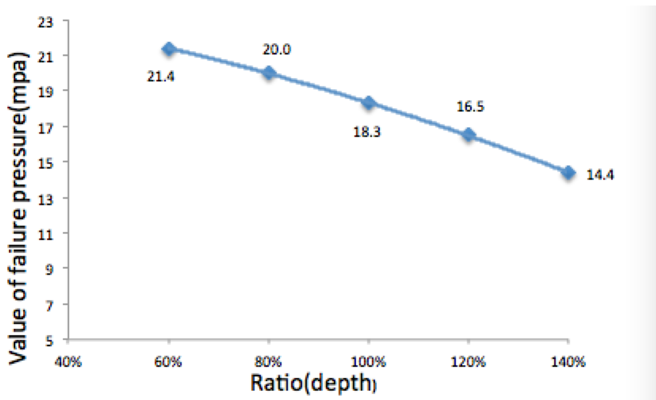


Figure 21: The plot of burst pressure among varied depths

To observe the changing trend of burst pressure with different number of defects, the number was increased from one to four when the other parameters of defects remained the same. When there was only one defect in the pipeline it was called a basic defect, which was a rectangular artificial defect with a depth of 5.39 mm, length of 39.6 mm and width of 32.2. When the number of defects increased, they were called interacting defects, and each one was identical to the basic defect above. The value of spacing between the two longitudinally aligned defects was kept at 20.5 mm, and the spacing between the circumferential aligned defects was kept at 9.6 mm. The specific location assigned for different numbers of defects is shown in Figure (22):

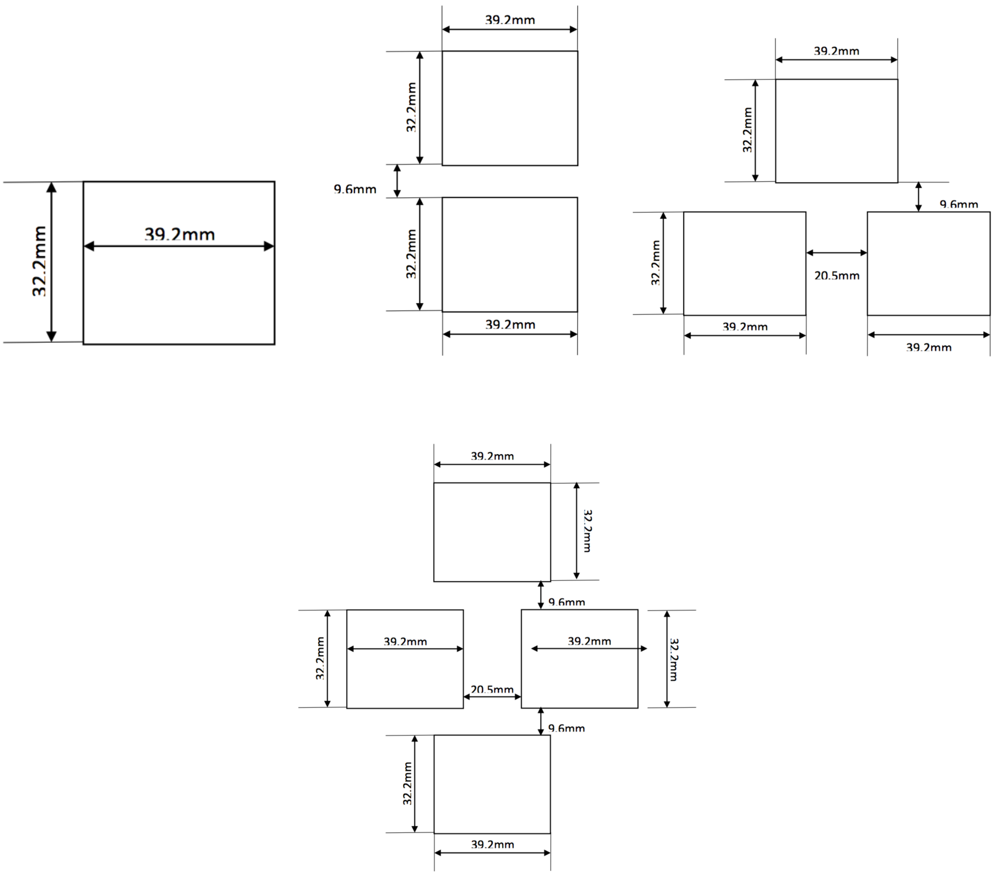


Figure 22: The location of different number of defects of the samples

The other parameters of the defects were the same as those described above. Using simulation, the results of burst pressure with different numbers of defects are shown in Figure (23).

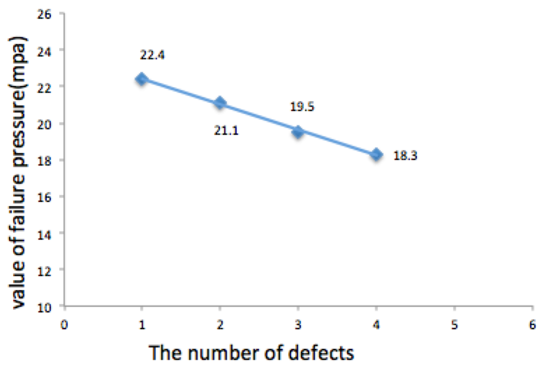


Figure 23: The plot of burst pressure among different numbers of defects

3.4 Results and Discussion

Based on FEM, through building the model of the pipeline, mesh generation and von Mises Stress contour can get the stress of distribution, and by combining the failure criteria can further get the burst pressure of the pipeline. Conducting sets of simulations on pipelines with different dimensional sizes and numbers of defects allows us to obtain the changing trend of burst pressure.

Figure 19 demonstrates that by changing the width of the defects, the burst pressure of pipelines was influenced a small amount, and these changes are insignificant. To some degree, when the depth, axial length and the number of defects maintain the same value, changing the width of defects had almost no influence on the burst pressure.

It is evident to see the variation trend of bust pressure with different lengths of defects from Figure 20. The burst pressure of pipelines decreased as the length of defects grew and this change occurred rapidly at the beginning; however, when the length reached a certain point the rate of change gradually became smaller. This result illustrates that the length has a big influence on burst pressure to a certain degree, and this influence is minimized when the length reaches a certain point.

Figure 21 shows that the depth of defects is an important factor that influences burst pressure by indicating that the pressure saw a sharp decrease as the defect depth increased. This is because while the depth of the defect is increasing, the wall thickness of the pipelines is getting thinner, and the capacity for bearing the pressure of the pipeline is declining.

Figure 23 shows that burst pressure is influenced by the number of defects, and the value decreases sharply with an increasing number of defects in the pipeline. This emphasizes that the number of defects should be considered as a failure factor, along with the length and depth of defects when assessing the integrity of pipelines.

Chapter 4 Evaluation Criteria for Defects in Corroded Pipelines

4.1 Introduction of the Evaluation Criteria

The evaluation of corroded defects includes a comprehensive analysis of the condition of a pipeline. It focuses on analyzing the burst pressure of a corroded pipeline. Researchers have used many evaluation criteria; however, even for isolated defects, the available assessment criteria come with a certain level of conservatism, and each criterion predicts a different value of burst pressure under the same situation of corrosion (Zhu X K, 2003).

The ASME B31G, Modified ASME B31G, DNV and PCORRC equations are all criteria being used for evaluating the burst pressure of the corroded pipeline. However, DNV RP-F101 is one of significant and conventional pipeline safety evaluation criteria issued by an authorized institution — Det Norske Veritas (DNV) in the corrosion engineering field. The primary reason for the strong practicability of DNV RP-F101 is that this criterion is obtained based on full-scale experiments and finite element analysis, and the conservatism of calculations of internal pressure by this model is relatively small. Another reason is that the safety theory being used in these criteria is the same as the one used in the DNV OS-F101 criteria. Hence, it is more close to the actual situation of submarine pipeline engineering by using the DNV RP-F101 criteria to evaluate the residual strength of the corroded pipeline.

Two different methods have been mentioned in Chapter Two when using the DNV model to evaluate the burst pressure of pipelines, the calibrated safety factors approach and allowable stress approach. The partial safety factor approach not only considers the uncertainty of pipeline material but also considers the uncertainty of defect detecting tests, which makes both the measuring method and computational process of this approach complicated. However, the allowable stress method does not consider the uncertainty of the factors referred above, leading this approach to be more straightforward and simpler use than the partial safety factor method. Therefore, in the field area, engineers are more used to applying the allowable stress method to evaluate residual strength. The following section of this chapter will evaluate the burst pressure of corroded pipelines with an isolated defect and interacting defects by using the allowable stress approach.

When using the allowable stress approach in the DNV model, the burst pressure of pipelines with a single defect can be calculated by Eq(2). However, in actual situations of pipeline corrosion, not only for an isolated defect but also for multiple defects along pipelines, these defects are interacted. If the burst pressure of pipelines is calculated based on the theory of an isolated defect, the interaction between these defects would be ignored, leading the results of the calculation to fail to correspond with objective reality, potentially allowing hidden problems in the operation of pipelines to create a safety situation.

Technically speaking, the evaluation criteria of the burst pressure of pipelines with interacted defects are only valid when the pipeline is only loaded by internal pressure. Eq (3, 4) can be used to determine whether the defects are interacted or not. If so, the failure status of pipelines would be evaluated by the following steps:

Step 1: Construct a series of axial projection lines with a circumferential angular spacing, see Eq(6):

$$Z = 360\sqrt{\frac{t}{D}} \qquad \text{Eq(6)}$$

Step 2: Consider each projection line in turn. If defects lie within $\pm Z$, they should be projected onto the current projection line, Figure (24).

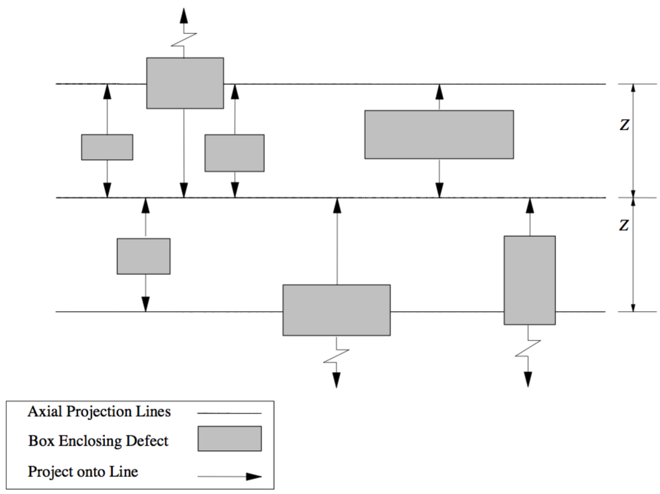


Figure 24: Projection of circumferentially interacting defects

Step 3: Where defects overlap, they should be combined to form a composite defect. This is formed based on the combined length, and the depth of the deepest defect, Figure (25). If the composite defect consists of an overlapping internal and external defect, then the depth of the composite defect is the sum of the maximum depth of the internal and external defects.

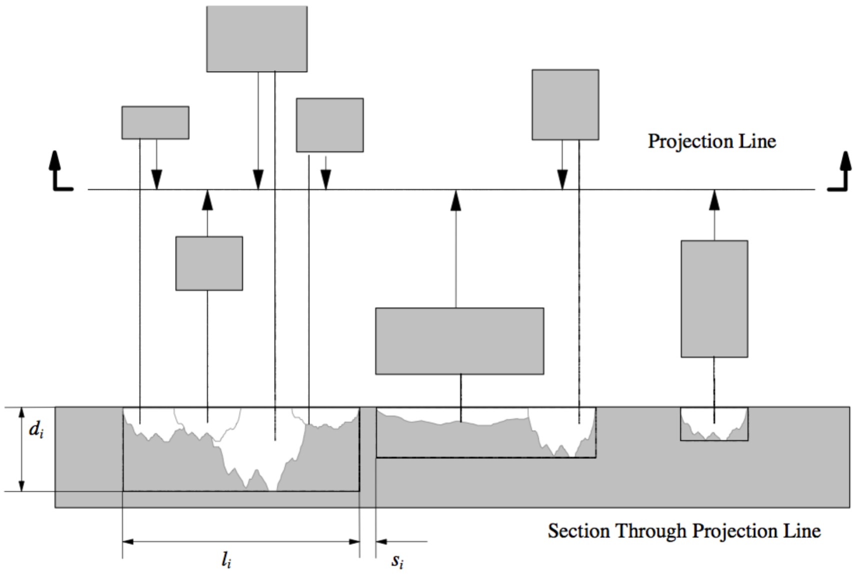


Figure 25: Projection of overlapping sites and the formation of a composite defect

Step 4: Calculate the allowable corroded pipe pressure（P_1，P_2，$\ldots P_n$）of each defect to the Nth defect, treating each defect, or composite defect, as a single defect, Eq (7):

$$P_i = \frac{2t\sigma_u(1-\frac{d_i}{t})}{(D-t)(1-\frac{\frac{d_i}{t}}{Q_i})}$$

where, $$Q_i = \sqrt{1+0.31(\frac{l_i}{\sqrt{Dt}})^2} \qquad \text{Eq (7)}$$

i = (1, 2, 3, …. .n)

Guidance note:

Steps 5 to 7 estimate the allowable corroded pipe pressure of all combinations of adjacent defects. The allowable corroded pipe pressure of the combined defect *nm* (i.e. defined by single defect *n* to single defect *m*, where n = 1 ... N and m = n ... N) is denoted P_{nm}.

Step 5: Calculate the combined length of all combinations of adjacent defects, Figure (26, 27). For defects *n* to *m* the total length is given by:

$$l_{nm} = l_m + \sum_{i=n}^{i=m-1} (l_i + S_i) \qquad n, m = 1 \ldots N$$

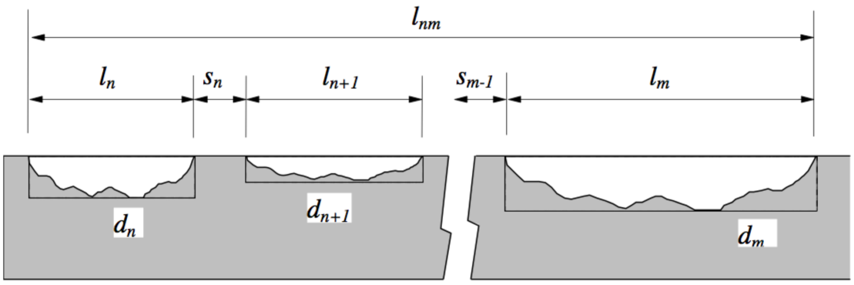


Figure 26: Combining interacting defects

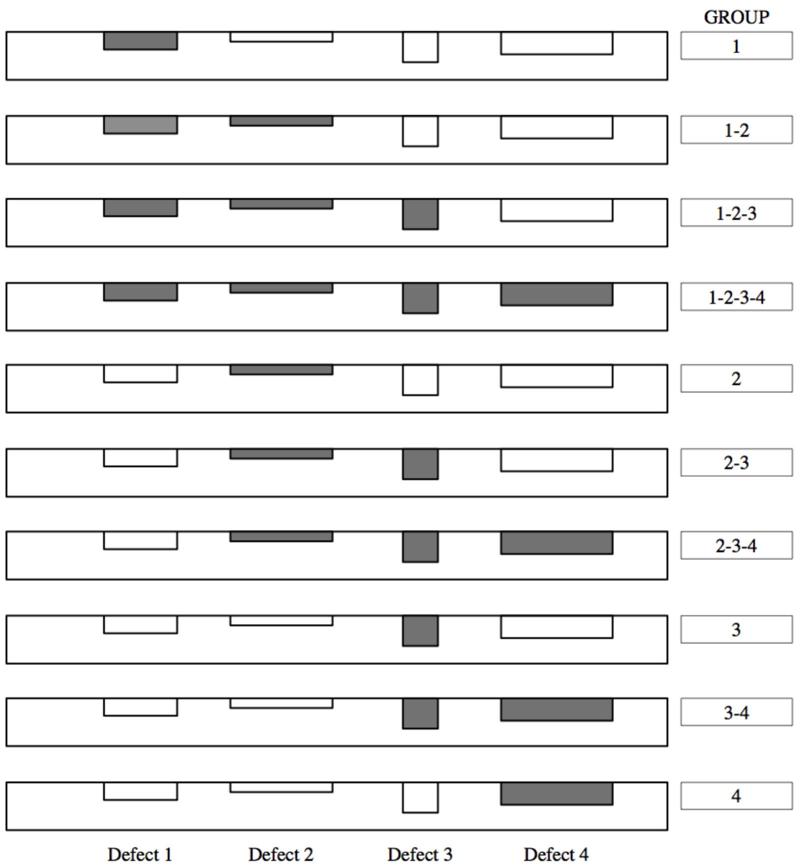


Figure 27: Example of the grouping of adjacent defects

Step 6: Calculate the effective depth of the combined defect formed from all of the interacting defects from n to m, as Eq (8):

$$d_{nm}=\frac{\sum_{i=n}^{i=m} d_i l_i}{l_{nm}} \qquad \text{Eq (8)}$$

Step 7: Calculate the allowable corroded pipe pressure of the combined defect from n to m, using l_{nm} and d_{nm} in the single defect, Eq (9):

$$P_{nm} = \frac{2t\sigma_u(1-\frac{d_{nm}}{t})}{(D-t)(1-\frac{\frac{d_{nm}}{t}}{Q_{nm}})} \qquad \text{Eq (9)}$$

where, $Q_{nm} = \sqrt{1+0.31(\frac{l_{nm}}{\sqrt{Dt}})^2}$

$n = 1 \ldots N, \quad m = n \ldots N$

Step 8: The allowable corroded pipe pressure for the current projection line is taken as the minimum of the failure pressures of all of the individual defects (P_1 to P_N), and of all the combinations of individual defects (p_{nm}), on the current projection line, Eq (10).

$$P_f = \min (P_1, P_2, \ldots \; P_N, \; P_{nm}) \qquad \text{Eq(10)}$$

Based on the analysis above, the flow chart for calculating the burst pressure of the corroded pipeline by using the DNV model is in Figure (28):

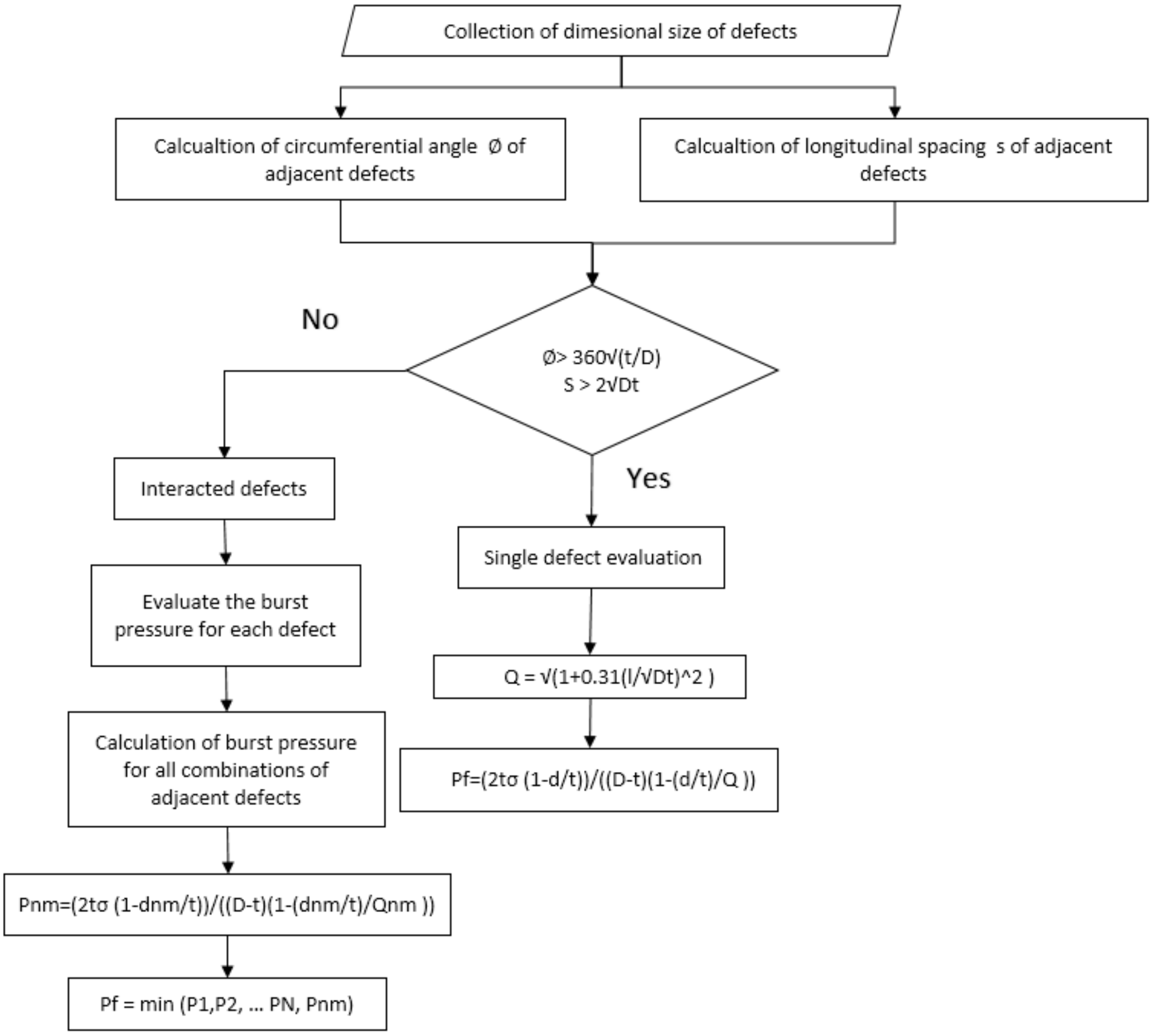


Figure 28: Flow chart of DNV model calculation

4.2 Comparison of the DNV Model and FEM

To assess the reliability of the DNV model, this work calculated the burst pressure with both the DNV model and FEM using the same set of data to observe the difference in the results calculated by these two methods.

In this process, one parameter of defects was changed (the length changed from 60% to 180% of the original dimensional size). The values of length used were: 23.8 mm ($0.6l_0$), 31.7 mm ($0.8l_0$), 39.6 mm (l_0), 47.5 mm ($1.2l_0$), 55.4 mm ($1.4l_0$), 63.4 mm

($1.6l_0$) and 71.3 mm ($1.8l_0$). The other geometric dimensions related to the defect remained at the same value, which was a depth of 5.62 mm and width of 32 mm. The dimensions of the pipelines were an outside diameter of 458.8 mm and a wall thickness of 8.1 mm.

The number of defects in this case is two, and the spacing between defects is 9.9 mm. Based on the assessment criterion of interacting defects, Eq (3,4), the burst pressure would be interacted by the adjacent defect compared with when there is an isolated defect in the pipeline. Hence, for multiple defects, they would be projected onto a projection line, and the combined defects would be used to determine the burst pressure in the end. After the calculation, the results of the burst pressure of pipelines with different lengths of defects are shown in Table (2).

Table 2: Value of burst pressure by DNV and FEM

Ratio(length)	Burst Pressure (DNV)(MPa)	Burst Pressure (FEM)(MPa)
60%	24.58	22.81
80%	23.74	21.79
100%	22.78	20.92
120%	21.77	19.88
140%	20.78	19.01
160%	19.80	18.11
180%	18.90	17.74

4.3 Results and Discussion

The plot of these results is demonstrated in Figure (29), where the upper line represents the changing trend of burst pressure with different lengths of defects calculated by the DNV model and the lower line represents the results using the FEM model.

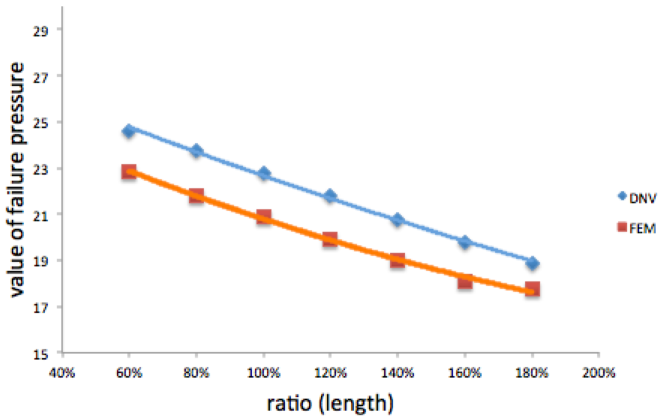


Figure 29: Comparison of burst pressure between DNV and FEM

Comparing the results from Figure (29), the burst pressures both decreased when the defect became longer. When the length of defects changed to the same degree, the rate of burst pressure change compared to the length of the defect using the DNV model and FEM was almost the same. However, the DNV model highly overpredicts the burst pressure.

Chapter 5 Revising the DNV Model

Until now, the issued evaluation criteria for analyzing the integrity of pipelines all have had their own practicability and conservatism problems. Even under the same corrosive conditions, the results of the integrity of pipelines evaluated using different criteria are different as well (Bjornoy OH M. M., 2001). To achieve more accurate and practicable corrosion evaluation criteria, continually revising and optimizing the old criteria to minimize its conservatism is necessary. For instance, three different revised versions of the ASME B31G criteria have been issued, which are ASME B31G-1984, ASME B31G-1991 and ASME B31G-2009, where ASME B31G-1991 made a partial modification and enhancement based on ASME B31G-1984, and ASME B31G-2009 made a considerable revision to ASME B31G-1991 based on the foundation of massive experiments to further overcome the conservatism of ASME B31G (Orazem, 2014).

Through comparing the results of burst pressure of pipelines by using the DNV Model and FEM model, the work concluded that the DNV model overpredict the pressure, which would lead technicians to overestimate the bearing capacity of pipelines. In this chapter, to relax the conservatism built into the DNV model and to predict the burst pressure of corroded pipelines reliably, the work used FEM modeling results and regression analysis to revise the DNV model.

5.1 Concept of Revising the Model

The reason the results calculated by the DNV model are conservative is that the DNV model does not completely consider the parameter information of corrosion defects. Based on the FEM results in chapter 3, the number of defects (n) is shown to be an important failure factor. This is because the difference in the number of defects can change the influence of the length or depth on burst pressure, and then vary the value of burst pressure. However, the DNV model does not consider "n" as a failure factor, even though multiple defects could be assessed as having interacting defects, the results are still not positive. In other words, when the number of defects is more than one, in the DNV model, the definition of the equation of length or depth of defects is not precise. It does not reasonably quantify the actual situation of the defects, causing the burst pressure calculated by the DNV model to be different. The results analyzed by FEM also show that the depth of defects has a significant influence on burst pressure. Therefore, the accuracy of the definition of the equation of depth for the DNV model has a significant influence on the results of the calculation. Hence, to improve the precision of the DNV model, a new definition of "d" is needed. This paper calls it as "d_{new}", which is an equivalent value of the actual depth of all defects in the pipeline, representing an "average" depth of all defects.

5.2 Methodology

Since "d_{new}" represents an average depth, it would be influenced by the number of defects; in this way, "n" should be considered into the equation of "d_{new}". To establish the equation of "d_{new}" and build the relationship between "d_{new}" and "n", this work used the following scheme, see Figure (30):

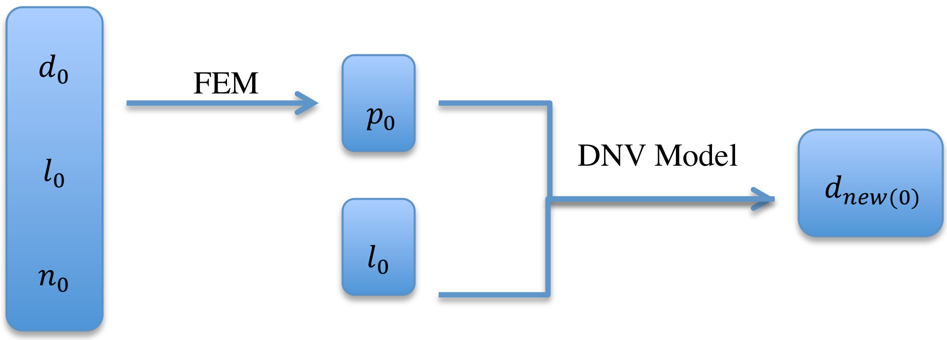


Figure 30: Concept of Revising Model

Using this 3-dimensional solid model built in FEM, the burst pressure can be assessed for all defects of the corroded pipeline. With the assumption of a set of defects with a dimensional size of d_0, l_0, n_0 , a corresponding value of burst pressure (p_0) can be predicted. If the DNV model is used with p_0 and l_0 as the known quantities, the value of the corresponding d can be calculated. The work defined it as $\mathrm{d}_{\mathrm{new}(0)}$. This $\mathrm{d}_{\mathrm{new}(0)}$ was different from "d" in the DNV model; it was related to the other parameters of the defects, and "n" was included as well, which is also the equivalent depth this work cited above, and in this way, "n" is also introduced to the model. Hence, this theory resolves the problem that did not consider "n" as a failure factor in the DNV model by building the equation of "d_{new}", it also makes the revised model more comprehensive, as it considers the additional influence of various factors on burst pressure.

Hence, using FEM to obtain different burst pressures under different corroded situations, and then through the described concept above, using the results obtained by FEM model and the DNV model, the value of relevant different sets of d_{new} can be calculated. The data being used in the simulation were as following, see Eq (11)

$$l_i = \text{a } l_0 \quad (\text{a}=0.6, 0.8, \ldots 1.8)$$

$$d_i = \text{b } d_0 \quad (\text{b}=0.6, 0.8, \ldots 1.4) \qquad \text{Eq(11)}$$

$$n_i = (1, 2, 3, 4)$$

Where, d_0, l_0, n_0 are the original dimensional sizes of the defects when changing the size of the defects for simulation. By gradually changing the original dimensional size of the defects, assuming the original length value of the defects is l_0, the length changed from $0.6l_0, 0.8l_0, \ldots \ldots$ to $1.8l_0$. The value of the depth changed in the same way, and the number of defects changed from 1 to 4. Additionally, the values of the length, depth, and number of defects were chosen by an arbitrary combination from the data above as one set of parameters to be used in the simulation. This not only builds enough data to establish the equation between $d_{new\,(i)}$ with l_i, d_i, n_i in the following work, but also ensures the accuracy of the constructed equation.

Some of the values being used by FEM and the corresponding value of d_{new} being calculated are shown in Table (3):

Table 3: The value of d_{new} under different parameters

n	d(mm)	l (mm)	P (mpa)	d_{new} (mm)
4	5.39	23.76	21.22	7.35
4	5.39	31.68	19.27	7.27
4	5.39	47.52	17.43	6.92
4	5.39	55.44	16.86	6.75
4	5.39	63.36	16.45	6.57
4	5.39	71.28	16.17	6.39
4	3.23	39.60	21.44	6.33
4	4.31	39.60	20.00	6.74
4	6.47	39.60	16.56	7.35
4	7.55	39.60	14.48	7.56
2	5.39	39.60	21.18	6.43
3	5.39	39.60	19.56	6.88

Hence, after calculation, four corresponding sets of parameters for d, n, l and d_{new} were obtained using the concept above.

5.3 Regression Analysis

5.3.1 Introduction of Regression Analysis

Regression analysis is an important branch in modern applied statistics in corrosion analysis and is a scientific method for analyzing the law of qualitative change between different parameters. Regression analysis is used to conduct research that analyzes the relationship between one dependent variable with one or more independent variables, and for evaluating or predicting the impact of independent variables on a dependent variable. It is a multiple statistical analysis method used for researching the uncertain relations between different variables. Regression analysis is not only used for analyzing the influence of independent variables on the dependent variable, but also predicting the value of the dependent variable by using regression equations.

In the process of regression analysis, when the experimental formula being fitted is a linear function, the regression analysis is called a linear regression analysis. When the independent variable has more than one parameter, the analysis is called multiple linear regression analysis (Uys, 2011).

The theoretical model for multiple linear regression is in Eq (12):

$$y= \beta_0+ \beta_1 x_1+ \beta_2 x_2+.....+\beta_p x_p+ \varepsilon \qquad \text{Eq (12)}$$

where, β_0, $\beta_1 \ldots\ldots \beta_p$ are (p+1) unknown parameters, β_0 is a regression constant, β_1, $\beta_2 \ldots\ldots \beta_p$ are regression coefficients and ε is a random error. Assuming the random error is submitted to normal distribution N (0, δ^2), and having n samples $(X_{i1}, X_{i2} \ldots\ldots X_{ip}, Y_i)$, i= 1, 2……n, which are certain vectors and independent between each other, their values can be measured or controlled accurately. Through observed values for n samples $(X_{i1}, X_{i2} \ldots\ldots X_{ip}, Y_i)$ to evaluate the values for parameters of $\beta_0, \beta_1, \ldots\ldots \beta_p$, assuming the estimated values for $\beta_0, \beta_1, \ldots\ldots \beta_p$ are $\widehat{\beta_0}$, $\widehat{\beta_1} \ldots\ldots \widehat{\beta_p}$, then the equation (13)

$$\hat{Y} = \widehat{\beta_0}+ \widehat{\beta_1} x_1+ \widehat{\beta_2} x_2+\ldots\widehat{\beta_p} x_p \quad \ldots. \qquad \text{Eq(13)}$$

is called the multiple empirical regression equation of the dependent variable of Y on the independent variables of X_1, X_1,……,X_p, where $\widehat{\beta_0}$, $\widehat{\beta_1} \ldots\ldots \widehat{\beta_p}$ are empirical regression coefficients (Montgomery D. C., 2015).

5.3.2 Establishing Regression Equation and Testing

To develop the relationship between the four factors: d, n, l and d_{new}, this work used multiple linear regression analysis to fit these parameters with seeing d_{new}

as a dependent variable, and d, n and l independent variables by using MATLAB.

MATLAB is an advanced numerical analysis software. Its strong data processing ability has made it widely used in engineering practice. Based on the regression analysis in the paper, first, through programming to set two different matrixes of X and Y based on n sets of experimental data x_{ij}， y_i，（i＝1，2，…n, j=1 , 2 , 3）; and then by using the equation (14),

$$B = X^{-1}Y \tag{14}$$

to solve the coefficient of $\beta_0, \beta_1, \ldots\ldots \beta_p$; finally, through（b, bint, r, rint, stats）= regress (Y, X) to acquire each value of the parameters to test the regression model being calculated.

Hence, based on the theory of multiple linear regression analysis above, using the MATLAB regression model, the regression coefficient and its confidence interval, the value of the determination coefficient (R^2) and F for testing this regression equation are all calculated. The results are shown in Table (4):

Table 4: Results of linear regression

Parameters	Estimated value	Confidence interval
β_0	5.3996	(4.9436, 5.8556)
β_1	0.1974	(0.1442, 0.2505)
β_2	-0.0205	(-0.0277, -0.0132)
β_3	0.3504	(0.2842, 0.4165)
R^2=0.9226, F= 79.4307, p=0. 0000		

Based on the results of Table 4, the multiple linear regression equation which represents the relationship between d_{new}, d, l and n is shown in Equation (15):

$$d_{new} = 5.39+0.19d - 0.02l + 0.35n \qquad \text{Eq (15)}$$

In the process of practical analysis, whether the dependent variable of Y has a linear relationship with the independent variables of X_1, X_2,...... $X_p$or not can not be judged at the beginning. Hence, after getting the multiple linear regression equation, a significant test of F for the equation is needed.

The significant test of F thinks that when F $>$ F_a (p, n-p-1), it refuses the original assumption. That is to say under the significance level of a = 0.1, Y has a significant linear relationship with $X_1, X_1,\ldots,X_p$. The probability for making this result is over 90%, which is also to say that the regression equation is significant. In contrast, if F $\leq$ F_a (p, n-p-1), it means the regression equation is not significant.

Through calculation, F (3, 20) = 79.43> $F_{0.1}$(3, 20) = 2.38, which demonstrates that d_{new} has a linear relationship with the other three factors of d, l and n. The probability of this result occurring is over 90%.

The value of the determination coefficient of samples (R^2) represents the good or bad degree of fit of the regression equation, which is seen in Equation (16).

$$R^2 = \frac{SSR}{SST} \qquad \text{Eq (16)}$$

Where, $R^2 \epsilon(0,1)$, the larger value of R^2 represents the better fit for the regression equation with the observed value of samples. Here, R is the correlation coefficient of samples for $X_1, X_1, \ldots, X_p$, which represents a goodness of linear relation of $X_1, X_1, \ldots, X_p$ as a whole with Y. From the results of the table above, the value of R is 0.9605, which is very close to 1 and more than its critical value as well, which proves that the regression equation (15) fits the experimental data very well.

Using Equation (15), the regression relationship among these four factors is established. This equation establishes the value of d_{new} quickly and easily. Additionally, through these testing methods, the reasonability of this regression equation has also been proved.

Hence, "d" in the DNV model would be changed to "d_{new}" when the number of defects is greater than one. Then, the revised DNV model would take shape of the following Eq. (17).

$$p_f = \frac{2t\sigma_u(1-\frac{d_{new}}{t})}{(D-t)(1-\frac{\frac{d_{new}}{t}}{Q})}$$

where $$Q = \sqrt{1 + 0.31(\frac{l}{\sqrt{Dt}})^2} \qquad \text{Eq (17)}$$

$$d_{new} = 5.39+0.19d - 0.021 + 0.35n \qquad (n \neq 1)$$

$$d_{new} = d \qquad (n=1)$$

5.4 Results and Discussion

To examine the validity of the revised model, the burst pressure of the corroded pipeline was calculated using the revised model and the DNV model, respectively, and the results obtained by these two models were compared with lab test results. Five sets of experiments were conducted for determining the burst pressure of corroded pipelines. All the steel specimens were made of API 5L X80 and had different numbers of defects. All the defects were artificial and rectangular-shaped with almost the same dimensional size. The internal pressure was the only loading for pipelines in the process of tests. The details of the experiments were referenced by Benjamin et al (Benjamin, 2005). The results of the burst pressure by the two models and tests are shown in Table (5,6).

Table 5: Comparison of the value of burst pressure using DNV and Test

Specimen	$(p_f)_{test}$ (Mpa)	$(p_f)_{DNV}$ (Mpa)	Error (%)
1	22.68	23.11	1.90
2	21.14	22.78	7.76
3	20.87	19.66	-5.8
4	18.66	17.02	-8.8
5	18.77	17.45	-7.023

$$(\text{Error } (\%)=\frac{(p_f)_{DNV}-(p_f)_{test}}{(p_f)_{test}}\times 100\%) \qquad \text{Eq (18)}$$

Table 6: Comparison of the Result using the Revised model and test

Specimen	$(p_f)_{test}$ (MPa)	$(p_f)_{revised\ DNV}$ (MPa)	Error (%)
1	22.68	22.11	-2.51
2	21.14	21.18	0.19
3	20.87	21.30	2.06
4	18.66	18.59	-0.38
5	18.77	19.29	2.77

The results of the burst pressure calculated using the DNV model and the revised model were compared with those obtained by the experimental data. It is evident from the results in Tables (5) and (6) that the revised model is more accurate compared to the DNV model for assessing the integrity of corroded pipelines. The new revised model resolved the disadvantage of the overprediction of the DNV model. The value of error rate for representing the difference in the results calculated by the revised model were all below 3%. This means that the revised model is capable of being used to predict the burst pressure of pipelines, and the accuracy was similar to that of the test.

Chapter 6 Sensitivity Analysis

The analysis above tested the reliability of the revised DNV model. However, it did not evaluate how each variable in the revised model affects the burst pressure. These parameters will cause different influences on the burst pressure of corroded pipelines. Therefore, studying the effects of various factors has a great significance to establishing the prediction model accurately. Hence, to capture this, the work also conducted sensitivity analysis on each parameter (the depth of defects, the length of defects and the number of defects) for the revised DNV model using variance analysis.

The analysis of parameter sensitivity aims to obtain the effect of each parameter on the performance of the structure qualitatively or quantitatively, which would also provide a guideline for optimizing design in the future. A lot of theoretical researches about parameter sensitivity analysis are now being conducted. This paper first qualitatively analyzes on the effect of the parameters of the revised model on function value through variance analysis of orthogonal testing. Then, the method of single parameter sensitivity analysis is used to compare the different effects of each parameter (d, l, and n) of the revised model on the burst pressure (p).

6.1 Orthogonal Experiment

6.1.1 The Aim of the Orthogonal Experiment

In multi-factor and multi-level experiments, many sets of experiments will be needed if each level of each factor is matched to each other to conduct a comprehensive experiment. An orthogonal experiment is one of the most applicable methods in multi-factor tests, and it can greatly reduce the number of tests (Yan, 2012). The orthogonal experiment is conducted with some representative points, and these points have the features of uniform and orderliness, which are selected from the comprehensive experiment.

Based on the revised model obtained from the last chapter, the parameters that influence the function value include the depth of defects, the length of defects and also the number of defects. The purpose of this experiment is to study the effect of these three factors on the function values (burst pressure) through the theory of orthogonal experiment, seeing the three parameters of the revised model as experimental factors and conducting a three factors total combination experiment.

6.1.2 Design of the Experiment

The orthogonal table is the major tool in the design of the orthogonal experiment and is commonly used in practice. The general orthogonal table is represented as $L_n(m^k)$, where L represents the orthogonal table; n represents the rows of the orthogonal table, which means the number of experiments that would be required; K represents the columns of the orthogonal table, which means the number of factors that would be allowed in the experiments; and m represents the level of each factor. The orthogonal table has two important properties:

1. The emerge number of different numbers in each column is equal.

2. In any two columns, the emerge number of each order number is equal when treating two numbers of the same row as order numbers. Thus, the match of each level of each factor is balanced when arranging the experiments based on the orthogonal table.

Based on the analysis above, the work defines the depth of defects, the length of defects and the number of defects as experimental factors. The experimental levels of each factor are shown in Table 7.

$L_9(3^4)$ is chosen as the orthogonal table based on the levels of factors, arranging each factor in Table 7 into column1, 2, 3 of the orthogonal table; Using the new revised model, the burst pressure corresponding to each set of parameters in Table 7 is calculated. The plan and results for the variance analysis experiment are shown in Table 8.

Table 7: Level of factors for the orthogonal experiment

Factor \ Level	1	2	3
A: d (mm)	3.23	5.39	7.54
B: l (mm)	31.7	39.6	71.3
C: n	2	3	4

Table 8: Experimental scheme for the orthogonal experiment

Factor / Test No.	D (mm)	l (mm)	n	P （mp）
1	(1) 3.23	(1) 31.7	(1) 2	23.09
2	(1) 3.23	(2) 39.6	(2) 3	21.46
3	(1) 3.23	(3) 71.3	(3) 4	17.73
4	(2) 5.39	(1) 31.7	(2) 3	21.30
5	(2) 5.39	(2) 39.6	(3) 4	18.59
6	(2) 5.39	(3) 71.3	(1) 2	18.68
7	(3) 7.54	(1) 31.7	(3) 4	16.28
8	(3) 7.54	(2) 39.6	(1) 2	19.97
9	(3) 7.54	(3) 71.3	(2) 3	15.82

6.1.3 Variance Analysis

The work used the variance analysis method to get the results of experiments. Variance analysis is an important statistical analysis method in an orthogonal experiment. In the present study, the variance analysis method was used to process the experimental data (Montgomery D. C., 2009). In this work, three factors were identified to study how they influenced the results (burst pressure) of the revised model. The process for variance analysis is as follows, in Figure (31).

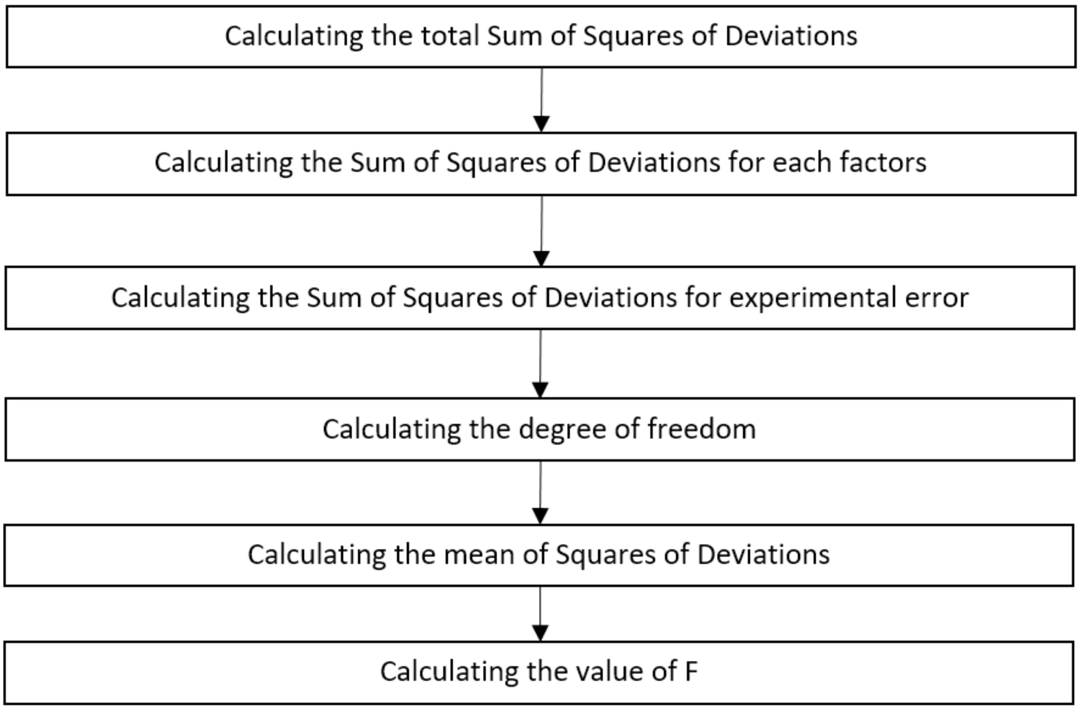


Figure 31: Flow chart of variance analysis

Based on the variance analysis steps above, the calculations are as follows:

(1). Sum of Squares of Deviations

According to the experimental results from the Variance Analysis Table, the value of sum of squares of deviations could be calculated in Eq group (19)

T_1= 23.09 + 21.46+17.73 = 62.28, $T_1^{\,2}$= 3878.79

T_2= 21.30 + 18.59 +18.68 = 58.57, $T_2^{\,2}$= 3430.44

T_3= 16.28+19.97+15.82 = 52.07, $T_3^{\,2}$= 2711.28 Eq (19)

$Q_A = \frac{1}{3}(T_1^{\,2} + T_2^{\,2} + T_3^{\,2}) = 3340.17$

$P = \frac{1}{9}(T_1 + T_2 + T_3)^2 = 3322.36$

$S_A = Q_A - P = 17.8$

Hence, the SSD for factor A (d) is 17.81.

Based on the same theory, the other values of the Sum of the Squares of Deviations could be calculated as well, which are:

$$S_B = 14.7$$

$$S_C = 14.4$$

$$S_E = 1.1$$

(2). Calculation of the degree of freedom

The total degree of freedom = The number of experiments － 1 = 8

The degree of freedom for each factor = The level number of each factor － 1 = 2

(3). Calculation of the Mean Sum of the Squares of Deviations

The SSD for each factor included several terms, and to eliminate the influences on the results caused by the value of SSD, the value of the mean sum of the squares of deviations for each factor was needed to be calculated by using the value of SSD for each factor divided the accordingly degree of freedom of the factor. For example: for factor A, the value of its mean sum of the square of deviation is in Eq (20):

$$V_a = \frac{S_a}{f_a} = \frac{17.8}{2} = 8.9 \qquad \text{Eq(20)}$$

(4). Calculation of the value of F

The value of F equals to the value of the mean sum of the square of deviation for each factor divided by the value of the mean sum of square of deviation for error; for example, the value of F for factor A is calculated as follows in Eq (21):

$$F_A = \frac{V_A}{V_E} = \frac{8.9}{0.55} = 16.2 \qquad \text{Eq(21)}$$

By using the same way to calculate the sum of squares of deviations, the degrees of freedom, the mean sum of squares of deviations and the value of F for the other two factors, the results are shown in Tables 9 and 10.

Table 9: Variance Analysis Calculation Table

Header	A	B	C		y
Test No. / Column No.	1	2	3	4	
1	1	1	1	1	23.09
2	1	2	2	2	21.46
3	1	3	3	3	17.73
4	2	1	2	3	21.30
5	2	2	3	1	18.59
6	2	3	1	2	18.68
7	3	1	3	2	16.28
8	3	2	1	3	19.97
9	3	3	2	1	15.82
T_1	62.28	60.67	61.74	57.50	T=172.92
T_2	58.57	60.02	58.58	56.42	
T_3	52.07	52.23	52.60	59.00	
S	17.8	14.7	14.4	1.1	

Table 10: Result of Variance Analysis

Factor	Sum of Squares of Deviations (S)	Degree of Freedom (f)	Mean Sum of Squares of Deviations (V)	Value of F
A (d)	17.8	2	8.9	16.2
B (l)	14.7	2	7.35	13.3
C (n)	14.4	2	7.2	13.1
e	1.1	2	0.55	
T	48	8	$F_{0.90}(2,2) = 9.0$	

6.2 Single Parameter Sensitivity Analysis

The single parameter sensitivity analysis method is mainly used to obtain the sensitivity by observing the change of a target function with the change of each single parameter（when analyzing the sensitivity of one parameter, keep the other parameters constant） (Otwinowski, 2006). Clear principal and convenient operation are the features of this method.

For the revised DNV model, the sensitivity of the target function for each parameter is defined by its value of the partial differential equation, and then the effect of the change of each factor on the target function could be compared. For example, to compare the different influence of these three factors on the results of the revised model, the work calculated the partial derivative of d, l, and n for the revised model. Through changing the value of the length of defects to compare the trend lines for the three partial differential equations, the results are shown in Figure (32):

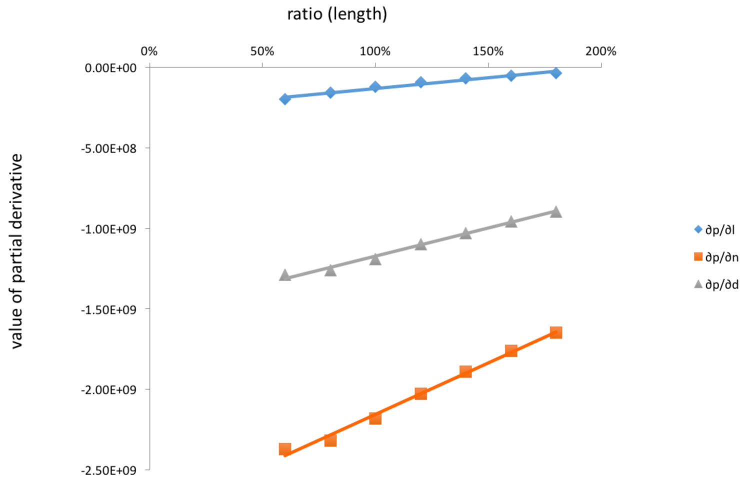


Figure 32: Plot of the partial derivative among different lengths of defects

6.3 Results and Discussion

Seen From Table (10), when 0.9 was chosen as a test level, the value of F for factors A, B and C all exceeded the critical value, which meant the depth, length and the number of defects all had a significant influence on the burst pressure of pipelines. This also explains the justification for considering "n" as a failure factor when developing the DNV model.

Figure (32) shows that when the value of the dimensions of defects changes each time, the value of function calculated by these three partial differential equations is ranked by: the value of the partial derivative of n top is the largest, d is second and l is the smallest. The results represent that the parameters of n and d both have more influence than the parameter of l for the value of function in the revised model. In terms of its physical interpretation, the number (bottom line) and the depth (middle line) both have more influence than the length of the defect on burst pressure, and this result is consistent with the FEM results as well.

Chapter 7 Summary and Conclusion

The analysis of the residual life of corroded pipelines focuses on analyzing the residual strength of pipelines. The purpose of the assessment of residual strength is to determine if the stress exceeds the ultimate tensile stress when the pipeline is under pressure, and whether it could work in normal conditions under this pressure. This assessment also confirms the maximum internal pressure (burst pressure) of the corroded pipeline.

7.1 Summary of the Paper

This work used the FEM model to calculate the burst pressure of corroded pipelines to determine the different degrees of d, l, w, and n that could potentially influence the burst pressure of corroded pipelines. From the simulation results it was observed that d and n both have a significant influence on burst pressure; l has a minor influence and w has almost no influence on pressure.

The work also compared the results of burst pressure using an FEM model and a conventional DNV model. The results showed that the DNV model overpredicts the burst pressure. The FEM results demonstrated that burst pressure can also be influenced by the number of defects; however, the conventional model did not consider it as a failure factor, which made the results of the conventional model different from the FEM results.

When revising the conventional model, the work re-defined the depth of defects as a "d_{new}" (an equivalent depth of all defects), and this d_{new} is influenced by "n" (the number of defects); therefore, "n" has been introduced into the revised model to resolve the disadvantage built into the DNV model.

The revised model was also validated by comparing the results with lab tests. Comparing the results, the analysis showed that the minimum error rate was 0.19% and the maximum error rate was 2.77%. Hence, the developed model could replace lab testing to calculate the burst pressure to some degree.

After revising the model, the work also conducted a sensitivity analysis to see how each parameter of a defect could influence burst pressure. Using variance analysis for the revised model it is observed that the depth, length and number of defects all had a significant influence on burst pressure. Using partial derivative calculations in the revised model for the number, depth and length of defects it was determined that both the number and the depth have more influence than the length of defects on burst pressure. This also further explains the importance of considering the number of defects as a failure factor when revising the DNV model.

7.2 Conclusion

The burst pressure is calculated by evaluation criteria using the DNV model and FEM. Comparing the results of the DNV model and FEM, the work found the difference in the results obtained using these two methods, and further proved the disadvantages of the DNV model. This work revised the DNV model by combining the FEM results and regression analysis. The practice of taking advantage of considering the number of defects as another safety factor and developing a revised model could be used in more general corroded situations, not only to resolve the conservatism of the DNV model, but also to use this revised model to more precisely predict the burst pressure of pipelines. These both could reduce the frequency of switching the pipelines, saving millions of dollars for the industry. The costliest components involved in constructing a pipeline are designing and material costs, particularly the use of steel, which can comprise up to half the costs for the industry (Turner, 2011). Hence, the developed model facilitates the assessment of pipeline integrity and is also useful for the industry.

7.3 Future Work

To verify the revised model, future work needs to include more extensive testing of the proposed model and a comparison of the results with lab tests; to develop the revised model, future research needs to consider more uncertain considerations in the DNV model; for example, the spacing between different defects, to better revise the model, since the burst pressure of pipelines is influenced by the spacing as well.

Bibliography

A. Limam, L.-H. L. (2012). On the collapse of dented tubes under combined bending and internal pressure. *International Journal of Mechanical Sciences*, 55.

Alves J L, R. D. (2003). Numerical Evalution of load capacity of corroded pipes[C]. *International conference on Pipeline Engineering and Construction*, (pp. 1228-1237).

Arafin, M. A. (2011). Effect of bainitic microstructure on the susceptibility of pipeline steels to hydrogen induced cracking. *Materials Science and Engineering*, 4927-4940.

Bayly, D. &. (1994). Pressure specification break pipelines. *Aspect '94*, 3-24.

Benjamin, A. C. (2005). Burst Tests on Pipeline Containing Interacting Corrosion Defects. *24th International Conference on Offshore Mechanics and Arctic Engienering*.

Bjornoy OH, M. M. (2001). Assessment of corroded pipelines: past, present and future. *Internaitonal Offshore and Polar Engineering Conference*, (pp. 93-100). Stavanger, Norway.

Bjornoy OH, S. G. (2001). Background and development of DNV-RP-F101 "Corroded Pipeline. *International Offshore and Polar Engineering Conference[C]*, (pp. 102-109). Stavanger, Norway.

Canada, S. C. (2016). *Standards Council of Canada*. Retrieved from www.scc.ca: http://www.scc.ca/en/standardsdb/standards/5033

Choi J B, G. B. (2003). Development of limit load solutions for corroded gas pipelines [J]. *International Journal of Pressure Vessels and Piping*, 121-128.

Chouchaoui, B. P. (1992). Burst Pressure Predictions of Line Pipe Containing Single Corrosion Pits using the Finite Element Method. *Proc. 11th International Conference on Offshore Mechanics and Arctic Engineering*, *5*, pp. 203-210.

Coflexip Stena Offshore, N. H. (2001, Janurary). Retrieved from www.dnvgl.com: http://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2001-01/Os-F201.pdf

Cosham, A. &. (2004). The assessment of corrosion in pipelines - guidance in the pipeline defect assessment manual (PDAM). *Pipeline Pigging and Integrity Management Conference* (pp. 1-31). Amsterdam: Penspen Integrity.

Dayton, P. K. (1995). Aquatic Conservation Marine and Freswater Ecosystems. *Environmental effects of marine fishing*, 205-232. doi:10.1002/aqc.3270050305

Felippa, C. A. (2001). Partitioned analysis of coupled machanical systems. *Computer Methods in Applied Mechanics and Engineering*, 3247-3270.

Friswell, M. I. (2007). Damage identification using inverse methods. *Philosophical Transactions of the Royal Society A*. doi:10.1098/rsta,2006,1930

Fu, B. (Nov, 1996). Advance methods for integrity assessment on corroded pipelines. *Advanced methods for integrity assessment on corroded pipelines* (pp. 19-22). Houston, USA: ASME.

Graf, M. K. (2003). High-strength large-diameter pipe for long-distance high pressure gas pipelines. *The Thirteenth International Offshore and Polar Engineering Conference*, (pp. 1-8). Honolulu.

Hopkins, A. P. (2007). Best Practice for the assessment of defects in Pipelines-Corrosion[J]. *Engineering Failure Analysis*, 1245-1265.

Junior, P. A. (2015). A Comprehensive Introduction of the Finite Element Method for Undergraduate Courses. *International journal of engineering research and applications*, 94.

Kennedy, J. (2993). *Oil and gas pipeline fundamentals*. Tulsa.

Kim, Y. W. (2012). Dewetting of silica surfaces upon reactions with supercritical CO2 and brine: pore-scale studies in Micromodels. *American Chemical Society*, 4228-4235.

Liolios, A. A. (2011). A numerical approach for the seismic analysis of reinforced concrete structures environmentally damaged and cable-strengthened. *Third*

Serbian (28th) Congress on Theoretical and Applied Mechanics, (pp. C-29-c-161). Serbian.

Moan, T. (2009). Development of accidental collapse limit state criteria for offshore structures. *Structure Safety*, 124-135.

Montgomery, D. C. (2009). *Design and Analysis of experiments*. New Jersey: Hoboken: John Wiley & Sons Inc.

Montgomery, D. C. (2015). *Introduction to linear regression analysis*. New Jersey: Hoboken: John Wiley & Sons, Inc. .

Netto TA, F. U. (2005). The effect of corrosion defects on the burst pressure of pipelines [J]. *Journal of Constructional Steel Research*, 1185-1204.

Orazem, M. E. (2014). Underground pipeline corrosion - detection, analysis and prevention.

Osage, D. A. (2004). API:579 A Comprehensive Fitness-for-Service Standard. *ASME 2003 Pressure Vessels and Piping Conference*, (pp. 71-84). Cleneland. doi:10.1115/PVP2003-2028

Otwinowski, Z. &. (2006). International tables for crystallography . 226-235.

Popoola, L. T. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*. doi:10.1186/2228-5547-4-35

RD, S. (2007). Rupture tests of Pipeline segments containing long real corrosion defects [J]. *Experimental Technique*, 46-51.

Rita C. C. Silva, J. N. (2008). Automatic finite element solid modeling, burst and error analyses of corroded pipelines. *International Journal of Mechanics*, 77-86.

Song, G. L. (1999). Corrosion mechanisms of magnesium alloys. . In *Advance Engineering Materials* (pp. 11-33).

T.A.Netto, U. S. (2005). The effect of corrosion defects on the burst of pipelines. *Journal of construction steel research*, 1185-1204.

Taylor, J. R. (1994). *Risk analysis for process plant, pipeline and transport*. Oxon: Routledge; 1st ed edition (January 11, 1994).

Turner, W. L. (2011). *Cost-benefit Analysis of a Natural Gas Lateral Pipeline to the Annapolis Valley*. Wolfville: Acadia University.

Uys, S. J. (2011). A variable selection proposal for multiple linear regression analysis. *Journal of Statistical Computation and Simulation*, 81.

Veritas, D. N. (2004). *Corroded Pipelines, Recommended Practice DNV-RP-F101*.

Vertas, D. N. (2010). *Rules and standards*. Retrieved from DHV.GL: Burst Pressure Predictions of Line Pipe Containing Single Corrosion Pits using the Finite Element Method

Wang, J. E. (2010). An efficient field assessment of offshore pipeline damage. *Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering* (pp. 943-950). Shanghai: The Americian Society of Mechanical Engineers. doi:10.1115/OMAE2010-20919

Yan, Y. (2012). Fuzzy load forecasting of electric power system. *Journal of Computers*, 1903-1910. doi:10.4304/JCP.7.8.

Zhu X K, L. B. (2003). Strength criteria and analytic predictions of fialure pressure. *Proceedings of the Thirteenth International Offshore and Polar Engineering Conference*, (pp. 8-15). Honolulu, USA.