RESIDUAL STRENGTH OF STEEL COUPONS AND PLATES
SUBJECTED TO CORROSION DAMAGE

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SUBJECTED TO CORROSION DAMAGE

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ABSTRACT

Structural steel is widely popular in the construction, energy and transportation industry. The unique properties of structural steel come from the chemical composition and the manufacturing process of the steel. The material properties of the steel can be altered by adding small quantities of other elements during the manufacturing process. High strength low alloy steel is often used in the construction of the naval vessels. The high strength low alloy steel (HSLA) provide better mechanical properties and greater resistance to the corrosion damage. The carbon content in the high strength steel is 0.05- 0.25%. Other elements like copper, silicon, chromium, and phosphorus are added in small quantities for improving the strength and corrosion resistance. Despite having the high corrosion resistance, the sea environment with high humidity and saline water is a favorable condition for the corrosion process. The damage assessment due to corrosion in naval vessels is critical for the maintenance and safety. The damage transpired by the corrosion is a complex phenomenon. It depends on the extent of corrosion, nature of corrosion and the location of the corrosion. The corrosion can be broadly classified into uniform corrosion, pitting corrosion, groove corrosion and galvanic corrosion. The various nature of the corrosion affects the residual strength of the steel structure in different ways.

Visual inspection is a common method for corrosion damage inspection. Visual inspection does not take account of structural analysis and failure studies. Corroded
parts of the naval vessels are often replaced before any significant loss of the strength. Replacing corroded part is an expensive and time-consuming exercise. Delay in the repair of the damaged part can cause series safety concerns. This assignment was conducted to study the residual strength in the steel coupons and plates subjected to the accelerated corrosion damage.

In this assignment, residual strength of ASTM A-572 steel coupons and steel plates were established for tensile and compressive buckling loading condition. The effect of uniform corrosion and the pitting corrosion were studied. Study on the steel stiffened panels subjected to corrosion damage is presented in the doctorate thesis of Mr. Srikanth Bajaj. The main aim of this study is to derive a relationship between the corrosion damage and the loss of the strength in the steel structural member.

In order to achieve the artificial corrosion damage electrochemical corrosion process, Q-Fog chamber and CNC machine were used. ASTM A572 grade 60 structural steel was used for the experimental testing. To verify the experimental results, finite element analysis (FEA) was conducted on the equivalent test samples. FEA software Abaqus was used to conduct the finite element analysis. Corroded and non-corroded test specimens were tested for tensile test and compressive buckling test. The results acquired from the experiment, FEA model and analytical calculations were analyzed and compared. The residual strength in the steel coupons and plates due to corrosion damage is studied. The relation between percentage corrosion and the strength loss is obtained based on the experimental, FEA and analytical results.
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CHAPTER 1
INTRODUCTION

Steel is preferred building material in the construction industry. Steel is an alloy of iron, carbon and other elements. The metals do not occur in nature in pure form. The metals are extracted from the ores by electrolysis and chemical reactions. The extracted pure metal is chemically unstable with the surrounding environment. Some metals like copper, gold, and platinum are found in metallic state and stable in their pure form. The pure form of the metal has the tendency to revert to the original mineral form. The way in which the metals revert to their original form is by corrosion [1]. The corrosion in nature is generally caused by oxidation and reduction process. The pure metals have the tendency to release the free electron during a chemical reaction. The process of losing the electron is also known as oxidation. The electrons lost from the metals react with the surrounding gases. The element that gains the free electron is known as reduction.

Corrosion damage is a prevalent problem in many industries. The implications of the corrosion damage are observed in the cost, safety, and lifespan of the structure. The National Association of Corrosion Engineer (NACE) publishes the report on the numerous costs associated with the corrosion damage. The Department of Defense (DoD) estimated the annual navy ships corrosion cost for 2005 was $ 2.4 Billion [2]. The annual navy ships corrosion cost increased to the $ 3.15 Billion in the year 2010. The corrosion has massive implication on the financial aspect of naval vessels maintenance.

Corrosion
is an electrochemical reaction between the metal and its surrounding environment. The rate of corrosion and the nature of corrosion depends on the surrounding environment. The rate of corrosion is high in marine environment due to humidity and salted seawater. The damage due to corrosion affect the sectional and material properties of the structure. The reduction in the section changes the slenderness ratio, radius of gyration and cross-section area. It also changes the modulus of elasticity, yield strength, and ultimate load carrying capacity. This change in the material and sectional properties in the structure can cause stress concentration, buckling and excessive deflection in the structure.

Conventionally corrosion inspection is carried out by the visual inspection. The corrosion damage is then categorized based on the level of degradation. The visual inspection is a simple and quick method but it cannot accurately determine the residual load carrying capacity. In recent times, modern techniques like radiology, eddy current, magnetic particles, and ultrasonic gauge are used to determine the corrosion damage. The modern technique gives highly accurate and reliable results of corrosion damage. The primary way to resolve the corrosion damage is by replacing the damaged structural part. The cost of manufacturing and replacing the specific part of the structure is tremendous. The time for replacement is also a critical factor as the ships cannot be operational during that time. The overall cost of the replacing the corroded part has both financial and scheduling implications. This can be avoided by analyzing and calculating the residual strength of the damaged part of the structure. The standardized method to analyses the corrosion damage and accurately calculate the residual strength is utmost important.
1.1 Problem Statement

Steel is widely popular in many industries for its mechanical properties. Steel has an excellent weight to strength ratio. The ductility and malleability properties make it perfect material in several industries. Steel properties can be modified easily by adding the elements like copper, platinum, phosphorus, and nickel in the manufacturing process. High strength low corrosion steel is generally used in the construction of navy ships. The major parts of the ship including hull, deck, frames, and bulkhead are made of structural steel. The structural elements like hull and frames are made up of stiffened panels. Stiffened panels consist of plates, small beams (stiffeners) and girders. Plates receive the hydraulic pressure from the water, stiffeners support the loads from the plates and the girders support the load from stiffeners. The unstiffened plate is weak in the compressive load and it can easily buckle under compressive force. The unstiffened plate is also weak in the torsional buckling. The stiffener improves the compressive and torsional load carrying capacity of the plate by multiple times. The geometric design of the stiffened panel gives high mass to strength ratio for the stiffened panels.

The steel exposed to the external weather conditions are susceptible to the corrosion. The corrosion rate is very high in the sea environment due to saline water, humidity and temperature. The common types of corrosion observed in the navy ships are uniform corrosion, pitting corrosion, galvanic corrosion, and groove corrosion. Uniform corrosion occurs at the hull of the ship. Groove corrosion generally occurs at the welded joints. Pitting corrosion is very common on the deck of the ship. The strength of the structural elements deteriorates due to the corrosion of the metal.
To understand the effect of corrosion on the stiffened panels it is important to study the effect of corrosion on the basic building parts of the panel. Residual strength in the steel coupons and plates are studied in this assignment. ASTM A-572 grade 60 ksi steel was used in the experiment to determine the loss of strength due to corrosion. The steel coupons and the steel plates were tested under compressive and the tensile loading condition.

1.2 Research Objective

Corrosion study is a very recent field of science and is being studied widely due to safety and financial aspects. The currently established method to tackle the corrosion is to perform the visual inspection of the corroded part. Categorize the corrosion damage into various classes and replace the part if corrosion is higher than a certain critical limit. This method is proven to be costly and time-consuming. This can be avoided by exercising the structural analysis of the corroded part. Various types of corrosion are being studied in this research and the results were verified by experimental and analytical methods. The main objects of the research are as follows:

1. Develop an experimental setup to simulate the corrosion process according to standard practices.
2. Develop the relationship between the residual strength in the steel coupons subjected to uniform corrosion damage.
3. Develop the relationship between the residual strength in the steel plates subjected to uniform and pitting corrosion damage.
4. Develop finite element model to simulate the testing of corroded steel coupon and plate.
5. Comparison between the residual strength obtained by the mechanical testing, theoretical calculation, and finite element modeling to verify the best modeling method.

6. Development of quantitative rating system for steel corrosion based on the experimental and analytical results.

7. Probabilistic risk analysis for the corroded steel coupons and plates to analyze the failure rate and set the standard for the corrosion damage.

1.3 Research Methodology

The mechanical properties of the steel coupons and the steel plates with various levels of corrosion damage are studied. An extensive literature review was done to understand the process of corrosion, the rate of corrosion and nature of corrosion. Previous research practices and results were studied to comprehend the corrosion damage. The experimental techniques adopted to simulate the natural corrosion were studied and the standard corrosion practices were implemented. The steel coupons and the plates were loaded in the uniaxial plane. The steel coupons were tested for the tensile test while the steel plates were tested for the compressive buckling tests. Finite element analysis using Abaqus was conducted with loading and boundary condition analogous to the experimental setup. The results obtained from the experimental analysis and finite element analysis were compared with the theoretical results.

1.4 Thesis Outline

The thesis assignment is divided into 7 chapters. Research significance and the objective of the study are described in the chapter 1. Corrosion chemistry, nature of corrosion and corrosion prevention techniques are presented in chapter 2. Prior
research on corrosion of stiffened panels, plates, and coupons are studied in Chapter 3. Finite element analysis for corrosion specimen is also reviewed in the literature review. Chapter 4 describes the corrosion procedure implemented in the present assignment and details about the experimental setup. Chapter 5 presents the finite element analysis for corrosion of steel coupons and plates. Chapter 6 summarizes the results and the discussion based on the experimental results. Chapter 7 present the conclusion and recommendation based on the findings of the assignment.
CHAPTER 2

INTRODUCTION TO CORROSION

The following section provides the information on corrosion progression in structural steel and the corrosion protection measures. The chemical reaction of corrosion process and the factors affecting the rate of corrosion are discussed. Various corrosion types and the standard corrosion inspection techniques are described to understand the corrosion to understand the significance of the corrosion damage.

2.1 Corrosion Definition and Chemistry

Corrosion is defined as a degradation of a material due to external environmental conditions. The corrosion is not only associated with the metals but also other materials like polymers, fibers, and plastic. The corrosion of metals is significant compared to other materials. Thus, Metallic corrosion is studied in the details. The rate of corrosion for metals is higher than other materials and it changes sectional and material properties.

The metallic elements are impure in a natural state. The elements are extracted from the ores by electrolysis or reduction technique. Metals like aluminum are extracted by electrolysis process while the iron is extracted by the reduction process. The metals extracted from the ores are not in their natural form. These metals try to revert to natural form by oxidation. The more chemically stable form of these metals is its oxide,
hydroxide or sulfide [3]. Steel consists of mostly iron and other metals in small quantities. Iron is a highly corrosive element and pure iron can corrode at a very high rate of corrosion. The residual product due to corrosion of iron is commonly known as rust. Figure 1 shows the lifecycle of iron from hematite iron ore to pure iron and back to the impure state.

Figure 1: Steel life cycle from iron ore to steel and reverse to a stable form.

The oxidation process of the iron is shown in equation (2.1). When iron combines with the oxygen in presence of water the metal is oxidized. The oxidation process forms the free ions and electrons. The free electrons reduce the oxygen and form the hydroxide. The metal ion forms a solid component on the surface of the metal [4].

- Oxidation of Iron:

\[ \text{Fe} = \text{Fe}^{+2} + 2\text{e} \quad (2.1) \]

- Reduction of Oxygen:

\[ 4\text{H}^{+} + \text{O}_2 + 4\text{e}^- = 2\text{H}_2\text{O} \quad (2.2) \]
The iron and the hydroxide ions then combine which form rust:

\[
\text{Fe}^{+2} + 2\text{OH}^- = \text{Fe(OH)}_2 = \text{Fe(OH)}_3
\]  

(2.3)

Figure 2: Steel life cycle from iron ore to steel and reverse to stable form [5].

The corrosion is caused by the electrochemical chemical reaction. There are four fundamental components in the electrochemical cell: Anode, cathode, potential difference between anode & cathode and electrolyte solution to conduct the electrons. All four components must be present for corrosion to occur. Metals have the tendency to lose the electrons when they involve in a chemical reaction. The metal acting as anode loses the electrons, which is known as the oxidation process. The electrons lost from metal ends up on forming a nonmetallic ion. Cathode action reduces the oxygen from air forming hydroxide ions. The hydroxide ion formed immediately oxidizes to form rust. The typical steel electrochemical cell is shown in figure 2 [6].
The severity of corrosion damage depends on the four fundamental factors described above. The corrosion is measured in the rate at which the corrosion takes place. The unit for rate of corrosion is mm/year or µm/year. The rate of corrosion is calculated by expression (2.4) [7].

\[ R = \frac{k w}{\rho A t} \]  

(2.4)

Where,

\( w \) = weight loss of metal
\( T \) = time in seconds
\( A \) = surface area of the metal exposed
\( \rho \) = density of the metal
\( K \) = constant

The rate of the corrosion is dependant on numerous environmental and material properties. Factors like temperature, humidity, water pH, electrochemical potential affect the rate of corrosion. The increase in the temperature tends to increase the electrochemical and diffusion process. The rate of corrosion increases with the increase in the temperature at constant humidity. The steel panels near the engine room are likely to get corroded faster due to high temperature. Humidity and time of wetness play an important role in the corrosion process. The rate of corrosion increases with the increase in the humidity. The humidity level at the sea is very high and thus the corrosion of the steel used in the navy ships is much faster. The concentration of salts in the water also increases the corrosion rate. The chloride ions increase the conductivity of the electrolyte and ultimately increasing the corrosion rate. Thus the hull of the ship gets corroded much faster than then other parts. In general, the rate of corrosion is higher in the acidic water.
than the alkaline water. In case of steel, very high pH forms a protective coating of the iron oxide and that reduces the rate of corrosion.

2.2 Corrosion Types

Corrosion of a material is a natural phenomenon with complex behavior. The nature of the corrosion is based on the surrounding environmental condition and the composition of the material. National Association of corrosion engineers (NACE) distinguishes the corrosion in eight forms [8]. Nature of the metallic corrosion is shown in Figure 3.

1. Uniform corrosion
2. Galvanic corrosion
3. Erosion corrosion
4. Crevice corrosion
5. Pitting corrosion
6. Leaching corrosion
7. Intergranual corrosion

Figure 3: Types of the corrosion [9].
2.2.1. Uniform Corrosion

Uniform corrosion is the very common type of corrosion. In uniform corrosion, the exposed surface of the metal corrodes at the uniform rate. Uniform corrosion takes place when the entire metal surface is exposed to the distribution of cathodic reactants. In uniform corrosion, there is no preferential location for cathodic or anodic reaction. This type of corrosion is responsible for major corrosion damage. Uniform corrosion is easily measured by the loss in the sectional thickness. In uniform corrosion, the formation cracks and the stress concentration points are not the major issues. Thus, failure due to uniform corrosion can be predicted and prevented effortlessly.

![Figure 4: Uniform corrosion of steel pipes](image)

2.2.2. Galvanic Corrosion

Galvanic corrosion is also known as bimetallic corrosion as it involves two metals in corrosion process. The corrosion of the metals takes place due to the flow of electrons. When two different metals are placed in contact with each other the potential difference
between them cause the oxidation and reduction of the metals. This cause the corrosion of the one metal. The metal acting as an anode oxidizes and the metal acting as a cathode reduces. Corrosion of steel nut in contact with the copper bolt is a typical example of galvanic corrosion.

Figure 5: Galvanic corrosion of steel nut in contact with the copper bolt [11].

2.2.3. Erosion Corrosion

Erosion is the accelerated corrosion due to the movement of the corrosive fluid and the metal surface. Erosion corrosion is often seen by abrasion of slurry, cavitation and impinging liquid. When the surface of the metal gets corroded the corrosive product gets eroded due to wear and tear. This exposes the uncorroded metallic part to the outside environment. The exposed metal is then starting corroding and increase the rate of the corrosion.
2.2.4. Crevice Corrosion

The crevice is the localized corrosion occurs at the shielded parts exposed to the corrosion. The corrosion attack on the metal surface adjacent to the crevice or the opening between two surfaces. This type of corrosion can form between two metal surfaces or one metal and one nonmetal surfaces. Crevice corrosion initiates due to the difference in the concentration oxygen inside the crevice. The outside crevice act as a cathode with high oxygen content and pH. The chloride content is lower at the outside and higher inside the crevice. This difference in aeration and chloride concentration starts the electrochemical cell. This type of corrosion is common in bolts, holes, rivets, and joints.
2.2.5. Pitting Corrosion

Pitting corrosion is one of the most destructive types of corrosion. Pitting corrosion is very localized corrosion and it occurs on the ship deck and hull. The pits formed due to corrosion are small in diameter. The volume of metal loss in this corrosion is small compared to the uniform corrosion but it causes more damage than the uniform corrosion. Pitting corrosion is initiated by the localized chemical attack, poor application of protective coating or impurities in the metal structure. The pits formed can cause the stress concentration at the weakest part of the structure and ultimately fail the complete structure. It is hard to detect the pitting corrosion due to the small size of the pits and the pits are often covered with the corrosion product. It is also hard to detect the depth of the pit and the cracks formed due to pitting corrosion.
2.2.6. Leaching Corrosion

Leaching corrosion is the corrosion of one metal from an alloy. Leaching corrosion is also known as dealloying or selective corrosion. In leaching corrosion less noble metal is removed from the alloy by microscale galvanic mechanism. Metals have different electrochemical potential in the same electrolyte. The potential difference between the metals causes a galvanic reaction at the local level. The common metals to de-alloy are zinc, iron, and cobalt. In zinc brass alloy the leaching corrosion of the zinc takes place. Leaching corrosion can be prevented by selecting the metal with similar electrochemical potential. Environmental control can minimize the leaching corrosion process. Sacrificial anode cathodic protection can be used to prevent the corrosion.
2.2.7. Intergranular Corrosion

Intergranular corrosion is the form of corrosion in which the crystalline boundaries of the material are more susceptible to the corrosion than the matrix. Certain alloys exposed to the temperature changes the characteristics and become susceptible to intergranular corrosion. The intergranular corrosion can be caused by the impurities in the metal. In certain aluminum alloys, a small amount of iron segregate the grain boundaries and cause intergranular corrosion.
2.2.8. Stress Cracking Corrosion

Stress cracking corrosion occurs when the material is in the tension and the crack growth happens due to the corrosion. This type of corrosion can fail the ductile material suddenly under the tensile forces. In stress cracking corrosion, the surface of the metal is hardly attacked by microscopic cracks form on the surface. This type of corrosion is easily prevented by cathodic protection method.

![Stress cracking corrosion of metal](image)

Figure 11: Stress cracking corrosion of metal [17].

2.3 Effect of Corrosion on Structural Steel

The corrosion damage is simply considered as the loss of material. Various types of corrosion are listed in the above section. While the various corrosion types reduce the strength of the structure in different ways, they ultimately lead to the loss of material. The loss of material changes the geometric properties of the member like the radius of
gyration, a moment of inertia and cross-sectional area. The Structural damages due to corrosion are listed below [18].

- Loss of strength

  Corrosion reduces the effective cross-sectional area of the structural member. This eventually reduces the axial load carrying capacity and the flexural capacity of the member. The corroded structure becomes vulnerable to the design loads and the strong wind/earthquake can increase the stress concentration significantly. This is observed extensively in oil refineries and gas industry. In reinforced concrete structure the loss of the cross-sectional area of reinforcing steel can reduce the flexural capacity of the member.

- Fatigue

  The corrosion effect on fatigue strength of steel is very critical. The fatigue crack propagation of the corroded steel is a common problem. The development of pitting corrosion reduce the fatigue strength of the structural member significantly. This problem is generally observed in the connectors and reinforced concrete members.

- Reduced bond strength

  In reinforced concrete member the strength of the section depends on the bond between the steel reinforcement and the concrete. When the steel in the reinforced concrete member corrodes the product of corrosion expands. This corrosion product does not bond and interacts with the surrounding concrete properly. This ultimately reduces the load carrying capacity of the section.
• Limited ductility

In the seismic design of the structure, the ductility of the structure is important to sustain the dynamic loading. The corrosion can considerably reduce the ductility of the steel in the reinforced concrete. The corroded section has lower ductility and therefore the plastic deformation is limited. This results in the low seismic response of the structural system.

• Reduced shear capacity

Corrosion decreases the effective cross section of transverse reinforcement in concrete beam and column. In slabs, the reduction in the shear capacity can lead to the punching failure. In foundation design, the corrosion can cause the shear failure of the footing or anchorage failure.

C. Guedes Soares, Y. Garbatov and A. Zayed studied the effect of environmental factors on steel plate corrosion under marine immersion conditions. Seawater contains a high percentage of chloride, which is a very effective electrolyte. The concentration of salt in the open sea is roughly constant everywhere. High concentration of chloride ions increases the rate of corrosion significantly. While the pollution of the water and living organism near seashore also increases the corrosion rate. It is therefore very difficult to develop the perfect corrosion model for the open sea environment. The corrosion model contains a number of variables. The corrosion of the material increases with the increase in the temperature, increase in the concentration of the oxygen content etc. Guedes Soares and Garbatov proposed the time-dependent standard corrosion model. The model developed was dependent on three factors namely transition time, coating life and the long-term thickness of the corrosive waste [46].
\[ \frac{\partial d_n(t)}{\partial t} = \frac{d_\infty}{\tau_t} \exp \left( -\frac{t - \tau_c}{\tau_t} \right) \quad \text{For } t > \tau_c \]

\[ = 0 \quad \text{For } t \leq \tau_c \quad (2.5) \]

\[ d_n(t) = d_\infty \left[ 1 - \exp \left( -\frac{t - \tau_c}{\tau_t} \right) \right] \quad \text{For } t > \tau_c \]

\[ = 0 \quad \text{For } t \leq \tau_c \quad (2.6) \]

Where,

\[ \tau_t = \text{Transition Time} \]

\[ \tau_c = \text{Coating Life} \]

\[ d_\infty = \text{Long-term corrosion wastage} \]

The above equation is considering only time-dependent and all the other factors are considered as a constant. This is not a perfect corrosion model. The graph in figure 12 shows the corrosion rate and the corrosion depth with respect to the time. The second graph shows the mean corrosive depth observed and estimated with respect to the time.

Figure 12: Corrosion rate with respect to the time [46].
2.4 Corrosion Inspection Methods

Inspection plays an important role in the modern engineering design and maintenance. The inspection for the modern design starts before the fabrication of the parts and conducted till the lifespan of the structure. Inspection is done for raw construction material as well as for century’s old structure. Inspection and detection of the corrosion damage depend on the expected risk and the failure consequences. Corrosion inspections are conducted regularly based on the guidelines laid down by the concern authorities. Diagnosis and the identification of the corrosion type are important to ascertainment the cause of corrosion. Corrosion inspection also helps to propose the possible prevention and mitigation methods. Corrosion inspection is carried out by the following methods

- Visual Inspection

  Visual inspection is carried out by the experienced inspector. The visual inspection is very common for the places which are accessible physically. The inspector determines the nature of corrosion like pitting corrosion, uniform corrosion, crevice corrosion and erosion-corrosion. The inspector then categorizes the structure based on the degree of corrosion. Sketches and photographs can be used to document the degree of corrosion. Corrosion like pitting corrosion can be documented by using the optical and mechanical tools. Uniform corrosion is hard to determine by visual inspection. Thickness loss and weight loss is calculated by ultrasonic gauge. The stress cracking is also hard to detect with the eyes. Therefore. Other techniques like the magnetic particles and radiology used for the corrosion detection
Radiography Corrosion Inspection [20]

Radiography corrosion inspection method is also known as x-ray method. Radiography method is used in the inspection of corrosion under insulation (CUI) as shown in Figure 14. Corrosion of the metal under the insulation is hard to evaluate visually. Real-time radiography (RTR) and computed radiography (CR) are preferred for covered structure. Radiography technique is fast and observable. The radiography technique needs the access to both sides of the structure. The x-ray possesses health and safety hazards.
• Ultrasonic Inspection

Ultrasonic corrosion inspection is a non-destructive method for measurement of material thickness. The setup is shown in Figure 15. The ultrasonic wave flight time calculates the thickness of the structural material. This method is effective in the detection of uniform corrosion and the thickness loss. The ultrasonic inspection gives very accurate results and can be used where the coating and other padding are present. The ultrasonic method does not need the access to both sides of the structure. This method is only reliable for small areas. The ultrasonic gauge needs calibration for each material type. The contact between the material surface and the ultrasonic receiver is vital to get precise results.

Figure 15: Inspection of oil pipe using ultrasonic technique [22].
• Magnetic Particle Inspection [23]

Magnetic particle inspection used to detect the discontinuities in the iron, nickel and cobalt alloys. The material is magnetized with the direct or indirect method. The magnetized material creates the magnetic flux around itself. The surface cracks and irregularities in the material allow the magnetic flux to leak. Figure 16 shows the cracks on the metal. To identify the leaks magnetic particles like iron oxide is sprayed on the material. These magnetic particles are fluorescent and illuminate by the ultraviolet light. The Size and length of the cracks and subsurface damage are documented.

![Figure 16: Corrosion inspection using magnetic particles [24].](image)

• Field Signature Method

Field signature method of inspection is non–intrusive and continuously monitors corrosion. Field signature method detects erosion and localized cracks inside pipelines. Feeding an electric current through the structure section monitors the real-time
corrosion damage. Field signature method differentiates between localized attacks and overall corrosion. FSM is very accurate and sensitive method of corrosion inspection.

Choosing corrosion inspection method is based on the accessibility and the type of structure under inspection. The Navy uses the time-based system for the maintenance of the ships. When the ship is scheduled for the inspection the ship was opened and vented before the inspection. The inspection is generally done by the visual inspection method. Places which are not accessible are inspected by the ultrasonic method of inspection [26].

2.5 Corrosion Prevention Methods

Several protection methods can reduce the corrosion damage of the structure. For offshore structures and ships, the coating and the cathodic protection methods are commonly used. As described earlier the corrosion is an electrochemical process and it
requires moisture, oxygen and the potential difference to start the corrosion of the metal. In absence of either the corrosion does not occur. The primary corrosion protection methods are described below [27].

- Active Corrosion Protection

The active corrosion protection system works by influencing the electrochemical corrosion reaction. The reaction of the iron oxide formation can be avoided by using active corrosion protection system. The arrangement of active anode corrosion protection works using an automated electronic control unit. Electronic control unit works together with an active anode and a reference anode. Both active and reference anode are fitted below the waterline. The reference anode senses the electrical voltage difference of the surrounding water. The reference anode sends a signal to the control unit, which in turn sends a suitable current to the active anode. The amount of current supplied is based on the water temperature and chemical composition. The active anode then emits ions into the water surrounding the ship hull. These ions effectively prevent corrosion of the naval vessel.

Figure 18: Active corrosion protection for naval vessels [28].
• Passive Corrosion Protection

In passive corrosion, isolation of the metal from the corrosive agents prevents the damage. The coating, layers are used to separate the metal from the corrosive agents. This method is very common in bridges, ships and reinforcing bars. Wear and tear can destroy the protective layer and expose the metal to surrounding environment. After the coating is damaged the metal may corrode in very short time. Corrosion started under the coating is hard to determine and cause substantial damage.

![Protective layer](image)

Figure 19: Passive protection layer on reinforcing steel rebar [29].

• Permanent corrosion protection

The key importance of the permanent protection is to offer the protection at the extremely important parts of the structure. The environmental situations like climate condition, chemical factors are relatively minor in this situation. The places with low temperature, low humidity, and low abrasion are generally protected by permanent protection methods. The passive methods for permanent protection are listed below.
a) Tin Plating  
b) Galvanizing  
c) Copper Plating  
d) Enameling  

Figure 20: Coating of zinc layer on the steel [30].

Each protection method has its own advantages and disadvantages. The factors considered in the corrosion protection system are cost, surrounding environment, time and the size of the structure. In navy ships coating and cathodic protection (CP) are very popular methods for corrosion protection. Cathodic protection method is generally used for the protection of the hull which is in constant contact with the water. While the walls and the deck of the ship were protected by the coating.
The design of the structural members can also affect the lifespan of the coating and the corrosion damage. The small structural components are more difficult to protect against the corrosion than the larger parts. The parts are designed in such a way that the moisture and derby traps are avoided. The structure is accessible for supervision and maintenance. The parts of the structure are managed carefully and any contact between two different metals are avoided.
CHAPTER 3
LITERATURE REVIEW

The background of the plate theory, literature analysis, and the FEA practices are described in this chapter. The literature study will be used to analyze the residual strength of the steel plates and coupons. This section provides information on failure mode of the steel plate and coupons. The finite element analysis studied in this chapter will be used to model the FEA model of steel plates and the steel coupon.

3.1 Basic Introduction

Steel is an alloy of iron, carbon and additional elements. Iron is the base metal in the steel and other elements are present in small percentages. The carbon content in the steel varies from 0.002% to 2.14% of its total weight. The other elements like copper, chromium, Nickel, Phosphorus, and manganese are used in a small percentage. The chemical and physical properties of the steel are controlled by changing the concentration of the various elements during the manufacturing process of steel. These qualities include hardness, yield strength, tensile strength, corrosion protection and tempering behavior. Pure iron has the very less resistance to the atoms and thus it is highly ductile material. Addition of the carbon and additional elements act as a hardening agent. When the carbon content is very high, the steel becomes brittle and commonly
known as pig iron. Pig iron generally contains more than 2.1% of carbon percentage. Steel is widely used in various industries for its high strength to weight ratio. Steel is ductile material compare to other building materials like concrete and timber. The typical stress- strain curve for the steel is shown in Figure 22. The behavior of the steel under loading can be categorized into four parts.

- **Elastic behavior**

  When the load is applied to the ductile material, it undergoes deformation. Initially, the stress in the material due to the external loads is proportional to the strain. When the load is removed in the elastic state the material resorts to the original position. This is known as the elastic behavior of the ductile material. The slope of the stress-strain curve is known as the modulus of elasticity. The area under the stress-strain curve is known as the strain energy. Elastic behavior is beneficial in the design of the structural member.

- **Yielding point**

  Yielding of the steel is where the strain in the steel increases while the stress remains same. Many ductile materials, polymers, and ceramics have a specific yielding point.

- **Strain hardening**

  After the yielding point, the stress-strain curve drops slightly. The deformation continues with the increase in the stress. The stress increase due the process is known as strain hardening or work hardening. Strain hardening is the strengthening of a metal by plastic deformation mechanism.
- Necking

As the loading continues the local strain increases disproportionally in a small area known as necking. The local cross section becomes significantly smaller than the original sample. Further increase in the loads causes fracture of the material sample.

![Stress-strain curve for structural steel](image)

Figure 22: Stress-strain curve for structural steel [32].

The steel used in this experiment is ASTM A-572 grade 60 steel. This is also known as high strength low alloy (HSLA) steel. ASTM A-572 grade 60 is ductile and easy to procedure steel. It can be machined and welded easily. It is available in grade 55, 60 and 65. This steel is generally used in bridge plates, gusset plates, and steel stiffeners. The typical chemical composition is shown in Table 1 [33].
Table 1: Chemical composition of high strength low alloy steel.

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.23</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.35</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.04</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.05</td>
</tr>
</tbody>
</table>

3.2 Steel Stiffened Panels, coupons and plates

Structural stiffened panels are the principal element in the modern ship construction. The structural steel plate is weak in flexure and bucking load carrying capacity. The plates are supported by the stiffener to resist the bending and torsional stresses. When the steel plate is stiffened with another plate element, it is called as a stiffened panel. Steel plates and stiffened panels are used for deck, hull and partition walls assembly in naval vessels. The stiffener can be attached in various shapes and alignment based on the loading direction. The images in Figure 23 shows the different types of stiffened panels.

Figure 23: Stiffened panel types [34].
In naval vessels, the continuous stiffeners in longitudinal and transverse direction are provided. The stiffeners are generally welded to the main plate. There are some areas where the rivets are used. The plates are generally supported by the stiffeners and depending on the position of the stiffeners the flexibility and the rotational stiffness of the plate is determined. The plates in the ship have simply supported connection at the edges. Deck beams are used to give additional resistance to the pressure of the water on the sides of the hull. The following figure shows the major structural parts of the naval vessel [35].

Figure 24: Naval vessel structural details [36].
3.3 Loading and Failure Analysis

Naval vessels are subjected to the various types of forces, in this assignment the forces acting on the stiffened panels of the ship are considered. The primary load on the ship is due to the cargo weight, hydraulic pressure, waves and the environmental factors. The loading on the naval vessels is dynamic loading due to continuous alteration in the waves. The hydraulic pressure and the waves create flexural compressive forces on the deck and the hull of the vessel. The stress is generated due to sagging and the hogging of the ship hull. Hogging defines as a beam which curves upward from the middle. Sagging defines as a beam which curves downward from the middle. The factors affect sagging
and hogging of the ship is cargo load, waves, and the weight distribution. Deflection of the main frame of the ship due to hogging and sagging is shown in Figure 26.

Figure 26: Naval vessel sagging and hogging [37].
Most of the marine accidents involve the failure of the hull. The failure is generally crack in the midship, split-off of hull girder or due to the propagation of the crack. The primary load on the ship hull is due to the buoyancy. This bending moment is highest at the center of the hull. The secondary load applies to the skin structure of the ship. Secondary loads are calculated for the localized area and under local forces. Secondary loads are considered on the complex stiffened panels. Tertiary hull forces are responsible for an individual section like hull plate in between stiffness.

Constant uniform stress is applied to the deck and strake (bottom) plates while the hull plate carries a linear stress distribution. As the ship traverses the supporting waves, it becomes obvious that these stresses will reverse. Therefore, the deck and strike plates must be capable of resisting the longitudinal compressive stresses. Being subjected to this loading, the buckling strength of the plates becomes a key structural design criterion.

The corrosion of the metal in the marine environment is discussed earlier. For naval vessels pitting corrosion, galvanic corrosion, uniform corrosion is very common. The rate of corrosion due to salt water and high humidity is very high. The degree of corrosion at hull and deck plates are different. Corrosion can affect the steel plates in a localized manner or spread uniformly throughout the plate’s surface. It is obvious that the reduction in the cross-sectional area of the plate reduces the strength of the plate. In the corrosion study location of the corroded area is also important. For example, the corrosion at the center of the plate is more critical than the corrosion at the edges of the plate.
In this assignment, the study of the tertiary forces is considered. The effect of corrosion on steel coupons and plates under both tensile and compressive forces are considered. To analyze the tensile forces the ASTM standard tensile test can be used while for the compressive buckling analysis different testing configurations are available. The tensile test can determine the modulus of elasticity, yield stress, tensile strength, fracture toughness and the elongation of the sample. A compressive buckling test can determine the ultimate buckling strength, deflected shape, and compressive stress. The critical buckling load can be calculated by various methods. Energy method, finite stripe method, and finite element analysis can be used to determine the critical buckling load.

3.3 Literature Analysis

3.3.1 Plate Theory

C. Guedes Soares developed design equations for the compressive buckling strength of unstiffened plate element with initial imperfection in 1987. The study was based on the rectangular steel plates which are common in the construction of the modern ships. The plate elements in the ship structure are stiffened to increase the strength of the structure. However, the structure is designed in such a way that the global failure of the stiffened panel does not occur and localized failure of the plates between stiffeners are allowed to fail. The design strength of the plates is therefore very important to analyzed [38].

The paper was mainly focused on the initial imperfections in the plates and the residual stresses in the steel plates. The boundary condition for the plates in this case used are simply supported in all four edges. The boundary is not necessarily same in all
cases. The important parameter which governs the strength of the plates was reduced slenderness and is defined by the following equation.

\[
\beta = \frac{b}{t} \times \sqrt{\frac{\sigma_o}{E}} \tag{3.1}
\]

Where,

\(b\) = width of the plate

\(t\) = Thickness of the plate

\(\sigma_o\) = Yield Stress of the material

\(E\) = Modulus of elasticity

Reduced slenderness is a non-dimensional quantity, which was derived from the Bryan expression. In ships the \(\beta\) can vary from 1 to 5. Thus, the strength of the plate changes from yield strength to the 40\% of the yield strength. This is only for the plate with simply supported at all four edges boundary condition.

The buckling load for a rectangular plate with all the edges simply supported can be calculated by the following equation. In this case, the plate is subjected to an in-plane compressive load \(P_x\) distributed along the one edge [39].

\[
EI\omega^4 + N\omega'' = 0 \tag{3.2}
\]

Now using the boundary condition for the simply supported edges. \(\omega = 0\) and \(M_{nn} = 0\) on \(\Gamma\).

\[
D \nabla^4 \omega + \frac{P_x}{b} \omega_x = 0 \tag{3.3}
\]

Where,
\[ D = \frac{E h^3}{12(4-v)} \] (3.4)

The boundary condition is defined by the following equations.

\[ M_{xx} = -D (\omega_{xx} + v \omega_{yy}) = 0 \] (3.5)

\[ M_{yy} = -D (\omega_{yy} + v \omega_{xx}) = 0 \] (3.6)

\[ \omega = \omega_{xx} = 0 \text{ on } x = (0|a) \] (3.7)

\[ \omega = \omega_{yy} = 0 \text{ on } x = (0|b) \] (3.8)

Figure 27: Simply supported plate under compressive loading [39].

Using the constant coefficient equation and boundary conditions. The equation can be written as:

\[ \omega = c \frac{1}{a} \sin \left( \frac{m \pi x}{a} \right) \sin \left( \frac{n \pi y}{b} \right) \] for \( m, n = 1, 2 \) (3.9)

\[ D \left[ \left( \frac{m \pi}{a} \right)^4 + 2 \left( \frac{m \pi}{a} \right)^2 \left( \frac{n \pi}{b} \right)^2 + \left( \frac{n \pi}{b} \right)^4 \right] - \frac{P_x}{b} \left( \frac{m \pi}{a} \right)^2 = 0 \] (3.10)

The critical buckling load can be calculated by determining the smallest Eigenvalue.
\( n = 1 \)

\[
P_x = D \left( \frac{\pi a}{m} \right)^2 \left[ \frac{m^2}{a^2} + \frac{b^2}{b^2} \right]
\]

(3.11)

\[
P_x = \frac{\pi^2 D m b}{b^2} + \frac{a^2}{b^2}
\]

(3.12)

The critical load can be written with the coefficient \( k_c \) defined as an aspect ratio of \( a/b \)

\[
(pB)_C = k_C \pi^2 \frac{D}{b}
\]

(3.13)

Where,

\[
k = \frac{mb + a}{c} \frac{2}{mb}
\]

(3.14)

Figure 28: Graph of \( k_c \) and \( a/b \) for various Eigenvalues [39].
For the various boundary conditions of the plate in compressive loading gives different values of \( k_c \). The following graph shows the value of the coefficient \( k_c \) for five different boundary conditions.

![Graph of \( k_c \) and \( a/b \) for different boundary conditions](image)

**Figure 29:** Graph of \( k_c \) and \( a/b \) for different boundary conditions [39].

For a very long slender plate where \( a/b \ll 1 \) the plate element is divided into strips of a unit length. The strips are divided longitudinally and vertically. The critical buckling load for both directions is then calculated.
Figure 30: Slender plate divided into vertical and horizontal strips [39].

The Sezawa’s formula for the buckling of the unite length element plate gives the following equation.

\[(N_x)_{Cr} = \frac{4\pi^2 D}{s^2}\] for the longitudinal stiffener and

\[(N_x)_{Cr} = \frac{\pi^2 D}{s^2}\] for the transverse stiffness.

Therefore, in the design process longitudinal stiffeners are generally used as it provides four times the strength of the transverse stiffeners. The buckling load is different from the ultimate collapse load. The collapse load is higher than the buckling load. After the buckling of the plate, the stresses in the plate redistributes and the plate takes the additional load until it reaches the failure. The critical load for a simply supported plate on all edges is given by following equation [40].
\[ PCr = \frac{4\pi^2D}{b} \]  

(3.15)

3.3.2 Pitting Corrosion

Effect of pitting corrosion on the ultimate strength of steel plates subjected to in-plane compression and bending is studied by Tatsuro Nakai, Hisao Matsushita, and Norio Yamamoto. The paper presented the ultimate buckling strength of a plate subjected to pitting corrosion is less than the buckling strength of a plate subjected to the uniform corrosion for similar thickness loss.

It is conservative to consider the ultimate strength of a plate at the minimum cross section for the pitting model. It was also observed that the reduction in the compressive strength of a plate subjected to pitting corrosion is smaller than the tensile strength of the same thickness loss. The following figure shows the pitting corrosion on the web of a ship hull. Initially each corrosion pit exits separately but after the increase in the corrosion, the pits join each other.

![Figure 31: Cross section of pitting corrosion on metal sample [41].](image)

The webs in the ship are to keep the relative distance between side shell and faceplate. The web is also very important to resist the shear force. In the ship structures, the shear force is relatively low with respect to the compressive force. Thus the thickness
of the web is much smaller in the ship stiffened panel and the reduction in the thickness reduces the strength of the plate significantly. The size of the pit is very important in the study so the data from the 14-year-old ship hull was used as a benchmark. The shape of the pit is a circular cone. The diameter of the pit varies from 25-35mm. The depth to the diameter of the pit is 1:8 [41].

The Tensile test of the pitted samples was carried out. The sample was machined by CNC machine and not corroded naturally. The samples are shown in Figure 32. The experiment showed that the loss of the tensile strength of the corroded steel is much severe than the loss of compressive strength. The location and the maximum thickness loss of the plate under compressive force is not the suitable parameter to determine the residual strength of the plate. The degree of pitting intensity (DOP) is used to predict the reduction in plate strength [41].

Figure 32: Pitting corrosion on steel coupons [41].
The paper presented by Jeom Kee Paik, Jae Myung Lee, Man Ju Ko shows the ultimate strength of the plate under shear force. In this case, the plate is simply supported from all four sides. The Elastic shear modulus is given by \( G = \frac{E}{2(1 - \nu)} \) and the plate bending rigidity is donated by \( D = \frac{Et^3}{12(1 - \nu^2)} \). The plate-reduced slenderness is defined as \( \beta = \frac{b}{t} \sqrt{\frac{\sigma_y}{E}} \). The paper presented an idealized corrosion of steel. The following image shows the various corrosion patterns. The first one is the uniform corrosion i.e. general corrosion. The second is localized corrosion in which the degradation of the material occurs at the localized location. In localized corrosion, the fatigue cracks arise sometimes. The formation of fatigue cracks reduces the strength of the structure further [42].

![Figure 33: Pitting corrosion on metal][42]

The following sample shows the pitting corrosion damage distribution. The degree of scatter-ness and the degree of pitting intensity is different for the different cases. The shape of the pitting corrosion is circular in shape and the size of this localized corrosion is 25-80 mm. The DOP (degree of pitting corrosion) is 10%, 20%, 30%, and 50% for sample a, b, c and d respectively. The degree of pitting corrosion is calculated by the following equation [42].

\[
DOP = \alpha = \frac{1}{ab \sum_{i=1}^{n} A_{pi}} \times 100(\%)
\quad (3.16)
\]

Where,
n = number of pits.

$A_{pi}$ = surface area of the $i$th pit.

$a$ and $b$ = length and breadth of the plate.

Figure 34: Pitting corrosion on the thin rectangular plate [42].

Figure 35: Pitting corrosion damage level [42].
The ultimate shear strength of the plate under shear loading for the pitting corrosion is dependent on the degree of pitting corrosion. While the ultimate strength of a plate under the compressive load is, governed by the smallest cross-sectional area.

3.3.3 Uniform Corrosion

In the tensile test assessment by Y. Garbatov, C. Soares, J. Parunov and J. Kodvanj the test was performed on the specimen cut from the corroded box girder. The box girder was corroded due to seawater. The corrosion type was uniform corrosion. The degradation of the material was defined as follows [43].

\[
D = \frac{V_o - V_c}{V_c} \times 100\% \tag{3.17}
\]

Where,

\( V_o = \) volume of uncorroded plate

\( V_c = \) volume of corroded plate

The volume of the corroded plate was defined as follows

\[
\int_{l_1}^{1} \int_{b_1}^{1} h(x, y) dx dy \tag{3.18}
\]

The equation shows the degradation of the material using the volume of the material. For the practical purpose, the mass loss due to corrosion is generally used. The thickness loss can also be calculated by the mass loss of the sample. As we know the loss of thickness is not uniform throughout the surface of the material so the method is not widely popular.
In the tensile testing, the tensile stress and strain are obtained by following equations. \( \delta \) is the controlled displacement, \( A_o \) is the total cross sectional area and \( L_o \) is the total length of the sample. In modern machines, the INSTRON machine can calculate the stress during the testing and the strain gauge can be used to calculate the strain in the sample.

\[
\sigma_e = \frac{P}{A_o} \tag{3.19}
\]

\[
\varepsilon = \frac{\delta}{L_o} \tag{3.20}
\]

The stress-strain analysis presented is based on the true stress-strain curve. The change in the modulus of elasticity, Tensile strength and the elongation with respect to the degree of corrosion is shown in Figure 37 [43].
Figure 37: Degree of corrosion of elastic modulus and tensile strength [43].

The paper showed that the reduction in the strength of the structural member reduces significantly due to the corrosion. The reduction in the yield strength of the material is nonlinear in nature while the reduction in the ultimate tensile strength of the material is a linear in nature. The experiment also shows the change in the material parameter and localized pitting are also important factors in the reduction of the strength of the material.

Figure 38: Degree of corrosion to percentage elongation [43].
3.3.3 Finite Element Modeling

Duo Ok, Yongchang Pu, Atilla Incecik studied computation of ultimate strength of locally corroded unstiffened plates under uniaxial compression. The study was focused on the localized pitting corrosion and finite element modeling. The study of uniform corrosion is easily derived from the reduction in the thickness of the plate. While the pitting corrosion and the localized corrosion is very difficult to formulate. Localized corrosion always starts from the point of the stress concentration. At higher stress region the coating on the material removes and the corrosion starts. The FEA model for the pitting corrosion is developed as follows.

![Diagram of FEA approach]

Figure 39: development of pitting corrosion model [44].
The general shape of the pitting corrosion in nature is semi-sphere or conical in the shape. In many studies, the pitting was done with the help of CNC machine. The CNC machined pitting is cylindrical in the shape and does not represent the natural corrosion. The corrosion approach is not the uniform distribution of the pits. Instead of that, the multiple pits are grouped together in the rectangular and fairly close to each other. The width and length of the rectangular area are based on the total dimension of the plate. Similarly, the depth of the rectangular area is based on the total depth of the plate. The same rectangular cross section is shown in Figure 40.

Figure 40: Rectangular corroded areas [44].

The approach to the grouping of the pits in a rectangular area is based on the fact that the ultimate and buckling strength of the plate is dependents on the smallest cross-sectional area. The scatter-ness of the pits does not play an important role in the ultimate strength of the plate. In this analysis, ANSYS shell layer model was used and the midpoint nodes were artificially moved to the bottom surfaces and align to interact with rest of the material.
Figure 41: Pitting corrosion ANSYS model [44].

Figure 42: Stress-strain graph for various degree of pitting corrosion [44].
The above graph shows the stress-strain graph for the corroded samples. The pit depth used in this case is 50% of the total depth of the plate. The strength reduction increases as the pitting length increases. The results show the length, breadth, and depth of the pits reduce the strength of the ultimate strength of the plate. The slenderness ratio has a very little effect on the reduction of the strength of the plate. Transverse location is very critical in the pitting corrosion. As the length of the transverse corrosion increases, the strength of the plate reduces drastically.

The paper on Finite element analysis of buckling of corroded ship plates presented by P.A. Slater, M.D. Pandey, and A.N. Sherbourne shows the generic buckling load versus volumetric metal loss. The study of the location of the corrosion also studied based on the Finite Element Analysis. The formulation of corrosion on a metal plate is extremely complicated. The session can occur as uniform, pitting, edge or groove corrosion. The location of the corrosion is also highly unpredictable.

While the actual corrosion patches are irregular in shape and in the depth and type of the corrosion. The corrosion on both sides of the plate is assumed to be equal. In the natural corrosion process, the session on either side of the plate is not equal. The unequal corrosion of the plate can significantly affect the ultimate buckling strength of the plate [45]. The following pattern and location of the corrosion is studied in the paper.

(i) Corrosion of center of the square.
(ii) Corrosion of the perimeter area around a square central area.
(iii) Corrosion of a square corner area.
(iv) Corrosion of two edge strips parallel to loading.
(v) Corrosion of a single edge strip parallels to loading.
The volumetric corrosion loss is calculated by the following equation.

\[ \frac{v_c}{v_u} = \frac{t_c}{t_u} \times \frac{A_C}{A_u} \]  \hspace{1cm} (3.21)

The study was conducted for the various percentage of the corrosion and at the five different locations. The normalized buckling load to the central area corrosion graph is presented in Figure 43.

![Figure 43: Normalized buckling load to the corrosion area graph [45].](image)

The effect of five corrosion pattern for the constant area loss is shown below. The normalized buckling load to the area loss of 20% is plotted for all five cases. The buckling load is highest for the corrosion on the outer perimeter of the square plate. While the buckling load is minimum for the corner corrosion. The corrosion of single edge strip and the central area is equally severe. The corrosion of central strip is more severe than the corrosion of the single edge corrosion.
Figure 44: Normalized buckling load to the area for various corrosion locations [45].
CHAPTER 4
CORROSION PROCEDURE FOR STEEL COUPONS AND PLATES

The corrosion of the material is slow and steady natural phenomenon. It takes years for a material to get corroded based on the surrounding environmental conditions. To study the corrosion phenomenon expedited corrosion process is required, which can replicate the natural corrosion damage. We know that the uniform corrosion is a very common phenomenon and it reduces the cross-section of the member uniformly but the uniform corrosion is not always that simple. In the case of uniform corrosion, the pits and grooves might form on the member that changes the behavior and the load carrying capacity of the structural element. It is important to simulate the laboratory experiment, which resembles the actual corrosion process.

4.1 Corrosion Methodology

In this assignment three, various types of corrosion processes were used to simulate the laboratory experimental corrosion. Steel coupons were corroded for the uniform corrosion. Steel plates were corroded for the uniform and the pitting corrosion. High strength A-572 grade 60 steel was used in the experiment. Percentage degradation for uniform corrosion is evaluated by the mass loss compared to the original mass.
Percentage degradation for the pitting corrosion is evaluated by the total surface area of the pores with respect to the total surface area.

1. ASTM B117 Q Fog Chamber method
2. Electrochemical Process
3. CNN Machine

4.1.1 ASTM B117 Q- Fog Chamber Method [47].

ASTM B 117 is the standardized method used in corrosion studies to simulate the actual corrosion process. This method provides the controlled environment for the corrosion progression. Correlation between the test situation and environmental corrosion can be done by long-term environmental exposure. The apparatus required for this process consists of fog chamber, water tank, atomizing nozzle, and heating arrangement. The water used in this process is type IV water specified in ASTM D-1193. This method is the most effective method to simulate the actual corrosion progression. This method is also known as cyclic corrosion testing.

The Test samples were cleansed with the acetone before starting a test. Acetone removes any dust particles and oil. The cleaning method depends on the nature of the surface. The test specimen then placed in the Q Fog chamber with the minimum surface in contact with the support. It is important to make sure that all surfaces of the test specimen are exposed to corrosive environment. The small wooden blocks were used to place the test specimen in the chamber. The test specimens were not allowed to contact any metallic material. The fog condensed on the top cover of the chamber shall not drip on the specimen. The shape of the Q-fog chamber cover is designed in a triangular shape to avoid dripping of condensed water from the top cover. The salt solution once used for
the fogging shall not be used again. Figure 45 shows the typical fog chamber arrangement in ASTM B-117.

![Figure 45: Fog collector arrangement for atomizer cabinet](image)

The known quantity of the NaCl salt was mixed in the water used as a fogging agent. In this experiment, 5% concentration on NaCl salt solution was used. The water used in this experiment was type IV with ASTM D-1193 standards. The chemical content of the salt was examined before using for the experiment. Sodium chloride with less than 0.3% impurities was used in the experiment. The pH of the salt solution kept between 6.5 to 7.5. The pH was measured by the pH meter. The pH value of the water solution was checked once in a day. The water and salt solution shall be free from any suspended particles and the salt shall be dissolved in the water completely.

The test specimen was kept in the chamber with controlled humidity and temperature. The purified water with a known quantity of the salt mixed in it was stored in the container. The salted water then sprayed on the test specimen through the
atomizer. The temperature and the test rate is maintained as per ASTM standards. The Q Fog chamber replicates the actual environmental condition and the test specimen is subjected to the series of different environmental cycles. Four measuring cups were placed in the chamber to verify the uniform spray of the salt solution in the chamber. The Four measuring cups were placed at the 4 corners of the chamber. The chamber is closed and the machine was programmed for the ASTM B-117 test method. The rate of the spray and the temperature inside the chamber were set to simulate the natural outside condition. The corrosion process was checked two times a day to verify the precise corrosive damage. The water filled in the four measuring cups were checked to verify the equal distribution of the spray. The water in the tank was periodically filled to the top level.

![Image of Q-Fog chamber cabinet](image)

Figure 46: Q-Fog chamber cabinet [47].
The Q fog chamber can operate in two ways, traditional salt spray and profession test. In this study, traditional salt spray technique was used to corrode the test specimen. The salt concentration and the rate of the spray were adjusted as per the ASTM specification to get the precise results. The test specimens of steel coupons, steel plates, and stiffened panel were corroded in this process. The corrosion type was uniform corrosion, pitting corrosion and groove corrosion. In this report steel coupon and steel plates are examined with uniform and pitting corrosion. Stiffened panels and groove corrosion is covered in Mr. Srikanth Bajaj’s doctorate thesis.

For uniform corrosion, the specimen was kept in the chamber without any coating on them. For pitting corrosion, a protective layer of pain was used to avoid the corrosion of the entire test specimen. The pits were exposed to the surrounding atmosphere for corrosion. The specimens were cleaned once in a day to expose the new metallic surface for the corrosion. During the cleaning process, the pits were cleaned carefully and not to damage the paint outside the pits.
The corrosion rate is determined from the mass loss in a particular time interval. The rate of the corrosion was calculated from the ASTM G-1 manual [48]. The constant \( K \) in the equation depends on the unit for the rate of corrosion. The standard values of the
constant K are given in Table 2.

\[
\text{Corrosion rate} = \frac{KW}{ATD}
\]  

(4.1)

Where,

\begin{align*}
K &= \text{Constant (table below)} \\
T &= \text{Time of exposure in hours} \\
A &= \text{Area in cm}^2 \\
W &= \text{Mass loss in grams} \\
D &= \text{Density in g/cm}^3
\end{align*}
Table 2: Constant K in corrosion rate equation [48].

<table>
<thead>
<tr>
<th>Corrosion Rate Units Desired</th>
<th>Constant (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mils per year (mpy)</td>
<td>3.45 x 10⁶</td>
</tr>
<tr>
<td>inches per year (ipy)</td>
<td>3.45 x 10⁻³</td>
</tr>
<tr>
<td>millimeters per year (mm/y)</td>
<td>2.87 x 10⁻²</td>
</tr>
<tr>
<td>micrometers per year (um/y)</td>
<td>8.76 x 10⁴</td>
</tr>
<tr>
<td>picometers per second (pm/s)</td>
<td>8.76 x 10⁷</td>
</tr>
<tr>
<td>grams per square meter per hour (g/m²·h)</td>
<td>1.00 x 10⁴ D</td>
</tr>
<tr>
<td>milligrams per square decimeter per day (mdd)</td>
<td>2.40 x 10⁶ D</td>
</tr>
<tr>
<td>micrograms per square meter per second (µg/m²·s)</td>
<td>2.78 x 10⁶ D</td>
</tr>
</tbody>
</table>

To measure the corrosion percentage the initial weight of the test specimen was noted and once in a day, the final weight of the specimen was noted to calculate the corrosion damage. The test specimen was cleaned with a light jet of purified water. In some cases, the soft metal brush was used to clean the test specimen. The cleaning of the specimen helps to calculate the accurate damage due to corrosion and it also removes the deposit of corrosion from the specimen. Removal of top corrosion deposit helps to speed up the corrosion process further. When the specimen reached the desired level of corrosion it was taken out of the chamber. The specimen then cleaned properly and dried with the hot blower. The final weight of the specimen was noted and percentage corrosion was calculated. The thickness of the sample was measured using an ultrasonic gauge. The thickness at six places was measured and the average thickness was recorded. The specimen was then kept in the dry place where it does not further corrode. The test
specimen was labeled with the serial number. Figure 49 shows the Olympus ultrasonic gauge used to measure the thickness loss in the plate.

![Figure 49: Measurement of thickness using the ultrasonic gauge.](image)

4.1.2 Electrochemical Corrosion Process [49].

The electrochemical technique is extensively applied in the research of corrosion and chemical industry. This is due to the well understanding of the mechanics of electrochemical process in corrosion [50]. ASTM G-3 provides the guidance on reporting, displaying, and plotting the corrosion data. The Stockholm sign convention is recommended for reporting. The positive direction implies oxidation and denoted as the noble direction. The corrosion potentials of most noble metals, such as gold, are more positive than the non-passive metals. The negative direction called as active direction. The negative direction is associated with reduction.
In electrochemical process atoms from one metal transfer to another electron accepting metal. The electrons are transferred in the presence of the conductor solution. In nature, the electrochemical process of the corrosion of the metal is a localized and very slow process. In the laboratory, the same principle was used to corrode the metal specimen. The corrosion rate is depending on the transfer of the electrons from one metal to another. Faraday’s law can describe the electrochemical process. As per the Faraday's law, the amount of corrosion is directly proportional to the current passing through the system. The following derivation can give the expression to calculate the time, current and the percentage of the corrosion.

\[
CR = \frac{m_{t}}{tA} = \frac{ItMnF}{tA} = \frac{Mi}{nF}
\]  

Where,

\[A = \text{Surface area}\]

\[i = \text{Current density, I/A}\]
\[ I = \text{Current in amperes} \]

\[ F = \text{Faraday’s constant (96500 C/equivalent.mol)} \]

\[ n = \text{Number of equivalents (mols of electrons) per mole} \]

\[ m = \text{Mass of metal oxidized} \]

\[ M = \text{Molecular weight of metal (g/mole)} \]

Based on the above equation the test setup was configured. In the experiment, the ASTM A-572 grade 60 steel was used as an electron donor and stainless-steel plate was used as an election receive. Test specimen in form of steel coupons, steel plates, and stiffened panels were used. The stainless steel used as a counter electrode was also used in the equivalent shape. The test specimen was kept in a watertight container. The stainless-steel counter electrode was placed on both sides of the test sample to ensure the uniform corrosion of the test specimen from all sides. The container was filled with the 5% NaCl solution. The water used in this experiment was type IV with ASTM D-1193 standards. The chemical content of the salt was examined before using for the experiment. Sodium chloride with less than 0.3% impurities was used in the experiment. Test specimen and the counter electrode were submerged in the salt water. To start the electron exchange between these two metals the DC current was passed through the test sample and the stainless-steel counter electrode. The anode was connected to the test specimen and the cathode was connected to the stainless-steel counter electrode. The high voltage capacity copper wire was used to connect the electrodes. DC power supply with 3A and 36 Volt capacities was used as a direct current source. The current and the voltage was calculated from the Faraday’s law. For uniform corrosion of steel coupon
1.12 Volt and 0.162 A of direct current was applied. The time and current calculation of the test samples are calculated by the following formulation.

\[ \Delta m = \frac{Mil}{Fz} \]  

(4.3)

Where,

\( \Delta m \) = Mass of steel consumed (grams)

\( M \) = Atomic weight of metal (56 grams or 0.1232 for Fe) I

\( I \) = Current (amperes)

\( t \) = Time (seconds)

\( z \) = ionic charge (2 in this case)

\( F \) = faraday’s constant (96,500 amperes/second)

The corrosion percentage is dependent on the current passing through the system and the time. The process can be expedited by passing the high value of current and reduce the time of the corrosion. This can lead to the uneven corrosion which is not considered in this assignment. To obtain the optimum results from the electrochemical corrosion process 0.162 A current was passed through the system. The time was then changed accordingly to achieve a various degree of corrosion. The salt water was changed periodically to keep the corrosion rate constant. The test specimens were cleaned regularly with a hot blower. The test specimen was weighed at a periodic interval to measure the percentage corrosion. When the specimen was corroded to the required percentage the test specimen then removed from the container and dried with a hot air blower. The specimen is then stored in the non-humid and dry place to avoid any further corrosion of the sample.
Figure 51: Corrosion of steel coupon using electrochemical process.

A constant current of 0.162 A was applied for uniform corrosion of steel coupons. The time required to achieve required corrosion percentage was calculated by Faraday's law. Following equations show the derivation of current and time required for the corrosion process. Table 4 shows the current and the time requirements for series 1 corrosion. Table 3 describes the uniform corrosion damage for various coupon series. The average corrosion damage for particular series was used for the analysis.
Material and sectional properties can be calculated for the steel coupon. The weight loss and the thickness loss for 10% corrosion are considered in following calculations.

- Density of the steel A-572 grade 60 = 7.988 g/cm³
- Total weight of the test sample = 124 g
- Reduced weight of the corroded area = 41 g
- 10% corrosion weight loss = 4.1 g
- Change in the thickness = 41-4.1 =36.9 g
- Area of sectional reduction = 10.78 cm³
- New weight of the sample = 36.9/7.988x10.78 = 0.428 g
- Change in thickness = 0.476-0.428 = 0.0479 cm = 48 mm

According to Faraday’s law,

\[
11640 \times i = \frac{\text{Thickness loss}}{\text{Time}} \tag{4.5}
\]

\[
i \times t = 0.015 \text{ amp days/cm}^2 \tag{4.6}
\]

\[
I = i \times A = 0.015 \times 10.78 = 0.162 \text{ ampere} \tag{4.7}
\]
Table 3: Average percentage corrosion by electrochemical method.

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Initial weight</th>
<th>Final weight</th>
<th>Weight loss</th>
<th>percentage corrosion</th>
<th>Average percentage corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% A1</td>
<td>122.8</td>
<td>120.84</td>
<td>1.96</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>5% A2</td>
<td>121.98</td>
<td>119.76</td>
<td>2.22</td>
<td>5.55</td>
<td></td>
</tr>
<tr>
<td>5% A3</td>
<td>121.89</td>
<td>119.84</td>
<td>2.05</td>
<td>5.125</td>
<td></td>
</tr>
<tr>
<td>5% A4</td>
<td>122.56</td>
<td>120.55</td>
<td>2.01</td>
<td>5.025</td>
<td></td>
</tr>
<tr>
<td>10% E1</td>
<td>123.1</td>
<td>119.15</td>
<td>3.95</td>
<td>9.875</td>
<td>5.15</td>
</tr>
<tr>
<td>10% E2</td>
<td>123.39</td>
<td>119.06</td>
<td>4.33</td>
<td>10.825</td>
<td>10.625</td>
</tr>
<tr>
<td>10% E3</td>
<td>123.29</td>
<td>118.95</td>
<td>4.34</td>
<td>10.85</td>
<td></td>
</tr>
<tr>
<td>10% E4</td>
<td>122.79</td>
<td>118.41</td>
<td>4.38</td>
<td>10.95</td>
<td></td>
</tr>
<tr>
<td>20% B1</td>
<td>123.37</td>
<td>115.1</td>
<td>8.27</td>
<td>20.675</td>
<td>19.568</td>
</tr>
<tr>
<td>20% B2</td>
<td>123.28</td>
<td>115.21</td>
<td>8.07</td>
<td>20.175</td>
<td></td>
</tr>
<tr>
<td>20% B3</td>
<td>123.07</td>
<td>115.42</td>
<td>7.65</td>
<td>19.125</td>
<td></td>
</tr>
<tr>
<td>20% B4</td>
<td>123.18</td>
<td>115.86</td>
<td>7.32</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>25% F1</td>
<td>123.37</td>
<td>113.2</td>
<td>10.17</td>
<td>25.425</td>
<td></td>
</tr>
<tr>
<td>25% F2</td>
<td>123.28</td>
<td>113.13</td>
<td>10.15</td>
<td>25.375</td>
<td>25.125</td>
</tr>
<tr>
<td>25% F3</td>
<td>123.07</td>
<td>113.43</td>
<td>9.64</td>
<td>24.1</td>
<td></td>
</tr>
<tr>
<td>25% F4</td>
<td>123.18</td>
<td>112.94</td>
<td>10.24</td>
<td>25.6</td>
<td></td>
</tr>
</tbody>
</table>
Table 4: Current and Time for uniform corrosion of steel coupon.

<table>
<thead>
<tr>
<th>Specimen Series</th>
<th>Current (A)</th>
<th>Time (hr)</th>
<th>Weight loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.162</td>
<td>12 hr</td>
<td>5%</td>
</tr>
<tr>
<td>E</td>
<td>0.162</td>
<td>24 hr</td>
<td>10%</td>
</tr>
<tr>
<td>B</td>
<td>0.162</td>
<td>48 hr</td>
<td>20%</td>
</tr>
<tr>
<td>F</td>
<td>0.162</td>
<td>60 hr</td>
<td>25%</td>
</tr>
</tbody>
</table>

A constant current of 2.10 Volt and 0.2 A was applied for uniform corrosion of steel plates. The time required to achieve required corrosion percentage was calculated by Faraday's law. DC power supply with 3A and 36 Volt capacities was used as a direct current source for corrosion of steel plate. The test samples were cleaned periodically to
measure the corrosion damage. The salt water was changed periodically for constant corrosion progression.

![Figure 53: Corrosion of steel plate using an electrochemical process](image1)

Figure 53: Corrosion of steel plate using an electrochemical process

![Figure 54: Corroded steel plate using electrochemical process](image2)

Figure 54: Corroded steel plate using electrochemical process.
4.1.3 CNC Machine

CNC stands for computer numeric control tool which is used in carving, machining wood, plastic, and metals. CNC machine works by means of controlled machined material removal. CNC machine relies on the digital input in the form of computer-aided design (CAD) file. The CNC machine interprets the design as per the digital input. CNC machine moves in two axes and oftentimes rotationally about one or more axes. The base moves longitudinally in the Z-axis to the cutter. Automated cuts improve the speed and the accuracy of the process. CNC machine typically uses drills, milling machines, electrical and chemical machining.

Figure 55: CNC machine used for pitting corrosion.

The natural corrosion can be simulated by using the precise machine-cut test sample. The CNC machine cuts the pitting corrosion samples. CAD model of the plate with the pits of required size was drawn. The CAD file used as a digital input for the CNC machine. The base plate of ASTM A572 was used for the manufacturing process. The base
plate checked for any surface and alignment issues. The base plate was cleaned before used for the manufacturing. To simulate the pitting corrosion on the plates. The typical width to depth ratio for pitting corrosion 8:1 to 12:1 is recommended. The pits are uniformly distributed and cylindrical in the shape. Pitting corrosion for 5%, 10% and 15% was manufactured at CNC workshop.

![Pitting corrosion samples cut by CNC machine.](image)

Figure 56: Pitting corrosion samples cut by CNC machine.

4.2 Test Specimen Series

To study the effect of uniform and pitting corrosion on high strength steel dog bone coupons and plates were tested. Steel plates and coupons were divided based on the percentage corrosion damage. The overview of each experimental corrosion series is summarized below.
The test samples are divided into 3 series.

1. Series 1: Uniformly corroded steel coupons

   Series 1 was used to evaluate the tensile capacity of uniformly corroded steel coupons. The series 1 is further divided into 5%, 10%, 15% and 20% of corrosion damage. For each percentage of corrosion four samples were tested to obtain the accuracy of the results. Standard ASTM testing sample for the tensile test was used. The table below shows the details of series 1.

![Steel coupon dimension details](image)

Figure 57: Steel coupon dimension details.

The total length of the steel coupon was 8 in. The width of the test sample was 0.5 in at the central part while 0.75 in at supporting ends. The thickness of the coupon was 0.187 in. The thickness of the test sample was measured with an ultrasonic gauge before corrosion process. The central effective length of the sample was 3 in. Table 5 shows the details for uniform corrosion of steel coupons.
Table 5: Uniform corrosion of steel coupons

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Corrosion type</th>
<th>Percentage corrosion</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Uniform</td>
<td>5%</td>
<td>4</td>
</tr>
<tr>
<td>E1</td>
<td>Uniform</td>
<td>10%</td>
<td>4</td>
</tr>
<tr>
<td>B1</td>
<td>Uniform</td>
<td>20%</td>
<td>4</td>
</tr>
<tr>
<td>F1</td>
<td>Uniform</td>
<td>25%</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 58: Steel coupons with the series number.

2. Series 2: Uniformly corroded steel plates

Series 2 was used to evaluate the compressive buckling capacity of the uniformly corroded steel plates. The series 2 is further divided into three types with 5%, 10% and
15% of corrosion damage. For each percentage of corrosion, four samples were used to obtain the accuracy of the results. Table 6 shows the details of series 2.

Table 6: Uniform corrosion of steel plates

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Corrosion type</th>
<th>Percentage corrosion</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>Uniform</td>
<td>5%</td>
<td>4</td>
</tr>
<tr>
<td>B2</td>
<td>Uniform</td>
<td>10%</td>
<td>4</td>
</tr>
<tr>
<td>C2</td>
<td>Uniform</td>
<td>15%</td>
<td>4</td>
</tr>
</tbody>
</table>

Steel plate with 4.5 in x 4.5 in the plate was used for the series 2. The thickness of the steel plate was 0.187 in. The thickness of the test sample was measured with an ultrasonic gauge before corrosion process. The test sample was checked for any alignment and surface defects.

Figure 59: Steel plates with uniform corrosion.
3. Series 3: Pitting corrosion of steel plates

Series 3 has uniformly corroded steel plates. The series 2 is further divided into 3 types with 5%, 10% and 15% of corrosion damage. For each percentage of corrosion, 4 samples were used to obtain the accuracy of the results. The table below shows the details of series 2.

![Diagram of pitting corrosion sample]

Figure 60: Dimension for typical pitting corrosion sample.

Steel plate with 4.5 in x 4.5 in plate was used for the series 3. The thickness of the steel plate was 0.187 in. The thickness of the test sample was measured with an ultrasonic gauge before corrosion process. The test sample was checked for any alignment and surface defects. Location and size of the pits are listed in the table below.

Table 7: Pitting corrosion of steel plates

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Corrosion type</th>
<th>Percentage corrosion</th>
<th>Pit size</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3</td>
<td>Pitting</td>
<td>5%</td>
<td>0.25</td>
<td>4</td>
</tr>
<tr>
<td>B3</td>
<td>Pitting</td>
<td>10%</td>
<td>0.25</td>
<td>4</td>
</tr>
<tr>
<td>C3</td>
<td>Pitting</td>
<td>15%</td>
<td>0.375</td>
<td>4</td>
</tr>
</tbody>
</table>
4.3 Mechanical Testing

To understand the behavior of the corroded structural member several tests were performed on the test samples. The steel coupon was tested for the tensile test while the plates and stiffened panels were tested for the compressive loading. The stiffened panels in the ship hull are subjected to the combined loading condition. The hydraulic pressure from the surrounding water act as a lateral load on the steel plates and panels. The details of testing and results for stiffened panels are discussed in the Doctorate’s thesis of Mr. Srikanth Bajaj.

4.3.1 Tensile Test [51].

Tensile test method for the metallic material is covered in the ASTM E8/E8M. The tensile test gives strength and ductility of the material under uniaxial stress. The tensile test gives the various material properties like yield strength, yield point elongation,
tensile strength, elongation, and reduction of area. These material properties play a key role in the design and analysis of the structure. The standard tensile test is conducted at room temperature 10 to 38 °C [50 to 100 °C].

Figure 62: Typical tensile test sample [51].

Table 8: Tensile test sample dimensions [51].

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Plate type 40 mm wide</th>
<th>Sheet type 12.5 mm wide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm [in]</td>
<td>mm [in]</td>
</tr>
<tr>
<td>G—gauge length</td>
<td>200.0 ± 0.2 [8.00 ± 0.01]</td>
<td>50.0 ± 0.1 [2.000 ± 0.005]</td>
</tr>
<tr>
<td>W—Width</td>
<td>40.0 ± 2.0 [1.500 ± 0.125]</td>
<td>12.5 ± 0.2 [0.500 ± 0.010]</td>
</tr>
<tr>
<td>T—Thickness</td>
<td>Thickness of material</td>
<td>Thickness of material</td>
</tr>
<tr>
<td>R—Radius of fillet, min</td>
<td>25 [1]</td>
<td>12.5 [0.500]</td>
</tr>
<tr>
<td>L—Overall length, min</td>
<td>450 [18]</td>
<td>200 [8]</td>
</tr>
<tr>
<td>A—Length of reduced parallel section, min</td>
<td>225 [9]</td>
<td>57 [2.25]</td>
</tr>
<tr>
<td>C—Width of grip section, approximate</td>
<td>50 [2]</td>
<td>20 [0.750]</td>
</tr>
</tbody>
</table>

The tensile test was performed on an MTS testing machine with ASTM E4 standards. The verification of the test speed was practiced according to ASTM E2658. Test specimen size for the tensile test is listed in above table. Various gripping devices
and wedges are available to fasten the test specimen with the machine. The threaded gripping
device, shoulder ended gripping, and wedge grip are some of the examples of gripping
devices. The wedge grips are furnished according to the ductility and surface condition. The
measured gripping force should be applied by testing machine on the test sample. Centre line
of the test sample should be in line with the center line of the head of the testing machine. Any
out of plane stresses should be avoided. The extensometer used in the tensile testing was
according to ASTM E83 specifications. The strain gauge of 1.5 in was used to measure the
actual strain in the specimen.

Figure 63: Hydraulic wedge grip used in the tensile testing [51].
The corroded steel coupon was cleaned from any residual corrosion particles. Test specimen were dried with a hot air blower to remove any moisture on the surface. The specimen was weighed before the testing to accurately calculate the final percentage of the corrosion. The change in the thickness and width of the steel coupon was measured for the record. The tensile test was performed as per ASTM E8 standards. The test specimen was tested on calibrated MTS machine. The bottom end of the sample was fixed first at the hydraulic grip of the MTS machine. Then the top clamp was lower to fix the other end of the steel coupon. The test was programmed on the MST software before starting the test. The strain gauge was calibrated to zero and set the maximum limit of 2- inch displacement. The idea behind 2 in displacement was to protect the strain gauge from getting damaged due to excessive strain. When the specimen reached to 2 in strain the machine will pause the test and user can remove the strain gauge and start the test again. The test was performed as a strain-controlled test. The Load cell was checked for the reading and calibrate the load cell to zero.
Figure 65: MTS testing machine setup.

The test is then started under constant supervision. The test was paused when it reached the maximum strain limit set during the programming of the test. The test was continued till the necking of the sample happens and ultimately breaking the sample. The strain data recorded and the stress data was exported into excel file. The stress-strain graph was drawn from the experimental data. The yield point and the ultimate strength of the uncorroded and corroded steel coupon were established. The slope of the line below yield point gives the modulus of the elasticity. All the material properties of the corroded steel coupons were then compared to the standard uncorroded material properties. The same test was simulated using the finite element analysis and the data from both the experimental and finite element analysis were compared to get the comprehensive idea.
4.3.2 Compressive Buckling Test [52] [53].

The compressive testing of metallic material is described in ASTM E9. The axial compression test for the vertical member is described in ASTM E2954. This method covers the vertical test members in axial compression. ASTM E2954 is applicable for reinforced plastic and polymer matrix. The methods were modified for metallic materials. In this method, various end conditions with constant cross-section are described. The test covers the short term loading effect on the test specimen. Long-term effect of loading, temperature variation, and chemical exposure effects are not covered by this test method.
The properties obtained from the uniaxial compressive test are the modulus of elasticity, bracing condition, compressive stress and proportional stress limit. Buckling test is very critical in this case as the plates in the ship hull experience compressive load. The plates in the ship hull are stiffened with the stiffener. Instron Testing machine was used for the compression testing.

Figure 67: Compression testing of steel plate [53].

Figure 68: Various loading and boundary conditions [53].
The plates tested in this experiment are 4.5 in x 4.5 in plates. The thickness of the plate was 0.1875 in. The steel plates with uniform corrosion and pitting corrosion were examined for critical buckling load. The boundary condition used for the test was simply supported at two ends and free at two ends. In simply supported condition the test specimen was allowed to rotate in the Z direction. The rotational pivot point was aligned with the centerline of the test sample. The test specimen was aligned perfectly with the loading direction and eccentric loading was avoided. The plates are tested in the Instron machine for the buckling test.

The steel plates were cleaned form any residual corrosion particles. The test samples were cleaned with a hot air gun to remove any surface moisture. The specimen was cut in the specified shape and checked for any alignment and manufacturing issues. The test specimen then positioned on the testing machine. The bottom part of the plate was placed in the 0.2 in V shape groove and then the top crosshead lowered to the test sample. The V shape groove was used to allow the rotation around Z direction. This gives the end conditions as a simply supported condition. The specimen was centered within the test frame. Digital leveler was used to check the alignment of testing platform. Strain gauges are not used in this test as the critical buckling load can be easily calculated from the load vs crosshead displacement graph. The load cell was calibrated to the zero before starting the test. The crosshead displacement was also set to zero before starting the test. The test was strain controlled. The visual output of load vs crosshead displacement was set to on the computer. The test was continued till the plate buckles and the strength drops after reaching the ultimate buckling load. The data and the graph of the test results were exported into excel file for further analysis. The test was performed for uniform
corroded steel plates as well as plates subjected to pitting corrosion. The buckling of the plates was simulated in the finite element analysis. The details about the analysis are discussed in the next chapter. The results from the finite element analysis and the experimental results are compared.

Figure 69: Uniform corrosion test sample positioned in the V-shaped groove.

Figure 70: pitting corrosion sample positioned for testing.
CHAPTER 5

FINITE ELEMENT MODEL

The experimental testing and analysis of a corroded specimen gives an accurate understanding of the effect of corrosion. The test results can signify the loss in the ultimate strength, buckling capacity and other parameters associated with the material properties. The literature showed that the corrosion is not a uniform phenomenon. The corrosion never occurs in a standardized form. For example, the ship hull can susceptible to the combination of uniform, pitting and groove corrosion. To study and understand such complex phenomenon finite element analysis programs are very helpful. The software known as Abaqus was used in this report to analyze the corrosion models.

5.1 Modeling of Corroded Steel Coupons and Plates.

Modeling the specimen in Abaqus is very crucial for two reasons. The inaccurate modeling of the model can give a very different result from the testing and effective modeling technique can save the analysis time. Modeling of a specimen can be done in the software like SolidWorks for complex geometry and import it in the Abaqus. In this case, the modeling was carried out in Abaqus itself. The uniformly corroded sample is very easy to model as there is a uniform loss in thickness. The plate and coupon were
modeled as a 2D deformable shell element. For modeling pitting corrosion 3D deformable solid element was used. The model was divided into different parts, two-part having the thickness of the pits and one part with the thickness of uncorroded metal thickness. In modeling, first two parts are a plate of 4.5 in x 4.5 in and a thickness of the corrosion pits was created. The circles of ¾ in and ¼ in diameter were drawn on the surface of the plates. The reverse extrusion was used to create the pits on a specimen. The single part of uncorroded thickness was created like a normal plate. The combination of three parts simulates the pitting corrosion of a specimen.

5.2 Material Properties

The material used in the testing was ASTM A-572 grade 60 steel. Correlation between material properties used in the lab experiment and in Abaqus should match to get accurate results. The elastic modulus of 29,000 ksi and poisons ratio of 0.3 was used as an elastic property. The compressive yield strength of a steel was used as 60 ksi. The material defined in the ASTM standards as a material with minimum yield strength. The actual yield strength of a material is generally slightly higher than the value mentioned by the manufacturer. The materials are as per ASTM standards so, the material strength from the testing results might be higher than the results from FEA modeling. Thus, the strength values obtained from the finite element analysis are on the conservative side. The material was not assigned to the parts immediately as the parts created in the first step are not separate. The parts were assembled together to work as a single model. For uniformly corroded sample the material can be assigned now using assignment manager.
The sectional properties of the specimen were identified. Pitting corrosion model was created as a 3D model. Assigning separate sectional properties to the specimen is not required. In this case, a homogeneous section with material properties mentioned above was used. While in case of the uniform corrosion the section was modeled as a shell element and has no thickness of its own. To assign the thickness to the shell element a section with the A-572 material properties and thickness similar to the plate thickness was created. The sectional properties was assigned after the assembly step. In case of the uniformly corroded section, the sectional properties were assigned at this stage.

5.3 Assembly

Assembly is a very critical stage in the modeling of any sample with multiple parts. The parts created in the modeling are separate from each other and does not signify anything until modeled together as one unit. The 3 parts were selected in assembly tab and created as a dependent assembly. The location of each part was modified as per the requirement. Once the all the parts are in right position they can be merged into one
single unit using merge command. The parts were merged together while retaining the copy of three separate parts. The merging was done on the geometry and removing the boundary line. For uniform corrosion samples, the single part was assembled as a dependant.

Figure 72: Modeling of steel coupon.

Figure 73: Modeling of pitting corrosion sample.
5.4 Element Meshing

The element in Abaqus meshed into a smaller mesh of 3 or 4 noded quadrangles. Before meshing the specimen creating partitions and datum plane is necessary. Partition plane and datum lines help to mesh the specimen in the required order. For pitting corrosion sample the 2 datum planes at the cross-section of the plate was created. The datum plane separated the uncorroded thickness from the corroded thickness of the specimen. The partition plane was created using partition by plane option. The middle part was partitioned using point and normal method.

After the model was ready for the meshing the model was seeded with a seed size of 0.125 in. The seeded model then meshed using the meshing tool. The elements options available for the mesh element are dependant on the element type. In uniformity corroded model "S4" element type was used in which 4 represents the number of nodes. In this type of the element type, there are total 6 degrees of freedom. The 6 degree of freedom includes 3 translation in x, y, z-direction and 3 rotations in the same direction. In pitting corroded model C3D8 element type was used.

The mesh size is crucial for the accuracy of the results. As the mesh size reduces the accuracy of the analysis increases. As the number of mesh increases, it takes considerable time to compute the results. While modeling finite element model a balance between accuracy and computation time is maintained. In this case, a mesh size of 0.125 in was used.
5.5 Restrain and Loads

To simulate the experimental testing results the restraint at the boundary was modeled as actual as possible. The loading and the rate of loading can also be controlled to simulate the real testing conditions. In this report, 2 types of loading conditions were considered.
For steel specimen subjected to compression buckling analysis, the specimen was simply supported at two opposite ends and other two ends are free. The one element nodes at one end are selected and restrained in u1, u2 and u3 direction which signifies the displacement in x, y, and z-direction respectively. While the rotation r1, r2, and r3 are not restrained. On the other edge the element nodes were selected and restrained in u1 and u3 direction. The displacement in direction u2 was allowed. The rotation r1, r2, and r3 were set free.

For tensile test specimen, the element nodes on one end were selected and restrained in the u1, u2, and u3 direction. As selected element nodes in more than one plane, the rotation was restrained. On the other end, similarly, the element nodes were selected at the end of the specimen and restrained in u2 and u3 direction. As the tensile force was applied in x-direction the specimen was allowed to displace in this direction.

![Figure 76: Boundary condition of steel plate.](image)

5.6 Interpretation of Results

Ultimate capacity can be calculated by using linear buckling analysis. Any testing specimen has some initial imperfections, Linear buckling analysis does not consider
those initial imperfections. To calculate the ultimate buckling load unit force is applied to the one end surface of the model. Similarly to calculate the tensile strength unit force was applied on one edge of the tensile specimen. Linear perturbation buckling analysis was selected as a step.

The analysis gives the eigenvalue. The first eigenvalue represents the ultimate buckling capacity of the specimen. The deflected shape of the specimen can be viewed and compared to the actual testing. Similarly, for the tensile test, the first eigenvalue gives tensile strength capacity of the sample.

Figure 77: Stress analysis of pitting corrosion.
Figure 78: pitting corrosion sample positioned for testing.

Figure 79: pitting corrosion sample positioned for testing.
CHAPTER 6

RESULTS AND DISCUSSION

The results obtained from the experimental, analytical and finite element analysis are described in this section. The results obtained from the different corrosion series were compared to finite element analysis. The results are divided into three sections.

- Tensile test on the un-corroded and uniformly corroded steel coupons
- Compressive buckling of un-corroded and uniformly corroded steel plate
- Compressive buckling of un-corroded and pitting corrosion of steel plate

The effect of pitting corrosion and groove corrosion on stiffened panels is discussed in the doctorate thesis of Mr. Srikanth Bajaj.

5.1 Tensile Test of Uniformly Corroded Steel Coupons.

The uniform corrosion of the steel coupons is achieved by both electrochemical methods based on Faraday's law and ASTM B-117 Q fog chamber method. The details of the corrosion percentage are provided in above section. The yield strength, modulus of elasticity and the ultimate strength is calculated for all 4 series of corrosion. The typical stress-strain graph for 5% corrosion of series 1 sample 1 is shown in Figure 80. The yield strength was calculated by 0.02 offset line.
The tensile strength of the corroded sample was calculated by the analytical method. The loss of cross-sectional area can be evaluated from the percentage mass loss and the density of the steel. The cross-sectional area and the known yield strength gives the yielding load for the section. Table 8 describes the yielding load for various percentages of uniform corrosion by the analytical method.

Table 9: Calculation of tensile strength by the analytical method.

<table>
<thead>
<tr>
<th>Test series</th>
<th>The volume of the sample (in²)</th>
<th>Cross-sectional area</th>
<th>Yield strength</th>
<th>Yielding load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorroded area</td>
<td>0.375</td>
<td>0.093</td>
<td>60</td>
<td>5.62</td>
</tr>
<tr>
<td>5</td>
<td>0.356</td>
<td>0.089</td>
<td>60</td>
<td>5.34</td>
</tr>
<tr>
<td>10</td>
<td>0.337</td>
<td>0.084</td>
<td>60</td>
<td>5.06</td>
</tr>
<tr>
<td>20</td>
<td>0.300</td>
<td>0.075</td>
<td>60</td>
<td>4.50</td>
</tr>
<tr>
<td>25</td>
<td>0.281</td>
<td>0.070</td>
<td>60</td>
<td>4.21</td>
</tr>
</tbody>
</table>
The weight loss due to corrosion in electrochemical process was recorded periodically. The mass loss for a test sample was required to calculate the percentage of corrosion. For particular series average percentage corrosion was recorded. The modulus of elasticity, yield stress was calculated from the stress-strain graph. The ultimate stress for the test sample was recorded. The yield load was calculated from the cross-sectional area and the yield stress obtained from the graph. Table 10 describes the yield stress and ultimate stress obtained from the mechanical tensile test.

Table 10: Mechanical testing results of steel coupons.

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Elastic modulus</th>
<th>Yield stress</th>
<th>Ultimate stress</th>
<th>Yielding load</th>
<th>Average yielding load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorroded</td>
<td>29666.26</td>
<td>59.81</td>
<td>70.65</td>
<td>5.58</td>
<td></td>
</tr>
<tr>
<td>Uncorroded</td>
<td>29765.46</td>
<td>60.45</td>
<td>70.53</td>
<td>5.55</td>
<td></td>
</tr>
<tr>
<td>Uncorroded</td>
<td>29545.5</td>
<td>60.35</td>
<td>71.41</td>
<td>5.64</td>
<td></td>
</tr>
<tr>
<td>Uncorroded</td>
<td>29625.84</td>
<td>59.42</td>
<td>71.27</td>
<td>5.54</td>
<td></td>
</tr>
<tr>
<td>5% A1</td>
<td>30001.81</td>
<td>60.01</td>
<td>70.101</td>
<td>5.35</td>
<td></td>
</tr>
<tr>
<td>5% A2</td>
<td>29795.13</td>
<td>62.02</td>
<td>72.35</td>
<td>5.33</td>
<td></td>
</tr>
<tr>
<td>5% A3</td>
<td>29663.99</td>
<td>61.68</td>
<td>71.98</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>5% A4</td>
<td>29631.24</td>
<td>61.52</td>
<td>72.04</td>
<td>5.38</td>
<td></td>
</tr>
<tr>
<td>10% E1</td>
<td>29620.22</td>
<td>62.21</td>
<td>72.46</td>
<td>5.16</td>
<td></td>
</tr>
<tr>
<td>10% E2</td>
<td>30042.21</td>
<td>62.56</td>
<td>72.64</td>
<td>5.19</td>
<td></td>
</tr>
<tr>
<td>10% E3</td>
<td>29979.4</td>
<td>59.56</td>
<td>70.27</td>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>10% E4</td>
<td>29415.5</td>
<td>61.12</td>
<td>70.67</td>
<td>5.07</td>
<td></td>
</tr>
<tr>
<td>20% B1</td>
<td>30339.15</td>
<td>60.55</td>
<td>70.66</td>
<td>4.53</td>
<td></td>
</tr>
</tbody>
</table>
The Yielding load and the ultimate load from finite element analysis was calculated by ODB output. The stress and the stain were checked at the center element of the test sample.

Table 11 shows the yielding load obtained from the finite element analysis.

**Table 11: Finite element model results for steel coupon.**

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>Elastic modulus</th>
<th>Yield stress</th>
<th>Ultimate stress</th>
<th>Yielding load</th>
<th>Average yielding load</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% B2</td>
<td>30432.9</td>
<td>60.668</td>
<td>70.54</td>
<td>4.52</td>
<td>4.49</td>
</tr>
<tr>
<td>20% B3</td>
<td>27117.8</td>
<td>60.21</td>
<td>71.23</td>
<td>4.49</td>
<td></td>
</tr>
<tr>
<td>20% B4</td>
<td>29095.7</td>
<td>60.16</td>
<td>70.89</td>
<td>4.43</td>
<td></td>
</tr>
<tr>
<td>25% F1</td>
<td>29776.5</td>
<td>59.57</td>
<td>69.52</td>
<td>4.25</td>
<td>4.13</td>
</tr>
<tr>
<td>25% F2</td>
<td>28251.6</td>
<td>58.54</td>
<td>69.17</td>
<td>4.17</td>
<td></td>
</tr>
<tr>
<td>25% F3</td>
<td>30788.13</td>
<td>56.28</td>
<td>66.65</td>
<td>4.01</td>
<td></td>
</tr>
<tr>
<td>25% F4</td>
<td>30125.12</td>
<td>57.66</td>
<td>68.82</td>
<td>4.11</td>
<td></td>
</tr>
</tbody>
</table>

The Yielding load and the ultimate load from finite element analysis was calculated by ODB output. The stress and the stain were checked at the center element of the test sample.

Table 11 shows the yielding load obtained from the finite element analysis.
The Yielding load obtained from the analytical, experimental and FEA model are compared. The yielding load obtained for the tensile test results are within 10% error. The results obtained from experimental, FEA and analytical model are consistent. Figure 81 shows the comparison between the various testing methods as a bar chart.

Table 12: Comparison of results from experimental, FEA and analytical method.

<table>
<thead>
<tr>
<th>Corrosion Percentage</th>
<th>Experimental results (Kip)</th>
<th>Finite Element Analysis (Kip)</th>
<th>Analytical Results (Kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>5.57</td>
<td>5.59</td>
<td>5.62</td>
</tr>
<tr>
<td>5%</td>
<td>5.36</td>
<td>5.46</td>
<td>5.34</td>
</tr>
<tr>
<td>10%</td>
<td>5.09</td>
<td>5.18</td>
<td>5.06</td>
</tr>
<tr>
<td>20%</td>
<td>4.49</td>
<td>4.58</td>
<td>4.50</td>
</tr>
<tr>
<td>25%</td>
<td>4.13</td>
<td>4.21</td>
<td>4.21</td>
</tr>
</tbody>
</table>

Figure 81: Comparison between experimental, FEA and analytical results.
The graph in Figure 82 shows the stress-strain curve for various degree of corrosion damage. The graph shows the significant loss in the yielding stress for higher corrosion percentages. The modulus of elasticity or the slope of the stress-strain curve was mostly constant as there is no change in material properties of the material. The ultimate strength or the tensile strength decreases as the percentage of the corrosion increases.

![Stress-strain graph for various percentage of corrosion](image)

Figure 82: Stress-strain graph for a various percentage of corrosion.

The graph in Figure 84 shows the percentage loss in tensile strength by various techniques. It is observed that as the percentage of corrosion increases, the yielding load capacity decreases. The percentage loss in the yielding load by mechanical testing follows non-linear path. The percentage loss in the yielding load was smaller for experimental method than analytical method at low corrosion percentages. As the corrosion percentage increases the percentage loss in the yield strength is higher for experimental method than analytical method.
Figure 83: Tensile test of steel coupons.

Figure 84: Corrosion percentage vs Strength loss for steel coupon.
5.2 Compressive Buckling of Uniformly Corroded Steel Plates

The uniform corrosion of the steel plate was achieved by both electrochemical methods based on Faraday’s law and ASTM B-117 Q fog chamber method. Modulus of elasticity, ultimate buckling load is calculated for all four series of corrosion. Figure 86 shows the Load vs deflection graph for 5% corrosion test sample.

![Deflected Shape of the Steel Plate](image)

Figure 85: Deflected Shape of the Steel Plate.

The critical buckling load was obtained from the Load vs deflection curve. Figure 85 shows the steel plate bent in the middle due to buckling load. Once the steel plate is bent the plate cannot take additional compressive force and the load vs deflection curve goes into negative slope.
Table 13 describes the sectional details and the critical buckling load calculated from the analytical analysis. Critical buckling load was calculated for first buckling mode (m=1). Table 14 shows the critical buckling load for uniform corrosion plate obtained by finite element analysis. The eigenvalue obtained from the buckling analysis multiplied by the breadth of the steel plate gives the ultimate buckling load.

Table 13: Critical Buckling Load of Uniform Corrosion Plate by Analytical Method.

<table>
<thead>
<tr>
<th>Corrosion Percentage</th>
<th>Remaining thickness</th>
<th>Remaining Volume</th>
<th>Stress</th>
<th>Critical load (Kip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.187</td>
<td>3.796</td>
<td>45.50</td>
<td>39.34</td>
</tr>
<tr>
<td>5%</td>
<td>0.178</td>
<td>3.607</td>
<td>41.06</td>
<td>34.17</td>
</tr>
<tr>
<td>10%</td>
<td>0.168</td>
<td>3.417</td>
<td>36.85</td>
<td>29.68</td>
</tr>
<tr>
<td>20%</td>
<td>0.159</td>
<td>3.227</td>
<td>32.87</td>
<td>24.16</td>
</tr>
<tr>
<td>25%</td>
<td>0.150</td>
<td>3.037</td>
<td>29.12</td>
<td>20.72</td>
</tr>
</tbody>
</table>
Table 14: Critical Buckling Load of Uniform Corrosion Plate by experimental and FEA.

<table>
<thead>
<tr>
<th>Corrosion Percentage</th>
<th>Eigen value</th>
<th>Critical load FEA</th>
<th>Critical load Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>8.107</td>
<td>36.48</td>
<td>38.39</td>
</tr>
<tr>
<td>5%</td>
<td>6.952</td>
<td>31.28</td>
<td>32.91</td>
</tr>
<tr>
<td>10%</td>
<td>5.943</td>
<td>26.74</td>
<td>27.98</td>
</tr>
<tr>
<td>20%</td>
<td>4.990</td>
<td>22.45</td>
<td>23.57</td>
</tr>
<tr>
<td>25%</td>
<td>4.160</td>
<td>18.72</td>
<td>19.65</td>
</tr>
</tbody>
</table>

The graph in Figure 87 shows the load vs deflection curve for various degree of corrosion damage for uniform corrosion steel plate. The graph shows the substantial loss in the ultimate buckling load for higher corrosion percentages. The slope for load vs deflection curve decreases as the percentage of corrosion increases. This shows that the un-corrosion test sample has higher stiffness and lower ductility. The ductility of the steel increases as the percentage of the corrosion increases. For compressive buckling test as the thickness of the plate decreases the slenderness also increases and it further reduces the critical buckling load carrying capacity.
The critical buckling load obtained from the experimental, analytical and finite element analysis are compared. Table 15 and Figure 88 shows the comparison between three testing method. The critical buckling load obtained from the all testing methods are within 10% difference.

Table 15: Comparison between Critical Buckling Load from Experimental, FEA and Analytical Method.

<table>
<thead>
<tr>
<th>Corrosion Percentage</th>
<th>Experimental results</th>
<th>Finite Element Analysis</th>
<th>Analytical Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>38.39</td>
<td>36.48</td>
<td>39.34</td>
</tr>
<tr>
<td>5%</td>
<td>32.91</td>
<td>31.28</td>
<td>34.17</td>
</tr>
<tr>
<td>10%</td>
<td>27.98</td>
<td>26.74</td>
<td>29.68</td>
</tr>
<tr>
<td>15%</td>
<td>23.57</td>
<td>22.45</td>
<td>24.16</td>
</tr>
<tr>
<td>20%</td>
<td>19.65</td>
<td>18.72</td>
<td>20.72</td>
</tr>
</tbody>
</table>
Figure 88: Comparison between Critical Buckling Load from Experimental, FEA and Analytical.

The graph below shows the percentage loss in the critical buckling load by various corrosion procedures. It is observed that the as the percentage of corrosion increases the loss in the critical buckling strength also increases. For 20% uniform corrosion damage the critical buckling strength decrease by almost 50%. As the corrosion percentage increases the percentage loss in the yield strength is higher for experimental method than analytical method. The results obtained formt the finite elment analysis was identical with the experimental results.
5.3 Compressive Buckling of Pitting Corroded Steel Plates.

The pitting corrosion of a steel plate was achieved by precise CNC machine cuts. Modulus of elasticity, ultimate buckling load was calculated for all four series of pitting corrosion. Table 16 describes the critical buckling load obtained by the experimental method and finite element analysis. It is very difficult to calculate the critical buckling load for the pitting corrosion by analytical method. First buckling mode is considered for calculation of critical buckling load. The eigenvalue obtained from the buckling analysis multiplied by the breath of the steel plate gives the ultimate buckling load.
Table 16: Comparison between Critical Buckling Load from Experimental and FEA Method.

<table>
<thead>
<tr>
<th>Corrosion Percentage</th>
<th>Critical buckling load FEA (kips)</th>
<th>Critical buckling load Experimental (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>36.86</td>
<td>39.34</td>
</tr>
<tr>
<td>5%</td>
<td>33.72</td>
<td>35.63</td>
</tr>
<tr>
<td>10%</td>
<td>30.97</td>
<td>32.87</td>
</tr>
<tr>
<td>15%</td>
<td>28.85</td>
<td>29.64</td>
</tr>
</tbody>
</table>

Figure 90 shows the load vs deflection curve for various degree of corrosion damage for pitting corrosion damage. The graph shows the substantial loss in the ultimate buckling load for higher corrosion percentages. The slope for load vs deflection curve is not showing any consistency. As the pitting corrosion is highly complex in nature and the formation of stress concentration locations can significantly impact the ductility and the ultimate buckling capacity of the plate.

![Figure 90: Load vs Deflection Curve for Uniaxial Plate Loading.](image)

The graph in Figure 91 shows the percentage loss in critical buckling load by various techniques. It is observed that the as the percentage of corrosion increases the
loss in the critical buckling strength also increases. For 20% pitting corrosion damage the
critical buckling strength decrease by almost 25%. As the corrosion percentage increases the
percentage loss in the yield strength is higher for experimental method than analytical
method. The results obtained form the finite element analysis were comparable for smaller
corrosion damage.

Figure 91: Corrosion Percentage vs Strength Loss for Steel Plate

![Graph showing corrosion percentage vs strength loss for steel plate]
The corrosion process is complex phenomenon and depends on various factors. The loss in the strength of the structure depends on the corrosion percentage, corrosion type and the location of the corrosion. Extensive experimental testing was performed to evaluate the effect of corrosion on the residual strength of the steel coupons and plates. The results acquired by the experimental analysis were verified by the analytical and finite element analysis. The understanding in the loss of strength due to corrosion damage is critical for the structural integrity. This chapter summarizes the conclusion obtained from the testing of the uniform and pitting corrosion of the steel coupons and plates.

- The tensile test results of uniform corrosion of steel coupons shows that the tensile strength loss obtained from experimental results were comparable with FEA and analytical analysis.
- The loss in the tensile yield strength was nonlinear in nature with respect to the percentage corrosion damage.
- The modulus of elasticity or the slope of the stress-strain curve was reduced slightly but constant for uniform corrosion tensile test.
- The percentage loss in the yielding load was smaller for experimental method than analytical method at low corrosion percentages. As the corrosion percentage
increases the percentage loss in the yield strength was higher for experimental method than analytical method.

- The compressive buckling test of uniform corrosion steel plate shows that the buckling load obtained from the experimental method are in consistency with Analytical and finite element analysis.

- 20% of uniform corrosion can reduce the critical buckling capacity of the plate by 50%.

- The un-corroded test sample has higher stiffness and lower ductility. As the percentage of the corrosion increases the material becomes more ductile under compressive buckling loading.

- The compressive buckling test of pitting corrosion steel plate shows that the buckling load obtained from the experimental method are in consistency with finite element analysis.

- 15% of pitting corrosion can reduce the critical buckling capacity of the plate by 25%.

- For higher pitting corrosion damage percentage loss in the critical buckling load for pitting corrosion is higher for experimental method than analytical method.
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