RELIABILITY ANALYSIS OF PITTING-CORRODED OFFSHORE PIPELINE UNDER UPHEAVAL BUCKLING CONDITION

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By

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Dissertation submitted in partial fulfillment of the requirements of the Bachelor of Civil Engineering (Hons)

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CERTIFICATION OF APPROVAL

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Approved by,

(DR. Zahiraniza Mustaffa)

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ABSTRACT

This research presents a development of a fatigue analysis for different corroded pipeline to estimate the pipeline reliability when subjected to upheaval buckling caused by thermal expansion. This assessment will be used to initialize the stress-strain diagram so that the result will be adaptable to predict the reliability and probability of failure for oil and gas pipelines under buckling. the input of this assessment was the pitting-corroded pipelines and the loads it is subjected to, the inputs are validated through a methodology that includes testing the pipeline for buckling under different rates of pitting-corrosion, the output was the reliability of the pipeline expressed via graphical presentation using MATLAB, the generated graphs indicates that a corrosion ratio of >2.34% is considered crucial for pipes subjected to upheaval buckling. Finite Element Modeling-ANSYS was used in this thesis to give the broadest possible comparison between the obtained results and the theoretical behavior of the pipe, it was used to follow up the stress-strain shape of sub-sea corroded pipelines under upheaval buckling during its propagation.

1 INTRODUCTION

Nowadays, offshore pipelines have a significant role in development of oil and gas industry in different parts of the world. This crucial industry is laid on seabed by various methods either embedded in a trench (buried method) or laid on uneven seabed (unburied method). Construction of unburied pipeline is the most common method for its rapid and economic performance.

In this method, however, the pipelines can be subjected to various lengths of buckling throughout the route during its life time, which may threaten the pipelines safety. When pipelines are installed, great care is taken to ensure they are as safe as possible to other seabed users.

1.1 Offshore Pipeline and Upheaval Buckling

Pipelines are used to transport oil and gas from wells to the shore and manufactured in variety of sizes from 4 inches (100 mm) up to 48 inches (1200 mm) in diameter. They are mainly constructed using steel.

Submarine pipelines are used to transport oil and gas between offshore facilities and also to facilities based on land. The pipelines are often laid in trenches, that are subsequently backfilled, so that they are protected from damage. The oil and gas that is pumped through the pipe is usually much hotter than the ambient water temperature and will cause the pipe to expand.

When a pipeline after its installation is operated at higher than ambient temperatures and pressures, it will try to expand. If the line is not free to expand, but restrained by for example soil friction, the pipe will be subjected to an axial compressive load. When the line is trenched and/or covered the lateral soil restraint exceeds the vertical uplift restraint created by the pipe's submerged weight, its bending stiffness and, when present, the soil cover. In that case the pipe will tend to move in the vertical plane - or along the trench slope when the pipe is laying in a trench without cover - and (partly) release the expansion force until a stable equilibrium position has been reached as illustrated in Figure 1.

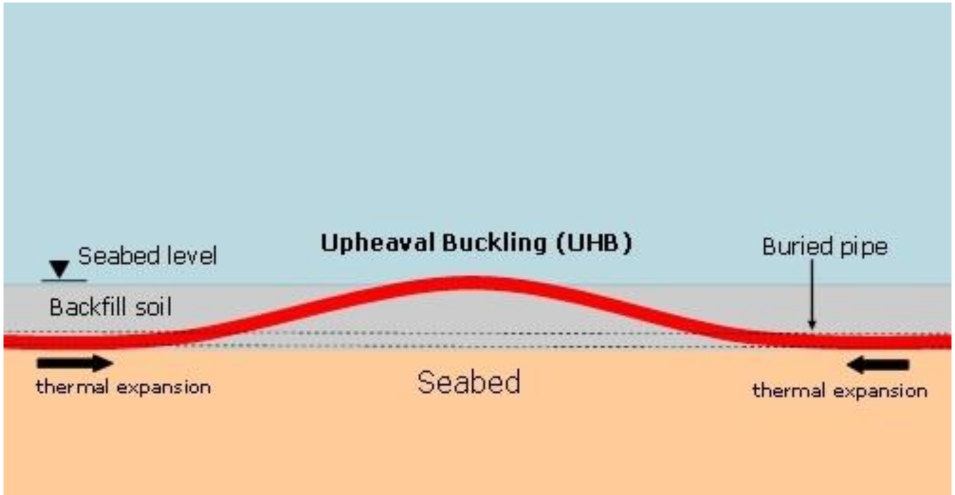


Figure 1 Upheaval bucking

For large compressive (buckling) loads pipeline response might however be unacceptable in terms of vertical displacements (the pipe protruding through the cover or moving out of the trench), excessive yielding of the pipe material, or both. This phenomenon is called upheaval or thermal buckling (offshore), also known as overbend instability (onshore), and constitutes a failure mode that has to be taken into account for the design of trenched and/or covered pipelines subjected to high temperatures and pressures(J. Guijt, A.S Norske Shell). Upheaval buckling is not an entirely new phenomenon for pipelines and has since the past been a concern.

1.2 Types of Upheaval Buckling

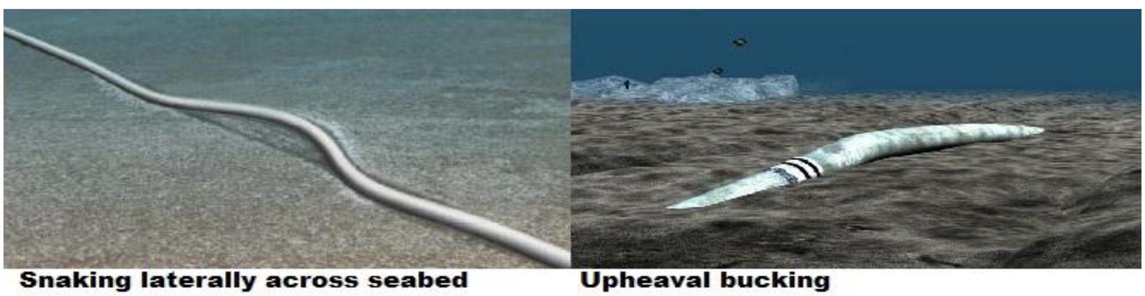


Figure 2 types of buckling in seabedded pipelines

In the cases where pipelines are neither trenched or buried, they experience a different mode of buckling when subjected to the same conditions of thermal expansion that causes upward lifting of the buried pipelines, the buckling in such cases will cause the pipeline to snake laterally across the seabed as shown in Figure 2. This type of buckling will cause less severity to the pipeline when compared to upheaval type of buckling because it is not common that the lateral expansion will become localized causing a serious buckle in the pipe.

When the pipeline is buried, The surrounding soil provides the only resistance for the buckling of the pipe, As the backfill material over the pipe is weaker than the in-situ material beneath the pipe it will tend to move upwards to the seabed surface and so be prone to damage. This is a well known area of concern for offshore pipeline designers and is usually called 'upheaval buckling'.

1.3 Type of Defects Occurring on Offshore Pipelines

The pipeline can be subjected to different defects that affects it's reliability during it's life span. The defects vary from manufacturing defects to environmental defects, but this research will be focusing on one defect in particular which is pitting-corrosion as it affects the pipeline on the long run .

1.4 Objectives of Assessment

1. To conduct experimental studies for pipelines exposed to corrosion conditions.
2. To produce comparable Stress-Strain curves.
3. To compare the fatigue assessment of the pipeline based on the experimental results.

1.5 Problem Statement

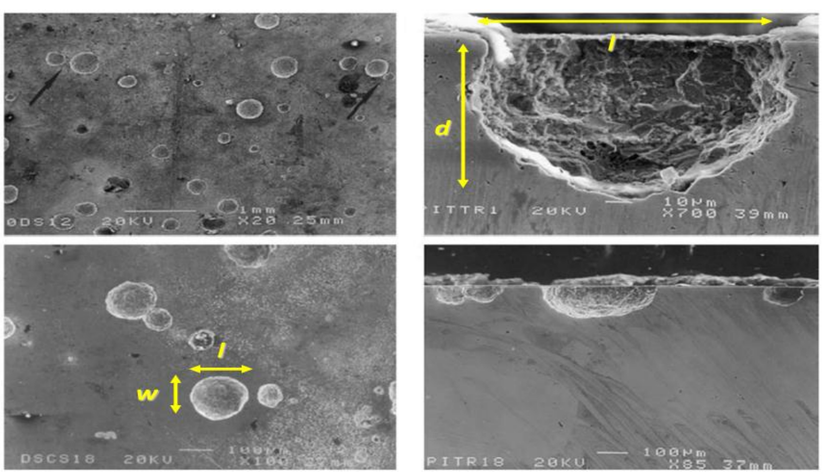
Subsea pipelines operating at high temperature can buckle vertically and laterally. The curvature and high strains in buckled pipelines can cause ovalisation, wrinkling and fracture. Additionally, low cycle fatigue and ratchetting may result from cyclic operation. Various factors affect the levels of strain generated by thermal buckling. One factor is of particular concern, which is pitting corrosion.

1.6 Corrosion Role Under Buckling

Corrosion is an electrochemical process. It is a time dependent mechanism and depends on the local environment within or adjacent to the pipeline. Corrosion usual appears as either general corrosion or localized (pitting) corrosion. It can occur on the internal or external surfaces of the pipe, in the base material, the seam weld, the girth weld, and/or the associated heat affected zone (HAZ).

Large scale uniform corrosion will reduce the cross sectional area of the pipe resulting in a drop in the fully constrained force (buckle driving force) of the flowline. This reduction will limit the lateral growth of a buckle feature. Localised or pitting corrosion however, will not significantly alter the axial force.

A considerable amount of time and effort has been devoted to the study of the static strength of corrosion defects in pipelines. Separately, great amount of researches has been made on pipelines subjected to buckling, that is why this research is focused on measuring the fatigue caused by upheaval buckling to an offshore pipeline which is already defected by pitting corrosion due to the lack of researches made about this type of pipeline failure.



Adapted from Rivas et.al. (2008)

Figure 3 corrosion effect on metal

1.7 Scope of Study

This research will focus on analyzing the effect of axial forces on a pipeline with different corrosion ratios via experiments in order to investigate the effect of pitting corrosion on stress, strains, and stiffness generated at the apex of a lateral buckle caused by thermal expansion. Throughout this project, a certain scope will be followed:

1. Prepare a suitable testing method for pipelines with different corrosion ratios that has the load and deformation as outcomes.
2. Developing the (stress-strain) curves for all levels of corrosion.
3. Develop the max. stress/max. strain vs. corrosion ratio to analyze the relationship and its effect under buckling condition.
4. Extract the relationship between corrosion ratio and stiffness under upheaval axial buckling.
5. To accurately model the behavior of the pipeline on ANSYS and analyze it

2 LITERATURE REVIEW

2.1 Fatigue Occurrence

The start-up and shutdown of a thermally buckled pipeline can lead to large variations in bending stress. In addition to that, pitting corrosion can increase the bending strains at the apex of a buckle. The large variations in bending stresses may result in low fatigue lives.

Piping fatigue will occur in pipe systems when the combination of static and dynamic stresses in the piping components exceed allowable values. Dynamic stress can result from vibration transmitted by connected machinery, forces generated inside the pipe from water hammer or pressure pulsations, or by fluid induced or other external loads. Static stress in the pipe is most commonly caused by a combination of pressure and thermal growth,which is the case in upheaval buckling therefore, the type of stress applied on the models is static/thermal stress as illustrated in Figure 4. Thermal stress can be very large particularly if supports are not installed or maintained properly.

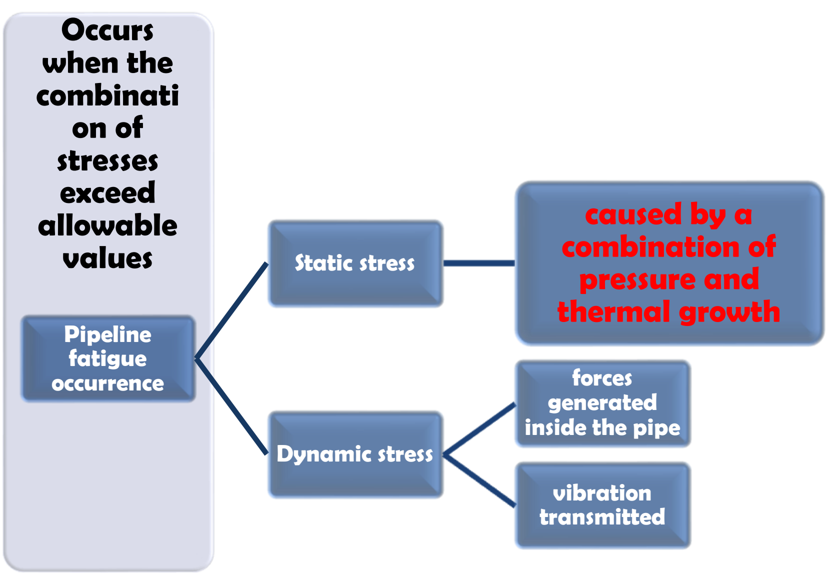


Figure 4 Pipeline fatigue occurrence

2.2 Pipe Fatigue Analysis

The forces acting on the buckle while the pipeline is operating are shown in Figure 5. A state of equilibrium exists between, the longitudinal force (which is driving the deflection of the pipeline) and the pipeline bending stiffness, axial friction and lateral frictional restraint (which are preventing further deflection of the buckle). In this state the majority of the pipeline will be in compression; the buckle apex however, will be in tension because of the applied bending moment.

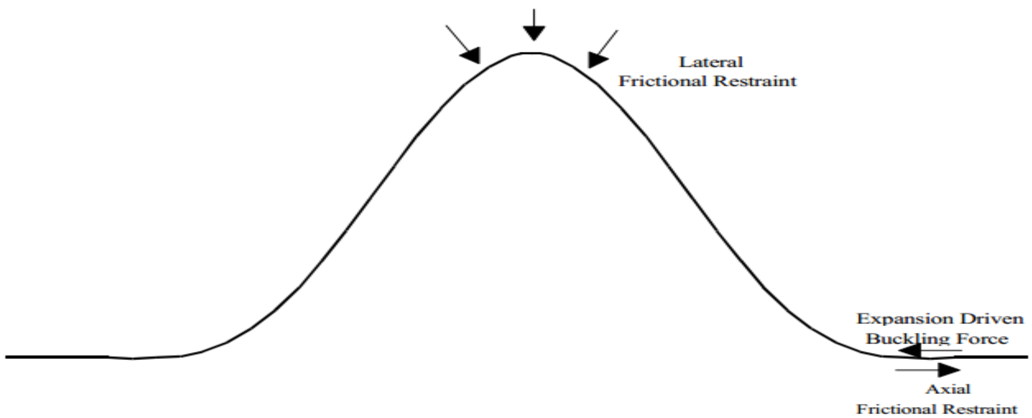


Figure 5 forces acting during upheaval buckling

2.3 Failure Modes of Upheaval Buckling

Global buckling of pipelines may be treated as the buckling of a bar (pipe) in compression. The global buckling may occur either downwards (free span), horizontally (lateral buckling on sea bed) or vertically (as upheaval buckling of buried pipelines or on a crest of exposed pipelines followed by a lateral turn-down), local buckling is a gross deformation of the pipe cross section.

Global buckling as discussed earlier is a response to compressive force generated by high temperature and high pressure (HP/HT), which will generally reduce the axial capacity of the pipeline. Pipelines exposed to high temperature and high pressure or pipeline with a low buckling capacity will be governed by global buckling. Three global buckling scenarios resulted from HT/HP are introduced:

1. Exposed pipelines on even seabed. Global buckling occurs in the horizontal plane, post buckling configuration may be allowed.
2. Exposed pipelines in uneven seabed. Global buckling occurs first in the vertical plane (cause feed-in and uplift) and subsequently in the horizontal plane, or combined scenarios with scenario 1, post buckling configuration may be allowed.
3. Buried/covered pipelines, global buckling in the vertical plane, so called upheaval buckling. Global buckling is a load response, not a failure mode. However, global buckling will imply some failure modes such as:

1. **Local buckling**, for pipeline subjected to combined pressure. Longitudinal force and bending, local buckling may occur. The failure mode may be yielding of the cross section or buckling on the compressive side of the pipe.
2. **Fracture,** which is caused by tensile strain, generally includes brittle fracture and plastic collapse.
3. **Fatigue,** pipeline components such as riser, unsupported free spans, welding should be assessed for fatigue. Potential cyclic loading fatigue damages, which may include vortexinduced-vibrations (VIV), wave induced hydrodynamic loads, cyclic pressure and thermal expansion loads.
4. **Ratcheting,** ratcheting generally describes the accumulated plastic deformations under cyclic loads in pipelines that exposed to high temperature and high pressure.
5. **Bursting,** it is governed by tensile hoop stress, which may occur in the tensile part of pipeline.

2.4 Stiffness Assessment Based on Stress-Strain Curves

Based on the outcomes of the experiment, The load and deformation can be used for fatigue assessment and calculation as defined by the following formulas:

$$volume\ V = \pi r^2 \mathrm{h} \tag{1}$$

$$stress = \frac{F}{A} \tag{2}$$

$$strain = \frac{\zeta}{L} \tag{3}$$

Where ***V*** is the volume of the removed steel that resembles the corrosion effect, ***h*** is the depth of the bores made on the pipeline ***F*** is the load applied by the Universal Testing Machine (UTM), ***A*** is a parameter defining the area of the pipeline, ζ is the deformation made by the UTM machine and ***L*** is the length of the pipeline. which are dependant on the material and structural detail.

2.5 UTM testing

The testing of the pipelines under the Universal Testing Machine machine was mainly purposed to apply vertical load on the two pipes (with pitting and without pitting) as in figure 6 in order to generate a relationship between the differences and the effect of pitting corrosion on the pipeline.

Figure 6 UTM testing of the pipeline (left no pitting, right with pitting corrosion)

Pipelines with different corrosion ratios were all tested under the same rate of 0.1 N/s and a limit of 950 KN with the expected outcomes to be the blucking load (KN) and deflection (mm), but the change in behavior of the same material under the same load will indicate the significance of corrosion effect.

These loads applied represent typical upheaval operating conditions:

- The pressure load represents the difference between the external pressure on the pipeline and the internal pressure of the fluid.
- The temperature load is applied after the pressure to mimic the steady heating of a pipe on startup.
- The temperature load causes the expansion of the model.

This expansion provides the buckle driving load For modeling the axial compressive load.

3 METHODOLOGY

3.1 Specifications of Testing Specimen

The pipeline that was used in this research was a 10 inch carbon steel pipe that was used by Petronas with a design life of 30 years. The pipe specifications are tabulated in Table 1 and Table 2 below:

Table 1 Specifications of Testing Specimen

	Description	Data		
1	Length	244 mm		
2	Nominal diameter	10.33 inch (262.5mm)		
3	D_{out}	273.5mm		
	D_{in}	251.5mm		
	Nominal wall thickness	11.00mm		
4	Corrosion allowance	0mm		
5	Material Type	Carbon Steel		
6	Material Grade	API 5L X65		
7	Pipe manufacturing Process	Seamless		
8	Design Pressure	250 bar		
9	Hydrotest Pressure	448 bar		
10	Product	Dense Phase Gas		
11	Installation Year	2008		
12	Design Life	30 Years		
13	Design Temperature	48 °C		
14	Operating Pressure (Floating storage/Onshore Terminal)	250 / 183.2 bar		
15	Operating Temperature (Floating Storage/ Onshore Terminal)	48 / 30 °C		
16	Hydrotest Temperature	24 °C		
17	Flowrate	70 mmscfd		
18	Product Density (max/min)	330 /219 kg/ m^3		
20		KP 0 to KP 40		
	Anti-Corrosion Coating	2.25mm 3LPE		
21	Field Joint Coating	2 layer HSS compatible with pipeline coating (2.5mm thick)	KP 40 to 136	KP 136 to 138
22	Infill Coating	-	0.685mm FBE	0.685mm FBE

Table 2 Material Data

	Description Data	Value
	Mechanical Data	
1	SMYS	448 MPa
2	SMTS	530 MPa
3	Young Modulus	207000 Mpa
4	Poisson's Ratio	0.3
5	Coefficient of Thermal Expansion	11.7 x 10^{-6}
6	Structural Damping Coefficient	0.126
	Thermal Conductivities	
7	Steel	45.35 W/mK
8	Concrete	2.1 W/mK
9	FBE	0.3 W/mK
10	3LPE	0.4 W/mK
11	Seabed Soil	1.7 W/mK
	Densities	
12	Steel	7850 kg/ m^3
13	Concrete (low density)	2500 kg/ m^3
14	FBE	1400 kg/ m^3
15	3LPE	947 kg/ m^3
16	Field joint coating (PUF infill system)	1000 kg/ m^3

Figure 7 Tested Cutted Pipelines

3.2 Experimental Tasks

This research outcomes were achieved through one practical experiment which will include two main tasks,

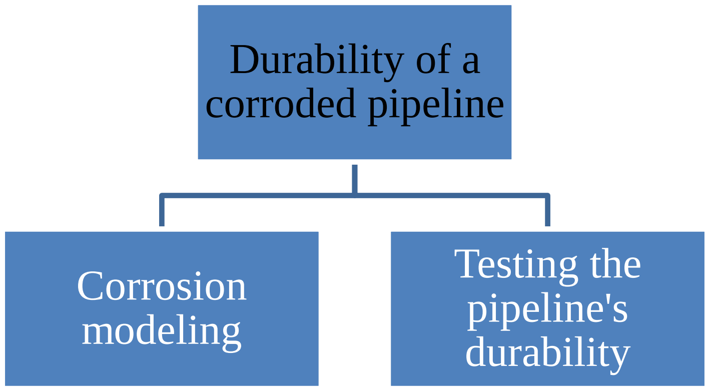


Figure 8 Experiment main tasks

Assembling a corroded pipeline in the lab can be made through adding chemicals, but the corrosion ratio generated will not be easily assumed, therefore in this research the modeling of the corrosion was made through grooving the pipeline as specified earlier, doing so also opened another comparison study between different volumes of corrosion and its fatigue analysis.

The grooving of pipes is made inside UTP steel workshop in block 20, the grooving is made using the machine illustrated in Figure 9,10.

.

Figure 9 Grooving machine

Figure 10 Roller Meter

The grooving machine which will be used allows the possibility of controlling the thickness that needs to be carved out, this is done by setting the roller meter to the desired thickness which is 8 mm in this case.

The other task is testing the pipelines under the UTM machine in order to generate all the numbers and comparisons discussed in the following section, the capacity of the UTP machine is 1000 KN, slow cyclic load of 0.1 N/s is appointed on the pipeline to avoid the hazard of a falling pipeline and the shifting of the applied load’s position due to the movement of the pipeline.

3.3 Corrosion Modeling

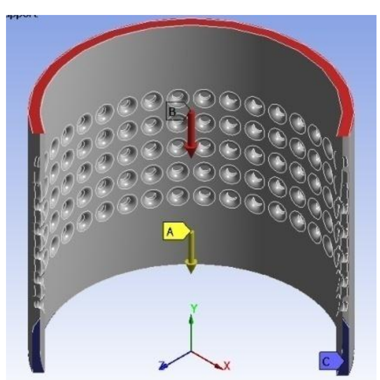


Figure 11 Carving pipelines wall

The nominal wall thickness selected for the grooving was 11 mm. This is the value used over the whole pipe length for model validation. To investigate the effect of localised corrosion three ratios of corrosion in the pipeline were modeled: (as in figure 11)

· 8mm deep, 11mm diameter, 35 holes.

· 8mm deep, 11mm diameter, 70 holes.

· 8mm deep, 11mm diameter, 105 holes.

In all cases the corrosion was modeled as fully circumferential and the axial length was 244mm. The corrosion was modeled by applying a reduced wall thickness definition to an element of 244 mm length at the apex of the buckle.

In real life situations, the corrosion affects the pipeline in a random orientation and spacing, while in lab modeling of corrosion circumferential corrosion is easily modeled and can still be assumed to model trough-type corrosion in the base of the pipeline. In the analysis of such a defect an attempt is made to characterize the corroded area by its projected length and area. The difficulty is describing a three-dimensional corroded area by a few parameters introduces large scatter in comparisons of predicted to actual failure stress.

Based on the above, the grooving of the pipeline to resemble the corrosion was made on the outer surface of the pipeline on the shape of (pitting) after identifying the diameter and depth of the pitting holes as identified in figure 12, figure 13 shows the process of grooving of the pipe to reduce the wall thickness in the form of pitting and in turn affect the mechanical properties of the pipeline under stress.

Figure 12 pitting locations

Figure 13 grooving process

The shape of the pittings obtained is similar to the real life situation in terms of shape as compared to (Figure 3).

3.4 Experimental Procedures

In order to achieve the objective of this paper, a certain set of experiments with designated outcomes that serves the assessment, the experimental parts included practical experiment and software experiments using (MATLAB) and (ANSYS) software.

The practical experiment included the following procedures:

1. Cut a pipeline into two 25 cm length pipes.
2. Place one pipeline on a UTM machine as illustrated in Figure 6 and test it under 950 KN stress and 250 mm deformation.
3. Carve the other pipeline in shapes of small pits that are 11 mm in diameter and 8 mm in depth as to reduce the wall thicknesses to resemble a corroded pipeline.
4. Place the corroded pipe on a UTM machine as illustrated in Figure 6,14 and test it under 950 KN stress and 250mm deformation.
5. Carve the pipe again adding more pittings in order to remove more mass from the pipeline.
6. Place the pipe on the Universal Testing Machine as in Figure 6,14 and operate to apply vertical load on the pipe again.
7. Repeat steps 5 and 6 in order to produce a more reliable and comparable result.

Figure 14 Universal Testing Machine

The practical experiment included using the MATHLAB in order to compute the corrosion ratio and develop a graph showing the relationship between the behavior of the Stress and Strain vs. the corrosion ratio.

(ANSYS) software was used to develop a case study of a pipeline subjected to buckling in order to be able to study the effect of the upheaval buckling on the defected pipeline in terms of FEM comparison.

3.5 Graphical Presentation using (MATLAB)

MATLAB software was used to generate the graph illustrating the comparison relationship between the pitting corroded pipeline and the non corroded pipeline in terms of buckling load vs. deflection.

In order to generate the load vs. deflection from the outcome data of the UTM, certain values were calculated for all the pipe's corrosion ratios, the Area wich perpendicular to the force direction was calculated using equation (4) for a hollow tube.

$$\text{Area of the pipeline} = A = \pi \Delta r^2 \tag{4}$$

$$= \pi(R^2 - r^2) = \pi(\frac{273.5^2}{2} - \frac{251.5^2}{2}) = 3.801\text{x}10^{-4}\text{m}^2$$

Dividing the load generated by the area of the pipeline ($\frac{F}{A}$) will give the Stress(σ) applied on the pipeline as in equation (5)

$$\sigma = \frac{F}{A} \tag{5}$$

same as dividing the deflection by the length of the pipeline gives the Strain (ε).

$$\varepsilon = \frac{\zeta}{L} \tag{6}$$

from this another graph showing the (stress vs. strain) was generated for both pipe cases.

Volume and *mass of corrosion* are calculated by getting the volume of the pitting holes through the pipe and their mass.

$$Vcorrosion = \pi \left(\frac{dia\ of\ pittings}{2}\right)^2 \text{depth of pittings} \tag{7}$$

$$= \pi \left(\frac{0.011}{2}\right)^2 0.0075 = 7.127X10^{-7}\ mm^3$$

$$Mass\ of\ corrosion\ m = density\ of\ steel\ x\ Vcorrosion\ x\ number\ of\ pittings \tag{8}$$

$$= 0.235$$

The above parameter was used to generate a relationship between (the stress ,strain vs. corrosion ratio) via a graph using MATLAB.

3.6 Validation Through Numerical Modelling (ANSYS)

Large deformations may take place during pipeline buckling, Additionally high strains can be induced by the bending of a pipeline with a corroded section. To accurately model this behavior, a non-linear analysis is required. ANSYS software have been used to model this assessment, in which certain components were generated in order to achieve the analysis as discussed with details in the following chapter, the first component is the model of the pipe geometry, The second is a material model, and the third is the simulation of the stresses applied on the buckling zone by the expanding pipeline.

ANSYS software was mainly used in this thesis in order to generate a similar model subjected to the same conditions and compare its performance with the practically tested specimen. There were two main analysis tasks, The first is to validate the model and the second is to investigate the effects of pitting corrosion.

4 RESULTS AND DISCUSSION

4.1 Stress vs. strain

Figure 15 below give the relationship between Stress and Strain for the four samples with four different corrosion ratios, the straight lines represent the durability obtained via practical experiments, the straight dotted lines represent the durability of the theoretical models obtained from ANSYS.

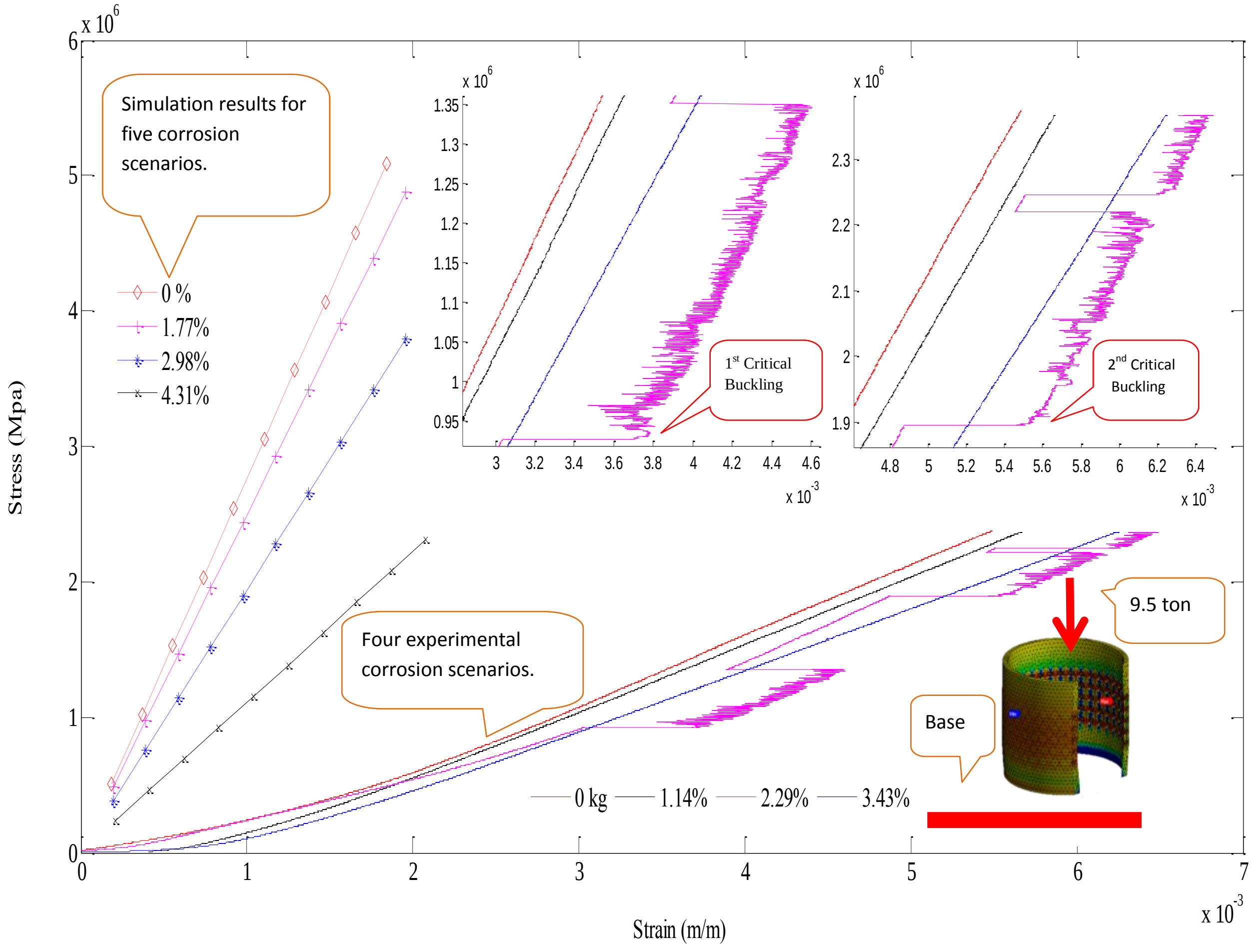


Figure 15 Stress vs. Strain

It can be shown that both practical and theoretical modeling tests were set under the linear/elastic section of the graph which illustrates the pipe before buckling in which the pipe can get back to the initial position, this was because the sensitivity of buckling load to detail changes in end conditions is not as significant as it is in linear/condition.

Tests of axially compressed pipes should be subjected to a different Scrutiny than other types of tests, and a study of the behavior can constitute buckling investigation, Therefore, The pipes were tested in axial compression, due to the pipe's specifications it had small margins against failure by local buckling, and their failure may have been induced beyond the limit of the UTM machine.

Both practical and theoretical scenarios expressed the same relationship of which the rigidity of the pipe reduces with the increase of corrosion ratio, the performance of the pipe becomes more linear with the increase of pitting holes as it is subjected to axial buckling load. This relationship occurs in real life cases of pitting corroded pipes subjected to upheaval buckling.

4.2 Critical Buckling

Through what this thesis aims for, the critical buckling load within elastic zone which indicates unpredictable deformations, possibly leading to complete loss of the pipe's buckling resistance capacity was obtained at a corrosion ratio of 2.29%.

Evaluating the performance of all the experimental specimens in Figure 15, it was noticed that the line representing the specimen with 2.29% corrosion ratio have experienced buckling characteristic of sudden failure shown in Figure 16,17. The Figures shows two sudden unpredictable jerks and the pipe deforms into a buckled configuration before returning to the original orientation.

The continuation of subjecting axial load to a pipe with 2.29% corrosion ratio will lead to a continuous buckling configuration jerks before the pipe suddenly fails under a load that is considered within its design elastic zone, which is the case exactly in pipes subjected to upheaval buckling in real life situation therefore the critical corrosion ratio for 10’’ carbon steel pipes is considered to be ≥ 2.29% according to the result of this thesis.

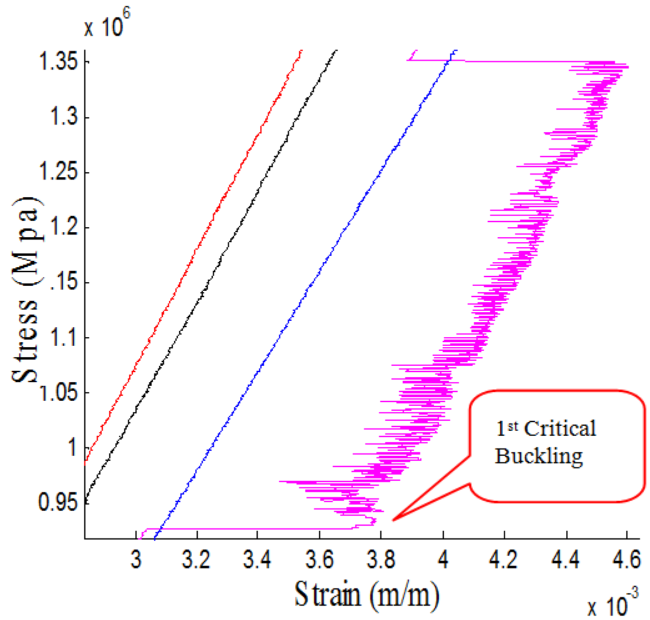


Figure 16 First Critical Buckling

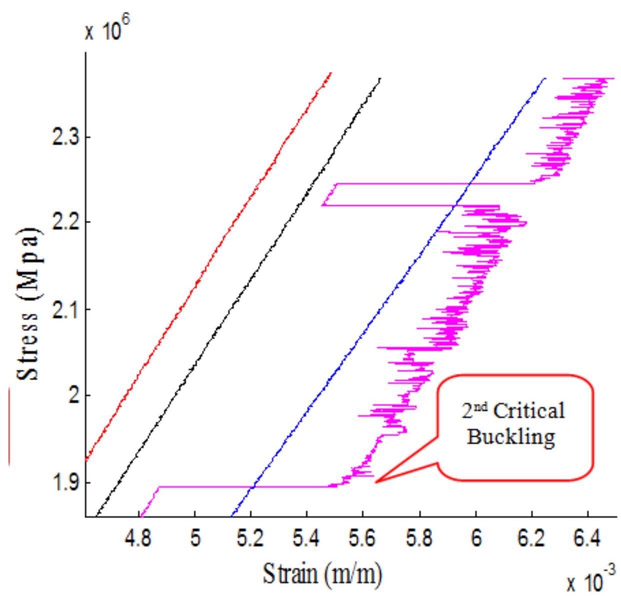


Figure 17 Second Critical Buckling

4.3 Failure Due To Excessive Deformation

Excessive Deformation was experienced in the specimen with a corrosion ratio of 3.43% (≥ 2.29%), in this specimen, it can be said that the pipe has already lost its structural integrity which is the loss of the load-carrying capacity of a section within the pipe or of the whole pipe itself. In specimens with less corrosion ratio, 950 kN load did not cause immediate or excessive deformation as the difference in linearity is clear in Figure 18, therefore it is obtained that 10'' carbon steel pipelines with corrosion ratio (≥ 3.43%) .

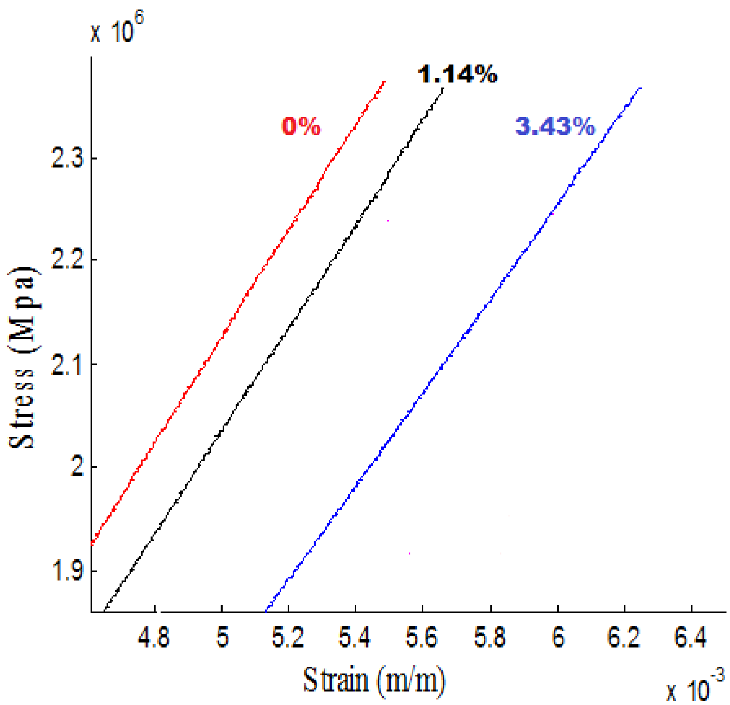


Figure 18 Difference in linearity between specimens

4.3.1 FEM- ANSYS Comparison

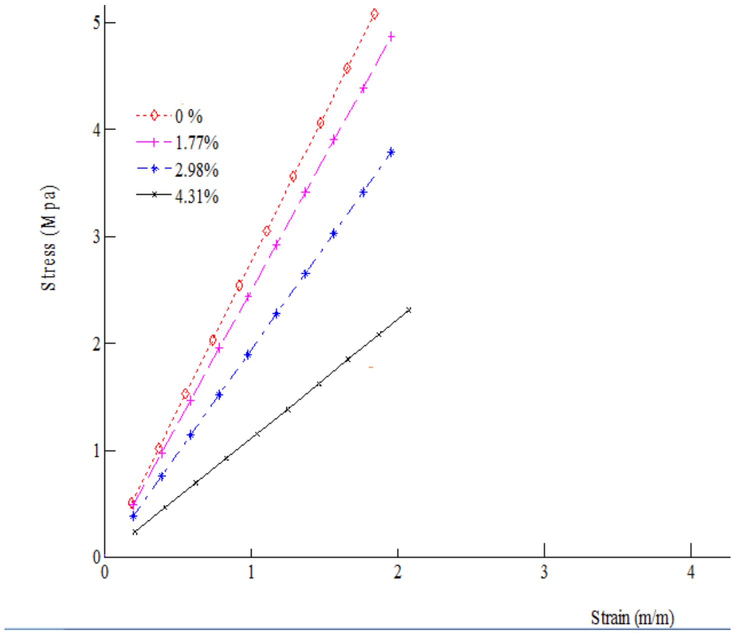


Figure 19 Stress-Strain Generated From FEM-ANSYS

The Finate Element Modeling from ANSYS indicated the same result of vast difference in linearity between specimens with corrosion ratio greater than 3% and specimens with less corrosion ratio which supports the declarations of the experimental graphs obtained.

4.4 Excessive Corrosion Effect on Pipelines Under Upheaval Buckling

A corrosion ratio of 3.43% is considered a cause of failure for the specified specimen due to the effect of this corrosion ratio on the pipe, by having a closer observation of the Stress Strain Curve generated by the pipeline with 3.43% corrosion ratio in Figure 20, it is observed that the pipe is already experiencing buckling signs of unpredictable deformations which will lead to complete loss of the pipe's buckling resistance capacity illustrated in the graph as sudden jerks in the orientation.

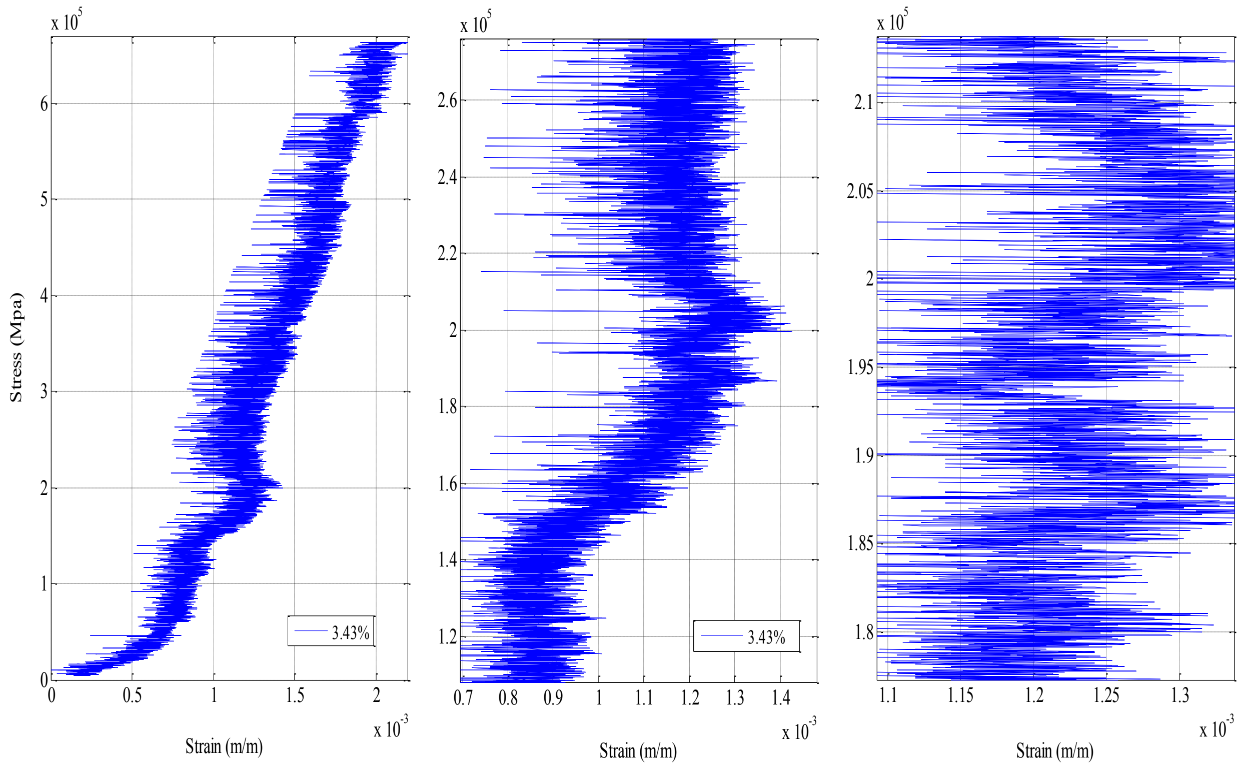


Figure 20 Stress vs. Strain (3.43% corrosion ratio)

4.4.1 FEM- ANSYS Comparison

The FEM predicted the failure of the specimen due to an excessive corrosion ratio of 4.31% (≥ 3.43%). The load multiplier of the model shown in Figure 21 predicts that buckling will occur when only 25.09% of design loads is apply on the corroded pipe. The pipe structure with corrosion rate ≥ 3.43% is not safe and unstable.

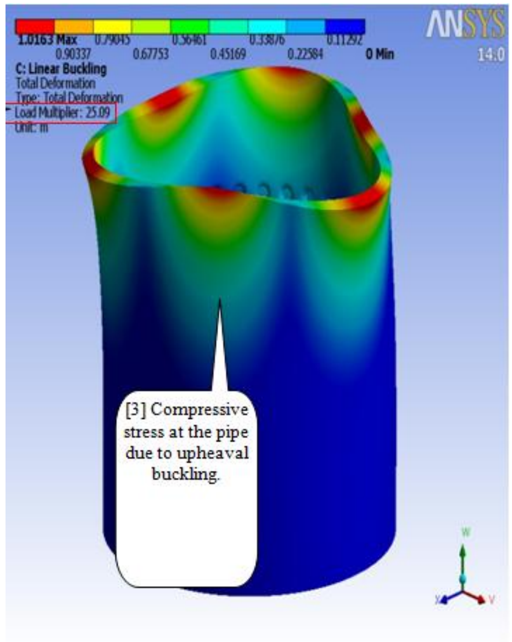


Figure 21 Effect of 4.31% Corrosion Ratio

4.5 Corrosion Effect on the pipe parameters

The table below shows the relationship between the change in pipe parameters with the increase of corrosion ratio, separately explained in the following sections each of the parameters is assessed.

Table 3 Corrosion Effect on Pipe Parameters

No.	Mass %[a]	Volume %[b]	Biaxiality	Damage ×E+5	Life cycles	Safety Factor	Strain m/m×E-3	Stress Pa× E+6	Deform. m × E-4
1	5.99%	5.969115	0.85883	2.16	4627.7	0.25641	-2.03	2.32	1.81
2	4.31%	4.311028	0.79235	1.86	5381.9	0.26925	-1.96	3.79	1.91
3	2.98%	2.984558	0.791	1.81	5516.1	0.2714	-1.94	4.88	1.96
4	1.77%	1.658088	0.78896	1.53	6546.2	0.28686	-1.84	5.08	1.87
5	0	0	0.419	0.78923	12700.	0.66675	-0.762	39.7	1.58

4.6 Stress / Strain Relationship with Corrosion Ratio

The experimental results generated from testing the specimens in the lab were used to draw the relationship between stress/strain and corrosion ratio. Figure 22 and figure 23 identifies the relationship between stress, strain and corrosion ratio, the graphs has four points in the corrosion ratio axis, the first point is when the corrosion ratio is assigned to be zero for the first pipe and it shows higher values of stress and strain, the second point is obtained from the corroded pipe which has a corrosion ratio of 0.235 shows a decrease in the value of stress and strain, the nature of this relationship indicates that the higher the corrosion ratio the more negative effect on the rigidity of a pipeline cause higher potential for failure under upheaval buckling.

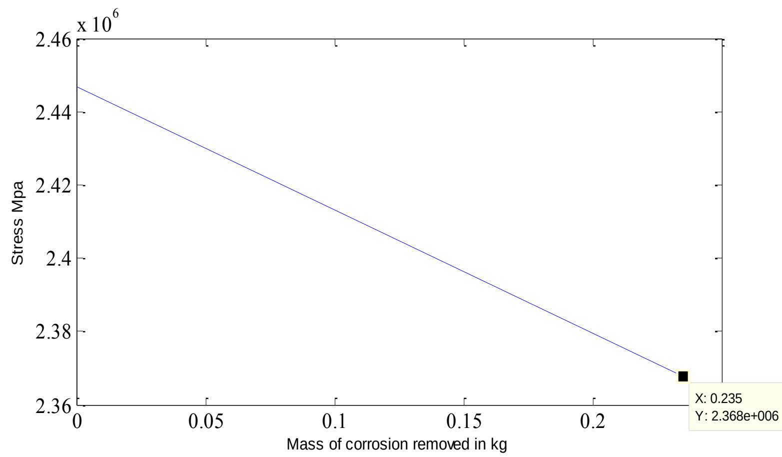


Figure 22 Stress vs. Corrosion Ratio

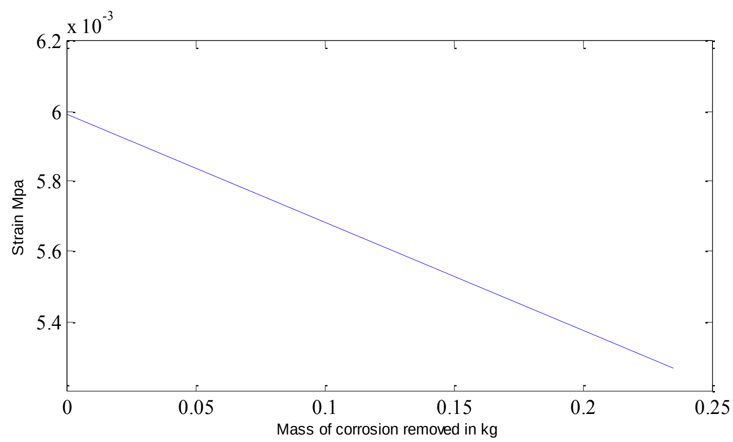


Figure 23 Strain vs. Corrosion Ratio

4.6.1 FEM-ANSYS Comparison

Table 4 Corrosion Ratio vs Stress (ANSYS)

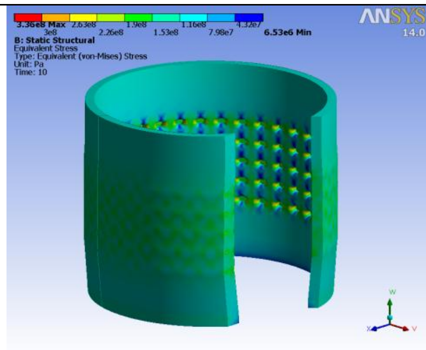
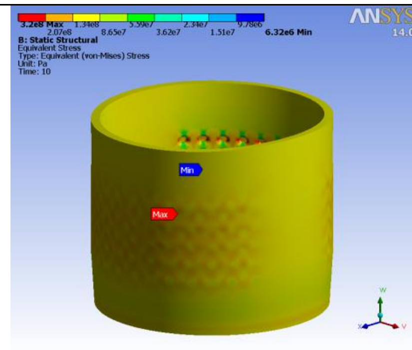
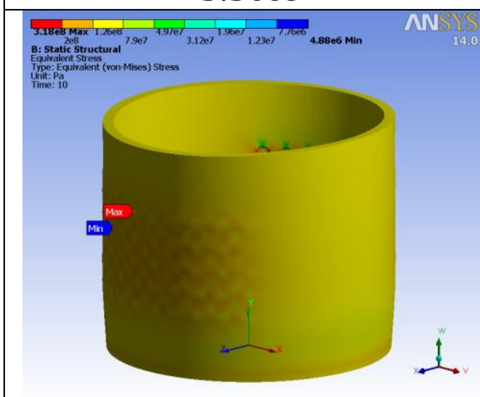
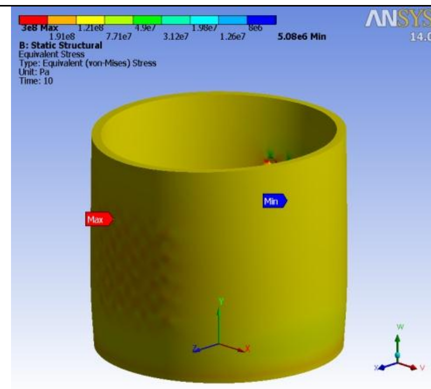
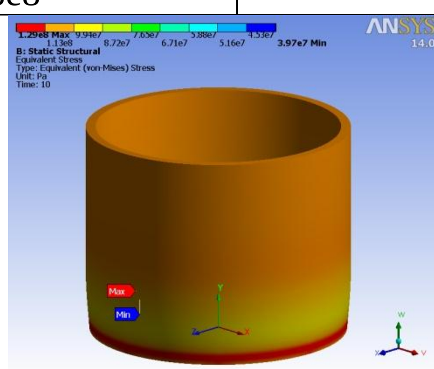
Stress	Corrosion ratio Peak stress	
	 5.99% 3.36e8	 4.31% 3.2e8
	 2.98% 3.18e8	 1.77% 3e8
	 0% 1.29e8	

Table 5 Corrosion Ratio vs Strain (ANSYS)

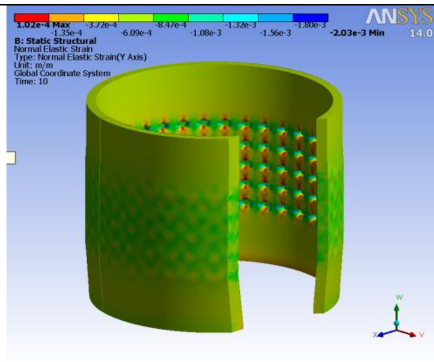
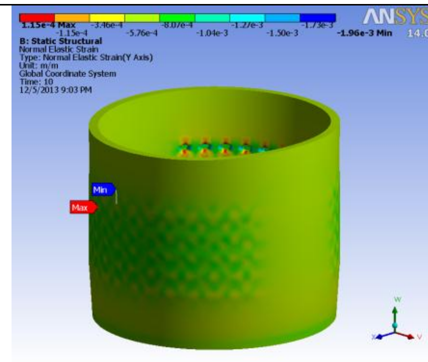
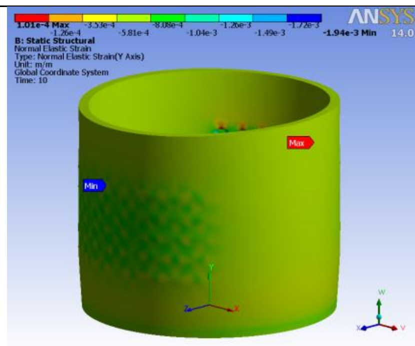
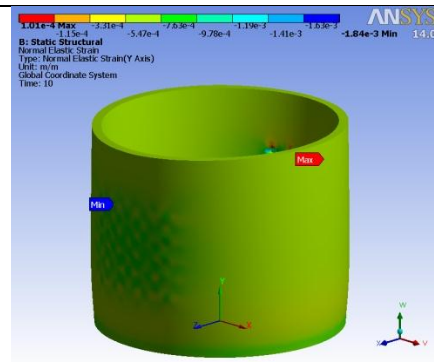
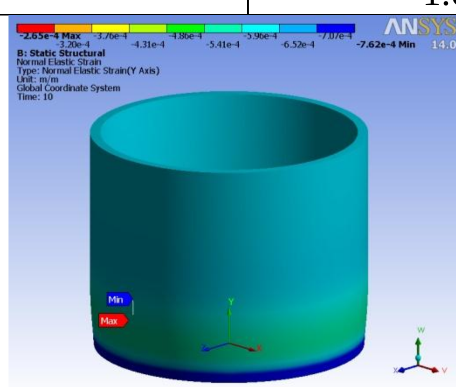
Strain	Corrosion ratio Peak strain	
	 5.99% 1.02e-4	 4.31% 1.15e-4
	 2.98% 1.01e-4	 1.77% 1.01e-4
	 0% -2.56e-4	

Table 4 and 5 shows the same relationship obtained from the experimental process which is a decrease in the value of stress and strain with the increase of corrosion ratio, this confirms that the nature of this relationship indicates the negative effect on the rigidity of a pipeline an increase in the corrosion raio will have on a buckling pipe.

4.7 Pitting Corrosion Effect On Damage and Life

Among the different types of corrosion damage, pitting is one of the mechanisms in triggering widespread fatigue crack initiation and reducing fatigue life of the material. Pitting Corrosion will bring down the fatigue life of the pipeline which will increase the material possibility of Damage under Upheaval buckling. The previous statement is supported by Figure 24 which was obtained from the FEM-ANSYS. Degrading nature of fatigue life on the materials is compounded by the corrosion interaction. the damage will be more than the design damage due to corrosion and fatigue loading through buckling axial force.

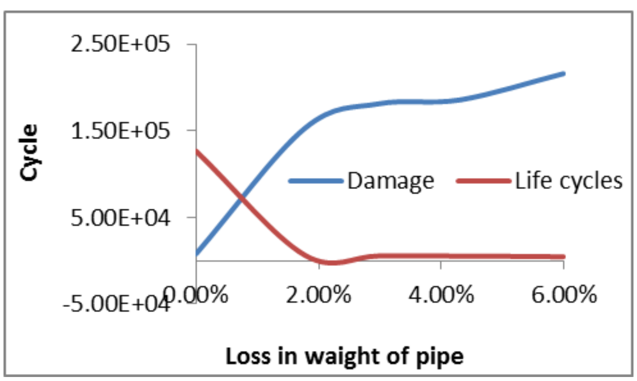


Figure 24 Damage/Life vs. corrosion ratio

The pitting corrosion is significant to damage increase because the pitting will form intrusions and extrusions in the buckling zone. The formation of intrusion and extrusion due to fatigue loading leads to notches. The corrosion media will enter the notches and forms oxide with the base metal and it will be passive to further corrosion. But the fatigue loading will disturb the passive layer and facilitate the media to corrode the fresh material, Hence it will drastically decrease the fatigue life of the material and decrease durability of loads from upheaval buckling.

4.8 Pitting Corrosion Effect On Safety Factor

The reduction in the pipe's safety factor illustrated in Figure 25 was due to the change in stresses caused by corrosion, stresses are classified into primary, secondary, and peak stresses which are detailed with relativity to safety factor below.

- Primary stresses.

These are developed by the imposed loading and are necessary to satisfy the equilibrium between external and internal forces in order to maintain the design safety factor. Moments of the piping system are also maintaining equilibrium with the forces in the non-corroded pipe , but in case of disturbance due to loss in weight generated from corrosion then the Primary stress value reduces and in turn the safety factor.

- Secondary stresses.

These are developed by the constraint of displacements of the pipeline. these displacements can be caused by the thermal expansion.

- Peak stresses.

Unlike loading condition of secondary stress which cause distortion, peak stresses cause no significant distortion. peak stresses are the highest stresses in the region under consideration and are responsible for causing fatigue failure due to changes in value, which is the reason for the curve generated for the specimens in Figure 25.

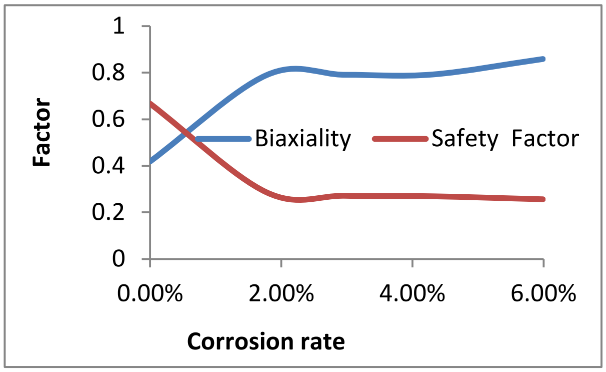


Figure 25 Biaxiality/ Safety factor vs. Corrosion rate

Even though the applied load in the experiment was completely cyclic axial, there is always induced shear and principal stresses present on pipelines, therefore, biaxial loading affection by pipping corrosion is being present in Figure 25 which illustrates the reduction in the value, even though the effect of secondary loading could reduce the fatigue life of any pipe significantly.

4.9 Deformation of the Pitting Corroded Specimen

In a non defected pipeline a common mode of deformation is involved under buckling in the direction perpendicular to the pipe's diameter. The instability mechanism which takes place in cases of pitting corrosion occurrence is illustrated in Figure 26, it involves the disturbance of elastic contrast in the load direction.

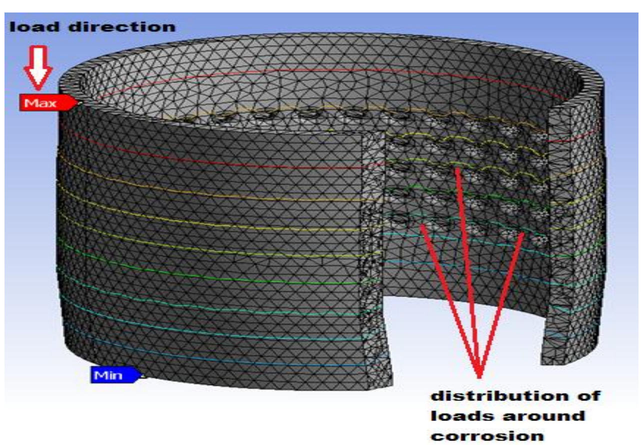
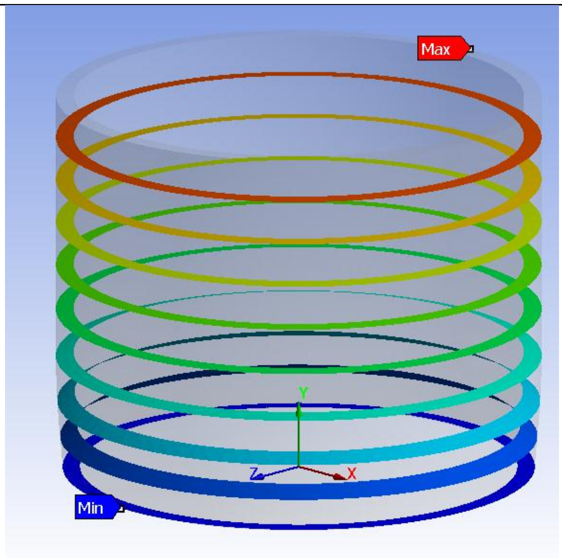
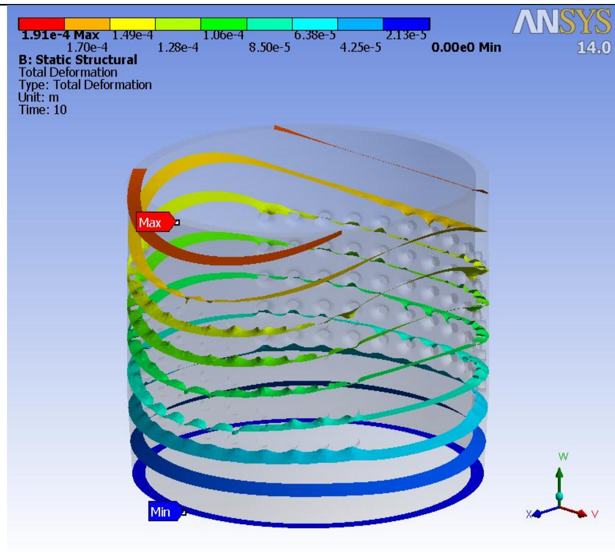


Figure 26 Load distribution around corrosion

Corrosion as defined previously is a loss of mass, which leaves pores lacking material to carry the load through the pipeline, therefore the unfilled positions results in a compressive stress in the direction transverse to the buckling loading axis, the surrounding material takes the extra loading which may be higher than the design until buckling takes place resulting in an undulated pipeline.

Using molecular simulation which to the previous statement, the scenario is demonstrated for the deformation of the pipeline in Table 6, the buckling deformation is observed to have greater length than that of the non-corroded pipe.

Table 6 Deformation

deformation	 0% corrosion ratio 1.58e-4 design allowable deformation	 4.31% corrosion ratio 1.91e-4 new peak deformation n

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The understanding of upheaval buckling and its Veining parameters has been substantially improved over the last few years, allowing safer and more economic design, installation and protection of high temperature pipelines. The overall design against upheaval buckling has to be strongly integrated with the requirements for and the availability of survey data to further improve reliability and minimize costs.

Therefore, having achieved the objectives of this research paper through the assessments in Chapter 4, the integration of the results and it's implication on pipeline design will have a significant effect in reducing the hazard generated by upheaval buckling via a more considerable design.

5.1 Recommendations

Other than the experimental innovations there are also technological innovations that can help to overcome Up Heaval Buckling. Because UHB is closely allied with offshore pipelines, the technological innovations on the mitigation measures are more prevalent in the offshore industry. Some innovative techniques can be transferred to onshore pipelines in order to overcome potential UHB issues. These include:

- use of selected suitable backfill material.
- stabilization of over-bend sections by placing rocks, extra soil, mattresses, berms/dumps or geo-textile wraps over them.
- place continuous riprap stone pitching over the pipeline to enhance effective backfill weight.
- placing saddle/set-on weights, concrete slabs, articulated concrete mats or sand bags on the pipe concrete coating of pipes.

- using screw anchors can be an option where the terrain soil is unstable and has poor load-bearing capacity.
- continuous or intermittent use of geo-textiles to increase the effectiveness of the soil, and rock-dumps.
- in areas of non-cohesive soil, the buried pipeline may be installed with added slackness (in snaking configuration) so that the likely axial expansion will be distributed more uniformly and directed sideways over the turning points.
- where sections with steep slopes and sharp bends are unavoidable, explore the possibility of reducing wall thickness of the pipe by substituting higher grade material in order to decrease the buckle driving axial force due to thermal expansion.

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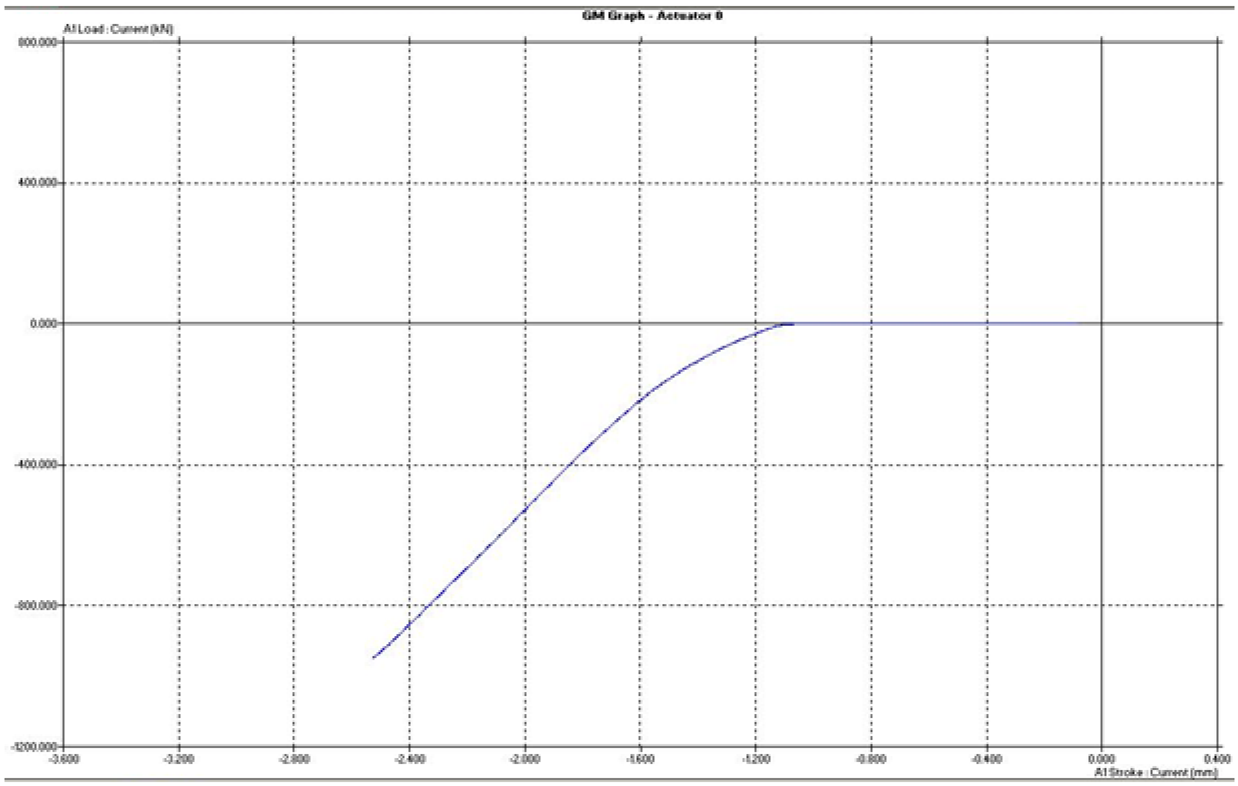
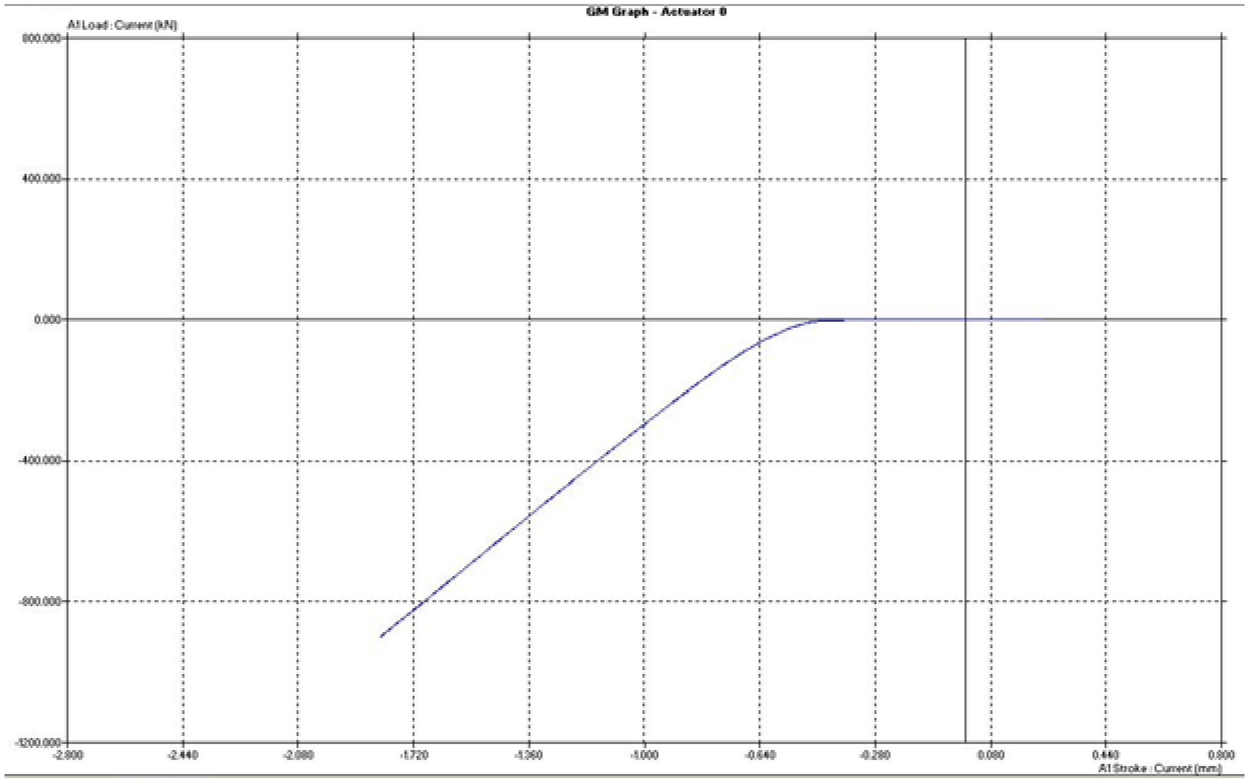
Appendix

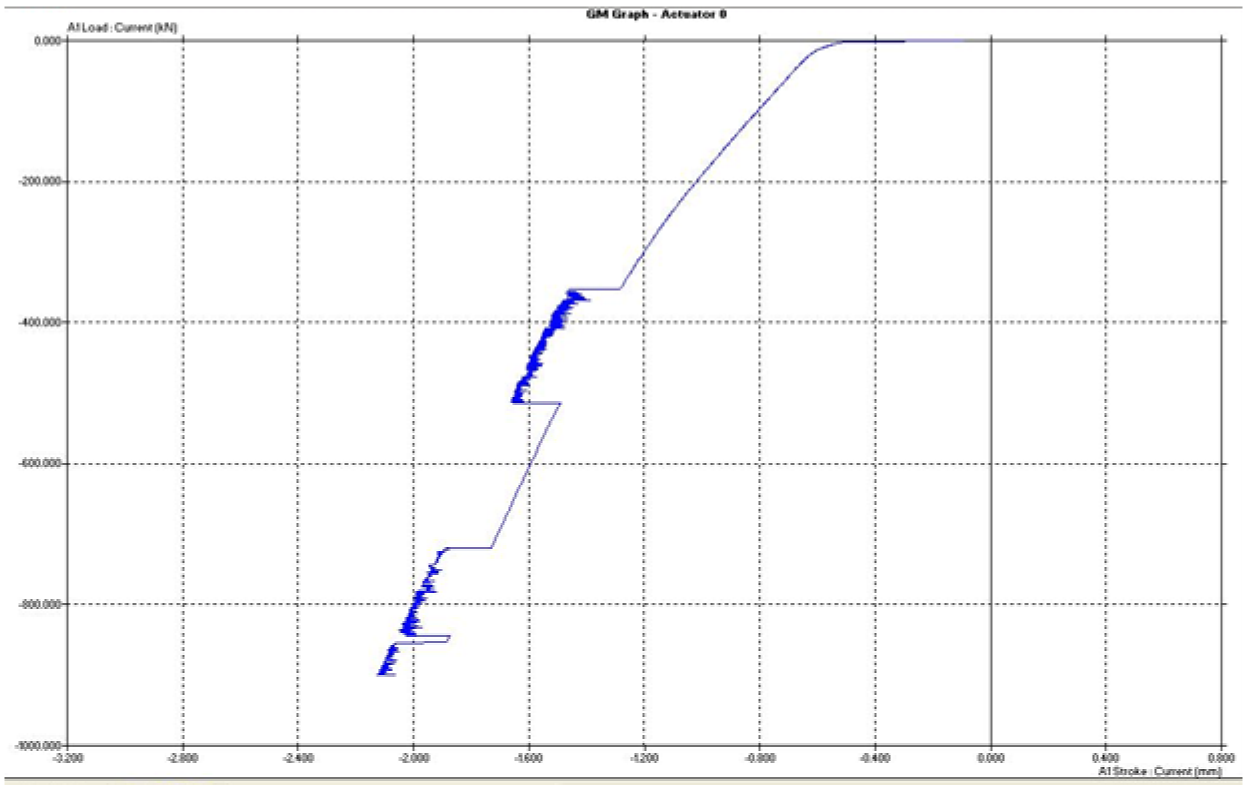
Appendix 1. load vs. deflection for 0% corroded specimen



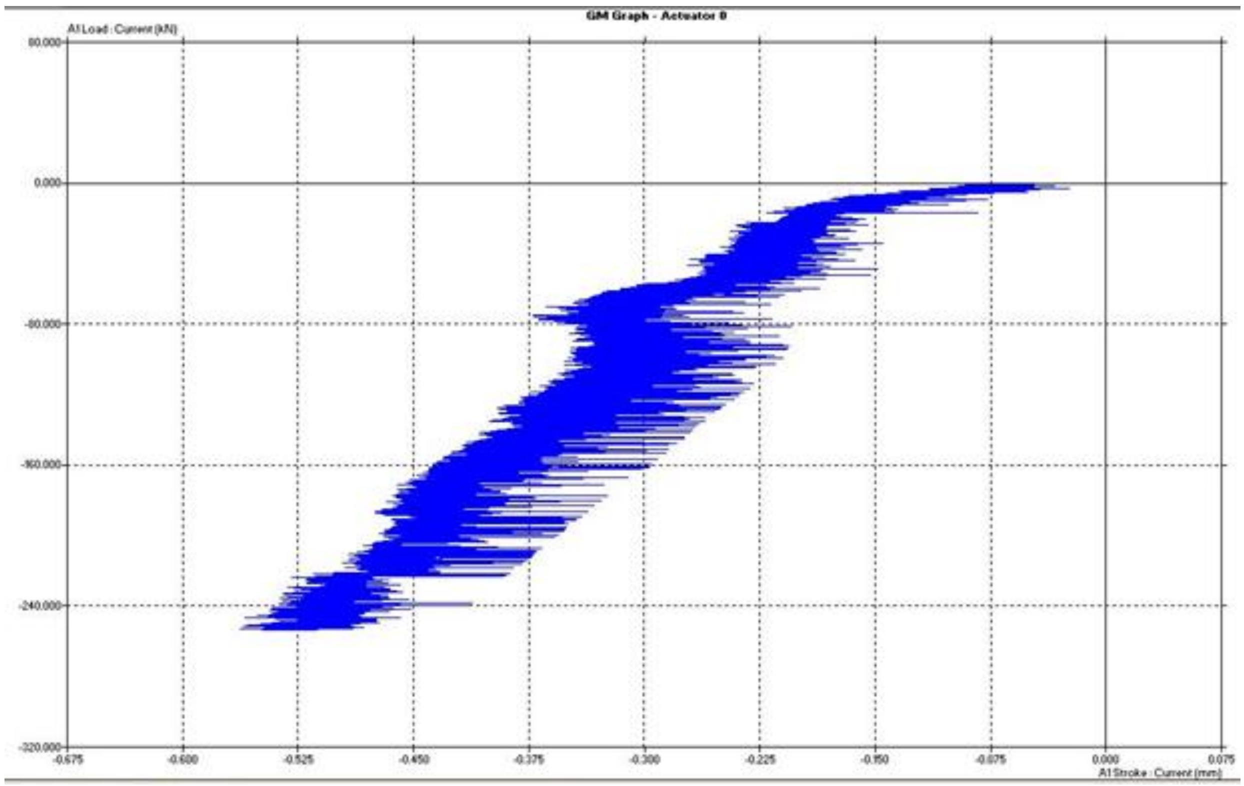
Appendix 2. load vs. deflection for 1.14% corroded specimen

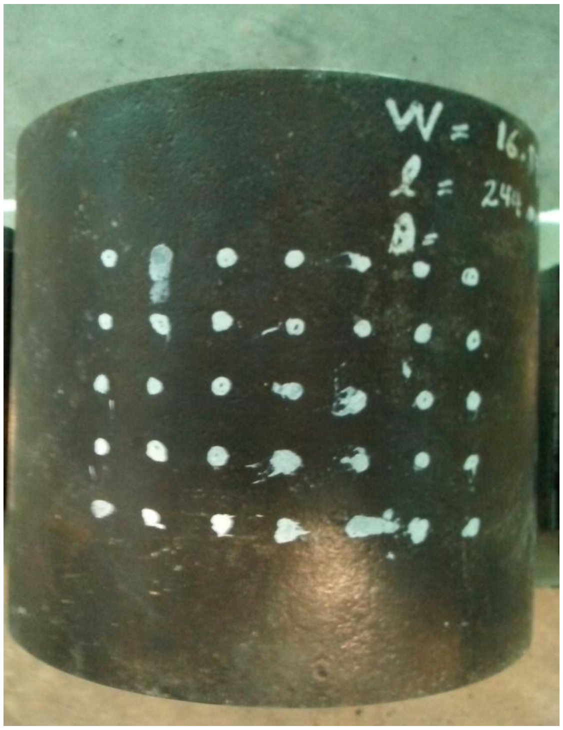
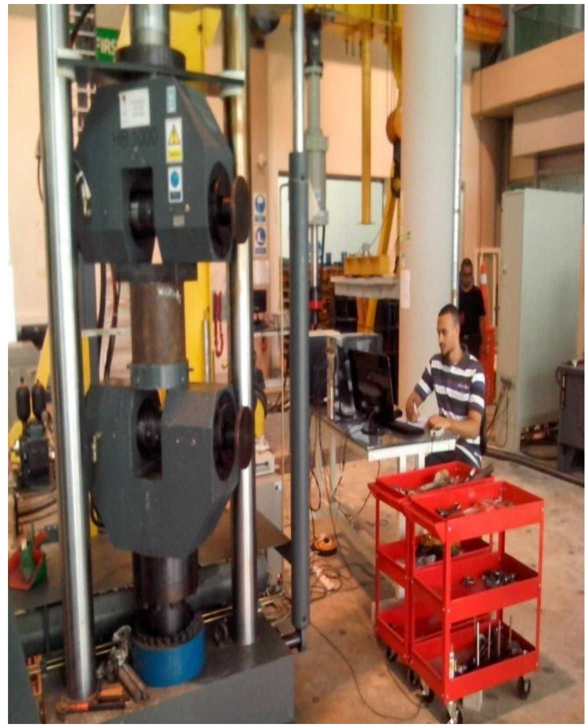
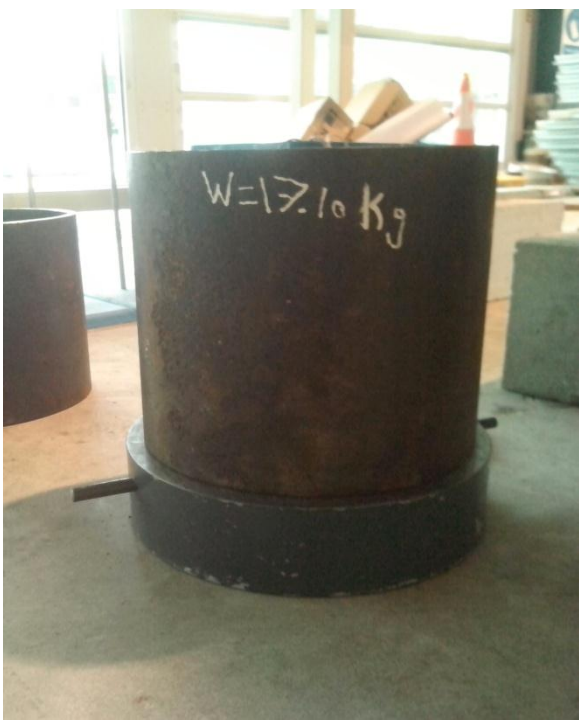


Appendix 3. load vs. deflection for 2.29% corroded specimen



Appendix 4. load vs. deflection for 3.43% corroded specimen






W=17.10 Kg