Stress Corrosion Cracking on Welding of Offshore Structure

by

Amirul Iman Bin Azizdin

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc. Prof. Dr Razali Bin Hamzah)

UNIVERSITI TEKNOLOGI PETRONAS

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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AMIRUL IMAN BIN AZIZDIN

ABSTRACT

The objective of this research is to study on Stress Corrosion Cracking on welding of offshore structure. Offshore structure such as topside will have deflections at the joint due to a combination of load on the decks. The deflections result tensile stress on the structure. The tensile stress and residual stress from welding process of the structure leads to occurrence of Stress Corrosion Cracking.

The scopes of study covers (a) conduct Stress Corrosion Cracking Tests using Bolt Loaded Double Beam Test, (b) conduct corrosion experiment with the affect of offshore environment which seawater with pH between 7.5 to 8.0 and temperature of 35°C and (c) examine Stress Corrosion Cracking for material A516 grade 70 with Shielded Metal Arc Welding (SMAW).

The offshore welding samples were gathered from the fabricator and the samples were used for testing and experimental works for this project. The sample inspected by using Liquid Penetrant Inspection to detect any discontinuities of the weld before any test conducted. The samples then were setup for Bolt Loaded Double Beam Testing to study the behavior of SCC. With these setup, the samples were examined under offshore condition in Salt Fog Corrosion Chamber for two weeks (336 hours). The losses in mass of the samples recorded to calculate the Corrosion Rate. The characteristics of the sample's microstructure were studied by using Optical Microscopy.

It was found that Stress Corrosion Cracking initiated and propagated in the sample when the deflections of the sample were higher than the design maximum allowable deflection of the joint of 37.17mm/5000mm length. There are two types of SCC present in the samples, which are Intergranular and Transgranular SCC. The presence of SCC increases the Corrosion Rate.

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LIST OF ABBREVIATIONS AND NOMENCLATURES

AISI	American Iron and Steel Institute
ASTM	American Standard for Testing and Material
ASW	Artificial Seawater
AWS	American Welding Society
Cl^-	Chloride
CO_2	Carbon Dioxide
EDX	Energy dispersive X-ray spectroscopy
H_2S	Hydrogen Sulfide
HAZ	Heat Affected Zone
MMA	Manual Metal Arc
MT	Magnetic Particle Testing
NACE	National Association of Corrosion Engineers
NaCl	Sodium Chloride
NDE/NDT	Non-Destructive Examination/ Non-Destructive Testing
PT	Liquid Penetrant Testing
RT	Radiographic Testing
SCC	Stress Corrosion Cracking
SEM	Scanning Electron Microscope
SMAW	Shielded Metal Arc Welding
UT	Ultrasonic Testing
VT	Visual Testing
WPS	Welding Procedure Specification

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Welding processes are extensively used in the fabrication and erection of offshore structures. Welding is a method by which metals are joint together with or without filler metal, using heat or pressures[1] depending on the process been used. In designing a platform, there are design maximum allowable deflections of joints. The amount of defections resulted from loads of the equipment installed and the operating loads. The deflection of the joint could lead to stress corrosion cracking to occur in the joint. With occurrences of stress corrosion cracking, the failure of the joint could happen even though not subjected to the maximum allowable deflection of the joint. The stress corrosion cracking could also affect the corrosion rate of the structure. The offshore environments itself are one of the factors to occurrence of stress corrosion cracking.

1.2 Problem Statement

Offshore structures extensively have high potential exposure to stress corrosion cracking in the weldment due to the effects of offshore environment. With the occurrence of the welds failures, it can lead to rapid and catastrophic failure of offshore structures. The design of the joint usually come with the designed maximum allowable deflections of joint. Within the allowable deflections margin, the joints are considered safe. At the same time, the deflections of the joint may lead to stress corrosion cracking and affect the corrosion rate of the joint. With occurrence of stress corrosion cracking, the design maximum allowable deflections of the joint should reconsider.

1.3 Objectives

The main objectives of this project are:

a. To demonstrate the Stress Corrosion Cracking of a weld joint using Bolt Loaded Double Beam Test.

b. To determine the type of Stress Corrosion Cracking occuring on the offshore weld joints.

c. To quantify the effects on corrosion rate due to the occurrence of Stress Corrosion Cracking.

1.4 Scopes of Study

To achieve the objective of this project, the scopes of study are:

a. To conduct Stress Corrosion Cracking Tests using Bolt Loaded Double Beam Test.

b. To conduct corrosion experiment under offshore environment using seawater with pH between 7.5 to 8.0 and temperature of 35°C.

c. To examine Stress Corrosion Cracking for material A516 grade 70 with Shielded Metal Arc Welding (SMAW) process.

1.5 Significant of the Project

This project studied the designed maximum allowable deflection of joints that could lead to stress corrosion cracking to occur. The joint defects from the different amount of deflections studied and the stress corrosion cracking observed. The effects of stress corrosion cracking to the corrosion rate calculated from the different values of deflection done in the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Offshore Environment

The oceans present a unique set of environment condition that dominates the procedure and the design to employ in offshore structure. The principal environment factors that will examine are:

a) Temperature
b) Seawater

2.1.1 Temperature

Temperature of the surrounding seawater has an important effect on the behavior of material; it may below the transition temperature for steel that leads to brittle failure under impact. Cold water contains more dissolved oxygen than warm water because the affect of growth of marine organisms [15].

2.1.2 Seawater

The dominant chemical characteristic of seawater is its dissolved salts, which typically constitutes 3.5% of its composition. This means that every 1 kg of seawater has approximately 35 grams of dissolved salts [15]. The average density of seawater at the surface of the ocean is 1.025 g/ml; seawater is denser than fresh water because of the added weight of the salts and electrostriction.

The principle ions are oxygen, sodium, magnesium, chloride, and sulfate as tabulate in ***Table 2.1***. Entrapped bubbles of seawater vapor, as in foam, may collapse suddenly be able to lead to corrosion of offshore structure.

Table 2.1: Seawater Composition [22]

ELEMENT	PERCENT
Oxygen	85.84
Hydrogen	10.82
Chlorine	1.94
Sodium	1.08
Magnesium	0.1292
Sulfur	0.091
Calcium	0.04
Potassium	0.04
Bromine	0.0067
Carbon	0.0028

Chloride (Cl^-) ion acts to reduce the protective oxidized coating and thus accelerates corrosion. Oxygen plays essential role in the corrosion of steel in the sea environment, whether steel is exposed, coated or encased in concrete. Carbon dioxide (CO_2) and hydrogen sulfide (H_2S) lowered the pH of seawater and a shift in pH will result in an extensive rearrangement of the completely ion-pairing system [16]. The seawater pH is in the range 7.5 to 8.4. In addition, H_2S may cause hydrogen embrittlement of steel.

2.2 Material of Offshore Structure

The material used for this project is ASTM A516 Grade 70 which used by the fabricator to fabricate the structure for Petronas Carigali Tangga Barat topside.

2.2.1 ASTM A516

ASTM A516 is material that entitle for Carbon steel plates for moderate and lower-temperature service. A516 generally used for fabrication of pressure vessel. ASTM specifications of chemical composition for A516 [22] are as shown in ***Table 2.2***.

Table 2.2: ASTM specification of chemical composition for A516 Grade 70

Material	Composition, %
Carbon	0.31
Manganese	0.85−1.20
Phosphorus	0.035
Sulphur	0.04
Silicon	0.15−0.40

The mechanical properties requirements given in ASTM specifications for A516 Grade 70[22] steel plate listed in ***Table 2.3***.

Table 2.3: The properties for A516 Grade 70 as per ASTM specifications.

Tensile strength	Yield strength	Minimum elongation in 200mm (8 in.), %	Minimum elongation in 50mm (2 in.), %
485−620 MPa	260 MPa	17	21

2.2.2 Weldability of A516 Grade 70

Weldability is a relative term that describes the ease with which sound welds possessing good mechanical properties can be produced in a material. The chief weldability factors are composition, heat input, and rate of cooling. These factors produce various effects, such as grain growth, phase changes, expansion, and contraction, which in turn determine weldability.

Steel with a carbon range of 0.15 to 0.30% can usually be welded satisfactorily without preheating, postheating, or special electrodes. For rather thick sections (>25mm, or 1 in.), however, special precautions such as 40 °C (100 °F) minimum preheat, 40 °C (100 °F) minimum temperature between weld passes, and a 540°C to 675 °C (1000 to 1250 °F) stress relief may be necessary.

2.3 Welding Process – Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding (SMAW), also known as manual metal arc (MMA) welding or informally as stick welding, is a manual arc welding process that uses a consumable electrode coated in flux to lay the weld.

An electric current, in the form of either alternating current or direct current from a welding power supply, used to form an electric arc between the electrode and the metals to join as illustrated in ***Figure 2.1***. As the weld lay, the flux coating of the electrode disintegrates, giving off vapors that serve as a shielding gas and providing a layer of slag, both of which protect the weld area from atmospheric contamination.

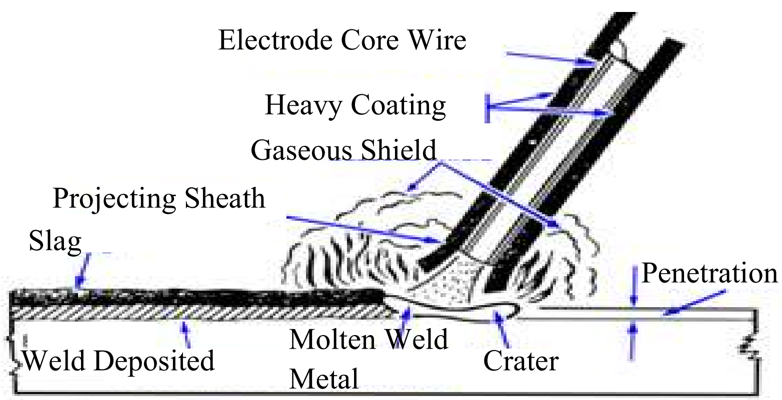


Figure 2.1: SMAW weld area [3]

Shielded metal arc welding equipment typically consists of a constant current welding power supply and an electrode, with an electrode holder, a work clamp, and welding cables also known as welding leads connecting the two [3] as shown in ***Figure 2.2***.

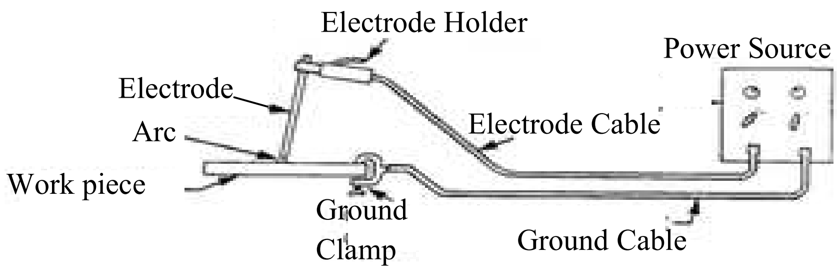


Figure 2.2: SMAW system setup [3].

2.3.1 Weld Microstructure

Weldments exhibit special microstructural features that need to be recognized and understood in order to predict acceptable corrosion service life of welded structure [1]. Weldment consist of a transition from base metal through a HAZ and into solidified weld metal and include five microstructurally distinct regions as shown in ***Figure 2.3*** normally identified as[2]:

a. <u>Fusion zone</u>

   The result of melting which fuses the base metal and filler metal to produces a zone with a composition that is most different from that of the base metal. The composition different produces a galvanic couple, which can influence the corrosion process in the vicinity of the weld. The fusion zone itself offers a microscopic galvanic effect.

b. <u>Unmixed region</u>

   The base metal is melted and then quickly solidified to produce a composition similar to the base metal.

c. <u>The partially melted region</u>

   Usually one or two grains into the HAZ relative to the fusion line. It is characterized by grain boundary liquation, which may result in liquation cracking. These cracks which are found in the grain boundaries on or two grains below the fusion line have identified as potential initiation site for hydrogen-promoted under bead cracking in high strength steel.

d. Heat affected zone (HAZ)

The HAZ is the portion of the weld joint which experienced peak temperature high enough to produce solid state microstructural changes but too low to cause any melting. Every position in the HAZ relative to the fusion line experiences a unique thermal experience during welding, in terms of both maximum temperature and cooling rate. Thus, each position has its own microstructural features and corrosion susceptibility.

e. The unaffected base metal

The part of the work piece that has not undergone any metallurgical change. Is likely to be in a state of high residual transverse and longitudinal shrinkage stress, depending on the degree of restraint imposed on the weld.

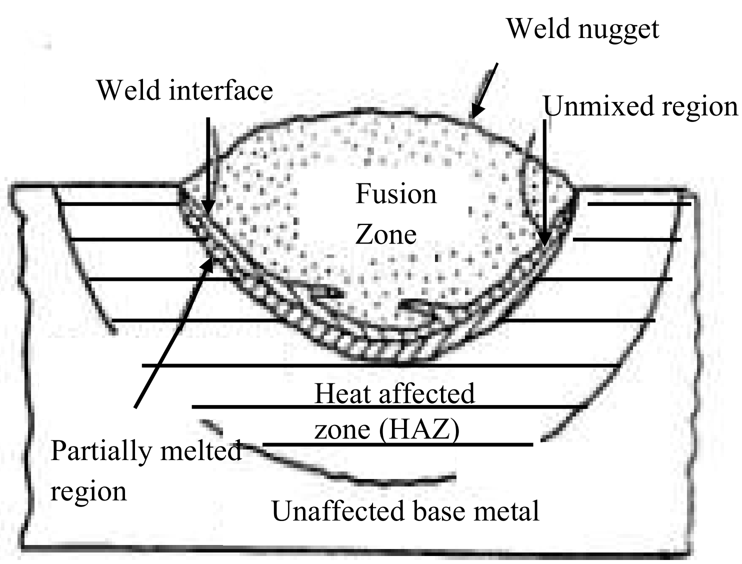


Figure 2.3: Schematic showing the regions of heterogeneous welds [2]

2.4 Welding Procedure and Specification

Welding Procedure Specification is a written set of specifications detailing the welding procedure, joint preparation, filler metal, current type and range as well as any required preheat, interpass temperature controls and postheat treatments.

A WPS is developed by engineering or inspection personnel using qualified welders to weld a specific type of metal and joint configuration that will be used on the job, while recording the welding parameters and variables. The completed joint is then tested in accordance with a specific Code or Standard.

The resulting information written on a form called a Procedure Qualification Record. The information from the Welding Procedure Qualification Record is used to write the WPS and as long as the procedure is carefully followed, the resulting welded products will have the required strength characteristics [18].

2.5 Weld Corrosion

Corrosion failure of welds occur even the proper base metal and filler metal have been selected, industry codes and standards have been followed and weld have been deposited that possess full weld penetration and have proper shape and contour [9]. It is unusual to find that, although the wrought form of a metal or alloy resist to corrosion in particular environment, the weld counterpart is not.

However, there are also many instances in which the weld exhibits corrosion resistance superior to that of the unwelded based metal. There also are times when weld behave in an erratic manner, displaying both resistance and susceptibility to corrosive attack.

The factors influencing corrosion of weldment are weldments design, fabrication technique, welding practice, welding sequence, moisture contamination and existence of organic or inorganic chemical species.

2.5.1 Metallurgical Factor for Corrosion of Weldments

The cycle of heating and cooling that occurs during welding process affect the microstructure and surface composition of welds and adjacent base metal. Consequently, the corrosion resistance of autogenously welds and welds made matching filler metal may be inferior that of properly annealed base metal because of:

a. Microsegregation
b. Precipitation of secondary phase
c. Formation of secondary phase
d. Recrystallization and grain growth in the weld heat-affected zone (HAZ)
e. Volatilization of alloying element from the molten weld pool
f. Contamination of the solidification weld pool

2.5.2 Forms of Weld Corrosion

Weldments can experience all the classical form of corrosion. The forms of weld corrosion that must be considered when designing welded structure are:

a. Galvanic corrosion
b. Pitting
c. Stress corrosion
d. Intergranular corrosion
e. Hydrogen cracking
f. Microbiologically influenced corrosion

For this project, weld corrosion that will be focus deeply is Stress Corrosion.

2.6 Stress Corrosion Cracking (SCC)

SCC defined as the corrosion attack on susceptible alloy due combined and synergistic interaction of tensile stress and conductive environment. SCC requires the simultaneous occurrence of the following three conditions as illustrated in ***Figure 2.4***:

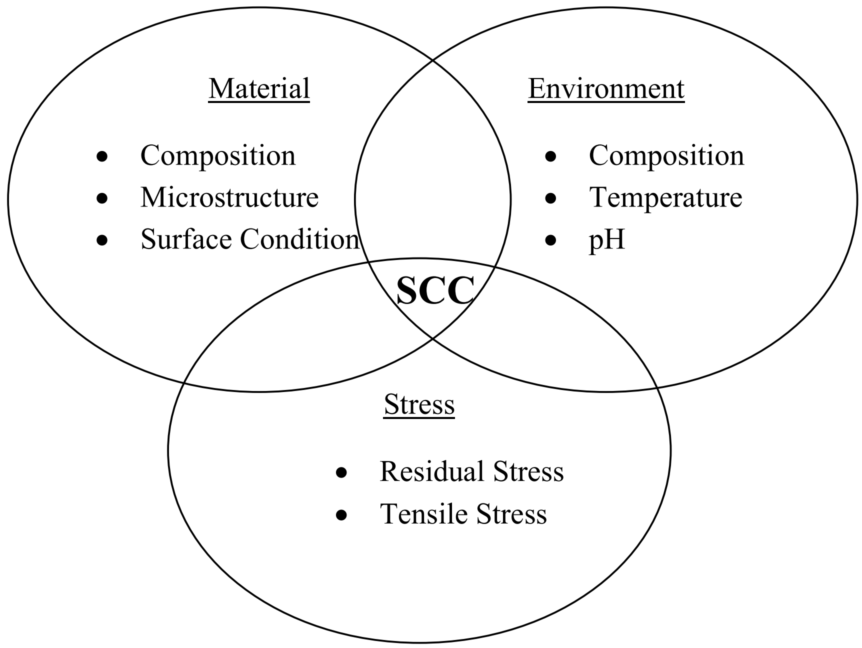


Figure 2.4: Factor influencing SCC [7]

2.6.1 Environmental Condition Influencing SCC

The environment that influencing the SCC is tabulate in ***Table 2.4***. Time for cracking ranges experimented under highly accelerated laboratory condition.

Table 2.4: Environment that cause Stress Corrosion Cracking [8]

Metal	**Environment**
Aluminum Base Alloy	NaCl solution, seawater, chloride solution and other halide solution
Copper Base Alloy	Ammonia, ammonium hydroxide, amines, mercury, sulfur dioxide, steam
Carbon Steel	Sodium hydroxide solution, Seawater, Ammonia, and sodium nitrates solutions, carbonates and bicarbonate
Stainless Steel	Aqueous chloride, sea water, sulfurous and polythionic acid

2.6.2 Theory of SCC

No unified theory for SCC is at present accepted. Theories attributed the failure to mechanical, chemical, fracture mechanics, surface energy, etc. the sequence of event involved in the SCC process usually divided into three stages as illustrated in ***Figure 2.5***:

a. Crack initiation and propagation
b. Steady-state crack propagation
c. Crack propagation

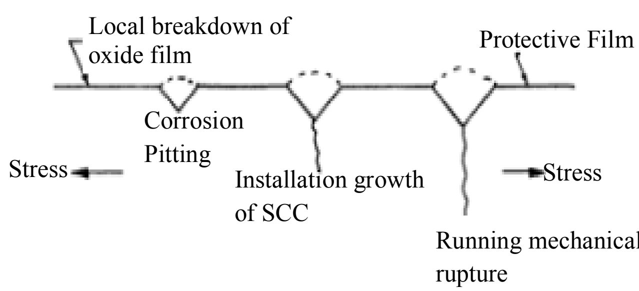


Figure 2.5: Growth and Propagation of SCC [14]

Tensile stress at the surface of the metal is an essential factor in SCC. Cracking has never been found in metal under compression. The tensile stresses may due to internal stress cause by metal deformation near weld or bolds, deformation cause by shrink fit, unequal cooling from high temperature, or volume change in the material caused by phase change or rearrangement of crystal structure, of residual stress from some prior cold work or metal forming operation or caused by applied stress. Welding often leaves residual stresses that lead to SCC in susceptible environment.

2.6.3 SCC of Welded Joint

Weld joint are particularly prone to SCC when the welding operation will leave a residual tensile stress in weld area unless effective postweld stress relief is carried out, stress concentration is usually present and the thermal cycle can produce a susceptible microstructure.

2.7 Types of Weld and Corrosion Tests

2.7.1 Non-Destructive Examination

There are various type of weld testing such as non destructive examination (NDE) techniques that used to detect weld defect and discontinuities and measure their size and orientation. NDE does not require the disabling or sacrifice of the system of interest, it is a highly-valuable technique that saves both money and time in product evaluation, troubleshooting, and research.

The most common NDE techniques used are Visual Testing (VT), Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), Radiographic Testing (RT) and Ultrasonic Testing (UT) [1].

2.7.2 Salt Fog Test in Corrosion Chamber

Salt spray test is an accelerated corrosion test that been conduct to determine the corrosion resistance of specimens against exposure of various environment type such as seawater environment. Corrosion rate calculated by (mm per year penetration) this formula as per NACE specification [9]:

$$CR(mils/year) = C \times \frac{weight\ loss}{A \times t} \times K \quad \text{...........Eqn. 2.1}$$

$$CR(mm/year) = 0.0254 \times CR(mils/year) \quad \text{...........Eqn. 2.2}$$

Where;

C = Conversion Factor (refer ***APPENDIX 2***),

K = Ratio of carbon steel density to that alloy density (refer ***APPENDIX 3***),

t = Time of exposure in hours,

A = Area of specimen.

2.7.2 Bolt Loaded Double Beam Test

Bolt Loaded Double Beam test are one of the test design for Stress Corrosion Cracking testing. The objective of the testing to provide information more quickly than can obtained in service experience. The schematic diagram for setup of Bolt Loaded Double Beam Test illustrated in ***Figure 2.6***.

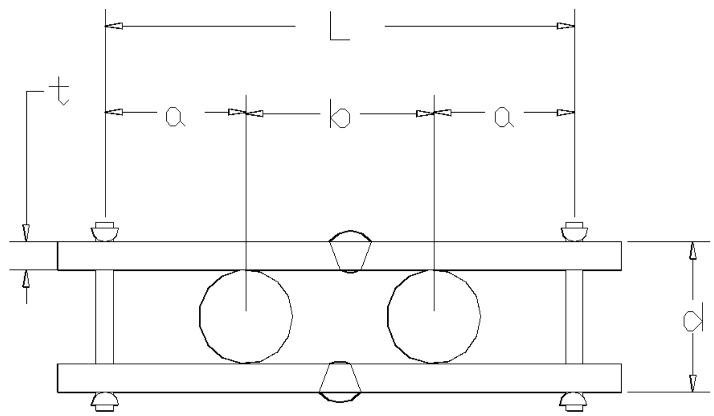


Figure 2.6: Schematic Diagram for Bolt Loaded Double Beam Test

Two beams bolt together with two solid metal act as fulcrum. Deflections developed by bolting the ends of two beams. From the deflections, tensile stress developed in the welds.

Tensile stress calculated by using ***Equation 2.3***.

$$f = \frac{\Delta d(3Et(3L - 4a)}{2a} \qquad \text{...........Eqn. 2.3}$$

Where;

Δd = Deflection of the beams,

E = Modulus of Elasticity of the carbon steel A516 (E = 210 X 10^6 Pa),

f = Tensile Stress develop,

a = Distance between fulcrum and bolts,

L = Distance between two bolts,

t = Thickness of each beams.

CHAPTER 3

METHODOLOGY

3.1 Introduction of Project's Methodology

Methodology and procedure is important to ensure that the project done correctly and obtained good result at the end of the project. The Gantt Chart of this project illustrated in ***APPENDIX 1***. The methodology and procedure to conduct the project is divided into Literature Review, Information Gathering, Laboratory Works, Data Analysis and Report Preparations. The summary of the methodologies are as illustrated in ***Figure 3.1***.

3.2 Literature Review

The total understanding of the problem is the first phase in order to make the objective of the project is clear that will guide through all the semester and become the starting point of this project.

The literature review done on the affect of offshore environment to offshore structure, material used in offshore structure, the relevant welding process, types of welding defects, and type of corrosion for welding failure. All the information referring to respective books, journals, and thesis develop by others.

3.3 Information Gathering

The design allowable deflection for the joint review from the designer that design Tangga Barat Cluster, topside module 6. The allowable deflection for the joint used in the bolted loaded double beam test.

The welding procedure for the joint gather from the fabricator. The parameter used in the welding process studied and will be used for welding the specimen for testing and laboratory works.

3.4 Laboratory Works

Based on the literature review, experiment and test method will obtained before conducting experimental work.

3.4.1 Shield Metal Arc Welding

The next phase of this project is to weld a work piece by using current offshore welding procedure and all the parameter followed exactly with the welding procedure.

3.4.2 Non-Destructive Examination

Welded structures be tested nondestructively, to check whether the weld have any discontinuities or imperfection. The most suitable method and available in UTP mechanical laboratory is:

a) Liquid Penetrant Inspection

   This technique consist of migrating by Capillary Action into discontinuities or cavities that are open to the surface. The discontinuities observes from the contrast color of the dye penetrant. The procedure for Liquid Penetrant Inspection listed in ***APPENDIX 8***.

3.4.3 Salt Fog Test in Corrosion Chamber

The work piece then is subject to salt fog test. The first specimen leave in the chamber without bolt loaded double beam test. The other three specimens leave in the chamber with bolt loaded double beam test.

The surface area, equivalent weight, metal density and the exposure time in the chamber have to be find out for calculate the corrosion rate by using ***Equation 2.1*** and ***Equation 2.2***.

All the specimens leaves in the chamber for 2 weeks (336 hours) and the parameter of the seawater control which is pH are between 7.5 to 8.0 and the temperature maintained at 35°C.

3.4.4 Bolt Loaded Double Beam Test

Bolt Loaded Double Beam Test is one of the test technique develop for study the behavior of Stress Corrosion Cracking. The setup of the test is as per discussed in Literature Review.

The specimen setup as such ways because to develop a beam deflection and will result tensile stress in the weldment. Tighten both bolts to develop beam deflection (Δd). Tensile stress developed calculated by using ***Equations 2.1***. The tensile stress will cause the Stress Corrosion Cracking to occur at the weldment.

3.4.5 Optical Microscopic Examination

The purposes of this examination are for determine the characteristics of the stress corrosion cracking occur in the specimen by observed the microstructure of the specimens. The examination done after 2 weeks (336 hours) in the Salt Fog Testing chamber. The microscopic examinations that used is Optical Microscopic. The procedure for optical microscopic examination listed in ***APPENDIX 9***.

3.5 Tools Required

3.5.1 Test Apparatus and Chemicals

Tools that need to complete all test and experimental work are Liquid Penetrant Inspections, Corrosion Chamber, Optical Microscopy, Grinder, Polisher, Etchants, and apparatus setup for Bolt Loaded Double Beam Test.

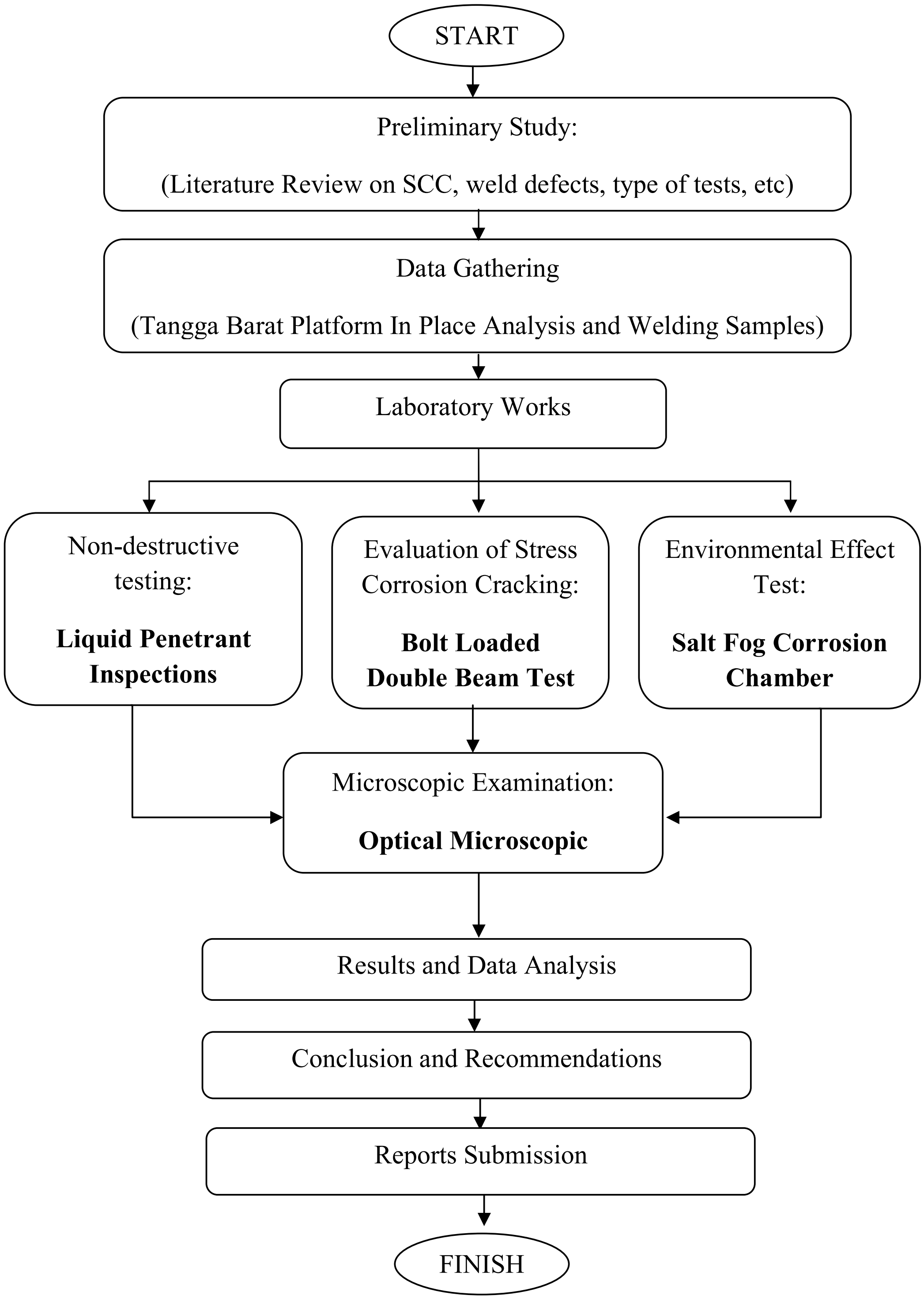


Figure 3.1: Summary of Methodology

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Gathering – Tangga Barat Offshore Structure

Tangga Barat Cluster which consist of Melor, Laho, Tangga and Tangga Barat gas field are located about 185 kilometres offshore Peninsular Malaysia in PM-313 Block at an average water depth of 70 metres. Petronas Carigali SDN BHD is planning to undertake the development of Tangga Barat Cluster Development (Phase 1) development which is scheduled to start production in 2010.

Tangga Barat Cluster Development (Phase 1) consist of developing three gas field with the total of 23 producing wells. The gas from Tangga Barat Cluster contains high level of CO2. Treatment and removal of CO2 is necessary to meet the export gas specification of less than 8 mole percent CO2 content.

Tangga Barat Cluster Development (Phase 1) consist of the following:

i. 1 Central Processing Platform

ii. 1 Drilling Riser Platform bridge connected to CPP

iii. 1 Flare Tripod Platform bridge connected to Drilling Riser Platform

iv. 2 remote drilling platform

v. 2 intra field pipelines

vi. 1 trunk line from CPP to Resak Complex

This research documents the structural in-place analysis carried out for Module 6 for detailed design of Tangga Barat Cluster development project. The analysis is performed in accordance to the structural detailed design basis and brief for CPP Topsides.

4.1.1 Maximum Joint Deflection

Module 6 is supported at four points. They are column leg at A61, A62, B61 and B62 as shown in ***Figure 4.1.*** The maximum relative vertical joint deflection is 37.17mm/5000mm length that occur under load combination of every deck. Basic loading on a typical platform decks tabulated in ***Table 4.1***.

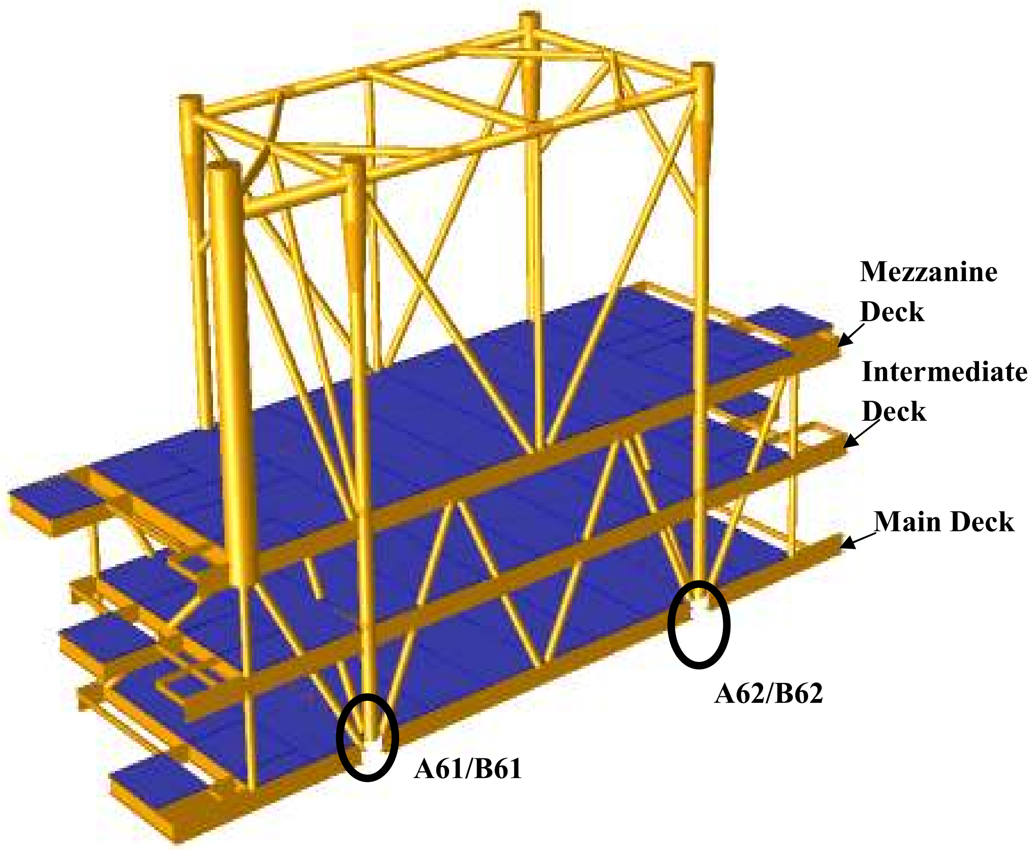


Figure 4.1: CPP topsides Module 6 with support leg joints.

Table 4.1: Basic Loading on a Typical Platform Decks

Location	Descriptions	Load(kN)
Mezzanine Deck	Crane Dead Load	529.740
	Crane Live Load	225.63
Intermediate Deck	OALL	1220.616
	Walkaway Live Load	710.064
	Laydown Area Live Load	1500.004
Main Deck	Structural Load	8479.94
	Equipment Dry Weight	4143.310
	Equipment Content Weight	958.398
	Piping Bulk Dry Weight	584.924
	Piping Bulk Content Weight	81.302
	Electrical Bulk Weight	1802.047
	Instrumentation Bulk Weight	311.860
	Total	**20,547.835**

The maximum support reaction from each leg of the jacket are used for designing testing for bolt loaded double beam testing to investigate stress corrosion cracking. The deflection of the bolt loaded double-beam resulting stress in the specimen and the stress will be not exceeding the amount of the maximum support reaction from each leg of the platform.

4.2 Data Gathering – Welding Procedure Specification

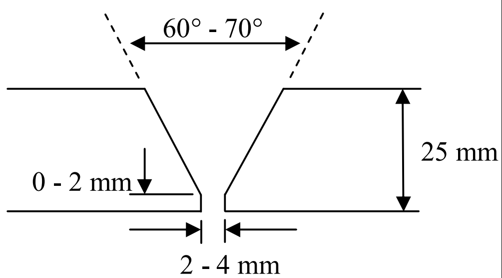
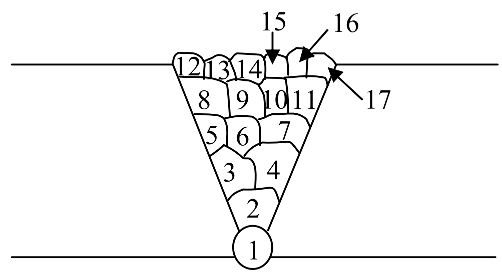
The Welding Procedure Specification (WPS) (procedure number FSP-HLE-17-49) prepared by Kencana HL SDN BHD for joint A61, B61, A62 and B62 for CPP topside Module 6. From the WPS, the joint welds by using manual Sheilded Metal Arc Welding (SMAW). The joint position of production weld is 1G and 2G. The interpass temperature are between range of 10°C to 300°C.

The filler metals used in the welding process are from E-70XX classes. These are the electrodes described in AWS specification A5.1 are applicable to the carbon steels. The E-60XX and E-70XX classes of electrodes provide sufficient strength to produce 100% weld joints in the steels [8].

4.2.1 Joint Design

The weld design for the joint with single vee weld grove and with 17 bead sequence. The base material type of this procedure are carbon steel A516 with thickness 25. The detail schematic of the joint are as illustrated in ***Table 4.2***.

Table 4.2: Design of Joint

Joint Details	**Bead Sequence**
	

4.2.2 Mechanical Test

In the WPS included the Hardness Test, Tensile Test and Bend Test done by Kencana HL SDN BHD subcontractor on the welded steel plate.

Table 4.3: Tensile Test Results

Maximum Loads	28363.00 kg
Tensile Strength	552.34 N/mm^2
Minimum Specified Tensile Strength	489.527 N/mm^2
Position of Fracture	Broke at Base Metal
Mode of Failure	Ductile

From ***Table 4.3***, the maximum loads that can be sustains by the test work piece before facture is 28,363 kg. The material can withstand the amount of load higher than the minimum specified load tensile strength of the material is higher than the minimum specified tensile strength. Mode of failure is ductile shows that the materials performed extensive plastic deformation take place before fractured.

Table 4.4: Bend Test Results

Angle of Bend	**Result**	**Remark**
180°	Satisfactory	No Visible Defect

From ***Table 4.4***, there is no effect of bend test at bend angle of 180° because of no visible defect detected. This showed that the welded plated have sufficient ductility to stand the bend without failure.

Table 4.5: Vickers Hardness Test (HV 10) Results

Indentor: Diamond Pyramid Angle 136°	
Load: 10 kgf	
Location	**Hardness Value**
Base Metal	174 kgf/mm^2
HAZ	210 kgf/mm^2
Weld Metal	192 kgf/mm^2

Table 4.5 shows that HAZ zone is the hardest zone of the specimen which could give high resistant to any shape change if force applied but appear to the most brittle zone because of the heat affect and high cooling rate.

4. 3 Data Gathering – Welded A516 Plate

Qualified welder from Kencana HL SDN BHD welded the carbon steel A516 plate by referring to the welding procedure (procedure number FSP-HLE-17-49). The plate used for corrosion test and stress corrosion cracking test. The plate dimension are 6 inches length, 8 inches wide and 1 inch thick (150mm X 200mm X 25mm). The welded plate shown in ***APPENDIX 4***.

4.4 Non Destructive Testing – Liquid Penetrant Inspections

Before conducting any test, the specimen received from Kencana HL SDN BHD examined by using Liquid Penetrant Inspection to detect weld defect and discontinuities. The results of the inspection shown in ***Figure 4.2***, ***Figure 4.3*** and ***Figure 4.4***.

(a) Top Welds	(b) Root Welds

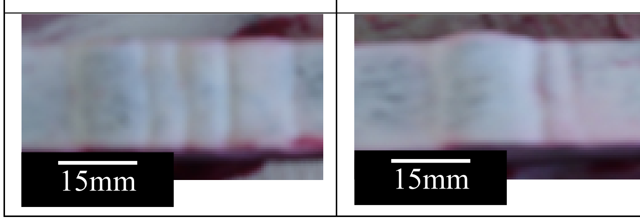


Figure 4.2: Liquid Penetrant Inspection of Specimen 1

Figure 4.2 shows the result of liquid penetrant inspection of specimen 1. There is no defect of welds detected by the inspection on the top and root of the welds. This shows that Specimen 1is with no defect before others testing conducted.

(a) Top Welds	(b) Root Welds

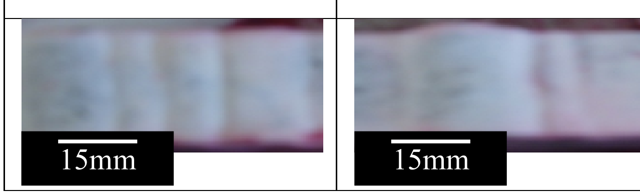


Figure 4.3: Liquid Penetrant Inspection of Specimen 2

Figure 4.3 shows the result of liquid penetrant inspection of specimen 2. There is also no defect of welds detected by the inspection on the top and root of the welds. This shows that Specimen 2 also is with no defect before others testing conducted.

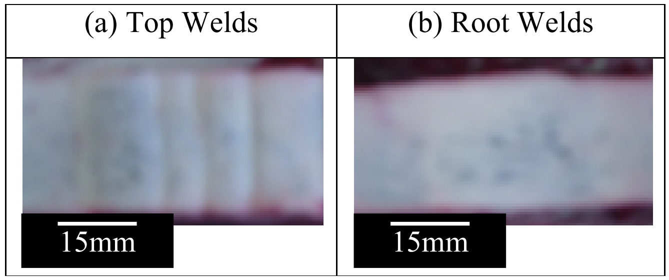


Figure 4.4: Liquid Penetrant Inspection of Specimen 3

Figure 4.4 shows the result of liquid penetrant inspection of specimen 3. There is also no defect of welds detected by the inspection on the top and root of the welds. This shows that Specimen 3 also is with no defect before others testing conducted.

4.5 Bolt Loaded Double Beam Test

The test specimen developed in standard bolt loaded double beam toward testing of weldment. The test specimens shown in ***Figure 4.3***.

Figure 4.5: Bolt Loaded Double Beam Specimen

By using ***Equation 2.3***, the amount of stress developed in weldments calculated from the values of deflection of the beam as tabulated in ***Table 4.6***. The details calculation showed in ***APPENDIX 6.***

Table 4.6: Amount of Stress, f, Developed In the Specimens

Specimen No.	$\Delta d\ (mm)$	a (mm)	E (MPa)	t (mm)	L (mm)	f (Pa)
1	6.070	38.1	210	12	127	137,667.6
2	7.442	38.1	210	12	127	168,784.6
3	8.305	38.1	210	12	127	188,357.4

Specimen 1 with deflections of 6.070mm/150mm length developed tensile stress of 137,667.6 Pa while Specimen 2 with deflections of 7.442mm/150mm length developed tensile stress of 168,784.6 Pa and Specimen 3 with deflection of 8.305mm/150mm length developed tensile stress of 188,357.4 Pa. The value of tensile stress increases if the deflections increase. With the maximum allowable of the joint given by the designer (37.17mm/5000mm length), the stress that develop in the joint are lower than the test specimen.

4.6 Non Destructive Testing – Liquid Penetrant Inspections

After 2 weeks tested in Salt Spray Chamber, the defect on the specimen examined by using Liquid Penetrant Inspection as shown in ***Appendix 5***. The results of the inspection shown in ***Figure 4.6***, ***Figure 4.7*** and ***Figure 4.8***.

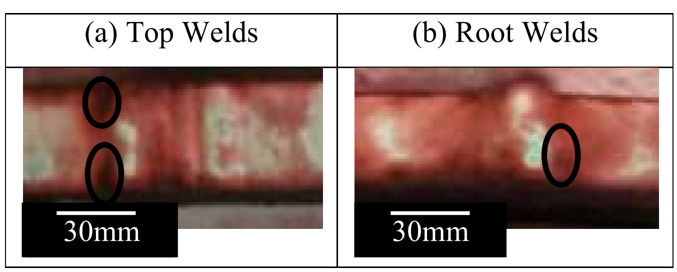


Figure 4.6: Liquid Penetrant Inspections of Specimen 1

There are defect (circle in ***Figure 4.6***) detected in the inspection at the weldment of Specimen 1. The defect of Specimen 1 is less compare to Specimen 2 and 3 because of amount of stress applied is less than the other two specimens.

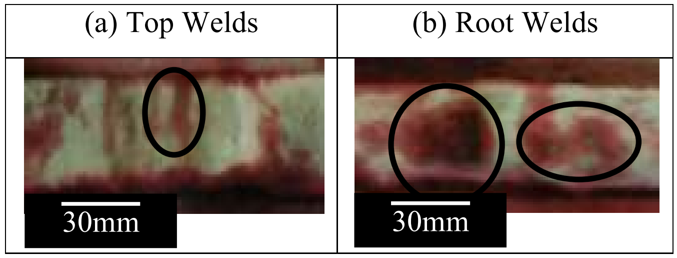


Figure 4.7: Liquid Penetrant Inspections of Specimen 2

There are defect (circle in ***Figure 4.7***) detected in the inspection at the weldment of Specimen 2. The defect existed between the weld metal and based metal. The defect of Specimen 2 is more compare to Specimen 1 because of amount of stress applied is higher than specimen 1.

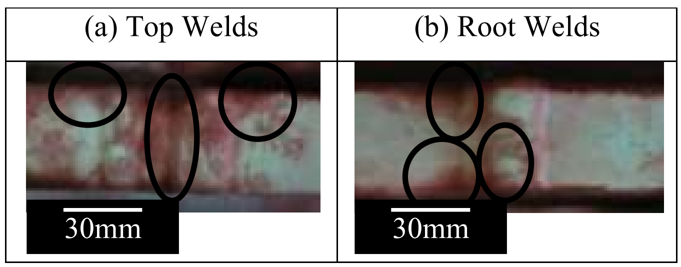


Figure 4.8: Liquid Penetrant Inspections of Specimen 3

A lot of defect (circle in ***Figure 4.8***) detected by the inspection at the weldment of Specimen 3 compare to the others two specimens. This showed that the beam with a large amount of stress result a high number of defects that could leads to failure of the structure.

4.7 Optical Microscopy

The microstructure of the specimen observed by using 50-magnification lens after all test conduct on the specimen. The micrograph of the specimens shown in ***Figure 4.9***, ***Figure 4.10, Figure 4.11 and Figure 4.12***.

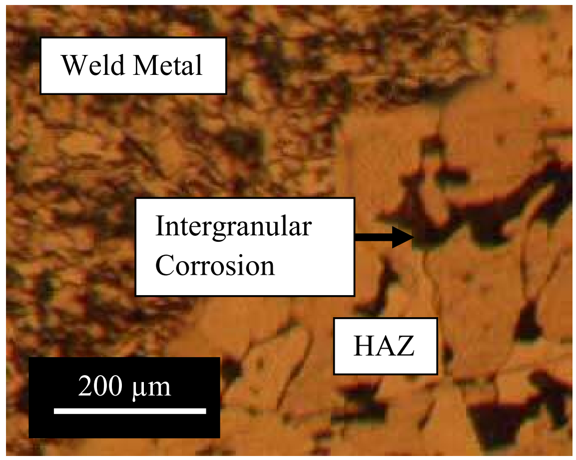


Figure 4.9: Specimen No. 0 Micrograph

This is the microstructure of Specimen No. 0 that not been test with bolt loaded double beam. This microstructure used as a benchmark to others three specimen microstructure. Intergranular cracking exist in the microstructure even that the specimen not applied with the tensile stress. This showed that the residual stress caused by welding process effects the grains boundaries in HAZ.

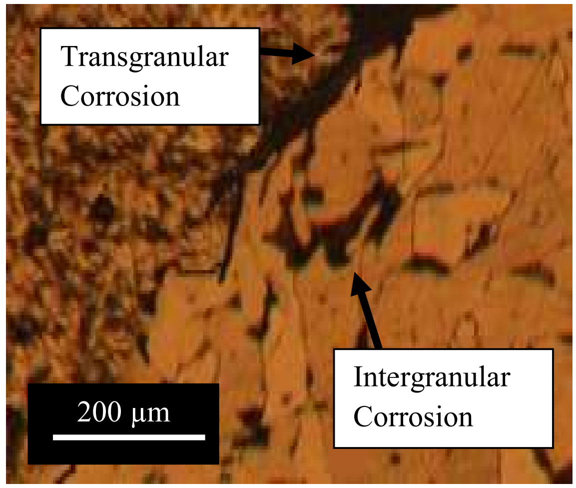


Figure 4.10: Specimen No. 1 Micrograph

The cracks of Specimen 1 are combination of Transgranular and Intergranular SCC. The Transgranular SCC caused by the tensile stress resulted from the deflection of the specimens while Intergranular SCC caused by the residual stress from the welding process. The magnitude of the crack is small compare to the other two specimen due to the less amount of resultant stress in bolt loaded double beam test.

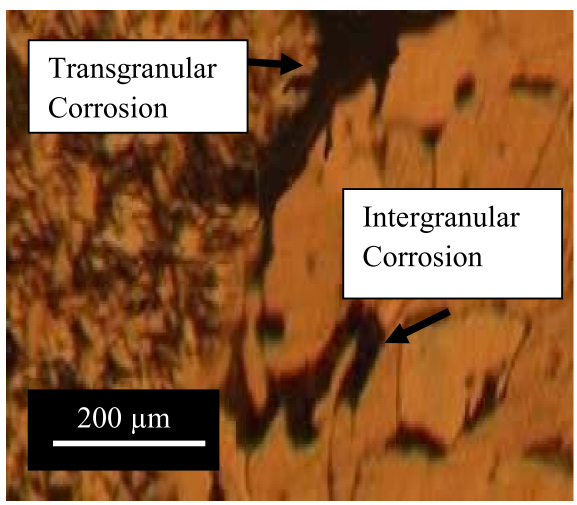


Figure 4.11: Specimen No. 2 Micrograph

The cracks of Specimen 2 are combination of Transgranular and Intergranular SCC. The Transgranular SCC caused by the tensile stress resulted from the deflection of the specimens while Intergranular SCC caused by the residual stress from the welding process. The magnitude of the crack is larger compare to the Speciment 1 due to the higher amount of resultant stress in bolt loaded double beam test.

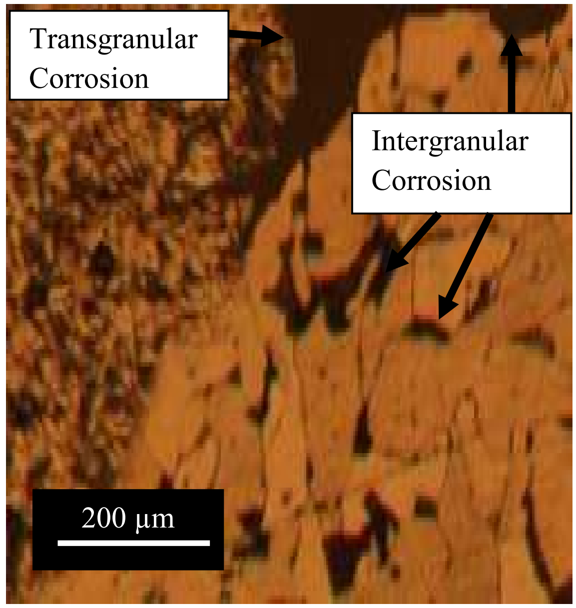


Figure 4.10: Specimen No. 3 Micrograph

The cracks of Specimen 3 are combination of Transgranular and Intergranular SCC. The Transgranular SCC caused by the tensile stress resulted from the deflection of the specimens while Intergranular SCC caused by the residual stress from the welding process. The magnitude of the crack is huge compare to the other two specimen because of this specimen resultant stress is the highest in bolt loaded double beam test.

4.8 Corrosion Rate

After 2 weeks (336 hours) specimens exposed in the Salt Spray Chamber, the weight loss of every specimen measured. The corrosion rate (mm/years) for each of the specimens calculated using ***Equation 2.1*** and ***Equation 2.2*** and tabulate in ***Table 4.7***. The calculation for Corrosion Rate showed in ***APPENDIX 7***.

Table 4.7: Corrosion Rate for Each of Specimens

Specimen No.	**C**	**Weight Loss (g)**	**Area (in^2)**	**Time (hours)**	**K**	**CR (mils/years)**	**CR (mm/years)**
0	67700	1.518	6.0	336	1.00	50.98	1.29
1	67700	2.342	6.0	336	1.00	78.65	2.00
2	67700	2.513	6.0	336	1.00	84.39	2.14
3	67700	3.102	6.0	336	1.00	104.17	2.65

The Corrosion Rate for Specimen 0 is 1.29 mm/year, for Specimen 1 is 2.00mm/year, for Specimen 2 is 2.14 mm/year and for Specimen 3 is 2.65mm/year. Specimen 3 shows the highest ability to corrode.

From the result, the specimen that was test with bolt loaded double beam test which resulting the stress corrosion cracking, the amount of corrosion rate (CR) are twice the CR of the specimen without SCC (specimen 0). The specimen with SCC occurance, the value of CR increase due to the stress resultant in the specimen during the bolt loaded double beam test.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The following conclusion could be drawn from the study:

a) From the bolt loaded double beam tests, the values of deflection of the specimens (6.07mm/150mm length, 7.442mm/150mm length, 8.305mm/150mm length) were much greater (6.07mm/150mm length ≈ 202.3mm/5000mm length) which is more than 5 times higher compare to the design maximum allowable vertical joint deflection (37.17mm/5000mm length). With the higher deflection than the design allowable vertical joint deflection, the Stress Corrosion Cracking occurs.

b) There were two types of Stress Corrosion Cracking present in the specimens, which is Intergranular and Transgranular SCC. The tensile stress applied on the specimen by the deflection of the beam is the factor of transgranular SCC. The intergranular SCC present because of the thermal exposure during welding and cutting process of the specimens.

c) The occurrences of Stress Corrosion Cracking increase the Corrosion Rate. Specimens with Bolt Loaded Double Beam Test (Specimen 1, Specimen 2 and Specimen 3) showed higher mass loss compares to the specimen without the Bolt Loaded Double Beam Test (Specimen 0). The Corrosion Rate for Specimen 1, Specimen 2 and Specimen 3 were 2.00 mm/year, 2.14 mm/year and 2.56 mm/year. The Corrosion Rate for Specimen 0 was 1.29 mm/year. These concluded that the Corrosion Rate for specimens which were subjected to Tensile Stress were higher than the stress free specimen.

5.2 Recommendations

The study could be done better if the following aspects could be consider in the future.

a) Further studies on the project needed because this project done with some limitations such as lack of welded specimen. The welded specimen available for this project is the welded plate with dimension of 6 inches length, 8 inches wide and 1 inch thick (150 mm X 200 mm X 25 mm). Due to bend the 1 inch (25 mm) plate for Bolt Loaded Double Beam Test, the length supposed to be 12 inches plate. Due to the lack of the specimen, the setup for test done by cutting the welded plate into 0.5-inch (12.7 mm) thickness. With 0.5-inch thickness, the specimens are possible to bend as shown in ***Appendix 5.*** However, the cutting process introduces heat that could affect the microstructure of the specimens.

b) The Non Destructive Testing used to detect the discontinuities and defect of the weldment in this project only Liquid Penetrant Inspection only. This is because Magnetic Particle Testing cannot be used because the available probe for this inspection is too big compare to dimension of the specimen (150 mm X 25 mm X 12.7 mm). Meanwhile the Radiographic Inspection apparatus are broke down. With the other inspection, the defect of the specimens could be detected effectively.

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APPENDICES

APPENDIX 1(a) FINAL YEAR PROJECT 1 GANTT CHART

No.	Detail / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic								Mid-Semester Break							
	Propose Topic															
	Supervisor Approval															
2	Preliminary Research Work															
	Introduction															
	Objective															
	List of reference/literature															
	Project planning															
3	Submission of Preliminary Report				15/8											
4	Project Work															
	Reference/Literature															
	Practical/Laboratory Work															
5	Submission of Progress Report									8/9						
6	Seminar									12/9						
7	Project Work Continue															
	Practical/Laboratory Work															
	Computer Modeling															
8	Submission of Interim Report															
9	Oral Presentation															

APPENDIX 1(b) FINAL YEAR PROJECT II GANTT CHART

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue	■	■	■					Mid-Semester Break							
2	Submission of Progress Report 1				●											
3	Project Work Continue				■	■	■	■								
4	Submission of Progress Report 2									●						
5	Seminar (compulsory)									●						
5	Project work continue									■	■	■	■			
6	Poster Exhibition											●				
7	Submission of Dissertation (soft bound)													●		
8	Oral Presentation														●	
9	Submission of Project Dissertation (Hard Bound)															●

APPENDIX 2: CORROSION RATE CONVERSION FACTORS

APPENDIX 3: DENSITIES OF COMMON ALLOYS

APPENDIX 4: Figure of Welded A516 Plate

APPENDIX 5: Figure of Corrode Specimens

APPENDIX 6: Calculation for Resultant Stress

For Specimen No. 1,

$$f = \frac{\Delta d(3Et(3L - 4a)}{2a}$$

$$= \frac{(0.00607)(3)(210 \times 10^6)(0.012)(3(0.127) - 4(0.0381)}{2(0.0381)} = 137{,}667.6$$

For Specimen No. 2,

$$f = \frac{\Delta d(3Et(3L - 4a)}{2a}$$

$$= \frac{(0.007442)(3)(210 \times 10^6)(0.012)(3(0.127) - 4(0.0381)}{2(0.0381)} = 168{,}784.4$$

For Specimen No.3,

$$f = \frac{\Delta d(3Et(3L - 4a)}{2a}$$

$$= \frac{(0.008305)(3)(210 \times 10^6)(0.012)(3(0.127) - 4(0.0381)}{2(0.0381)} = 188{,}357.4$$

APPENDIX 7: Calculation for Corrosion Rate

For specimen 0,

$$CR(mils/year) = C \times \frac{weight\ loss}{area \times time} \times K = 67700 \times \frac{1.518}{6 \times 336} \times 1.00$$

$$= 50.98\ mili\ inch\ per\ year$$

$$CR\left(\frac{mm}{year}\right) = 0.0254 \times CR\left(\frac{mils}{year}\right) = 0.0254 \times 50.98 = 1.29\ mm/year$$

For specimen 1,

$$CR\left(\frac{mils}{year}\right) = C \times \frac{weight\ loss}{area \times time} \times K = 67700 \times \frac{2.342}{6 \times 336} \times 1.00$$

$$= 78.65\ mili\ inch\ per\ year$$

$$CR\left(\frac{mm}{year}\right) = 0.0254 \times CR\left(\frac{mils}{year}\right) = 0.0254 \times 78.65 = 2.00\ mm/year$$

For specimen 2,

$$CR(mils/year) = C \times \frac{weight\ loss}{area \times time} \times K = 67700 \times \frac{2.513}{6 \times 336} \times 1.00$$

$$= 84.39\ mili\ inch\ per\ year$$

$$CR\left(\frac{mm}{year}\right) = 0.0254 \times CR\left(\frac{mils}{year}\right) = 0.0254 \times 84.39 = 2.14\ mm/year$$

For specimen 3,

$$CR(mils/year) = C \times \frac{weight\ loss}{area \times time} \times K = 67700 \times \frac{3.102}{6 \times 336} \times 1.00$$

$$= 104.17\ mili\ inch\ per\ year$$

$$CR\left(\frac{mm}{year}\right) = 0.0254 \times CR\left(\frac{mils}{year}\right) = 0.0254 \times 104.17 = 2.65\ mm/year$$

APPENDIX 8: Procedure for Liquid Penetrant Inspection

1. Pre-cleaning:
    - The test surface is cleaned to removed any dirt, paint, oil, grease or any loose scale that could either keep penetrant out of a defect, or cause irrelevant or false indication.
    - Cleaning method may include solvent, alkaline cleaning steps, vapor degreasing, or media blasting. The end goal of this step is to clean surface where any defects present are open to the surface, dry and free contamination.
2. Application of Penetrant:
    - The penetrant is then applied to the surface of the item being tested. The penetrant is allowed time to soak into any flaws (generally 10 to 30 minutes).
    - The soak time mainly depends upon the material being testing and the size of flaws sought. As expected, smaller flaws require along penetration time.
3. Excess Penetrant Removal:
    - The excess penetrant is then removed from the surface. Removal method is controlled by the type of penetrant used. When using solvent remover and lint-free cloth is important to not spray the solvent on the test surface directly because this can remove the penetrant from the flaws.
    - This process must be performed under controlled condition so that all penetrant on the surface is removed but penetrant trapped id real defect remains in place.
4. Application of the Developer:
    - After excess penetrant has been removed a white developer is applied to the sample. Several developer types are available including non-aqueous wet developer, dry powder, water suspendible and water soluble.
    - Commercially available in aerosol spray can and may employ acetone, isopropyl alcohol or a propellant that is a combination of two. Developer should form a thin even coating on the surface.
5. Inspection:
    - Inspection of the test surface should take place after 10 minutes development time. This time delay allows the blotting action to occur. Also of concern, if one waits too long after development the indication may bleed out such that interpretation is hindered.

APPENDIX 9: Procedure for Optical Microscopy Examination

1. Grinding:
   - To minimize thickness of damaged layer from to the sectioning process.
   - Typically done using rotating discs covered with SiC paper and using water as lubricant. Various available grades: 180, 240, 320, 400, 600 grit (grains per square inch).
   - Initial abrasive size establish a flat sample surface and remove damaged layer due to sectioning. Subsequent abrasive sizes remove damaged due to previous grinding steps.
   - Light pressure should be applied at the centre of the sample. Grind until all the blemishes from previous steps have been removed. Ensure the flatness of sample surface is maintained throughout the grinding steps.
   - Before proceeding to the next grinding steps, ensure the scratches from the current step are in a single orientation.
2. Polishing:
   - Consist of rotating discs covered with soft cloth impregnated with micro-particles of diamond or other media and lubricant. Typical "rough" polishing of 9, 6, 3 µm. Typical "final" polishing of 1, 0.25 µm diamond, or 0.06 µm Al2O3 or SiO2 suspensions.
   - Done after at least a 400 grit grinding.
   - Polishing should produce a scratch-free mirror-like finish on the sample.
3. Etching:
   - Two-fold purpose:
     - Remove final thin layer of deformation
     - Preferentially attack particular sites on the sample surface with the "highest energy", leading to various features to be distinguished in reflected light microscopy
   - A polished sample is etched by swabbing a cotton tip dipped in etchant, by immersing or spraying the sample with the etchant.
   - Should always be done in stages, beginning with light attack, an examination in the microscope and further etching only if required. An over-etched sample requires a repeat of the polishing procedure.
   - Common etchants for carbon steel A516 is 2% Nital.