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DEPARTMENT OF MECHANICAL ENGINEERING

Design and Construction of Corrosion Fatigue Test Setup

by

Michail Tziastoudis

Submitted in partial fulfillment of the requirements for the degree of
Diploma in Mechanical Engineering at the University of Thessaly

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Date Approved: [June 9th, 2021]

Design and Construction of Corrosion Fatigue Test Setup

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Abstract

The goal of this thesis is the design and construction of a corrosion fatigue test setup. In the beginning, some general information about the topic of corrosion fatigue and fatigue life in offshore structures is given. Then, test setup design ideas are explored and explained and final design photos and information are given. Afterwards, the procedure of construction of each part is described in detail and the first corrosion fatigue test is set. Finally, a corrosion fatigue test is performed and qualitative data are acquired and interpreted.

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Chapter 1 Introduction

1.1 Modern World

In modern world, the need for better understanding of materials, their properties and how we can use them properly to improve living conditions is growing steadily. Our new way of life and our endeavor for personal and collective progress creates needs we did not used to have.

Worldwide, we use more energy than ever and every year we use even more. In 1900 the worldwide energy consumption was 12.100 TWh (10^9 kWh), in 2000 this number was 112.424 TWh, almost a hundred times more and 157.064 TWh in 2018. Therefore, there is an increase of approximately 100 TWh in a period of a hundred years and then an increase of 45 TWh in only eight years. That is due to the continuous growth of the population as well as the industry productivity over the recent years.

However, this exponential growth in population, and therefore in energy consumption, has a limit and many believe that we are very close to it, if not beyond it. The environmental problems we have caused are most of them irreversible and we have reached a point where without change in our way of life these problems are may threaten our existence, either physically or through the economy.

1.2 Energy Sources

In the last years there have been many changes concerning environmental legislation affecting greatly the energy field. Research has been focused on new and cleaner ways to produce energy and renewable sources. Most popular renewable energy sources are solar and wind energy, which are developing rapidly. Some market data are that almost 50 billion dollars were invested to renewables globally in 2004 and 10 years later these investments have reached over 250 billion dollars.

In Greece there are numerous wind farms being installed in many mountain areas and islands, where they can operate with high efficiency due to strong and steady winds. In addition, many offshore wind farms have been installed in the United Kingdom, Netherlands and Belgium and is a matter of time before they are also installed near Greek coastlines. In 2019 the annual energy generation from wind in Europe was 456 TWh, in 2010 was 153 TWh while in 2000 was only 22.5 TWh.

Many solar farms can be seen all around Greece's fields and some land owners have turned to these investments instead of agriculture or farming with help from the government and European policies that make it easier for banks to loan money for such purposes. Moreover in the 24th of April 2020 an environmental bill passed and renewed the old one, making applications for renewable energy constructions easier. Looking at Greece's long term plans concerning energy, one could recognize that it will surpass the Renewable energy directive set by the European Union which indicates that by 2030 at least 32% of the energy must be produced by renewable sources. Consequently, there is an international effort to turn towards the goal of cleaner energy with fewer effects on the environment. That leads to reduced CO_2 footprint, less use of materials, more recycling and a more responsible lifestyle concerning the environment.

Although few can argue with these ideas, facts suggest that these changes require a very big effort from every single one of us. In particular, our technology and infrastructure might not be ready. Due to the intermittent operation of many renewable sources even with all the required installations a 100% dependency is impossible. This would require the storage of huge amounts of energy, e.g. in batteries. This is a step that we are not ready to take yet because batteries do not have the required capacity and the cost would be too big for any country to invest in order to change its whole power grid to operate accordingly. As an example, on a cloudy day with slow winds the only reliable solution keeping our society from shutting down is the use of traditional fossil fuels such as coal, petroleum and natural gas. That is why complete independency from fossil fuels is impossible and research on these fields is still necessary. Fossil fuels will most likely our primary source of energy for the next decades possibly.

Consequently, we need to ensure that all measures for the protection of human lives and the environment are taken. Coal mining and oil and gas extraction and transportation, especially in offshore situations, are some of the most deadly professions there are and there have been a number of accidents that lead to numerous fatalities in the past. In fact, the CDC (Center for Decease Control and Prevention) has reported that the United States oil and gas extraction industry has a collective fatality rate of over 27 deaths for every 100,000 workers, which is seven times higher than the fatality rate for other industries in the US. Furthermore, when accidents such as oil spills occur, although they may not be as deadly for humans, they are extremely deadly for marine creatures, have a negative impact on the environment and the global ecosystem.

With all that taken into account, every project concerning the extraction and transportation of oil or gas has to be confronted with severity and absolute caution so that no mistakes are made. More specifically, oil and gas tankers and productions platforms have to be immune to all the harsh and varying conditions they may encounter in the sea. Material selection and extensive study of the effect of environmental conditions are key to structural integrity of these constructions since a structural failure would be unacceptable and could cause a series of unpleasant results. The same applies to other constructions using marine technology to produce energy, such as offshore wind, tidal and wave energy. The structures of these renewable energy production systems, although they are smaller in scale than an oil rig, are quite complex and all the principles for safe offshore structures, such as an oil rig, apply also here. The big difference is in case of failure the danger for human lives and environmental issues is not as serious. The main worry would be the economic results and the setback for a project that would not meet its requirements and stopped being productive. In projects like offshore wind farms the economic factor has a bigger gravity since health hazards are less frequent. That results in a different way of study and material selection than constructions with human lives or the environment at stake. In any case, all offshore structures have to be designed to endure the unfriendly environment of the sea.

1.3 Fatigue & Corrosion

Offshore structures experience fatigue in the presence of corrosion. Fatigue is the weakening of a material caused by cyclic loading that results in progressive and localized structural damage and the growth of cracks. Corrosion is a natural process that converts a refined metal into a more chemically-stable form such as oxide, hydroxide, or sulfide. It is the gradual deterioration of materials by chemical and/or electrochemical reaction with their environment.

Concerning the structures we described above, every wave that reaches the structure can be considered as a load applied, its force, depending on its mass and velocity is the amplitude and the frequency of the waves is going to be the frequency of the repeated load. We can relocate the problem in a laboratory world, analyze it and depending on the data available, predict its life expectancy and other parameters related to the problem we examine. Typical structures in the sea can experience millions of wave-induced stress cycles of variable amplitude during their lifetime and that leads to fatigue.

Corrosion is a very common effect for all marine structures. It can be either localized or general and can lead to product contamination, loss in efficiency of products or parts, losses in production and finally economic losses. But especially in large constructions, localized corrosion has led to huge problems, even total destruction of the structure. Localized corrosion is often difficult to notice, especially in internal and small parts of the structure which may appear intact macroscopically but may be heavily corroded internally. Corrosion is a major factor concerning crack initiation and growth. A small crack in a weak part of the structure, in the toe of a welding for example, can start to develop after material is removed due to localized corrosion.

This is the reason why fatigue and corrosion are intertwined. Sometimes it is necessary to be studied together. It is almost certain that their coupled effect can complicate the behavior of materials. On the one hand, it is possible for the results to be magnified or accelerated, causing engineers to take extra measures, increasing safety factors or choosing stronger materials in their design of a structure. On the other hand, these measures have to be well considered and not exaggerated because in that case there may an unnecessary increase in the cost of the structure. Consequently, engineers and researchers have to study corrosion fatigue and collect enough data in order to determine the optimum situation that keeps the design costs at reasonable level while at the same time insuring the safety for all people involved in such projects.

1.4 Our research and the progress that has been made in the field

Corrosion fatigue in offshore structures is a quite complicated topic. It combines knowledge from several fields such as materials, fracture mechanics, welding technology, chemistry and more. Fracture mechanics had been given serious attention mainly since WWII and nowadays exist studies very similar to the topic we are focusing on. Some of those studies refer to crack propagation in large sea vessels such as ships and platforms, crack initiation and propagation due to fatigue, concerning large floating structures and many specific experimental studies for different kinds of metals used in offshore structures. There are also studies concerning fatigue life prediction of welded ship details and a large variety of experiments on welded metals used in this industry. Corrosion is also a well-known topic and there are countless experimental data for metallic corrosion in a variety of corrosive environments, with one of the most common being salt water. Finally, there are also statistical wave models to determine the hydrodynamic loading for fatigue and fracture analysis in ships.

It has always been hard even with modern technology, to develop an experimental procedure to simulate all the events that occur in offshore structures. The environment and the forces these structures are subjected to are difficult to represent in the laboratory and the time needed to complete a valid corrosion fatigue experiment takes days or even months, since the frequency of wave load is very low. That is why it is not common to perform such experiments in labs and there are only a few papers published on this subject.

The above constitutes the motivation for this thesis and the main reason we decided to study this topic. The main purpose of this thesis is to design and construct a setup for laboratory corrosion fatigue experiment and also collect useful data about corrosion fatigue in offshore structures and corrosion fatigue testing. The conditions we attempt to recreate in our lab experiment are fatigue, stemming from waves with simultaneous corrosion. The experiment is going to be performed in a salt water bath, and the water will recycle, keeping its salinity, its content and its temperature constant. The fatigue test will be performed in the weld of the material, since those are the weakest parts in most structures and the location where most cracks initiate and propagate.

There is a lot of information about corrosion and fatigue separately, while there exists very little information about how these are connected and interact. The interaction of corrosion and fatigue constitute a hot topic in today's research in structural mechanics. This is a topic that needs and can be further developed, and constitutes the purpose of this thesis.

Chapter 2 Fatigue, Corrosion and their combination

In this chapter, all the basic knowledge and definitions concerning our subject are going to presented. We define fatigue, corrosion and their basic properties and mechanisms. Subsequently, we try to explain the effect of those two combined in a more theoretical view.

2.1 Fatigue

Fatigue is the weakening of a material due to cyclic loading which is caused by localized damage that results in the initiation and growth of cracks. Once a fatigue crack has initiated, it will grow a small amount with each loading cycle, typically producing striations on some parts of the fracture surface. The crack will continue to grow until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the fracture toughness of the material, producing rapid propagation and typically complete fracture of the structure.

Fatigue failure is a process that can be divided in stages, and these stages are the following:

- After a certain amount of cycles, damage develops on the microscopic level and gradually forms a macroscopic crack.
- At each cycle the crack grows until it reaches a critical length.
- At the next few cycles after the critical point we have general failure of the component occurs

These three stages are also known as: crack initiation, crack propagation and failure. Depending on the materials, applications and many other factors, the first two stages of crack initiation and crack propagation are taken into account very differently, but we will discuss this issue that in the next pages.

Nomenclature and Formulas

$\mathbf{a_o}$	Initial crack length	$\mathbf{a_f}$	Final crack length
$\boldsymbol{\sigma_y}$	Yield stress	$\boldsymbol{\sigma_{UTS}}$	Ultimate tensile stress
$\boldsymbol{\Delta\sigma}$	Cyclic stress range	$\boldsymbol{\Delta K}$	Cyclic SIFR
$\mathbf{P_{max}}$	Maximum load	$\mathbf{P_{min}}$	Minimum load
K	Stress intensity factor (SIF)	**R**	Stress ratio
da/dN	Fatigue crack growth rate (mm/cycle)		
$\boldsymbol{\sigma_{max}}$	Maximum Stress	$\boldsymbol{\sigma_{min}}$	Minimum stress
$\boldsymbol{\sigma_m}$	Mean Stress	$\boldsymbol{\sigma_\alpha}$	Stress Amplitude
$\boldsymbol{\Delta\sigma}$	Stress Range	$\mathbf{S_e}$	Endurance limit

$$\sigma_m = (\sigma_{max} + \sigma_{min}) / 2 \qquad \sigma_a = (\sigma_{max} - \sigma_{min}) / 2$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \qquad R = \sigma_{min} / \sigma_{max}$$

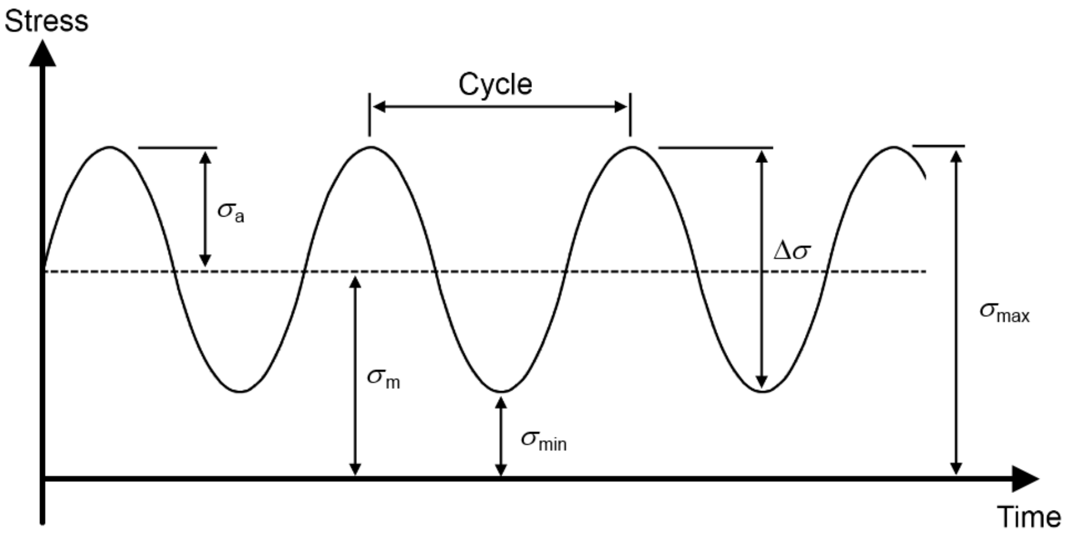


Figure 2.1.1 Stress cycles over time

Figure 2.1.2 shows a typical S-N curve, which describes the relation between cyclic stress amplitude and number of cycles to failure and is derived from fatigue tests. On the horizontal axis the number of cycles to failure is given on logarithmic scale. On the vertical axis (either linear or logarithmic) the stress amplitude of the cycle is given. Low cycle fatigue is defined by component failure in 10^3 load cycles or less. For load cycles above 10^3 until failure, it is considered high cycle fatigue, and above 10^6 very high cycle fatigue. If a component does not fail after approximately 10^6 - 10^7 cycles, depending on the application, the stress value applied is called endurance limit $\mathbf{S_e}$ and can theoretically have infinite life.

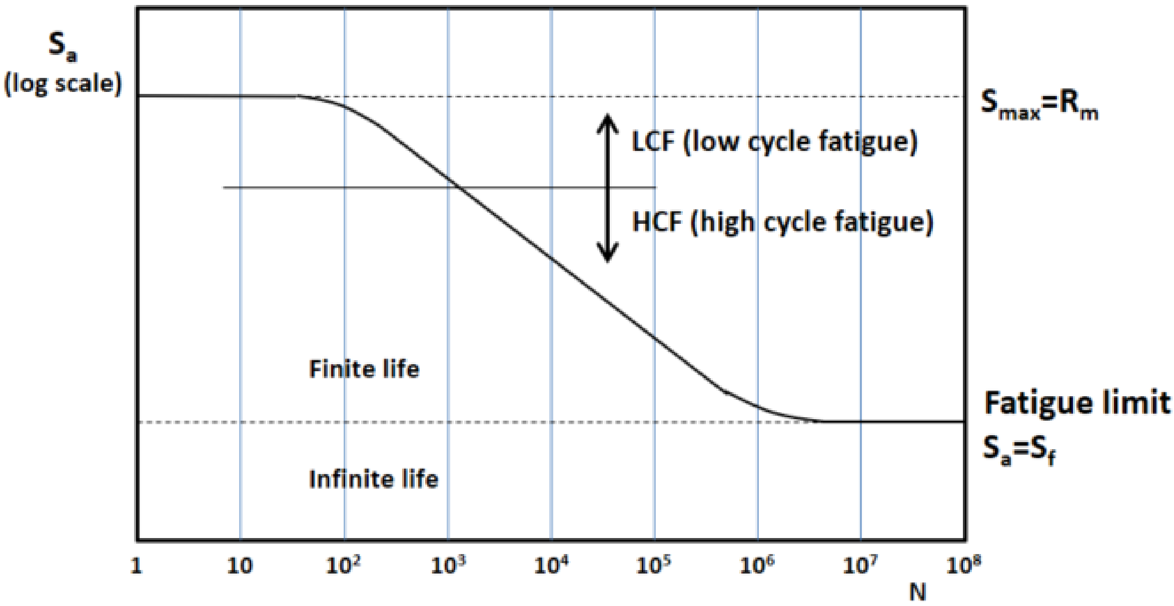


Figure 2.1.2 S-N curve

Figure 2.1.3 below, describes the relation between crack growth rate **da/dN** and the stress intensity factor range **ΔK,** both axes are seen on a logarithmic scale. The curve in this diagram can be divided in three parts; the first part on the left is the near threshold regime, where for $\Delta K_I < \Delta K_{th}$ there is no crack growth in our material. The second part is called the stable propagation regime, where ΔK_I has reached a critical value and now crack are able to propagate with a steady pace as time and fatigue cycles pass. We can observe that the relation between log(**ΔK)** and log**(da/dN)** is quasilinear as we have a nearly straight line and this relation was firstly proposed by Paris.

Paris Law: $da/dN = A(\Delta K)^m$, where **m** is the slope of the line

The last part of our line on the right of the diagram is the zone where very fast and unstable crack growth occurs which leads to total failure of our material. The critical value **K_{ic}** is what characterizes this zone in our diagram since when **K** reaches this value cracks start to spread and grow uncontrollably.

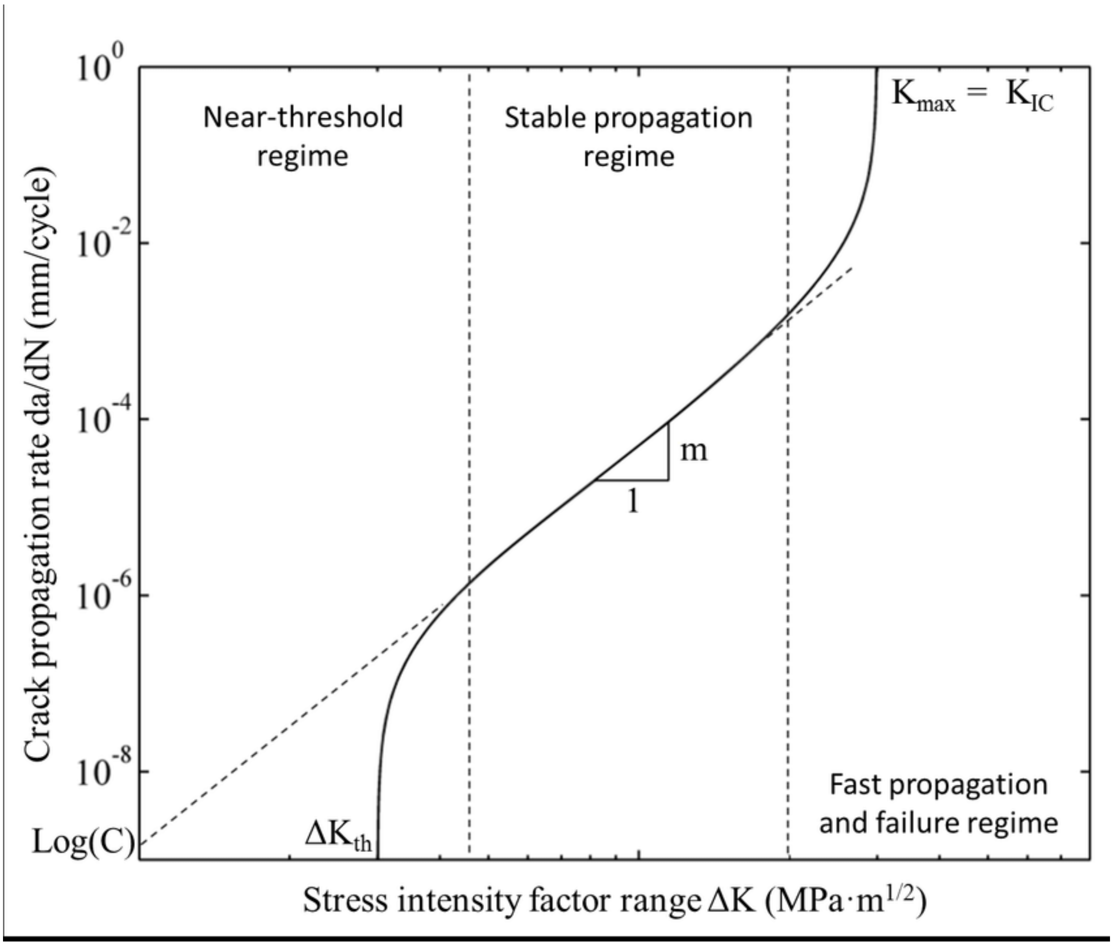


Figure 2.1.3

In many problems concerning different materials and applications, these diagrams can differ or be interpreted in different ways. As an example, for brittle materials, such as many ceramics, the majority of its life under cyclic loading will be described by the first stage of crack initiation, because as soon as a small macroscopic crack is formed, failure will follow very shortly. The central part of the line above would also be very shorter. On the contrary, in some other cases it is assumed that even at the beginning of a component’s life there are pre-existing cracks, whose length is the limit of the NDT (nondestructive testing) methods for crack detection. Consequently, the fatigue life of that component depends on the cycles needed for these undetectable cracks to reach the critical length, skipping that way the crack initiation stage.

An additional analytical tool, useful in life prediction of components under cyclic loading is Miner's rule, which it is probably the simplest cumulative damage model. It states that if there are **k** different stress levels and the average number of cycles to failure at the **k_i** stress, **Si**, is **Ni**, then the damage fraction, **C**, is:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

where:

- **n_i** is the number of cycles accumulated at stress **Si**.
- **C** is the fraction of life consumed by exposure to the cycles at the different stress levels. In general, when the damage fraction reaches 1, failure occurs.

Miner's rule has been very popular and is one of the simplest cumulative damage models despite some shortcomings due to its simplicity. For example, the past cycles of fatigue life or the sequence of stress cycles that the component was subjected to are not taken into account. Predicting fatigue life is of probabilistic nature and there are high stress cycles between low stress cycles, overloads and many other features that Miner's rule cannot predict and interpret in terms of their effect on fatigue life. More advanced methods have been developed of course, such as the Newmark equation, Manson and Halford, Subramanyan and others, that are each used in more specific problems.

2.2 Corrosion

When we refer to corrosion as engineers, we are usually referring to corrosion of some kind of metal. Corrosion is a natural process that converts a refined metal into a more chemically stable form such as oxide, hydroxide, or sulfide. It is the gradual destruction of materials by chemical and/or electrochemical reaction with their environment.

Usually this means electrochemical oxidation of metal in reaction with an oxidant such as oxygen, sulfates or other. Rusting, the formation of iron oxides, is a well-known example of electrochemical corrosion. This type of damage typically produces oxides or salts of the original metal and results in a distinctive orange color. Corrosion can also occur in materials other than metals, such as ceramics or polymers, although in this context, the term "degradation" is more common. Corrosion degrades the useful properties of materials and structures including strength, appearance and permeability to liquids and gases. Many environments can be considered corrosive, air, water, sea water, industrial environment, exhaust fumes etc. That is why corrosion is such a popular topic, because it can occur anywhere and corrosion damage happens every day around us and has tremendous effects on the economy and our daily life as well.

The mechanisms that describe the degradations of metals are oxidation – reduction reactions. At first, oxidation occurs, causing reactions in which metals react with oxygen in the air to produce metal oxides. Inside a corrosive environment, a metal acquires a positive charge by transferring electrons to the neutral oxygen atoms of an oxygen molecule in its effort to reach a more chemically stable state. As a result, oxygen atoms acquire a negative charge and form oxide ions (O^{2-}). Because metals have lost electrons to oxygen, they have been oxidized. Therefore the phenomenon of losing electrons is called oxidation. Conversely, the phenomenon of gaining electrons is called reduction, in which oxygen atoms have been reduced. Oxidation is always accompanied by a reduction and vice versa. An easy way to remember is by the acronym OIL RIG → Oxidation Is Loss, Reductions Is Gain.

In order for electrochemical corrosion to take place, two electrodes, one anode and one cathode, and an electrolyte are needed. In metals, the anode and cathode are the base metal and its alloying elements. The one with the lower electrochemical potential becomes the anode and the other one the cathode. For example, in aluminum alloys, aluminum is usually the anode and its alloying elements, such as copper which is significantly more electrochemically positive, becomes the cathode. The electrolyte in most cases is water or air humidity. Electrochemical corrosion can be represented in a cell in which oxidation reactions happen on the one side and reduction reactions on the other. These reactions are also called anodic and cathodic reactions. Those leading to reductions are cathodic and those leading to oxidation are anodic. Denoting with Me, the metal and n, the number of electrons transferred,

$Me^{n+} + ne^- \rightarrow Me$ Cathodic, as it leads to reduction.

$Me \rightarrow Me^{n+} + ne^-$ Anodic, as it leads to oxidation

Examining again the previous example with aluminum and copper as the two electrodes and water as the electrolyte, the procedure that takes place can be outlined as follows:

- Aluminum ions are created on its surface layers, due to aluminum’s tendency for oxidation $Al \rightarrow Al^{3+} + 3e^-$
- Positive ions are dissolved in water near the negatively charged surface of the aluminum
- An electrical dynamic difference is created between aluminum and the water solution with the positive ions

- The same happens on the copper electrode but its electrochemical potential value is the opposite as it is charged positively, and its ions negatively

  $Cu^{2+} + 2e^{-} \rightarrow Cu$

- Due to our electrolyte, a continuous production and transport of electrons takes place from our anode, the aluminum, to our cathode, the copper elements in the alloy.

Every electron that is “produced” is really taken from our anode and gradually leads to material deposition and the creation of “rust” on the surface of a metal. There are many types of corrosion, some less dangerous, some that can cause very serious problems in the whole structure, and some that can even protect a metal from further corrosion by creating a protective film of rust on the surface. Therefore, it is necessary to talk about some basic kinds of corrosion that usually occur in metals and be able to distinguish them.

Galvanic Corrosion

Galvanic corrosion, also called ' dissimilar metal corrosion', refers to corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte. It occurs when two (or more) dissimilar metals are brought into electrical contact under water. When a galvanic couple forms, one of the metals in the couple becomes the anode and corrodes faster than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone. Galvanic corrosion is a localized phenomenon and is limited to the contact zone. It is very common to occur in welds where there may exist dissimilarities between the base and weld metal, as well the different metallurgic zones formed after a welding where each zone has a different electrochemical potential and is differently prone to galvanic corrosion.

Figure 2.2.1

Pitting Corrosion

Pitting corrosion is a cavity, hole or pit that is formed due to corrosion in a small area or point. The pits or holes are obscured by a small amount of corrosion product (rust) on the surface. When a cathodic reaction in a large area (coating) sustains an anodic reaction in a small area (exposed metal), a pit, cavity or small hole will form. Oxidation occurs in the metal even when there is no supply of oxygen. It is usually constrained to specific areas. This creates a weak point where water or corrosive solutions attack the substrate. Adjacent materials will often appear unaffected. It occurs quickly and can easily be overlooked, which is the reason for being considered as the most dangerous form of corrosion. The scale and shape of these pits differ depending on the material but usually they follow the orientation of the grains. These pits can give birth to cracks and become the start of numerous of serious problems.

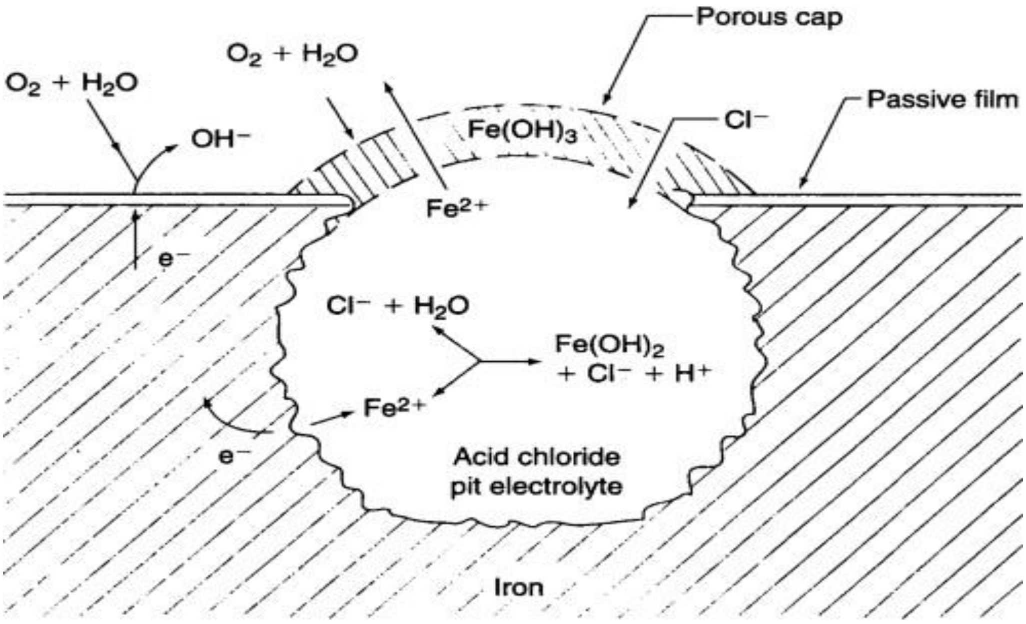


Figure 2.2.2

Crevice Corrosion

This type of corrosion occurs in cracks and other sheltered areas of a metal surface, which is exposed to a corrosive environment. A slit or a protected area can often cause intense localized corrosion on the metal surface, due to the appearance of different electrolyte concentrations inside and outside of it. In any case, the opening of the notch or slit should be large enough to allow for the liquid to penetrate and, at the same time, small enough for the liquid to remain stagnant. Crevice corrosion is initiated by changes in local chemistry within the crevice such as depletion of inhibitor in the crevice, depletion of oxygen in the crevice, shift to acid conditions or build-up of aggressive ion species (e.g. chloride) in the crevice.

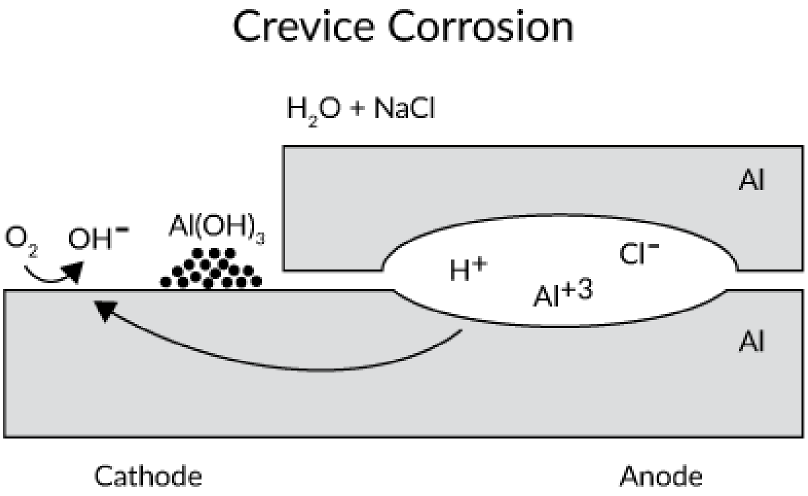


Figure 2.2.3

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the cracking induced from the combined influence of tensile stress and a corrosive environment. The effect of SCC on a material usually falls between dry cracking and the fatigue threshold of that material. The tensile stresses may be in the form of directly applied stresses or in the form of residual stresses. The problem itself can be quite complex. Cold deformation and forming, welding, heat treatment, machining and grinding can introduce residual stresses. The magnitude and importance of such stresses is often underestimated. The residual stresses set up as a result of welding operations tend to approach the yield strength. SCC usually occurs in certain specific alloy-environment-stress combinations. Microscopically the cracks can be pericrystaline, intercrystalline, have small width and form a lot of branches around the grains or through them.

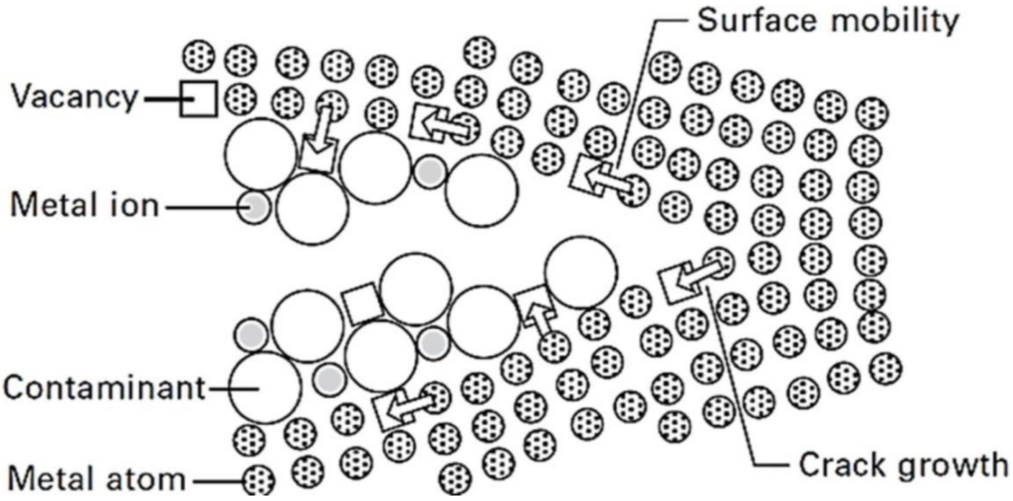


Figure 2.2.4

Hydrogen Embrittlement

Hydrogen embrittlement occurs when hydrogen atoms or molecules are absorbed by a metal causing it to become more brittle and reducing its mechanical capabilities such as yield strenth. As a result, that metal components fail at lower stress levels than expected due to cracking. This can occur during various manufacturing and assembly operations or operational use – anywhere that the metal comes into contact with hydrogen. Hydrogen can enter and diffuse within steel even at room temperature. Most common operations where HE can occur is acid pickling and electropainting, but hydrogen absorption can also occur if a metal is exposed to acidic or corrosive environment, where corrosion destroys its outer layer making way for hydrogen to be dissolved. Adsorbed hydrogen species recombine to form hydrogen molecules between grain borders of the metal, creating forces within the metal, at microscopic level. This pressure can increase to levels where the metal has reduced ductility, toughness, and tensile strength, up to the point where it cracks open (hydrogen-induced cracking, or HIC). This last mechanism is dangerous for metal weldings. If specific measures are not taken during the process of welding and after weld treatment to prevent hydrogen penetration and diffusion, HE can cause serious problems in the weld metal and heat affected zone.

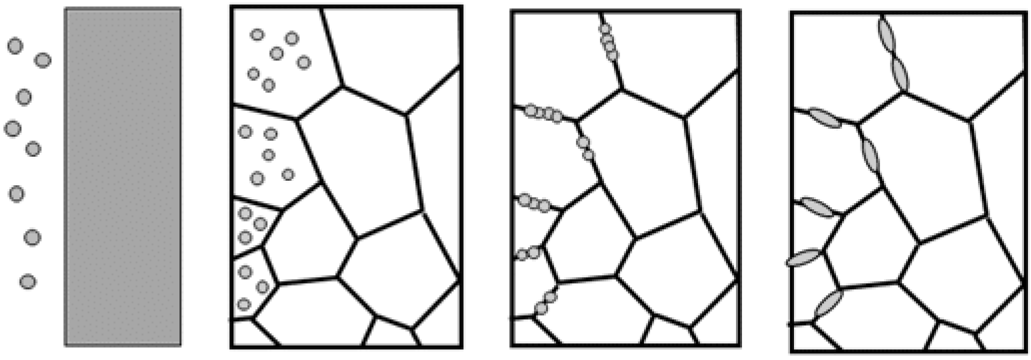


Figure 2.2.5

These are some of the most usual and dangerous kinds of corrosion as they can start a lot of problems, especially combined with pre-exesting imperfections and loads, that in other cases would not cause harm.

2.3 Corrosion and Fatigue Combined

In this section, we ananlyze the combination of the previous topics, how can they be combined, how they interact and their corresponding mechanisms.

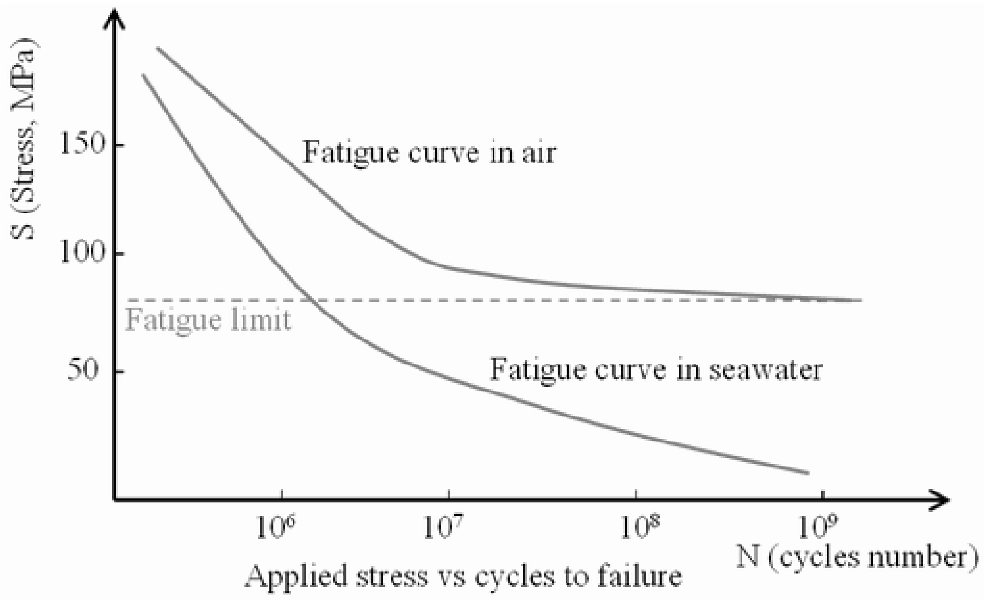


Figure 2.3.1

Firstly, previous experimental evidence has shown that corrosion accelerates the effect of fatigue in a metal component. Of course corrosion is very rarely the reason a component fails, but is usually the only reason a component starts to degrade, accelerating its failure. Corrosive environments lead to the creation of small cracks, debris, peels and other discontinuities on the surface of the metal, which in time can evovle into fatigue cracks. The quality of the surface can play a key role in the time needed for cracks to become critical and lead to failure. Fatigue cracks, when starting to spread, activate the same fatigue mechanisms discussed previously, for non corrosive environment.

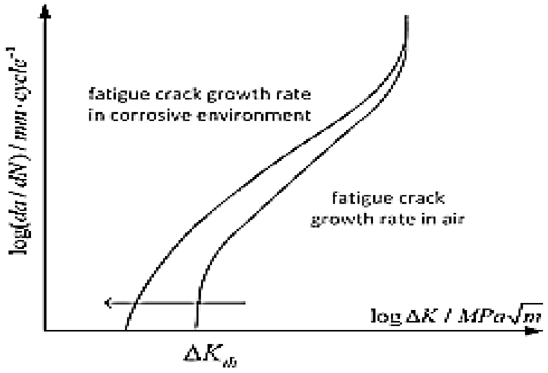


Figure 2.3.2

Although, fatigue cracks appear to develop faster than SCC cracks and in a bit different direction. Fatigue cracks usually spread perpendicular to the load applied and more straight than stress corrosion cracks, which typically branch more and follow grain borders. Failure occurs when the cracks become long enough to cross grain borders and eventually reduces the component cross section, causing overloading and leading to brittle fracture.

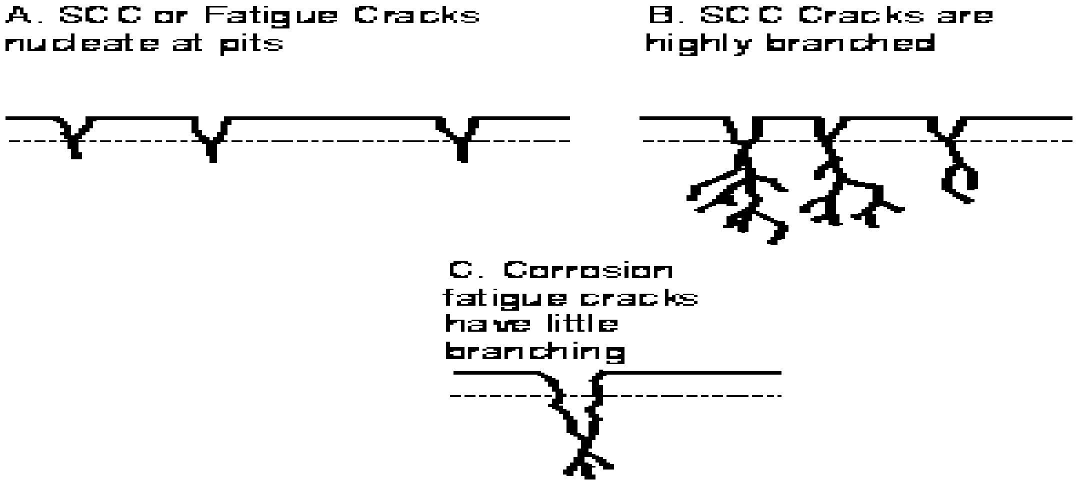


Figure 2.3.3

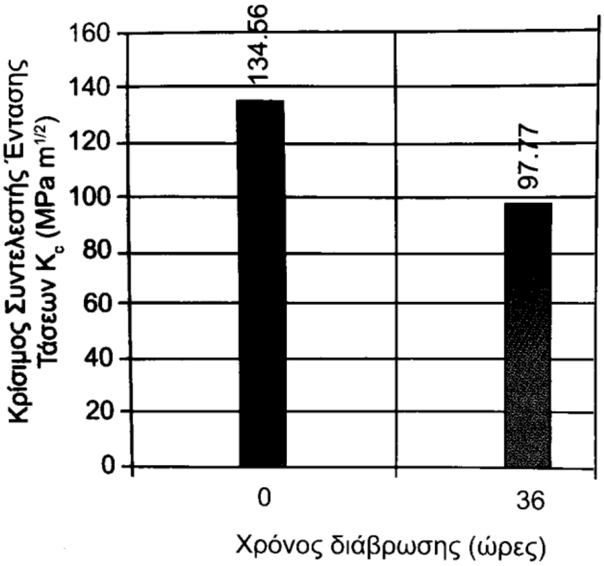


Figure 2.3.4

On this diagram the $\mathbf{K_{cr}}$ value is the vertical axis and its difference in the beginning of the experiment and after 36 hours of corrosion. The Kc value drops from 134.56 Mpa*m$^{1/2}$ to 97.77 Mpa*m$^{1/2}$, a 30% decrease.

As mentioned before, most real life environments can be considered corrosive for metals. There are countless types of materials and many different enviroments that these material must operate. Every time circumstances are different and there are no general rules that can be applied. Each time the environment, corrosive elements and all operating conditions must be carefully studied for the construction design.

$$\frac{da}{dt} = \left(\frac{da}{dN}\right)_f + \left(\frac{da}{dt}\right)_c + \left(\frac{da}{dt}\right)_{cf}$$

This equation describes crack propagation in corrosion fatigue,

- da/dt is the total rate of crack development
- $(da/dN)_f$ is the contribution because of fatigue excluding corrosion effects
- $(da/dt)_c$ is the contribution because of corrosion
- $(da/dt)_{cf}$ is the contribution of the interaction of corrosion and fatigue

All these factors have to be examined thoroughly in each structure in order to make it safer and cost-effective. Especially the last factor that takes into account the interaction of corrosion and fatigue has not been investigated so far and requires more studies. There is a lot of information about corrosion and fatigue seperately, but very little on how these are interconnected and interact. It is the topic that needs and can be further developed and constitutes the purpose of this thesis.

Chapter 3 Recent studies of Corrosion Fatigue

3.1 Industry problems related to corrosion fatigue

Offshore constructions are subjected to cyclic loading conditions in a highly corrosive environment which is the sea. As mentioned before, corrosion and fatigue have been researched thoroughly over the last decades, but the real issue now days is learning about the combined effect of these two phenomena. One of the biggest questions of corrosion fatigue research is to answer whether the combined effect of corrosion and fatigue is more damaging than the superposition of each one independently and to what extent.

3.1.1 Forces and cyclic loading in offshore structures

In this subsection we are going talk about the forces that offshore structures experience during their lifetime. Also, we are examining the cyclic loads, their frequency and amplitude, the factors that affect them and how all these affect the life of a structure. The most representative structures are offshore wind turbines and steel catenary risers but the same principles apply to all devices that exploit wave energy, tidal energy, sea currents or ocean thermal energy to produce electricity.

Offshore wind turbines

Wind turbines are constantly subjected to dynamic and cyclic loads caused be the wind and the sea. This situation becomes worse if they are in a very turbulent wind climate.

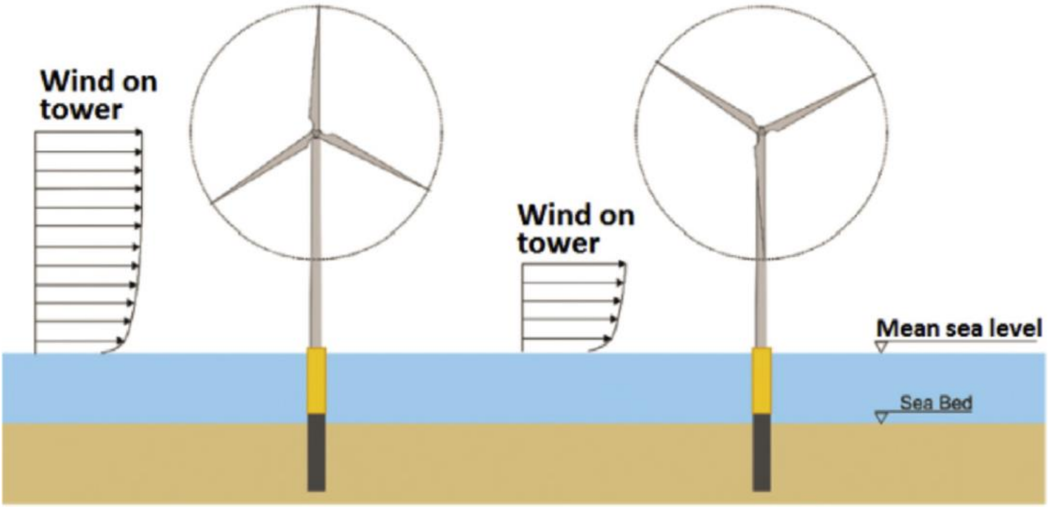


Figure 3.1

Figure 3.1.1.1

The components which are subjected to repeated bending stress may eventually fail by initiation and growth of cracks. Loads causing fatigue damage originate from a variety of sources, such as steady loads from high winds; wind shear, yaw error and motion, stochastic loads from turbulence, transient loads from such events as gusts, operational starts and stops loads; and resonance-induced loads from vibration of the structure. Fatigue analysis simply involves understanding how component parts of the wind turbine would perform in withstanding continuously varying loads for a particular period of time – along the lifespan scale of the wind turbine.

In many offshore structures and especially wind turbines the natural frequency with which the tower moves plays a key role in avoiding resonance phenomena. This frequency is also known as the Eigen-frequency and derives from several structural dimensions such as height of the tower, diameter of the support structure etc. The assessment of the first natural frequency of the offshore wind turbine is a very important part of structural analysis. The forcing frequencies that are commonly taken into considerations are: wind spectrum, operational intervals of the rotor and wave/current spectrum. These variables are taken into account and the tower is designed with a natural frequency that is not near the “dangerous” frequencies of the forces that will be subjected to. In case the frequencies of the forces and the turbine are aligned resonance occurs. Resonance causes combination and build-up of maximum amplitudes which impacts greater stress in the structure which may exceed the allowable design stress and consequently leads to structural collapse.

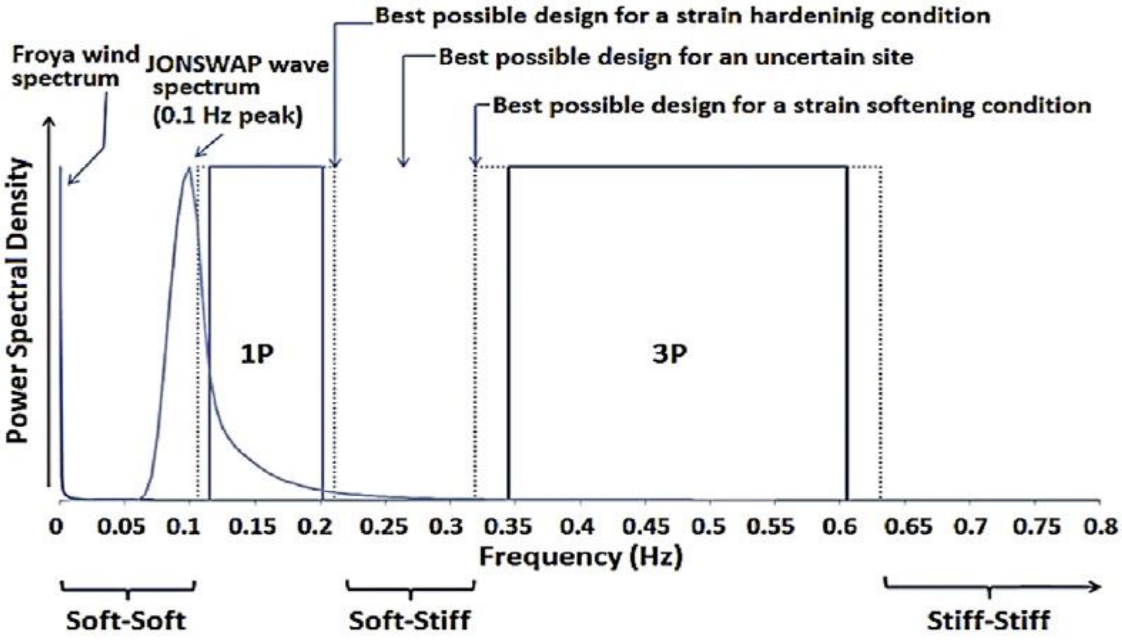


Figure 3.2

Steel Catenary Risers

Catenary risers are a common method of connecting a subsea pipeline to a deep-water floating or fixed oil production platform. They are used to transfer fluids like oil, gas, injection water, etc. between the platforms and the pipelines.

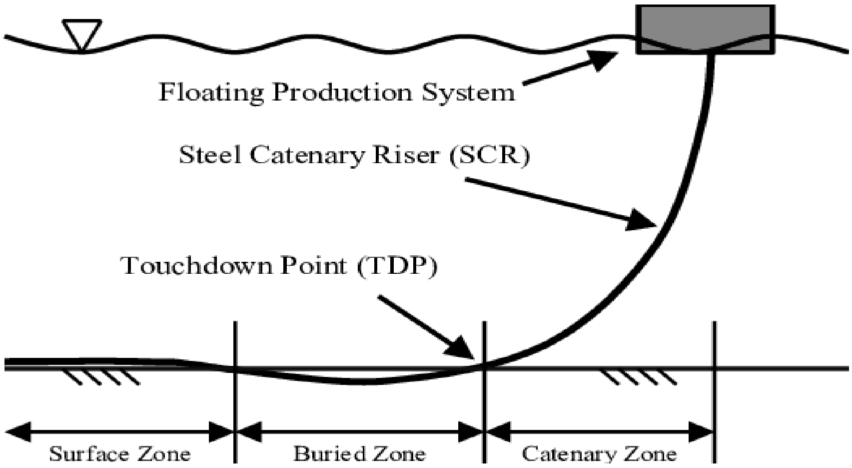


Figure 3.3

Risers travel all the way from the extraction point to the floating vessel and are subjected to stresses and cyclic loading due to currents and waves. Also due to the liquid that flows inside them and the high water depth they operate, they are subjected to internal and external pressure, which can often reach very high values. Steel Catenary Risers stress originates from environmental loading and is determined by vessel and riser dynamics. Therefore the resultant stress histories are strongly dependent on the field location, on the vessel employed and on characteristics and configuration of the riser. Stresses vary also along riser length. Finite Element Analysis is used for stress computation, life prediction and design of such structures. FEA models of the risers are created and their behavior is analyzed with simulations. They make static and dynamic analyses of offshore systems under environmental loading like waves and currents. Probabilistic data of the sea state are used as an input for the simulation and according to these data the fatigue life and probable weak areas of a component are computed. The sea states include information about wave height, wave peak period and frequency. Of course, sea state data are difficult and expensive to acquire. In order for the data to be accurate they have to respond to a specific site, which can be at remote areas in the sea and data collection can last several months or even years.

Fatigue is usually the main design challenge for Steel Catenary Risers. Main sources of fatigue loading are:

- First order wave frequency and second order low frequency vessel motions, due to waves and wind;

- Vortex Induced Vibration (VIV) of the riser, due to currents;
- Vortex Induced Vibration of the riser (HVIV), due to vessel heave;
- Vortex Induced Motion of the vessel, due to currents;
- Installation.

Wave frequency damage is governed by direct wave loading on the riser system and floater motions generated by first order waves. Low frequency damage is governed by second order floater motions due to fluctuating wind forces and second order wave excitation. Wave frequency loads have frequency between 0.05 Hz to 0.5 Hz while low frequency loads have frequency content less than 0.05 Hz. First and second order wave damage is strictly dependent on vessel motion characteristics. Due to their nature, steel catenary risers are very sensitive to vessel motion; therefore their fatigue behavior is influenced by the type of floater employed. Vortex induced vibration damage is mainly due to vortex shedding induced by currents. Deepwater risers are particularly susceptible to VIV because currents are typically higher in deepwater areas; moreover the great length of the riser lowers its natural frequency thereby lowering the magnitude of current required to excite VIV.
HVIV fatigue is generated by floater vertical motions (heave), that may cause riser intermittent VIV. Installation operation can induce additional fatigue cycles.

The relative importance of fatigue sources varies considerably also with the section considered along the riser. The main critical areas are the Hang Off point, where fatigue is mainly due to stress cycles induced by WF motions, and the Touch Down Zone, where fatigue is due to the continual lift off and set down of the riser on the seabed which produces significant bending stress cycling.

General fatigue design procedure

Concerning the fatigue design procedure, most standards follow a similar approach. The first step is knowing the long term stress distribution in the component considered. Depending on material information and joint class of the component a suitable S-N curve is selected. After replacing the long term distribution of stress range with a stress histogram consisting of a number of constant amplitude stress range blocks (σ_i) and the corresponding number of cycles (n_i), the accumulated damage (C) should be determined, following the well-known Miner’s Rule.

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

where:

ni = number of occurrences at a fixed stress range drawn from the load spectrum

Ni = number of cycles to failure at a fixed stress range drawn from the S-N curve

Different critical values of C are recommended in various Standards. For instance both British Standards and API RP2ALRFD recommend just C =1. On the other hand, DNV Standards consider different limit damage values, according to the safety class, meaning with safety class “the significance of the system with respect to the consequence of failure”. Some examples of different standards are given:

Safety class	Low	Normal	High
C critical	1/3	1/5	1/10

Cumulative damage allowable for DNV 2000

The ISO/DIS 13628-7 gives two different values, referring to components which can be inspected and components which cannot be inspected.

Component acceptable for inspection	1/3
Component not acceptable for inspection	1/10

Cumulative Damage allowable for ISO/DIS 13628-7

It should be noted that above striking differences in critical C values do not necessarily represent such significant differences in fatigue design. To compare fatigue design procedures from different specifications/recommendations, the entire procedure has to be examined, including load factors and load spectra, as well as the application range of the specification/recommendation under consideration. API and DNV Standards are typically used in the common international off-shore practice.

3.1.2 **Corrosion Zones**

Constructions at sea are not corroded uniformly. Different areas in the construction are affected by corrosion with different ways depending on the local conditions.

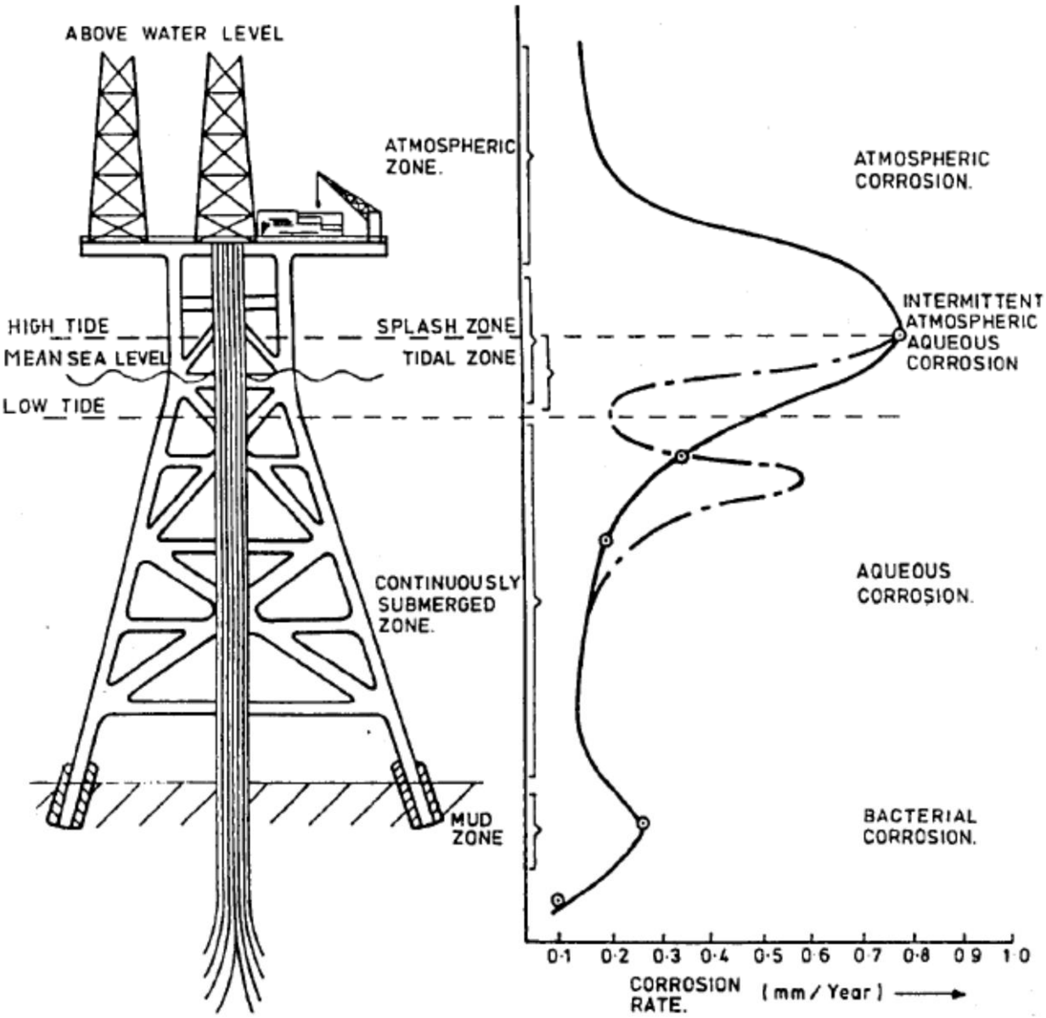


Figure 3.1.2.1

In each zone seen in the picture above, the rate of corrosion differs. These different corrosion zones are:

- Atmospheric zone, where corrosion passes in air and salt spray.
- Splash and tidal zone, where there are alternating periods of wet and dry, loaded also wave and tidal forces.
- Total immersion zone, water with decreasing oxygen level, subjected to underwater current and abrasion by sand and mud.
- Mud zone, where there is sea water mixed with sand and mud and also high level of anaerobic bacterial life.

These zones cause different type and rate of corrosion which complicates the design of the components. For example, in offshore wind turbines the upper part experiences atmospheric corrosion, the middle part is in the splash zone experiencing both atmospheric and aqueous corrosion and the base of the structure which is anchored in the sea bed experiences aqueous and bacterial corrosion. On the other hand, steel catenary risers used for oil transfer between the sea bed and offshore platforms are subjected to different types of corrosion as they pass through all zones.

Consequently, all these different environmental conditions have to be taken into account in order to select proper materials and predict accurately the life of a component. In order to achieve that it is necessary to have enough experimental data.

3.2 Laboratory tests

In order to have valid results and confirm FEA models, researchers had to develop some laboratory experiments that simulate corrosion fatigue life in offshore structures. Over the last three decades corrosion fatigue testing in laboratory environment has evolved and provided very useful data.

3.2.1 Corrosion Fatigue Factors

The goal of corrosion fatigue testing is to simulate the harsh environment that offshore structures are subjected to and export data about real life situations. Researchers have to take into account all variables concerning both fatigue and corrosion simultaneously. It is not an easy task to design and perform a realistic and successful corrosion fatigue test. There are a number of factors that have to be adjusted in order to achieve that. Most notable factors are:

Concentration of damaging species in aqueous or other liquid environments.
Sea salt or NaCl concentration is the most significant damaging species and that is what causes corrosion by making water more conductive. Another key factor is oxygen concentration in sea water. The more the dissolved oxygen content of the sea, the higher the electrode potential of the metal in the sea, the faster the corrosion rate of the metal. In addition, the interaction between salinity and dissolved oxygen is very important for corrosion. As salinity of water increases, water becomes more conductive, but oxygen content decreases. Oxygen concentration is higher on the surface of the sea and generally decreases as depth increases. That is the reason higher corrosion rate is observed in this area, also known as splash zone. There are also many other substances that can harm metals such as other chlorides, sulfur oxides and bacteria creating a corrosive biofilm around the metal surface. The concentration of microbiological life in the fluid has a direct relation to corrosion. Microbiological life enhances corrosion by either removing electrons from the material or forming additional corrosion products.

Temperature
Water temperature is a factor that mostly affects mechanical properties, fatigue and specifically crack growth rate. According to a recent study on metals used for offshore wind turbines a rise in temperature from 5^o to 20^o Celsius can double the crack growth rate due to the increase of speed in chemical reactions. Also at very low temperatures substantial reduction in fracture toughness is seen, which reduces the critical crack length. These contradictory statements suggest that different phenomena take place in different temperatures. A general truth is that extremely low or high temperatures can cause serious problems in offshore structures. Concerning corrosion, temperature does not seem to have a significant effect on its rate; although it is know that bacterial life is favored by higher water temperatures.

pH

The pH of sea water is approximately 8.3 and globally constant. In general, the pH of the sea water is conducive to the inhibition of seawater corrosion of steel. However, oxygen content seems to be the regulatory factor on corrosion and pH in not able to affect its action. Although the surface seawater pH is higher than that of the deep seawater, the corrosion of the surface seawater is far higher due to the photosynthesis of the seawater in the surface. During testing, the pH-level can be adjusted if necessary by adding chemical elements.

Forces and cyclic loading

Key factor for corrosion fatigue testing is making sure the forces on the testing specimens are similar to those applied in real life situations. In an ideal experiment, the cyclic loading conditions such as load amplitude, frequency and sequence of those should respond to real life data collected. Of course this cannot be achieved in every laboratory for various reasons; unavailable data, high costs and time limitations. But despite simplifications and imperfections in the procedure, laboratory experiments have been able to give valid results that come really close to reality.

In offshore structures components are designed to reach very high fatigue cycles in the region above 10^6 cycles. Taking into account the loads applied due to waves and currents this taken many years because of their low frequencies. Sea wave frequency spectrum starts at 0.05 Hz and goes up to 0.5 Hz and the waves with the highest amplitudes are met between 0.06 Hz and 0.01 Hz.

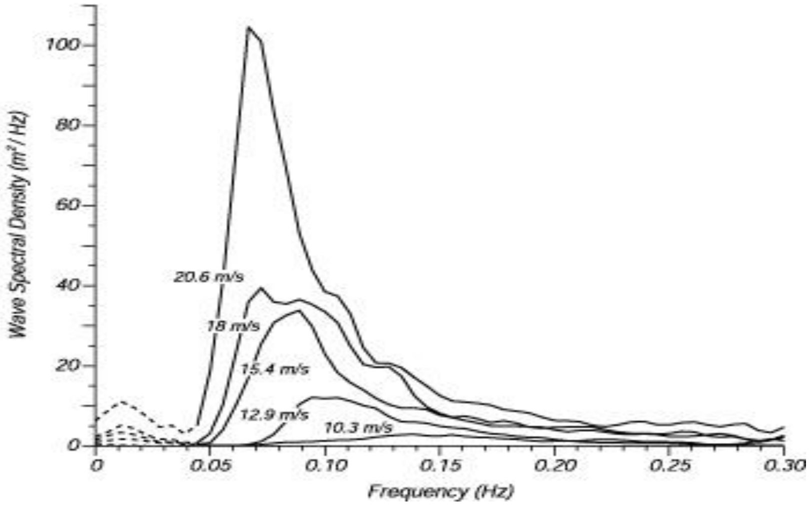


Figure 3.2.1.1

In order to study the combining effect of corrosion and fatigue the experiment has to be performed with a pace where corrosion is able to affect the specimen, just as in real life applications. That means the specimen has to stay in the corrosive environment for a long period while experiencing cyclic loading. Consequently, near-threshold fatigue experiments performed in the frequency range mentioned earlier (0.05 to 0.5

Hz) a period of up to one year may be required to generate the da/dN-K curve. Undoubtedly, this point is at least partly responsible for the general lack of data in this regime. Many laboratory experiments are performed with higher loading frequencies sacrificing this condition but extracting other useful data.

3.2.2 **Corrosion Fatigue Test Equipment**

In this paragraph we are going to describe all the equipment needed to perform a corrosion fatigue experiment according to the factors mentioned in the previous section.

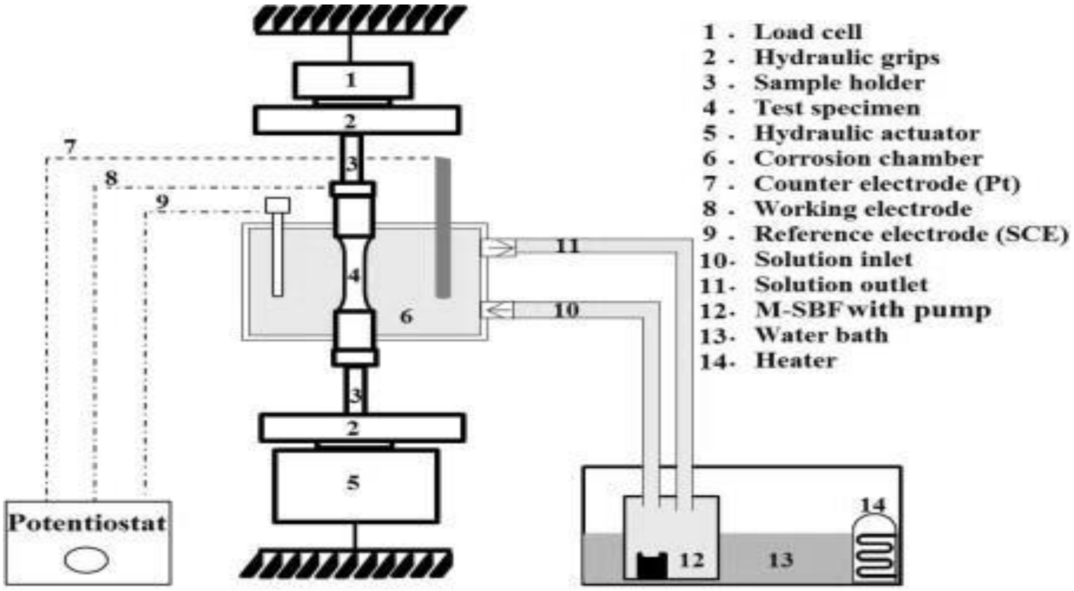


Figure 3.2.2.1

Environmental Chamber

The chamber is the part of the test setup which will contain the corrosive fluid and the specimen. In this component the specimen will be fatigue loaded while the sea water flows across it. To this purpose, the chamber will need to meet some requirements. Sealing of the chamber will be important. Leakage of the sea water fluid is not catastrophic but of course it is not desired. Sealing will therefore need to be done on the test bench itself. Furthermore there will need to be some additional space for mounting of strain gauges, clip-on gages, etc. Yet the dimensions of the chamber will need to be limited. An increase of chamber volume leads to an increase of pumping power, cooling power and filtration capacity. It is preferable to construct the chamber of a transparent material to have eyes on the specimen while testing. Therefore constructing the chamber out of acrylic is a viable solution.

Pump

The function of the pump is to circulate the sea water. It is critical for the pump to be corrosion resistant. Pumps used in aquariums of sea fish are designed to operate under these conditions and form a cheap solution. The head will be minimal 1.5 meters since this will be the estimated height of the chamber to the floor. Since there will be losses over the filter, cooling unit and bends, the head will need to be at least close to 4 meters. The flow rate has to be high enough to clean debris out of the chamber but it is not the intention to have water flowing across the specimen at high speed. Increasing flow velocity of the water will increase the corrosion rate. To simulate a splash zone, a peristaltic pump can be used as mentioned in 2.4. It is currently not the intention to simulate a splash zone, so opting for the aquarium pump is the logical decision. However the circuit will not need much adaptation to fit in a peristaltic pump in case splash zone-research is desired in the future.

Filter unit

In order to prevent problems in water flow a filter unit should be used. Beach sand particles have a size of 100 to 10,000 micrometer, sea salt 0.035 to 0.5 micrometer. As for rust particles their size is unknown and differs depending on the materials and corrosion severeness. A filter of 10 micrometers should be sufficient for most tests. For test-setups that are not recirculating, filtration of seawater containing rust is not needed. In recirculating setups however filtration is required and will need to be monitored during use of the setup, to avoid any unexpected anomalies. Furthermore to prevent clogging of the filter, pre-filtered sea water at 5 micron, will be used.

Cooling unit

The cooling unit will regulate the temperature of the water and keep it at a constant temperature during testing. The minimum temperature, the absolute lower limit of the cooling unit, will be the freezing point of sea water, -2°Celcius. This is the temperature at which ice crystals start to form. The surface temperature of sea water ranges about 2°C to 35°C worldwide. Most testing will happen at lower temperatures between 2°C and 15°C, which covers most cases for sea water temperatures. Therefore, it is not necessary to foresee a heating unit unless a special test takes place. At great depths in the oceans the temperature barely fluctuates and amounts to about 10°C. If deep-sea corrosion is investigated, this could be a reference temperature. It is crucial that also the cooling unit is corrosion resistant. As mentioned above, keeping the dimensions of the chamber small will result in smaller amount of work for the cooling unit. Smaller volume results in faster cooling, leading to a smaller start-up time for a test.

Instrumentation

Corrosion fatigue tests include several environmental variables. It is important to monitor these variables in order to have representative and comparable test results. The temperature in the chamber needs to be monitored. Normally the cooling unit will keep the temperature of the setup constant but it is safer to have a direct control inside the chamber as well. A pH meter will control the acidity of the sea water. In nature the sea water has a stable pH-value of 8.3 and should be kept constant in order to simulate real-life conditions. Furthermore a control of salinity will be required. The salinity might increase by evaporation and escape of water vapor. There is a direct link between conductivity and salinity, measuring the conductivity of the water is the working principle of the most commercial salinity meters. The concentration of microbiological life will not need to be monitored when working with artificial sea water or pre-filtered sea water. For this and other reasons (such as accessibility, chemical stability, no polluting particles, etc.) pre-filtered sea water is the most logical choice. There are many different measurement methods used in fatigue testing such as DCPD (direct current potential drop), infrared thermography, strain gauges, clip-on gage and other methods. DCPD cannot be used in a submerged environment because there will be interference with the measurement probes for salinity and pH as these are based on the conductivity of the water. Sea water is also not transparent in the infrared spectrum making infrared thermography inapplicable in the test-setup. Strain gauges however can be submerged and therefore used to monitor crack growth.

3.2.3 **Types of experiments**

In offshore structures, most problems appear in specific areas of the structure. One of these areas is the splash zone where constant change between immersion in sea water and contact with air causes severe corrosion. Cycling loading is also increased in intensity due to waves crashing on the structure and that is why component design near the splash zone is critical. A second weak spot in offshore structures are weldings. Weldings can be found in mooring chains, catenary risers and underwater oil or gas pipes. As mentioned in the 3.1 paragraph, cyclic loads, sea water corrosion, internal and external pressures are some of the conditions these components come up against. This is the reason most corrosion fatigue experiments are performed according to those critical conditions to “dangerous” structural components such as welds. In this paragraph we are going to examine some of those typical examples for corrosion fatigue experiments.

First example is an experiment about corrosion fatigue of steel catenary risers in sweet production. In this experiment the welds used in catenary risers were tested and below is a photo of the setup used.

Figure 3.2.3.1

In this experiment they used relatively large closed-type chamber that was made out of a corrosion resistant steel. The reason for this is that they tried to simulate deep sea oil application conditions, where there is lack of oxygen. The fluid inside it is circulating and the specimen is fully immersed in it. Salinity was around 3,5% and other substances dissolved in the water were $NaHCO_3$ and CO_2. The controlling parameters of the experiment were temperature, oxygen, pH and iron concentration. Small scale specimens were test in the servo-hydraulic frame in order to aquire crack frowth rate and endurance data. Starin gauges were used for the measurements of the weld cracks. Precautions for protecting the strain gauges are not mentioned but there may have been a protective layer around them in order to be submerged in water. A downside for this experiment is that the chamber is not transparent and it is difficult to inspect the process. A scheme of the setup and all instrumentation used is given below.

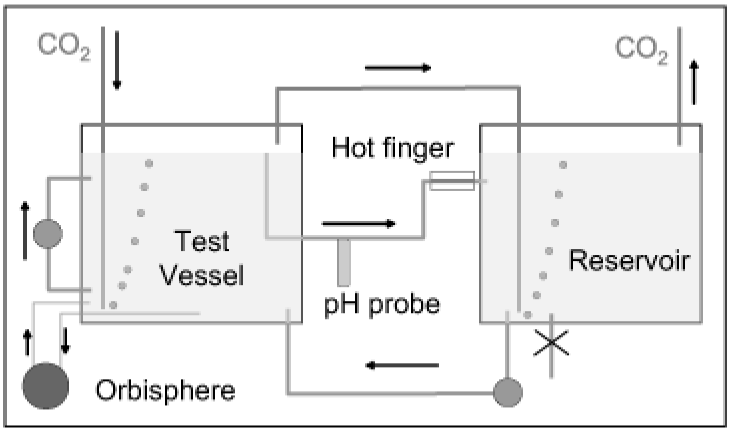


Figure 3.2.3.2

Our second example is a crack initiation test in corrosion fatigue loading at small scale specimen. As observed in the pictures below, this setup looks very different from the previous one.

Figure 3.2.3.3

An big acryllic box is used as the environmental chamber. The water is circulating between the box and a water container and peristaltic pumps are used to souse the specimen. The water used for the experiment is synthetic sea water according to A3 standard and contains 24.53% NaCl, 5.2% MgCl, 4.09% Na2SO4, 1.16% Ca2Cl and 0.201% NaHCO3. Also oxygen is always present as the box is open from its upper side. Also, the specimen is not fully immersed in water and with these conditions the splash zone environment is simulated. The only parameters that are controlled in the experiment is water flow and the solution is sprayed upon the specimen on both sides with a flow rate of 100 ml per minute through a 3 mm nozzle. The specimens tested are small-scale specimens that are loaded at an ultrasonic fatigue testing machine, which is recommended for testing VHCF (very high cycle fatigue) in a short time window. Although, high frequency testing along with the slow process of corrosion cannot represent real life situations and the results of this experiment are debatable since the setup is not heavily monitored. The interesting part of this experiment is the simutation of splash zone conditions, which definitely deserved some more research.

The test were caried out in specimens made of R5 steel under fully reversed tension at 20 kHz. There were three types of specimens, virgin specimens with no corrosion, pre-corroded specimens and specimens with salt water flow during testing. Pre-corrodes specimens showed a decrease of fatigue strength, around 50 MPa, compared to specimens without corrosion. In addition, there was a bigger scatter in values of the pre-corroded specimens compared to the virgin ones. The effect of corrosion during fatigue loading was also confirmed especially in VHCF. For the specimens with salt water flow, the fatigue strength at 10^7 cycles is around 300 MPa, not far from the value for pre-corroded specimens (360 MPa), whereas at $3*10^8$ cycles the fatigue strength is around 100 MPa only. At this fatigue life the fatigue strength decreasing was 71% compared to pre-corroded specimens and 74% compared to virgin specimens. The fatigue strength decreased significantly in the tests under real time artificial sea water flow due to the detrimental corrosive effect. Below are shown the S-N curves for each case.

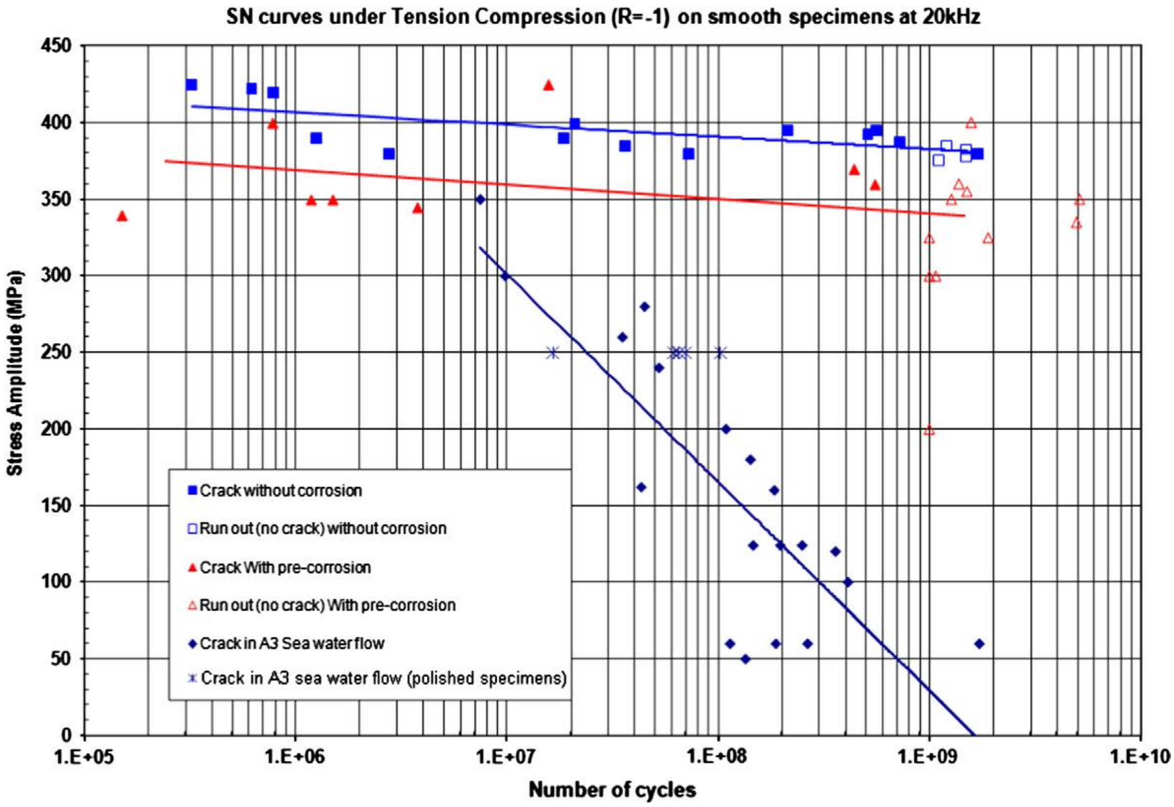


Figure 3.2.3.4

In this example we can see that despite the high frequency of the tests and small time window, corrosion was able to act and affect our samples fatigue strength. There was a signifficant change in their strenth compared to the virgin or the pre-corrodes specimens.

Through corrosion fatigue tests, many usefull data about material properties can be aquired that would help assure the integrity of marine structures that undergo small amplitude stress excursions. Some of those data are: realistic predictions of service stress history, accurate representation of nominal stresses at critical points such as welds (or hot spot stresses), characterisation of local weld geometry and assurance that this is camparable to that of actual structures. As for factors that complicate the application of data, like load inteactions, uncertainties, startup or transitions stresses, they can be included as extra factors of safety. It is very important to connect theoretical fatigue data with real life applications in order to make them safer and more cost effective.

Chapter 4 Construction

4.1 Major problems to be solved

One of the first tasks in building the experiment was to divide the problem in smaller parts and solve each one separately. Although many decisions concerning one problem affected directly or indirectly other parts it was very useful to do that and made the process easier.

4.1.1 Relative Movements of Parts

After the basic decisions about the scale and goal of simulation in our experiment, the most important technical decision was the configuration and the relative movement between the parts. We had to decide which parts were going to be fixed and which parts had to be moving and think of the design in each case. The main ideas were a specimen that is fixed on the water container and these two parts move as one, which mean no relative motion between specimen and container, thus less possibility of leakage. The other idea was a water container in a fixed position and a moving specimen, in which case the insulation problem is more intricate.

Corrosion fatigue experiments such as ours operate with a very low frequency of cyclic loading and as a result the experiment is possible to take several hours or even days to be completed. Considering also the damage on the hydraulic testing machine in case of a leakage of salty water we realized the necessity and difficulty of making the box completely waterproof.

At first, we searched for a way of insulating the specimen so it can move relative to the box slipping between the opening in its base without water coming through but could not find a secure enough solution. Our second thought was to secure the specimen on the box without the specimen moving relative to the box. That way the insulation problem became much simpler but caused the design of the construction’s support to be more complicated.

Insulation of fixed specimen on the box

Insulation in that case was quite simple since there would be no movement between the box and the specimen so we made a simplified version of the experiment with used specimens and plastic bottles. In this experiment we cut an opening about the size of the specimen in a plastic bottle. We then glued the specimen on the bottle applying silicone from both sides of the bottle. After some tries we added a rubber flange from one side of the bottle, right at the base where the specimen is in contact with the bottle.

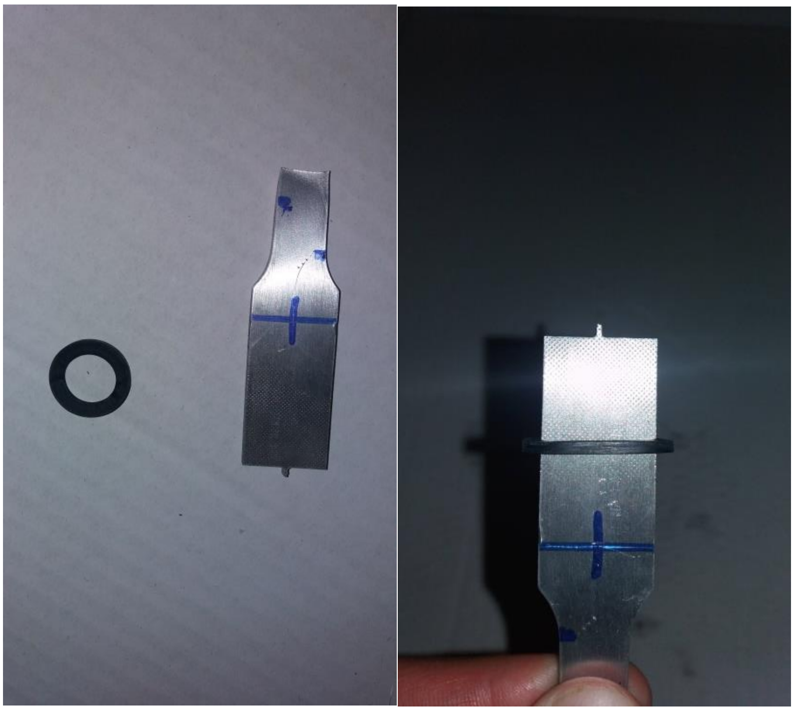


Figure 4.1.1.1

Emphasizing on the smooth and uniform application of the silicone, leaving no holes and weak spots, we managed to seal successfully the bottle. To test that, we filled the bottles with water and left them for two days. The first bottles we test, in which there was poor application of silicone, appeared to be dripping, while the bottles with the rubber flange and the uniform application of silicone remained dry and intact.

Figure 4.1.1.2

Design of construction support, fixed specimen on box

In our axial fatigue testing machine the bottom actuator is the moving part, thus resulting in the axial displacement needed for the fatigue test. In order for the specimen to be fixed in the box, the box had to be moving along with the bottom actuator.

Our idea was to make the support construction of the box fixed on the bottom actuator. The solution to that was to use clamps and tighten them on the flat surfaces of the actuator of the machine, as seen in the roughcast below.

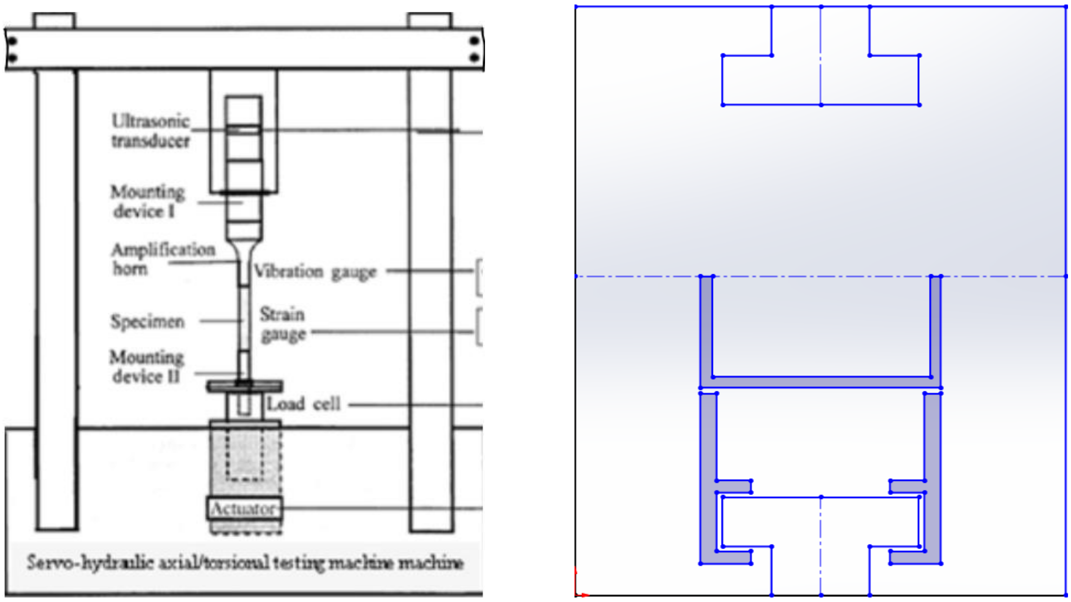


Figure 4.1.1.3

In the right picture, the highlighted with blue parts are the plastic box, where the experiment is performed, and the clamps that connect the box with the bottom actuator of the machine. This is the basic layout of this idea. On top of the clamps there has to be made a custom construction in order for the box to be securely connected to them.

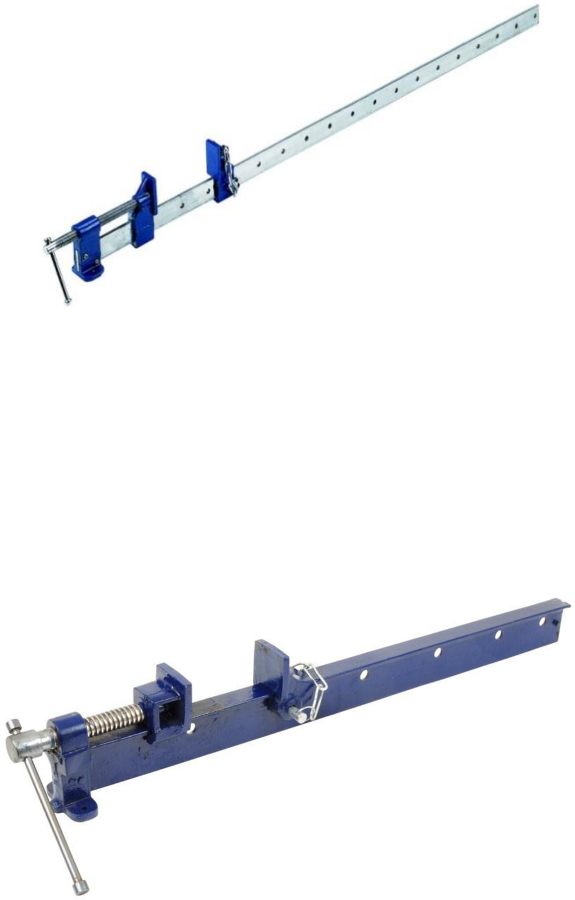


Figure 4.1.1.4

Unfortunately we did not proceed with this design but this is an alternative worth mentioning because of its fairly simple logic and low cost of manufacturing. The clamps are very easy to find in the market and the custom support construction should not be very difficult to design. Also there is very low risk of leakage of water from the tank if all the connections are made properly.

Box in fixed position and moving specimen

Finally, the solution we found was somewhere in the middle of the two ideas mentioned earlier. The box carrying the water for our experiment is securely fixed and not moving along with the specimen. The specimen also does not slip through the box itself but if tightly mounted on a flexible material and this material if glued on the surface of the box. The motion of the specimen is made possible due to the flexing of this material. The support construction is clamped on the two columns of the test machine and the box is sitting on a metal frame in the middle of the support construction. All these topics will be discussed in full detail in the next parts.

4.1.2 **Water insulation of box**

One other task was to make the box, in which the experiment was going to take place, fully waterproof. We had decided to make a box from plexiglass, and more importantly from plates of plexiglass, which is a type of plastic. As we discovered later plexiglass is not a very easy material to work with and needed certain special methods to process it. We had to make sure all the connections between the plates and the base are well connected and there are no holes or gaps that could result in leakage of water. Another major problem was the insulation between the box and the specimen. Since we used an extra component in the setup, a flexible bored cap, the hole in the bottom of the box became much bigger, in order for the flexible material to take up a larger surface area and be able to flex and work properly. We needed to ensure there was no leakage during contact of both the cap surface with the box and the cap with the specimen that goes through it.

4.1.3 **Water recycling system and peripherals**

In corrosion fatigue experiments, environmental conditions are very important for the validity and the results of the experiment. In our case the condition we had was the salinity of the water and its homogeneity in order to ensure the corrosion factors remained constant throughout the experiment. That is the reason for the recycling of the water in our box. This recycling took place between the box and a container with bigger volume. The water is pumped from the container to the box using a small scale pump through hoses and then returned to the container due to overflow.

4.1.4 **Construction support**

The construction support is a metal construction and consists of a frame, where the box sits on, clamps, with which the construction is mounted on the two columns of the test machine and metal plates which connect the clamps with the frame. These parts are connected with weldings between the plates and the clamps and screw connections between the plates and the frame. Designing and manufacturing this construction was tricky at some points, firstly because it took time to decide about the general setup, whether the specimen was going to be fixed on the box and the relative movements between the parts. Finally, we had to change our design completely after the final decision, about using a flexible cap in the bottom of the box, was made. Our two main options were to base the construction either on the test machine or make an external construction and base it on the floor, as we also wanted to avoid damage to the test machine. We decided the most simple and ergonomic design was to base the construction of the columns of the test machine. In order to protect the columns from scratches and wear we used rubber rings between their surface and the surface of the clamps.

4.2 Design and Solutions

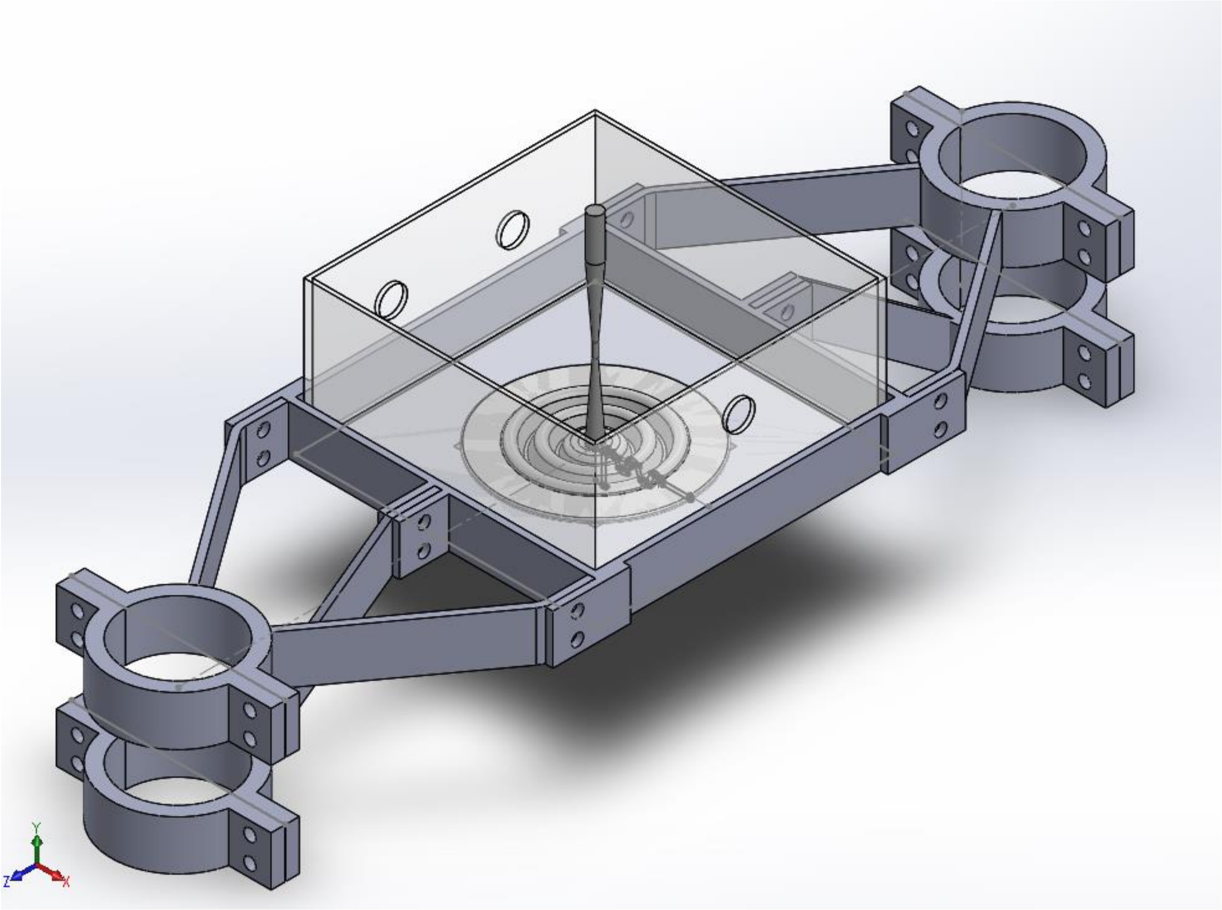


Figure 4.1 Construction design, Total Assembly

In the picture above is shown the design of our construction for the experiment. In the next paragraphs the design and the characteristics of each part is discussed and analyzed.

These parts analyzed are the water container, the construction support, which includes the metal frame, the rings and the plates, the bottom insulation component, the specimen and the peripheral components which are not shown above.

Everything was designed in SolidWorks software.

4.2.1 Water Container

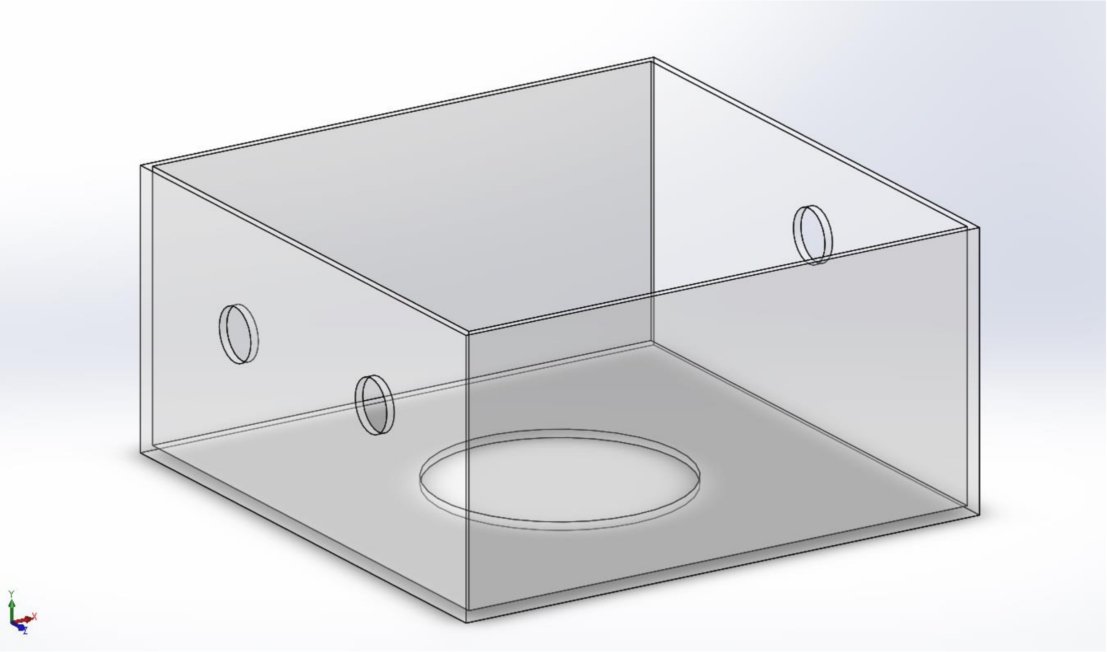


Figure 4.2.1.1 Design of container

The first component of our experiment and the place where it will take place is a water container, this transparent plastic box as shown above. It is a square box with side dimensions 206mm x 206mm and 103mm height. The thickness of the walls and the bottom is 3mm. The material we are going to use is plexiglass, which is a transparent and very light material suited for our purpose.

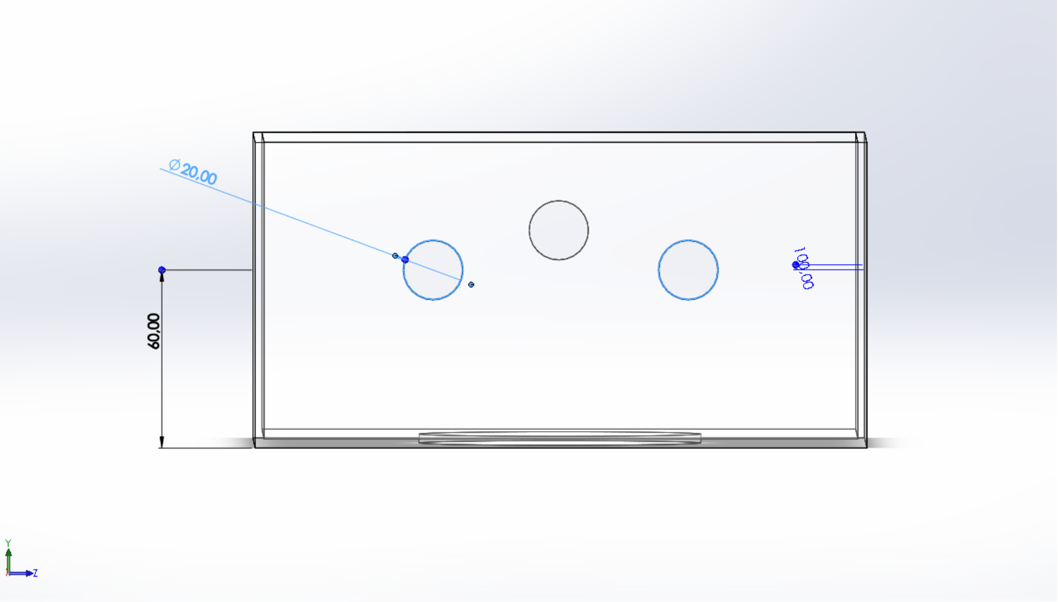


Figure 4.2.1.2 Side View of the container

There are three holes of 20mm diameter in the sides of our container. In one side there is only one hole, which will be the inlet of water for our container. The center of this hole is at 70mm height from the bottom surface. For the inlet a small scale pump is going to be used to pump the water from a bigger external container. Across, on the other side, there are two similar holes slightly lower, at 60mm height from the bottom surface. The reason for this is that these two holes are going to be the outlet of water and in order to achieve successful overflow we have to consider pressure drop phenomena as the water tries to go throw the hoses and the nozzles that connect the box with the hoses. All these components reduce the diameter of the flow surface and make it more difficult for the water to flow easily through the outlets. In an experiment that was performed, we observed that with only one outlet the water container topped up as the water flow rate in the inlet was bigger than the flow rate in the outlet. We concluded that we need at least two holes in order to avoid that and have a steady flow of water through the container.

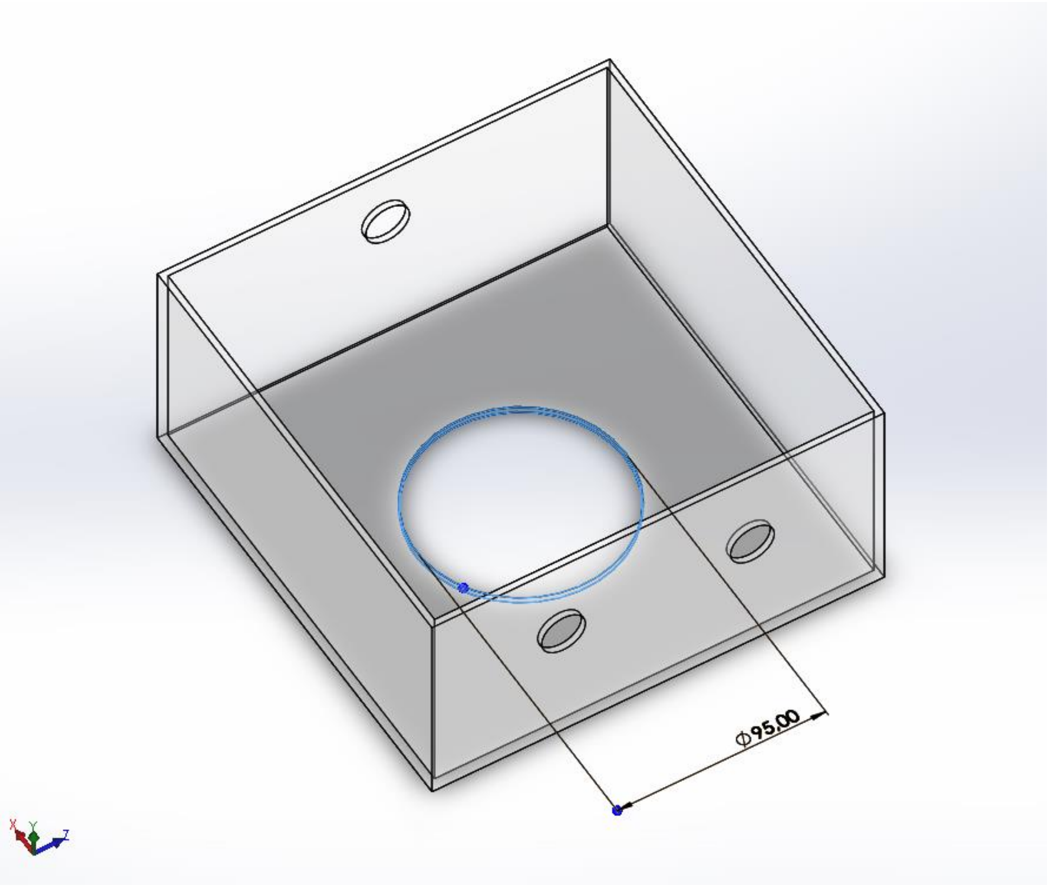


Figure 4.2.1.3

At the bottom of the container there is a larger hole with 95mm diameter where the insulation component is going to be glued.

Box Prototype, 1st Attempt

In order to make our prototype water container the first step was to gather all the materials and tools needed. These were:

- Plexiglass, we bought a plexiglass panel which was about half a square meter. This panel is enough for 5 of these containers with the dimensions referred earlier.
- Strong instant glue, suitable for plastics and acrylics such as plexiglass.
- Silicone, we chose a transparent silicone suitable for water insulation for the inside edges of the box.
- Sandpaper, to make the surfaces to be glued smoother and flat and remove debris after the plexiglass was cut .
- A box or something else that has sharp edges with 90 degrees angle and will be used as frame. That way the plates are glued properly with the right angles. In our case it was a wooden drawer.
- Clamps, in order to secure the plates on the frame until the glue is totally dry and stiff.

Figure 4.2.1.4 Plates of plexiglass

The steps for the construction of the box are the following: first we cut the big piece of plexiglass in smaller ones with the dimensions we needed. At first we tried to do that with a regular saw but it was not easy. The plexiglass is very fragile and easy to crack if cut the wrong way. Then with help from a craftsman working with glass we were able to cut the plexiglass with a heavy duty cutter for plastics. We removed all the debris from the cut surfaces and smoothed them out using a series of sandpapers going gradually from bigger grains of sand to smaller. At this point it is very important to beware of the surfaces not to become curved while they are rubbed with sandpapers, so that they can be glued stably and securely.

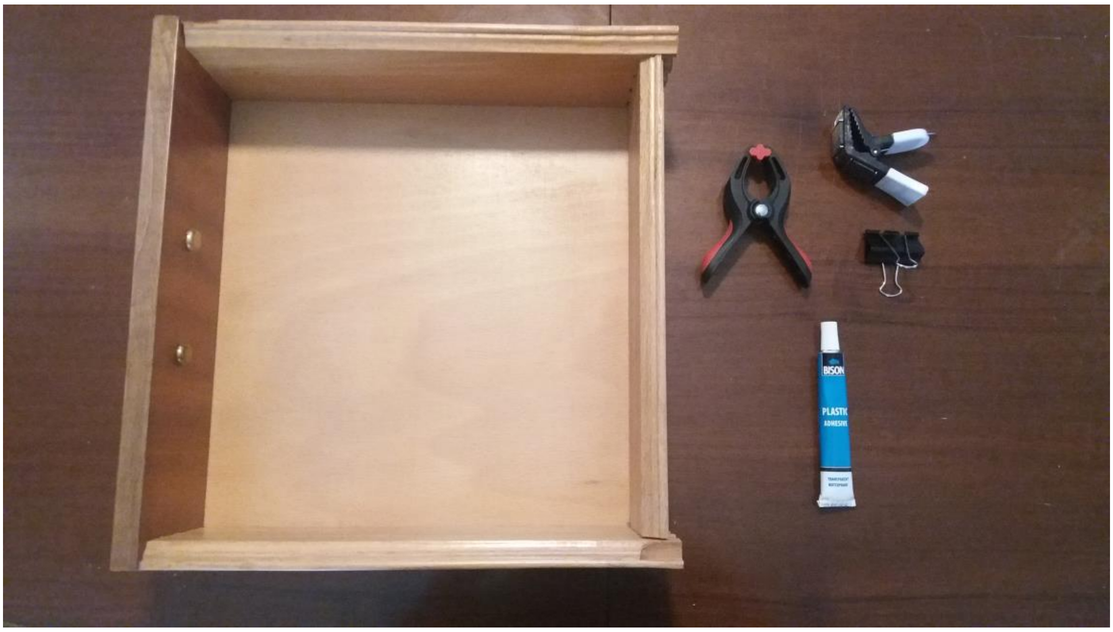


Figure 4.2.1.5

Next, we used a wooden drawer, as a frame for the container, and placed the bottom plate on one of its corners. We applied the glue on the surface of the plate we were going to glue and placed it on the bottom plate tightening it on the wall of the drawer using a clamp. It is important to make sure there is uniform application of glue and the placement is correct. We left each plate for several hours before proceeding with the next.

Figure 4.2.1.6

After we glued all the side plates we applied silicone on the joints of the plates in order to make the container fully waterproof. After the silicone dried our box was ready for testing. Before the application of silicon our construction had some flaws, such as small gaps on the corners and curved surfaces on the side plates because of some unmindful rubbing with the sandpapers. Nevertheless, we filled the container with water and after leaving it for two days we were happy to observe that there was no leakage whatsoever.

Figure 4.2.1.7 Application of silicone on the edges

At this point, some extra information about plexiglass has to be mentioned. While we were still researching the different ways and materials for the construction of this box, we contacted several craftsmen working with glass materials and plexiglass. They all agreed that plexiglass, as any plastic, is a “difficult” material to work with for such applications because of its brittleness and the fact that it melts very easily.

Cutting and gluing plexiglass need special tools and chemical components. The best way to cut plexiglass is to use a heavy duty cutter for plastics. This tool removes material at each pass and after a certain depth is achieved then the plexiglass can be broken securely without cracking. Other tools such as mechanical saws have to be used very carefully and ensure proper cutting conditions. For example, in case we tried to make a cut with a mechanical saw, the saw has to be set at its minimum frequency and maybe use water or some kind of oil to keep the temperature low, as it is very easy to melt the plexiglass and destroy it.

Furthermore, there are many ways to bond acrylic sheets using different kinds of glues and most of them will work fine for such applications. Ordinary glue is a viscous adhesive that is applied on two surfaces and due to its viscosity it fills the gaps between them. As is dries, it bonds on the surfaces which are held together by this dried glue.

The best way for gluing plexiglass is to use acrylic cement, which works very differently from glue, as it is a water thin liquid that does not fill gaps. Acrylic cement softens the plastic surfaces so that they merge. The molecules of the two pieces intertwine and the two surfaces become one, just as welding metal. It is also called “solvent welding”.

4.2.2 **Construction support**

The support of the container consists of three components, a metal frame in which the container will rest. This frame will be pieced together by welding and screw connections with two metal plates on each side. The metal plates will reach and clamp on the columns of the test machine, on which the experiment is performed.

The clamping on the columns of the machine will be achieved with two semicircular rings which will be tightened on the column. One half of the ring will be welded with the metal plate. Subsequently, the plate connects the clamping rings with the container. Below are the design and the overall layout of the construction. Each component is then analyzed further.

1. Metal Frame

2. Clamping Rings

3. Metal Plates

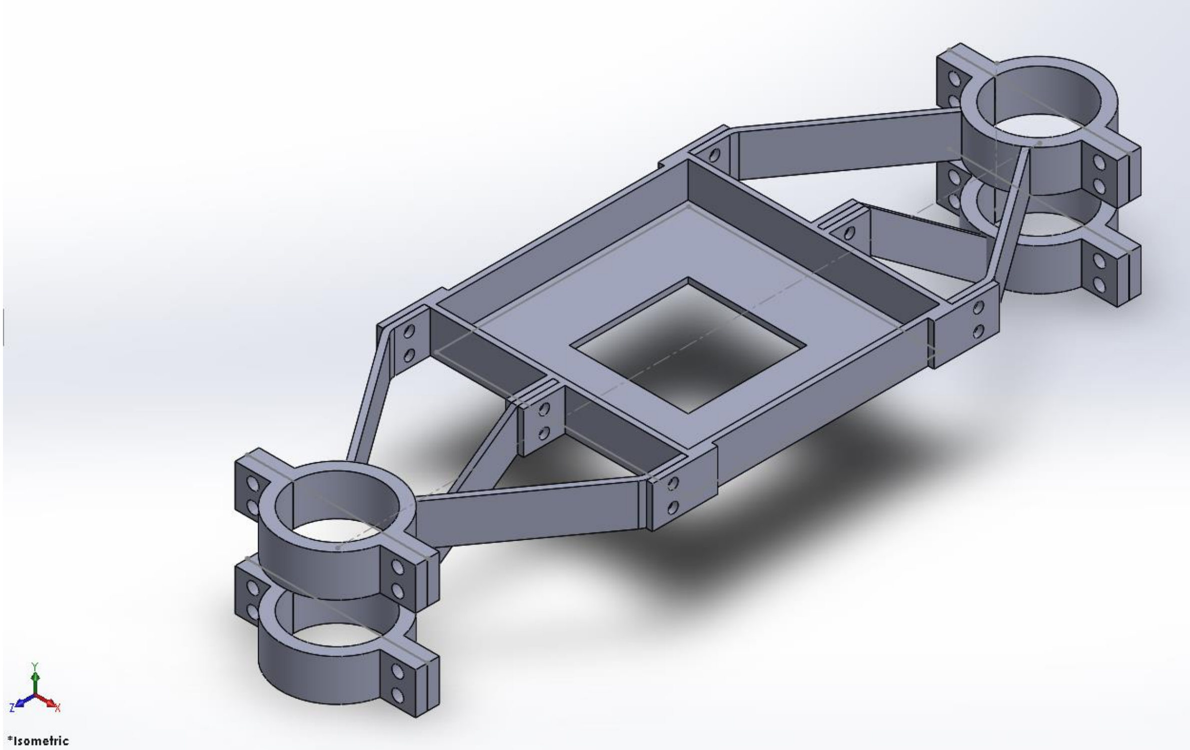


Figure 4.2.2.1 Solidworks Assembly Isometric view

As you can see at the level of the container there will be two diagonal plates that will be connected with screws and nuts to the container. The plates on the other side will be welded to the semicircular ring.

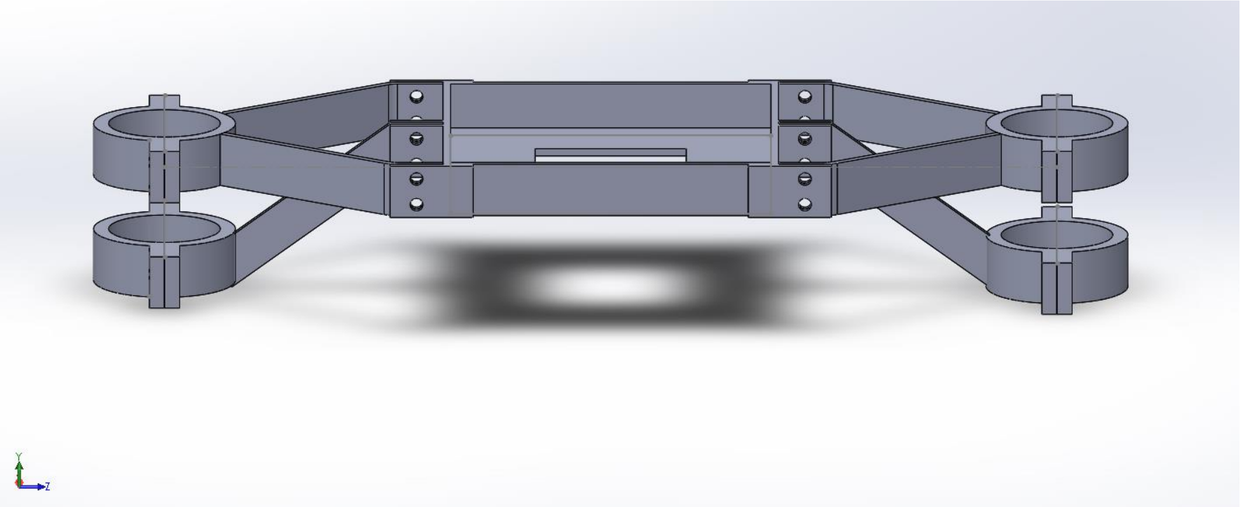


Figure 4.2.2.2 Side view

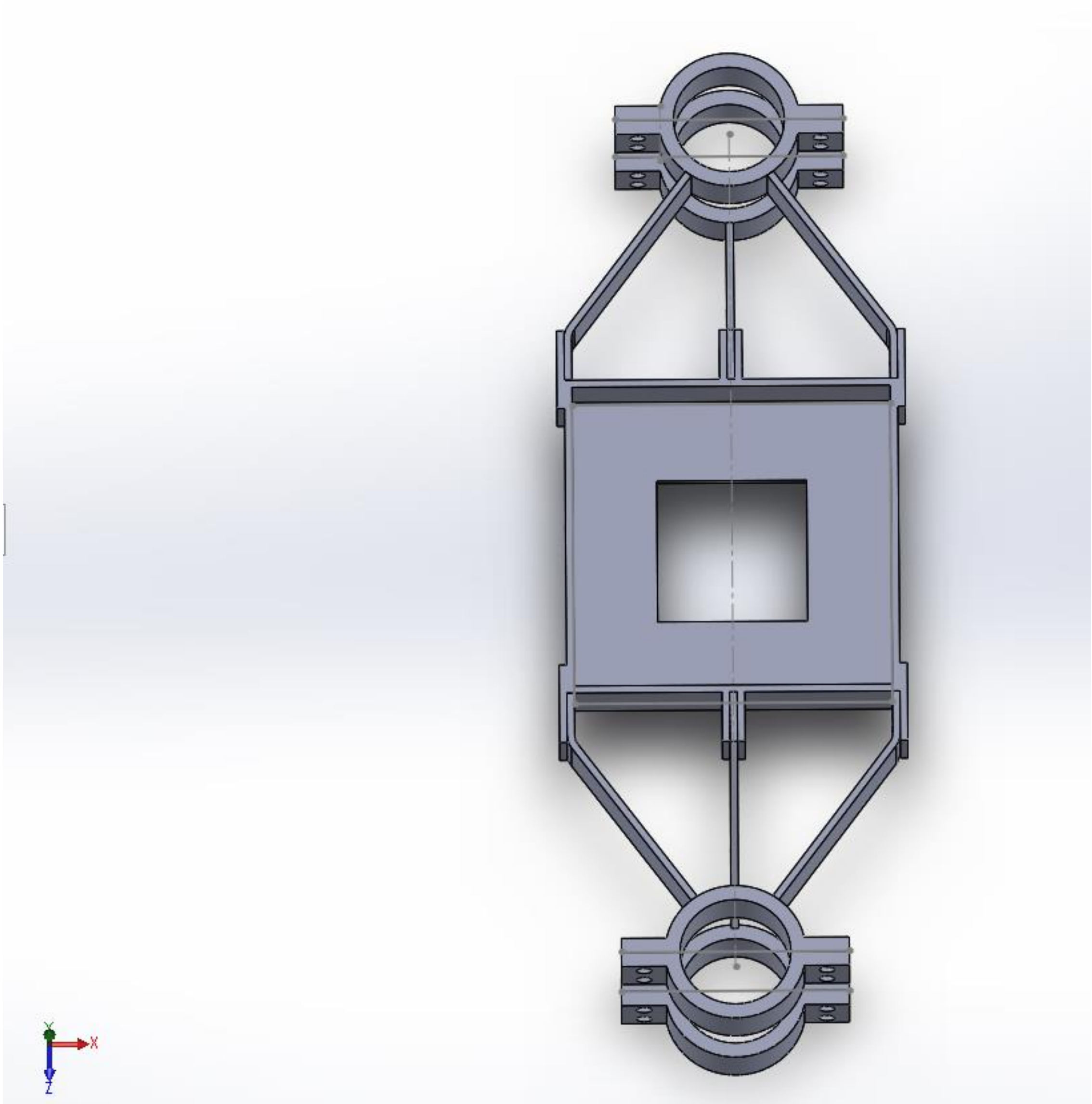


Figure 4.2.2.3 Top View

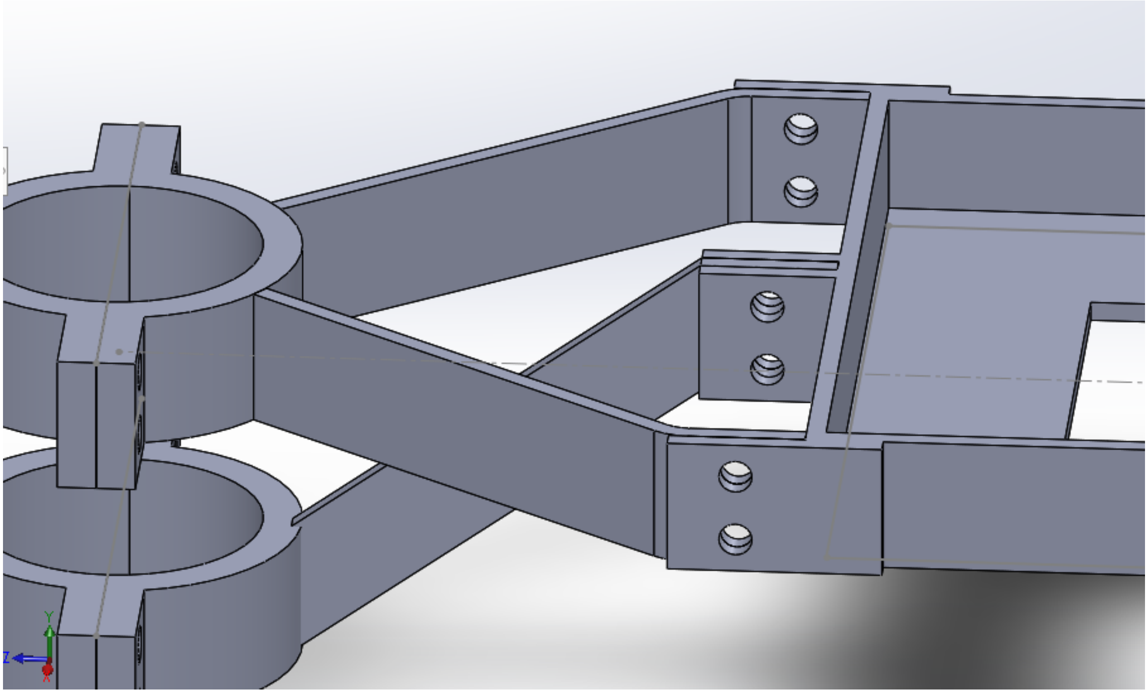


Figure 4.2.2.4 Connections of plate with frame

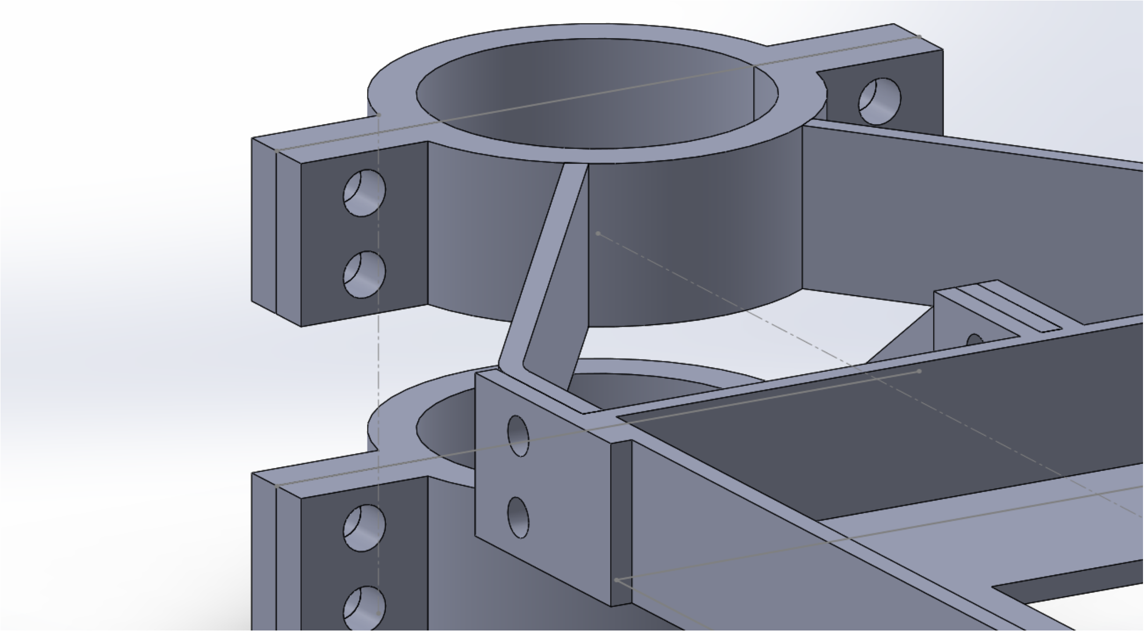


Figure 4.2.2.5 Connections of plates with clamping rings

Following is a further analysis of the individual components, the metal frame, plates and clamping rings.

Metal Frame

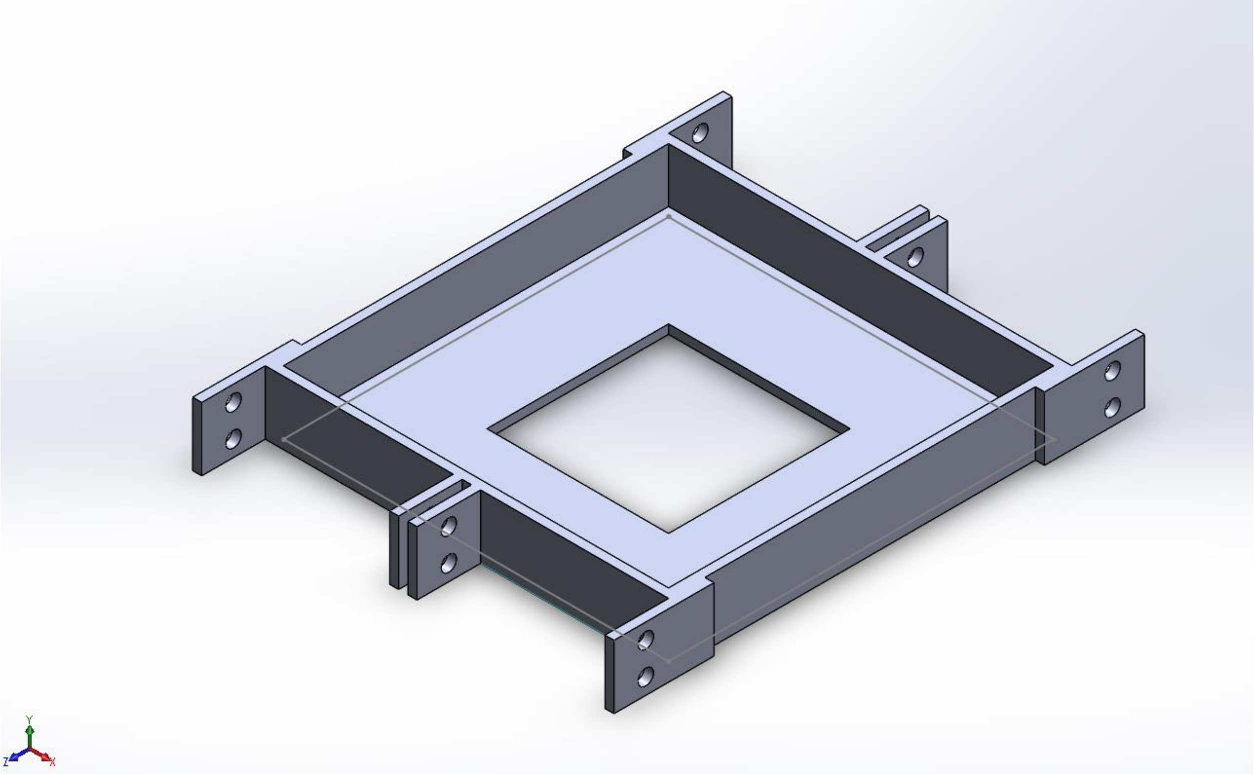


Figure 4.2.2.6 Metal Frame Isometric view

The metal frame will have dimensions 222mm x 222mm x 35mm and the thickness of the bottom and the walls is 5mm.

The container with water has dimensions of 206mm x 206mm. The frame is designed with tolerances of 3mm on each side so that the container has room for small movements for better alignment of the specimen on the machine.

These tolerances can be used to insert some rubber or some other soft material between the container and the frame in order for the container to wedge stably inside the frame.

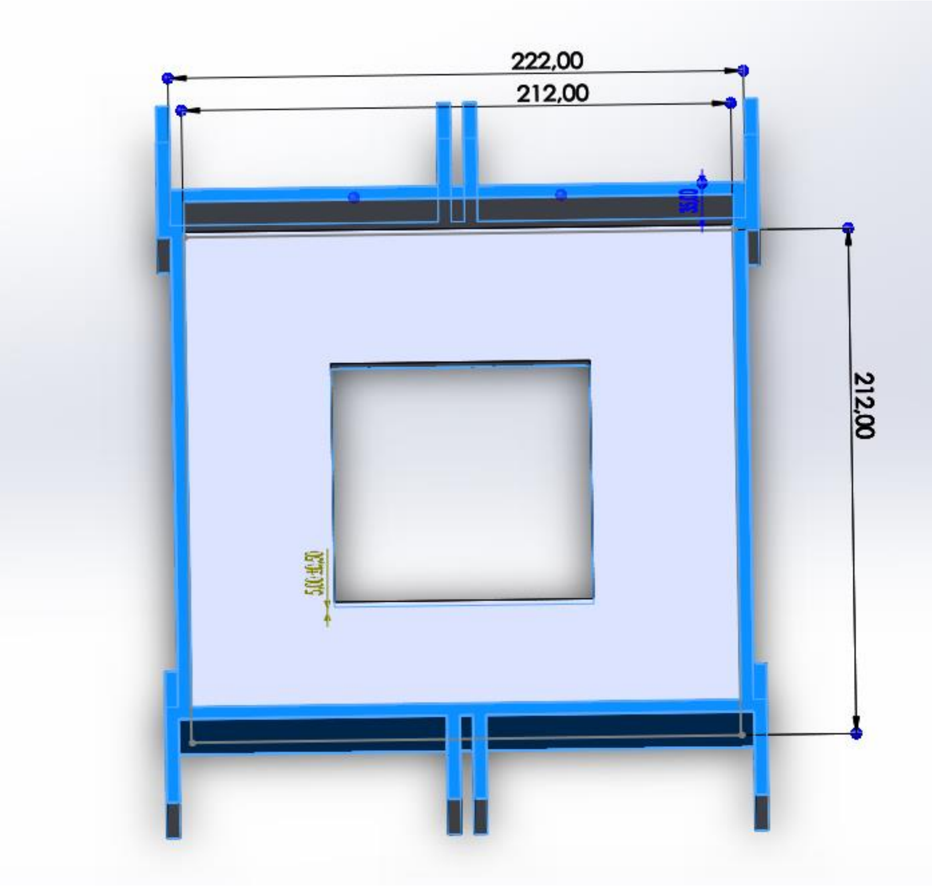


Figure 4.2.2.7 Top view with dimensions

There is a special configuration in the corners of the frame, the 'ears' will be welded onto the container and will protrude 35mm form the container as shown in the photos below. These ‘ears’ will be connected to the metal plates with screw connections.

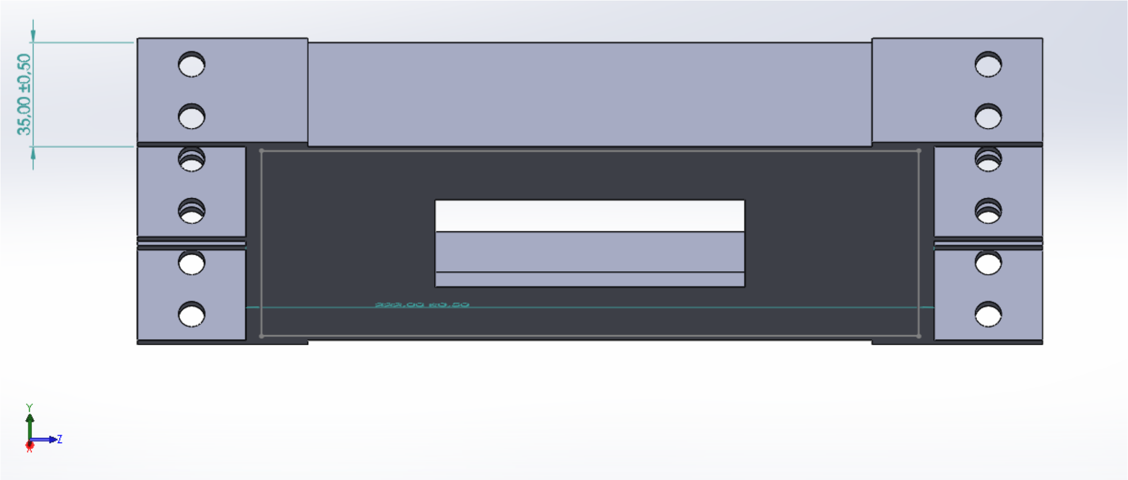


Figure 4.2.2.8 View of frame from below

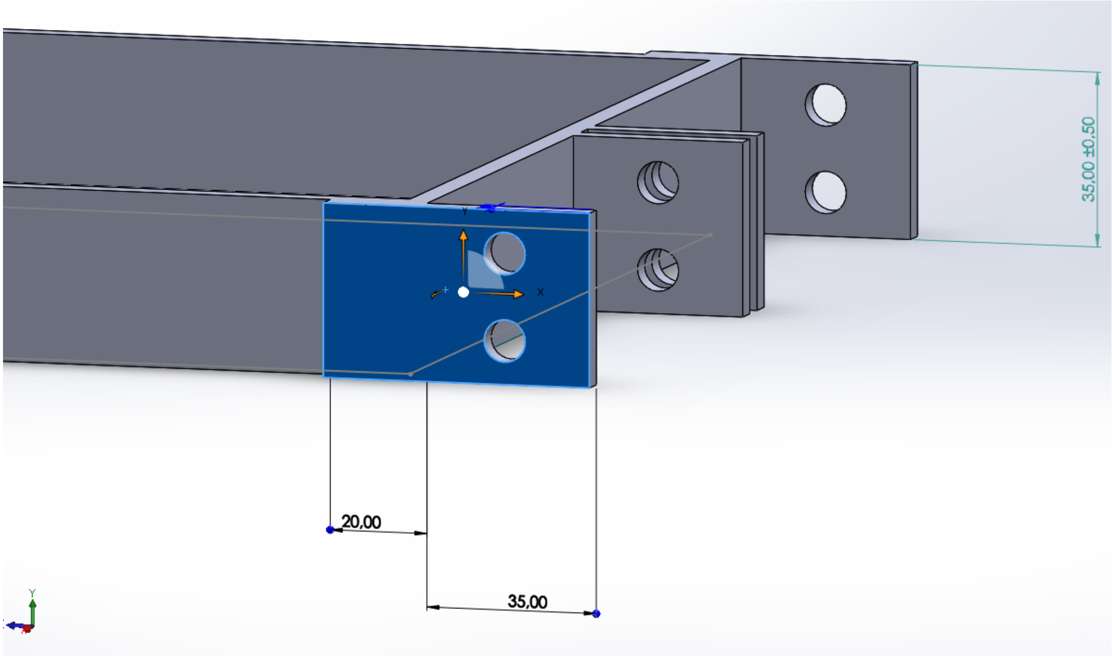


Figure 4.2.2.9 Side view of ‘ear’ configuration

There will be two holes of 8,5mm diameter in each projection. In the middle there will be two ‘ears’ instead of one for better balance and extra safety. Ideally the projections in the middle should receive the majority of vertical load applied and the ones in the edges should mostly support and balance the construction in case of oscillations or small shifts in the x axis.

Clamping Rings

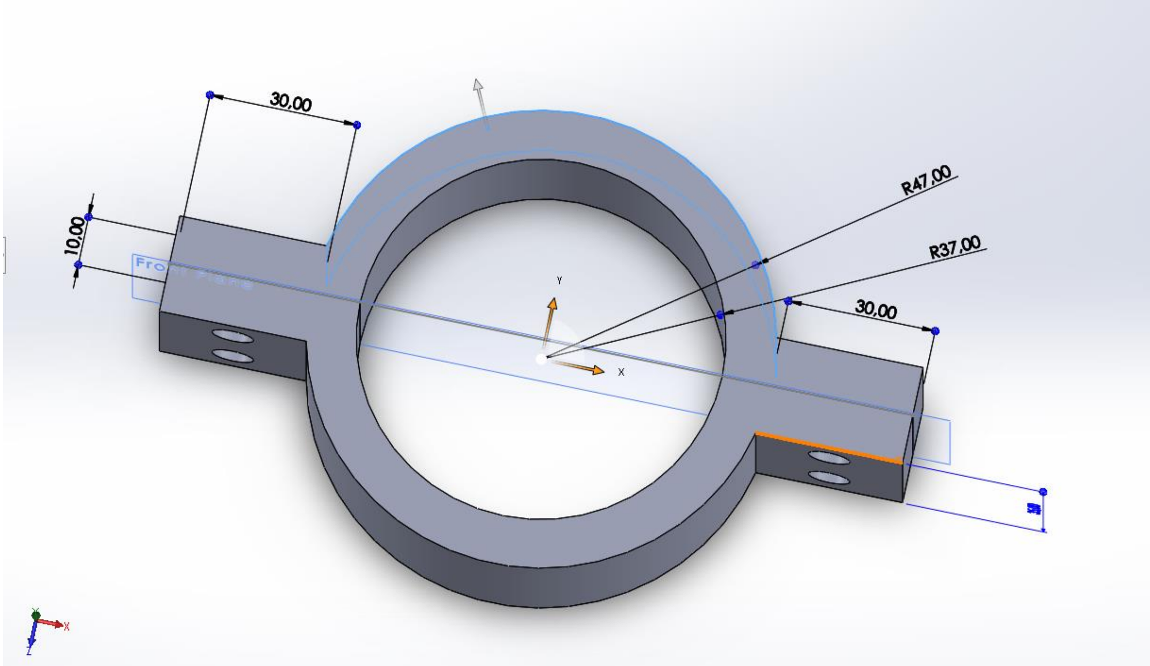


Figure 4.2.2.10 Clamping Ring design in Solidworks

The clamp consists of two identical semicircular pieces with protrusions, has an internal radius of 37mm and a thickness of 10mm. Their width is 20mm, the height is 35mm and the protrusion is 30mm and there are two holes with a diameter of 8.5mm so that the 2 pieces can be connected with screws.

Figure 4.2.2.11 Side view of clamping ring

The diameter of the machine column is 63.5mm while the inner diameter of the clamp is 74mm. This large gap exists so that a thick tire can be inserted between the clamp and the column. This tire, in addition to being non-slip, will also have the purpose of protecting the machine column from damage due to contact with the metal clamp.

Metal Plates

Metal Plates in x-z axis

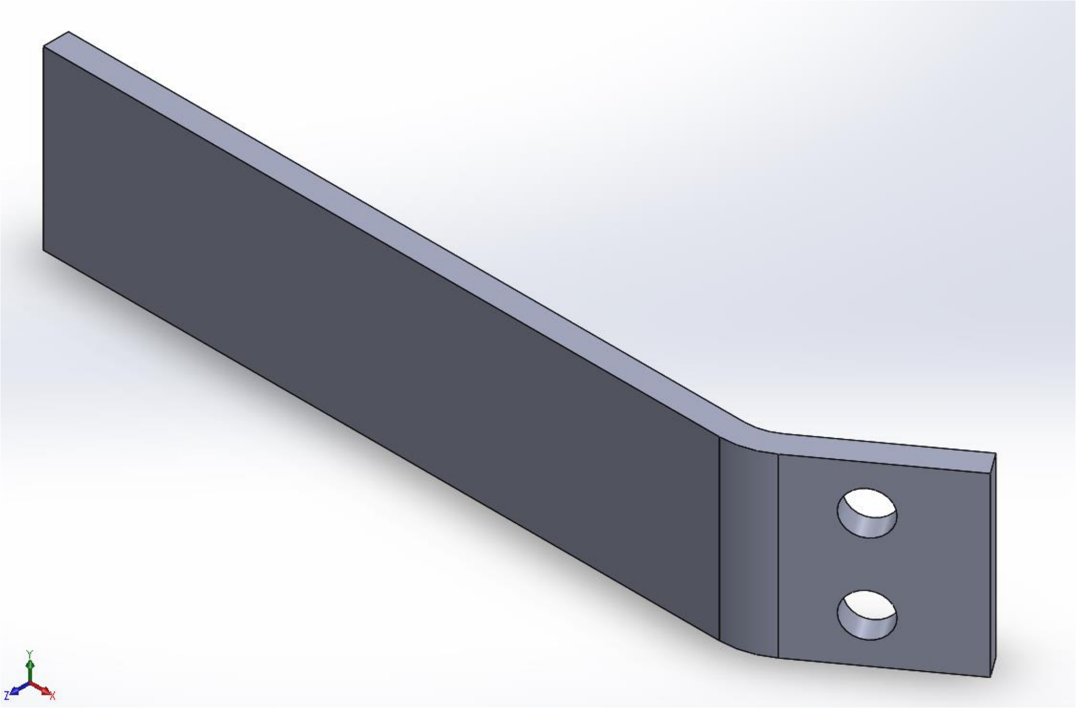


Figure 4.2.2.12 Metal plate in x-z axis design

The metal plates are the component that unites the two elements above. There will be 6 plates total, 4 at the level of the frame, diagonal on the x-z axis, connected to its corners and 2 diagonal on the y-z axis, connected in the ‘ears’ in the middle of the two faces of the frame. This way absolute stability of the construction will be ensured.

On one side these plates will be welded on the clamping ring and at the end of the other side they are folded in order to become parallel to the projections of the frame and connected to them using screws.

The thickness of the plates will be 5mm and their width 35mm. The holes are 8,5mm diameter and the inner fillet radius is 10mm.

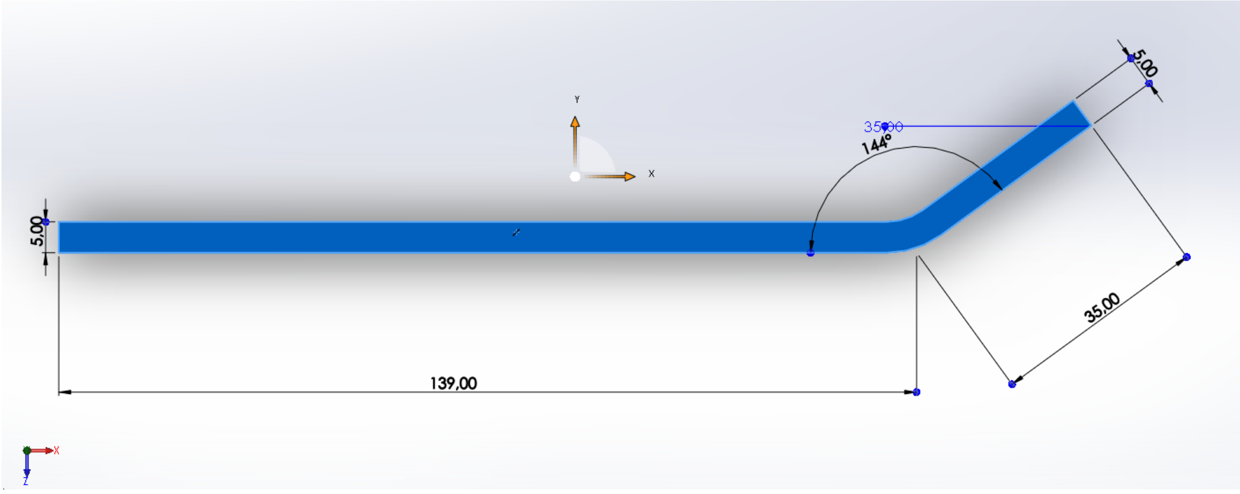


Figure 4.2.2.13 Diamensions of plate in x-z axis

Metal Plates in y-z axis

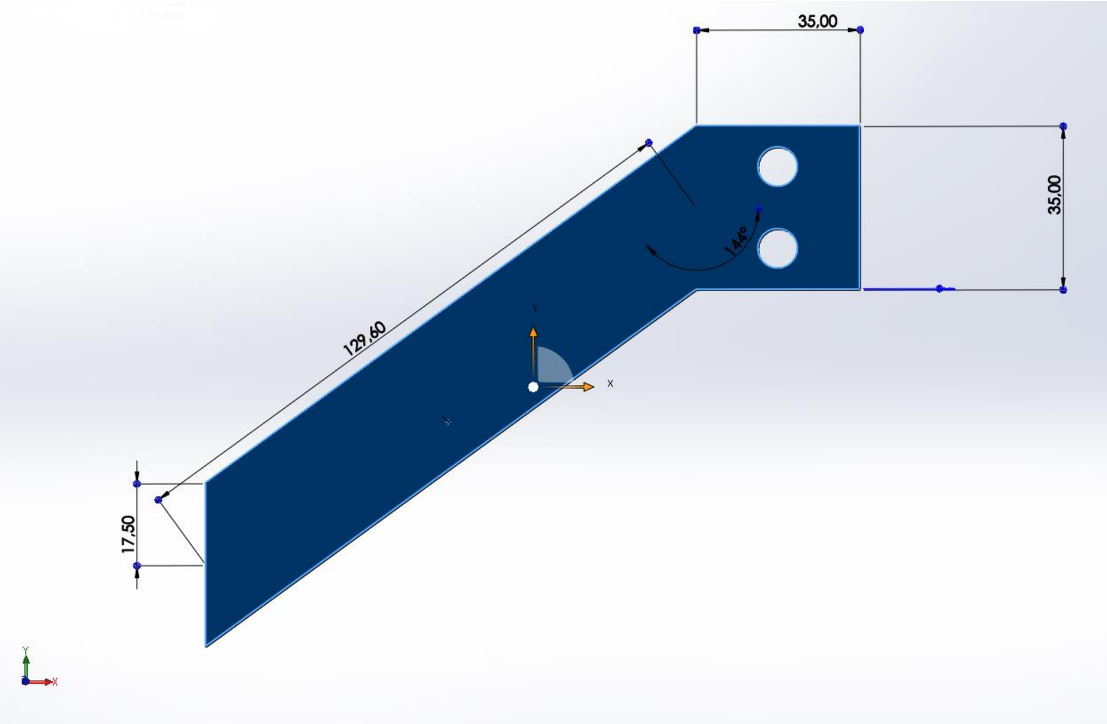


Figure 4.2.2.14 Metal plate in y-z axis design

The thickness of the plates will be 5mm and their width 35mm and the diameter of the holes is 8,5mm.

4.2.3 **Bottom insulation component**

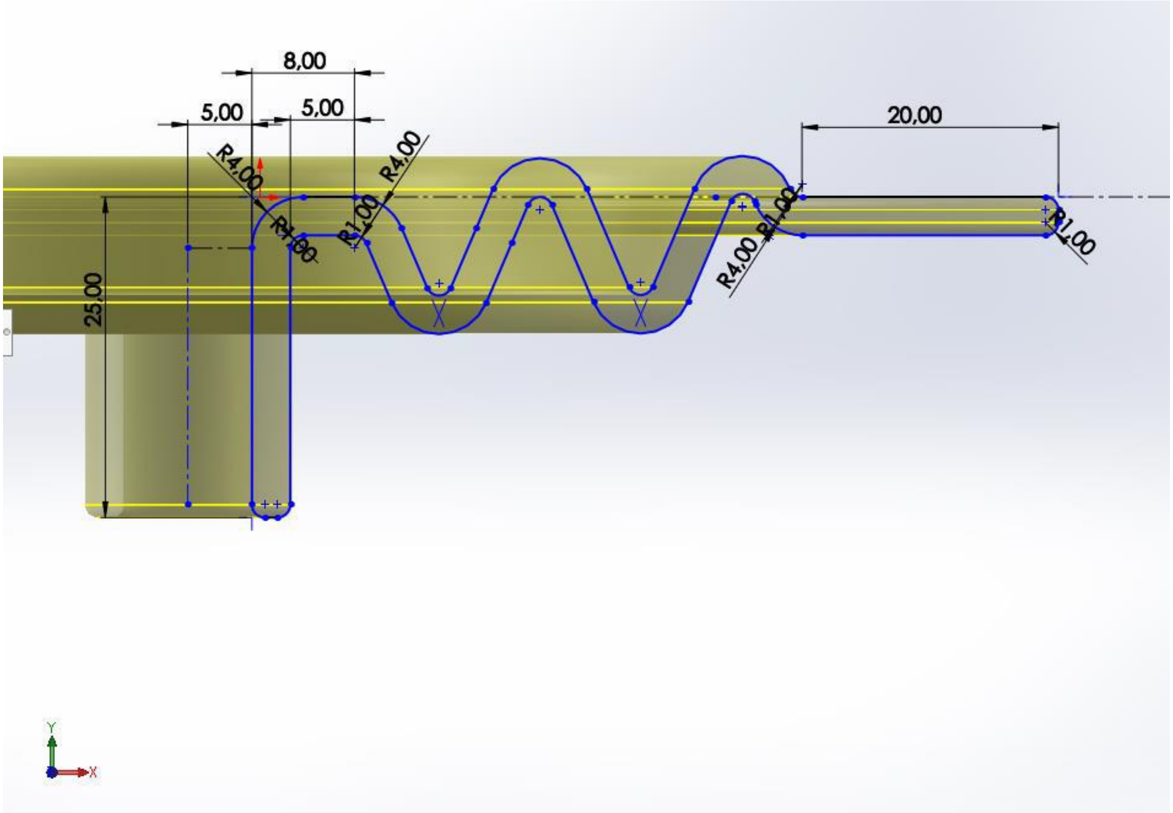


Figure 4.2.3.1 Design of rubber component for insulation

The material of this component is a flexible plastic, a rubber type material, and is made with 3D printing. The thickness is 3mm and its role is to insulate the box so that there are no leaks from the bottom of the container.

The outer ring is the surface that will stick to the container. A layer of silicone will be applied around the joint internally and externally, as an extra security measure.

The ripples in the material exist to receive all the deformations by stretching and furling during the experiment.

Finally, the inner cylinder will be in contact with the specimen and the specimen will be wedged in there. Externally a tightening ring will be applied to tighten the tire on the specimen.

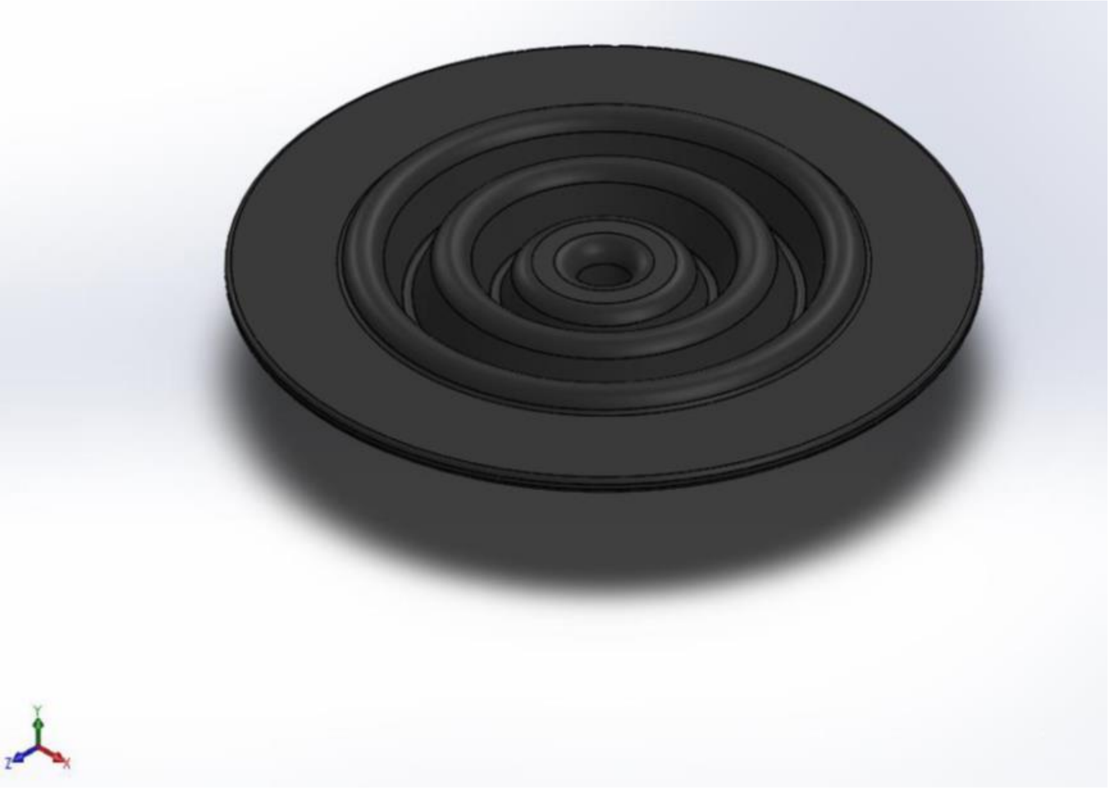


Figure 4.2.3.2 Isometric view of component

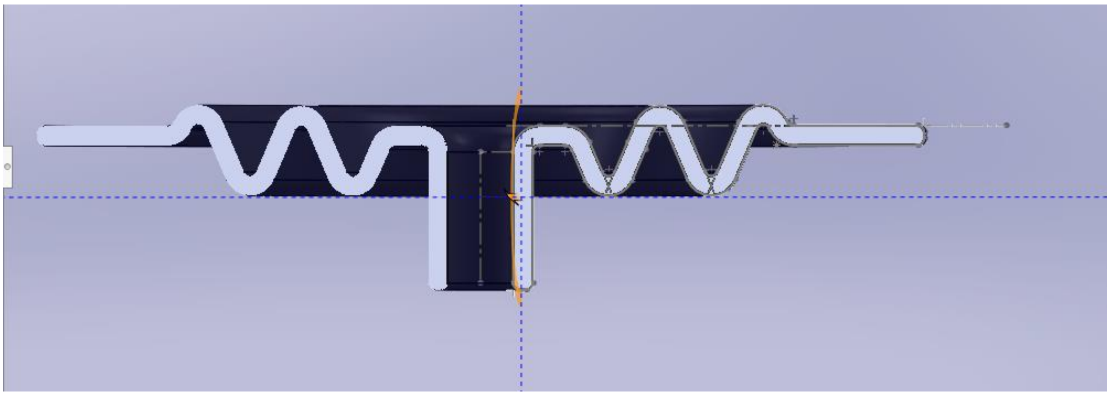


Figure 4.2.3.3 Side section view of component

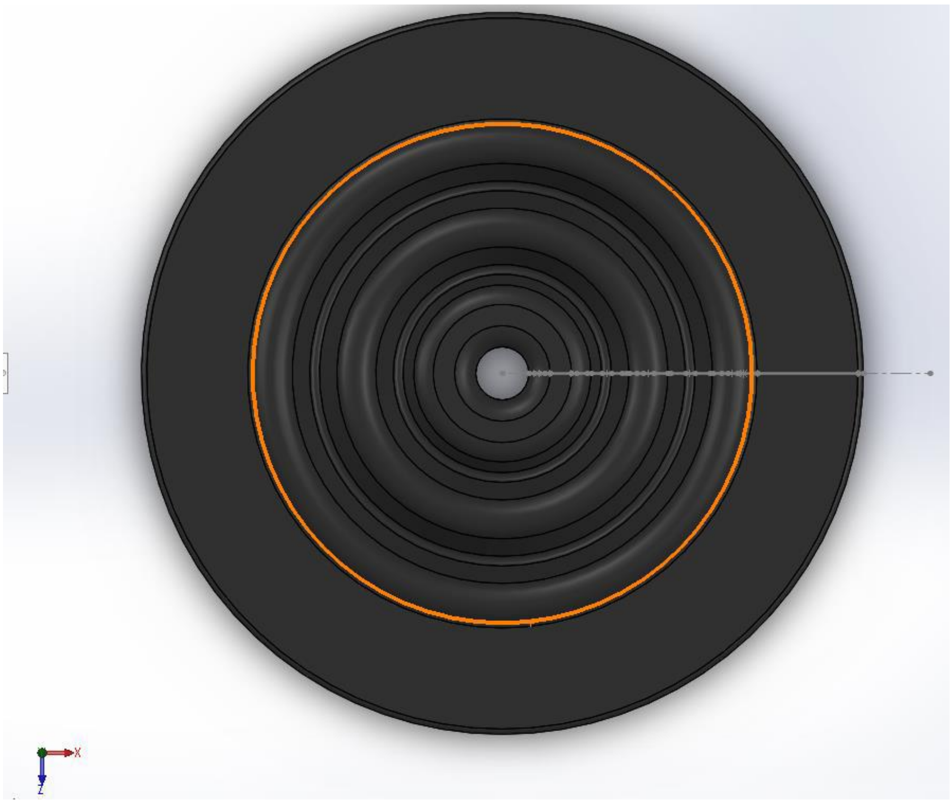


Figure 4.2.3.4 Top view

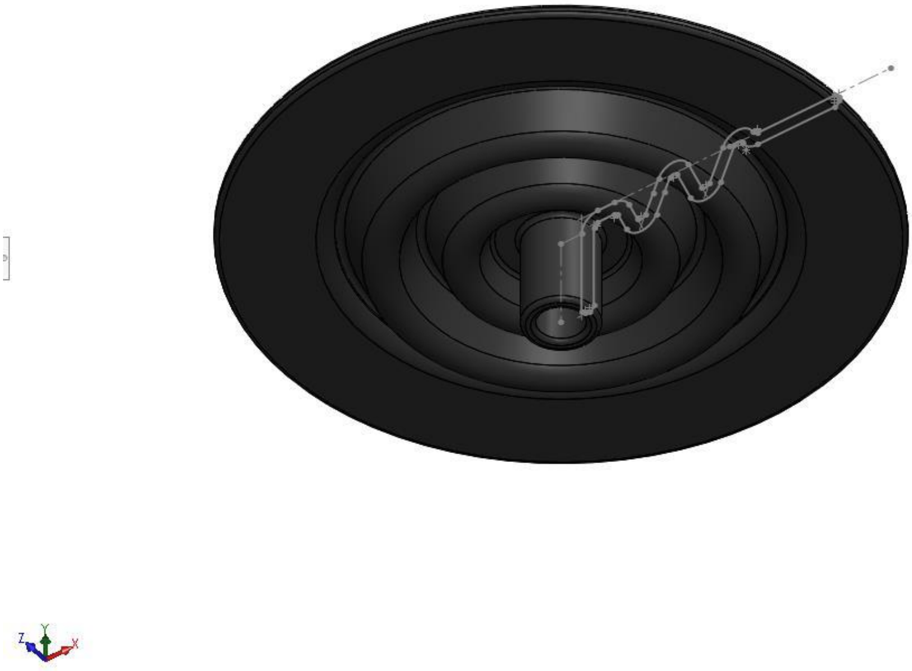


Figure 4.2.3.5 View of component from below

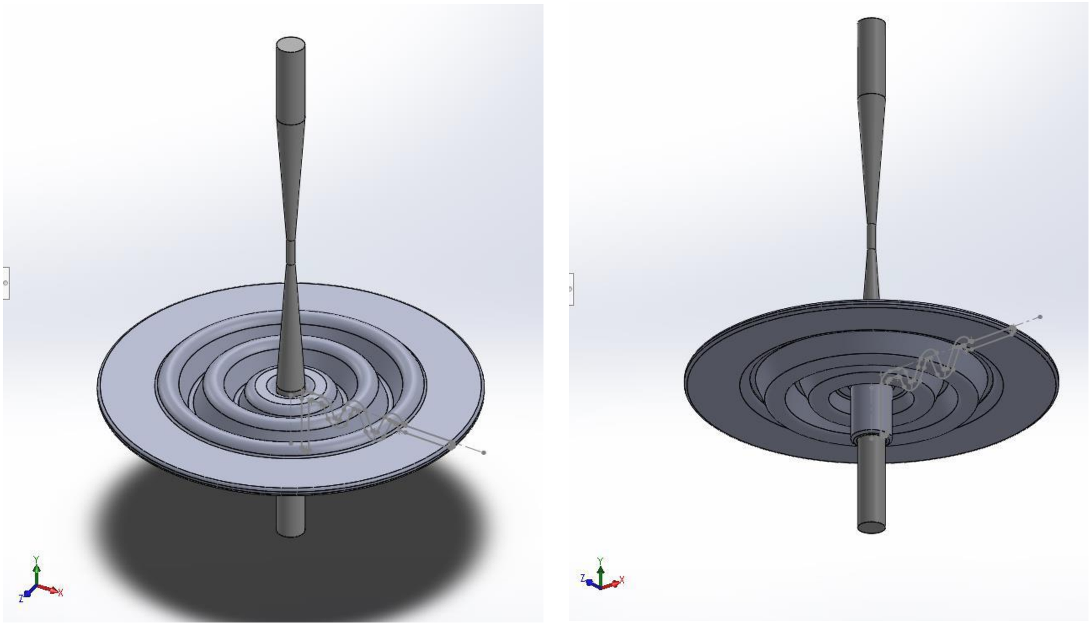


Figure 4.2.3.6 Assembly of component with specimen

3D Printed Prototype

Figure 4.2.3.7 3D Printed Component. Bottom at left, Top at right.

This 3D printed component's meterial is Thermoplastic Polyurethane or TPU. It is referred to as the bridge between rubbers and plastics. The material appears rubber-like, which means it can be extremely flexible, durable and smooth to the touch making it suitable for 3D printing applications such as ours.

It took about 6 hours of printing and was not an easy task because there are no flat surfaces on the part. The component was printed from top to bottom. On the top surface some extra material was added to flatten the surface in order to base the component. This extra material was later removed and that is why the top surface is not as smooth as the bottom.

Figure 4.2.3.8

4.2.4 **Specimen**

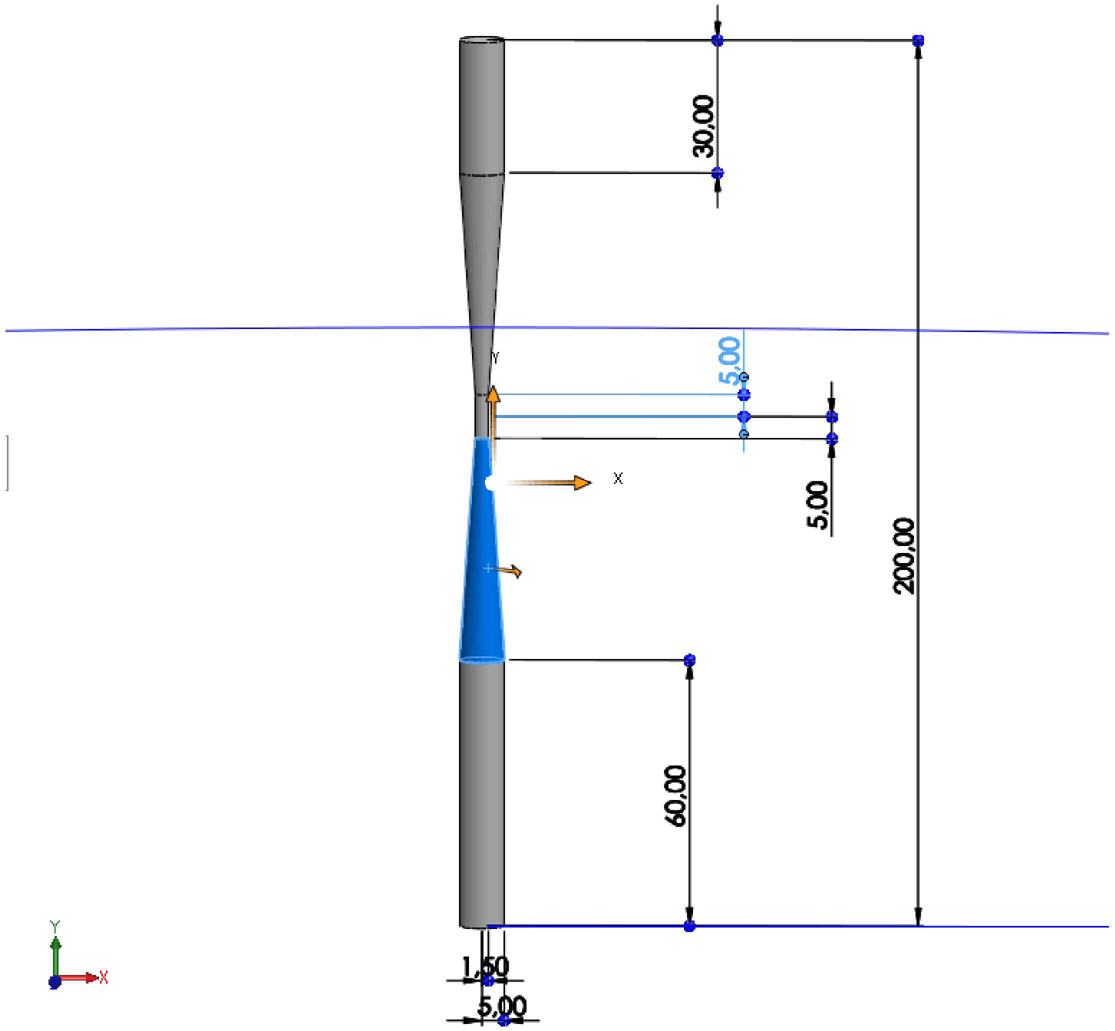


Figure 4.2 Front view of specimen with dimensions

The specimen should have a sufficient length in order to pass through the container and the bottom insulation component so that there are no leaks. The analysis for the length is the following:

- 10mm on each side for fastening to the grips, 20mm cumulatively
- 103mm to cover the height of the water filled container
- 25mm to cover the length of insulation component / rubber applied to the specimen
- 5mm to cover the thickness of the support frame
- 3mm to cover the thickness of the insulation component / rubber

So in total we have a minimum length of 156mm.

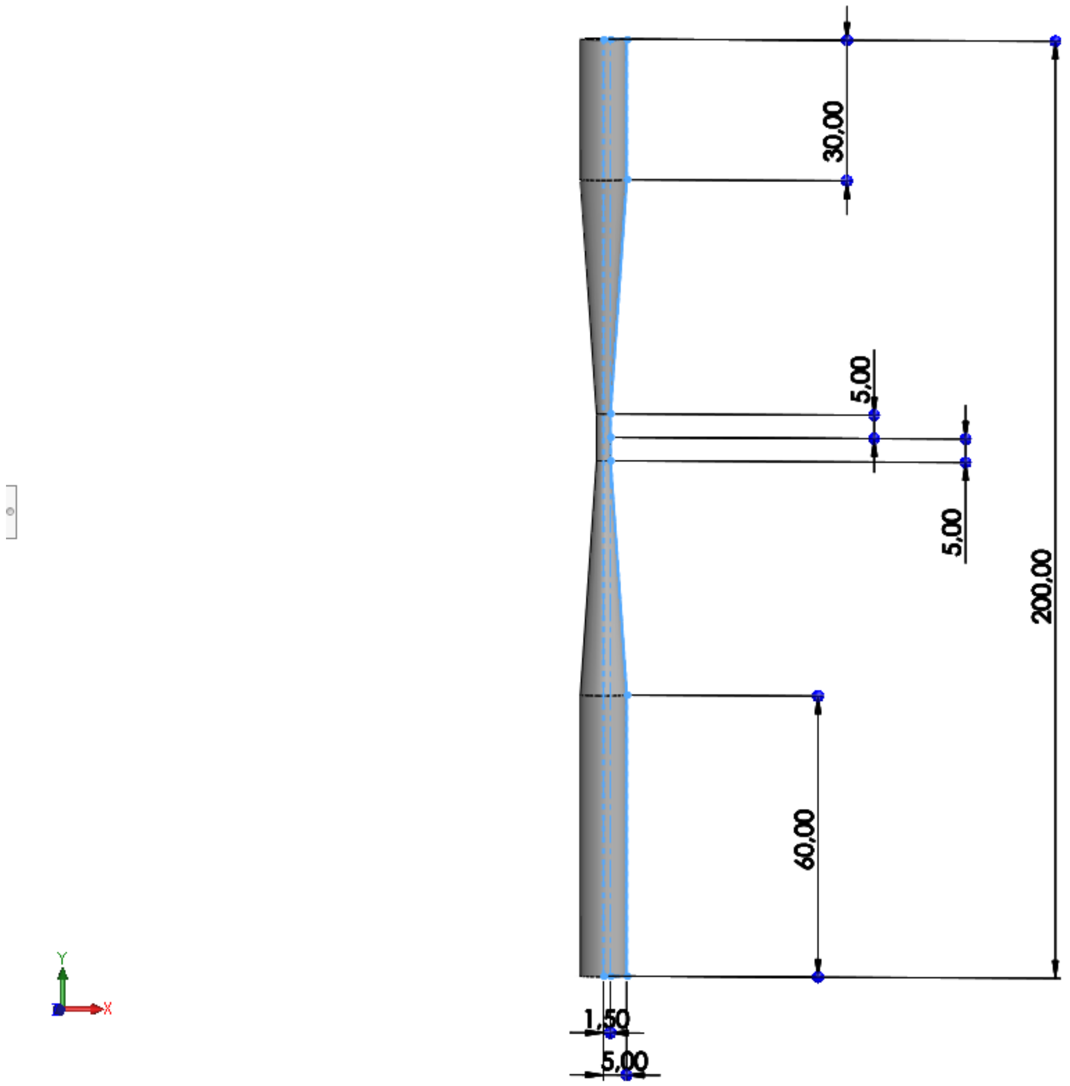


Figure 4.3

At the bottom, however, we need more length on the specimen at the initial diameter, where it will be fixed and the rubber will be tightened on the specimen. That is why there is this non-uniformity in lengths. Nevertheless, the area of diameter reduction where we will have the deformations has been kept symmetrical. Specifically, the area of reduced diameter is 110mm in total and the welded part's length is 10mm long. There are two areas of gradual diameter reduction and their lengths are 50mm upwards and 50mm downwards.

The initial diameter of the test specimen is 10mm and the minimum, in the welding area, is 3mm.

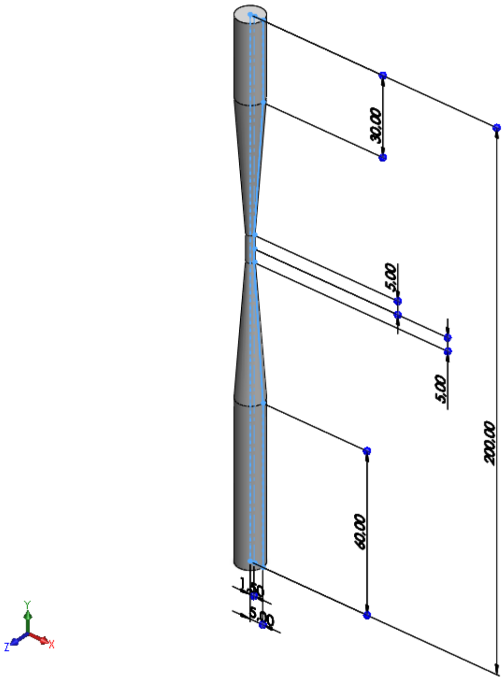


Figure 4.4

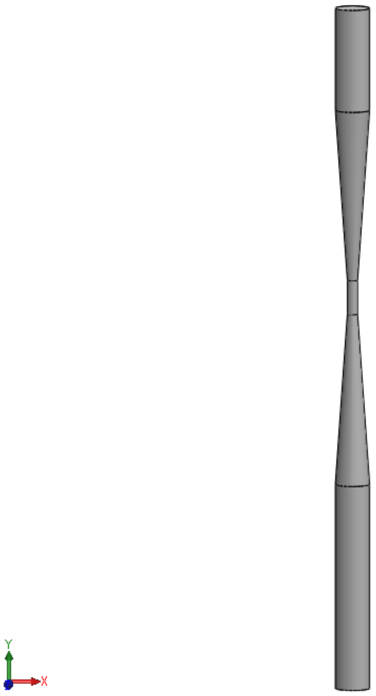


Figure 4.5

Specimen Manufacturing

Manufacturing the specimens for this type of experiment is not an easy task and this is the reason design had to change according to the abilities of the equipment and skills of the machinist. It is safe to say that the design above is not very realistic to be manufactured, unless advanced manufacturing processes are used, like laser cutting and some kind of very precise welding. A welded specimen with only 3mm diameter is very fragile and can easily be destroyed during the procedure of lathing. So the final diameter in the center became 7mm and the part of gradual diameter reduction became much shorter, around 15mm. Due to the steeper diameter reduction we ensure that loads are concentrated in the center of the specimen where it is welded, making sure the specimen will fail at the right spot.

The metal used for the specimens was st-37 and the manufacturing process was the following: first, circular rods of 12mm diameter were machined. Their edges became pointy, with 2mm diameter as shown below.

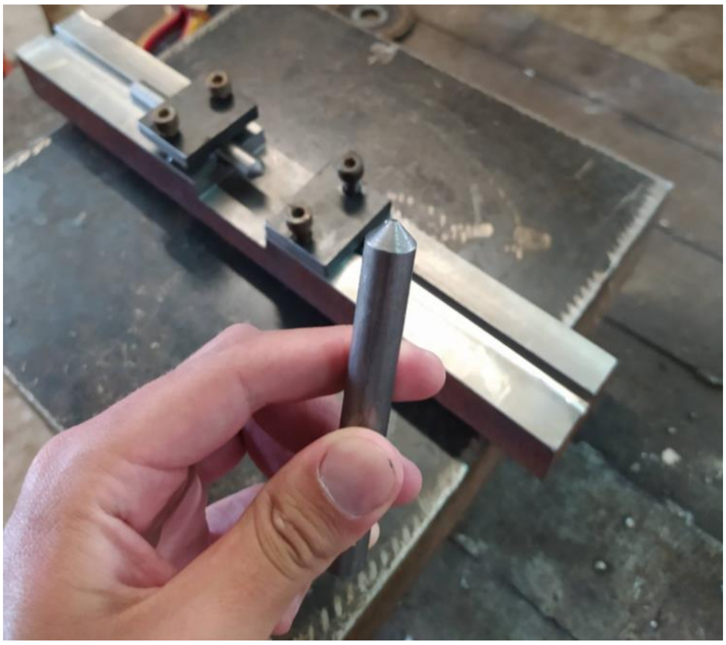


Figure 4.2.4.5

A convenience metal construction was made by the machinist in order to complete the weld of the two rods. This was necessary to insure that the specimen remained straight after the weld and also to be securely fastened during the welding process.

The weld was GMAW welding; the electrode was made from the same material as the rods and had a diameter of 1mm.

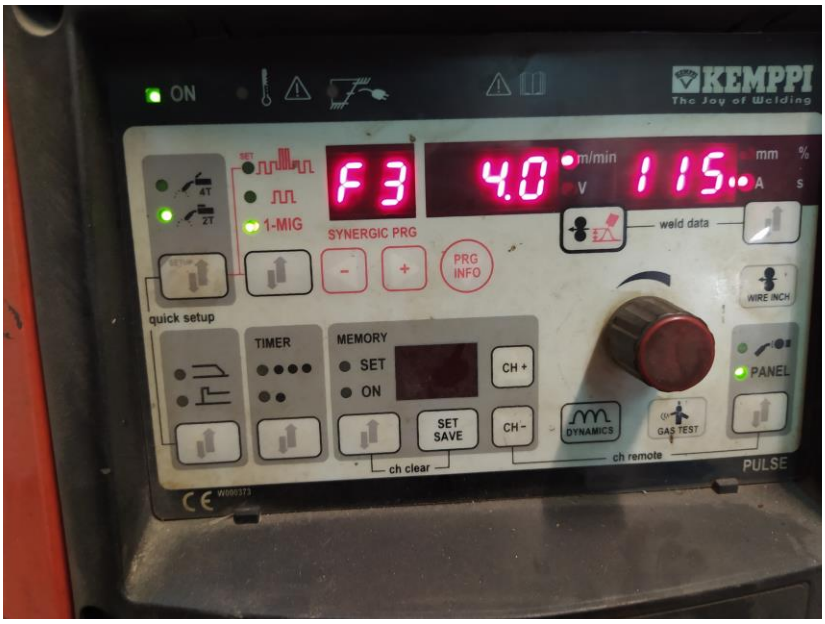


Figure 4.2.4.6 Welding Conditions

The welding conditions are shown above in **Figure 4.2.4.6**; although later the ampere value was lowered to 100A.

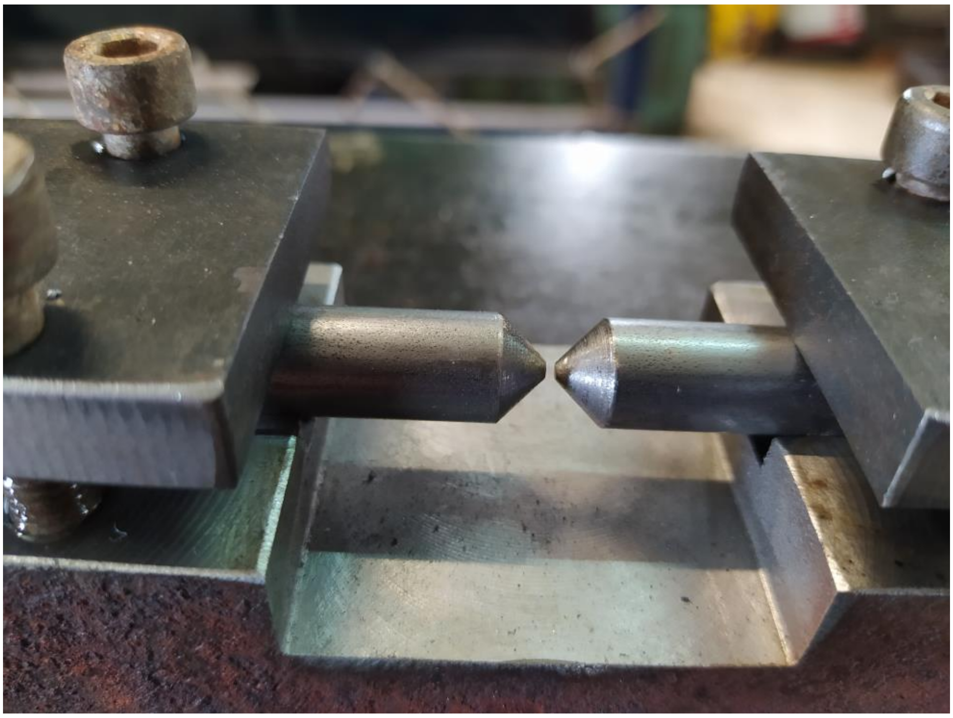


Figure 4.2.4.7 Right before welding

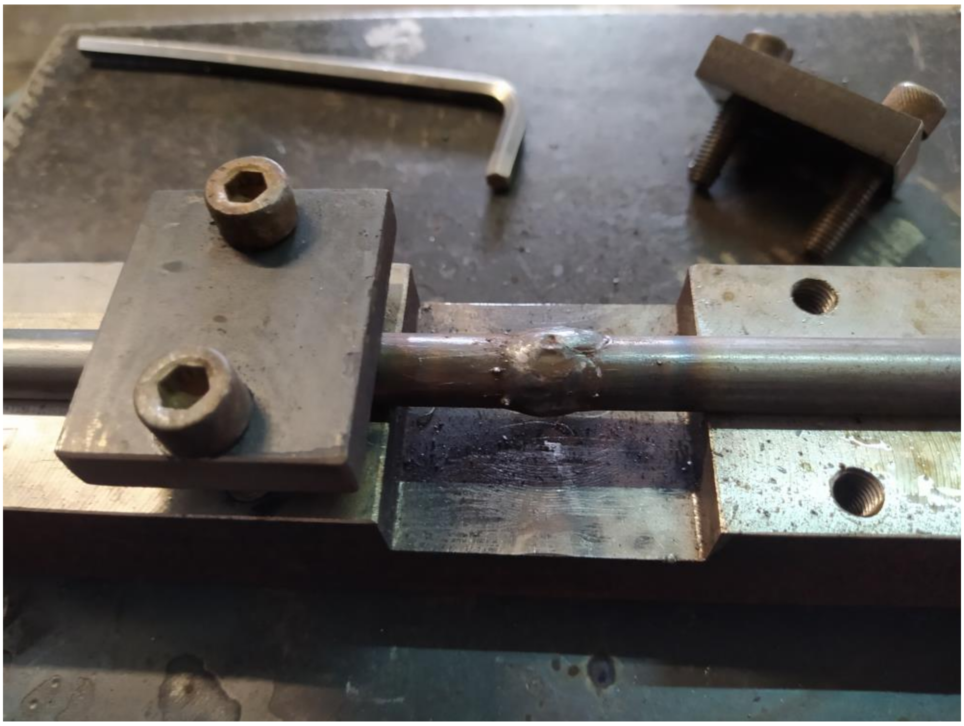


Figure 4.2.4.8 Welded Specimen

After the welding process, the specimens were machined in a lathe. The overall diameter was reduced to 11mm and in the center there was an extra reduction in diameter in the region of the weld. This region was 15mm long and the minimum diameter was 7mm. We manufactured 10 welded specimens and 5 specimens without weld but completely identical to the welded ones.

Figure 4.2.4.9 Final Specimens

4.2.5 **Peripheral components**

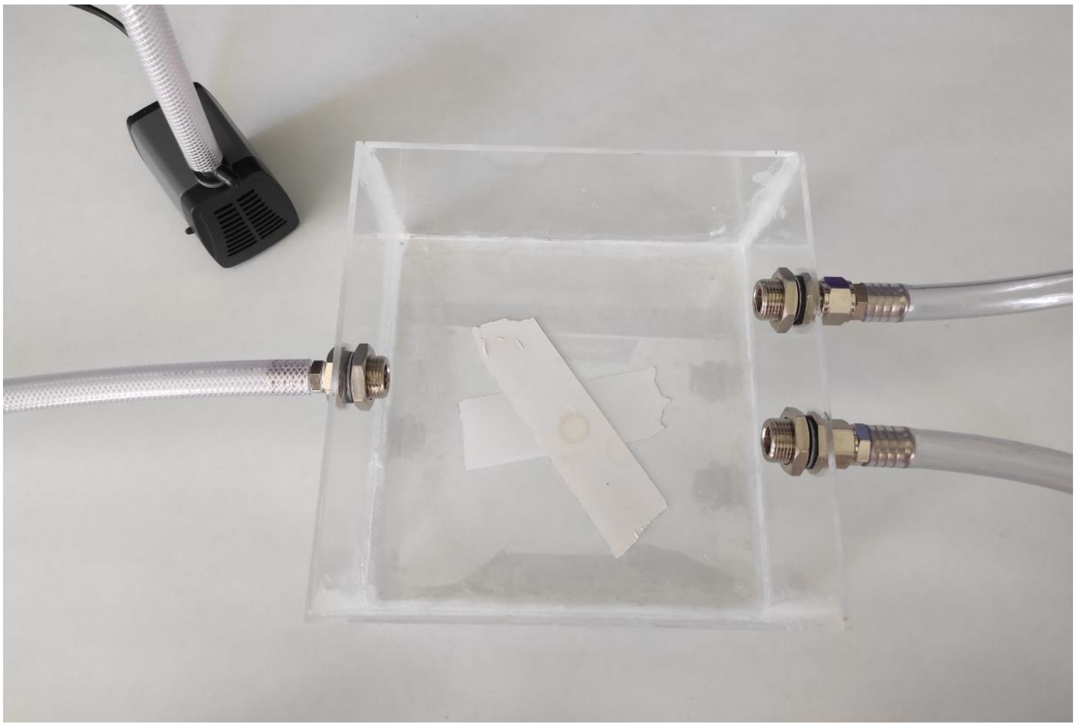


Figure 4.6 Experiment setup with peripheral components

As shown above, the setup of the corrosion fatigue experiment consists of the following components:

- Water container
- Small scale water pump
- Hoses
- Nozzles that connect the hoses on the container
- Water basin for the circulation of water (not shown above)

Figure 4.7 Hoses

The hose shown above are used to transfer the water from the basin to the container where the experiment takes place and back. The inlet hose is slightly smaller diameter and was chosen to match the nozzle of the water pump, which is 10mm diameter. So the inner diameter of the inlet hose is 10mm and the external is 15mm. The outlet hose’s diameters are 13mm and 18mm respectively. Also, the outlet hose is wider in order to reduce pressure inside it and make it easier for the water to flow.

Figure 4.8 Water pump

The water pump is a very important component in our experiment because it ensures the circulation of water in the container and the maintenance of the conditions during the experiment. This is a pump typically used in small aquariums; it is a fully submersible pump and can only work that way. It can move up to 500 liters of water per hour, can lift it up to 3 meters, its energy consumption is 7.7W and is directly connected to a plug without using any adapters that many other pumps require.

Figure 4.9 Nozzle for connection of hoses to the water container

In the picture above is shown one of the nozzles attached to the hole of the water container where a hose is connected. Two rubber flanges are used between the nut and the threaded component shown in the middle. That way cracks on the acrylic box are prevented and better insulation is achieved.

Although the holes in the box have diameters of 20mm, which is relatively big for such applications and the flow rate we desire, due to the necessity to use these components to avoid leaks the openings we are left in the end are quite smaller. This is why two outlet holes are needed to achieve overflow safely without the container filling up completely.

Figure 4.10 Connection of nozzle on container

4.3 Performing the experiment

After manufacture of all components, acrylic box, support structure, bottom insulation, peripheral equipment and specimens, they had to be combined and tested together.

4.3.1 Support Structure Position

At first, the support structure was mounted on our hydraulic testing machine to check if all dimensions and positioning was correct.

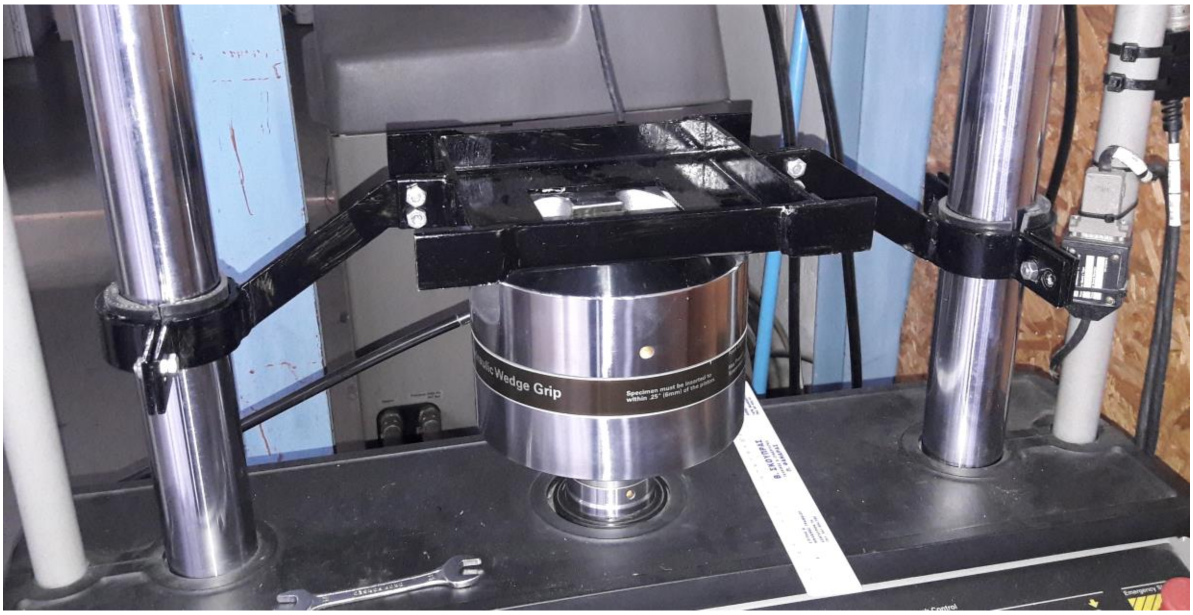


Figure 4.11

From the start, positioning appeared to be correct as all components were aligned. Between the pillars and the clamping rings a thick flexible material is used to prevent damages to the machine, providing also better grip. At first, the diagonal components were used to mount the structure. As seen above, there are no holes in the "ears" of the frame yet because we wanted to mount it first and then drill the ears, so that there are no misalignments and mistakes.

Figure 4.12 Before Drilling

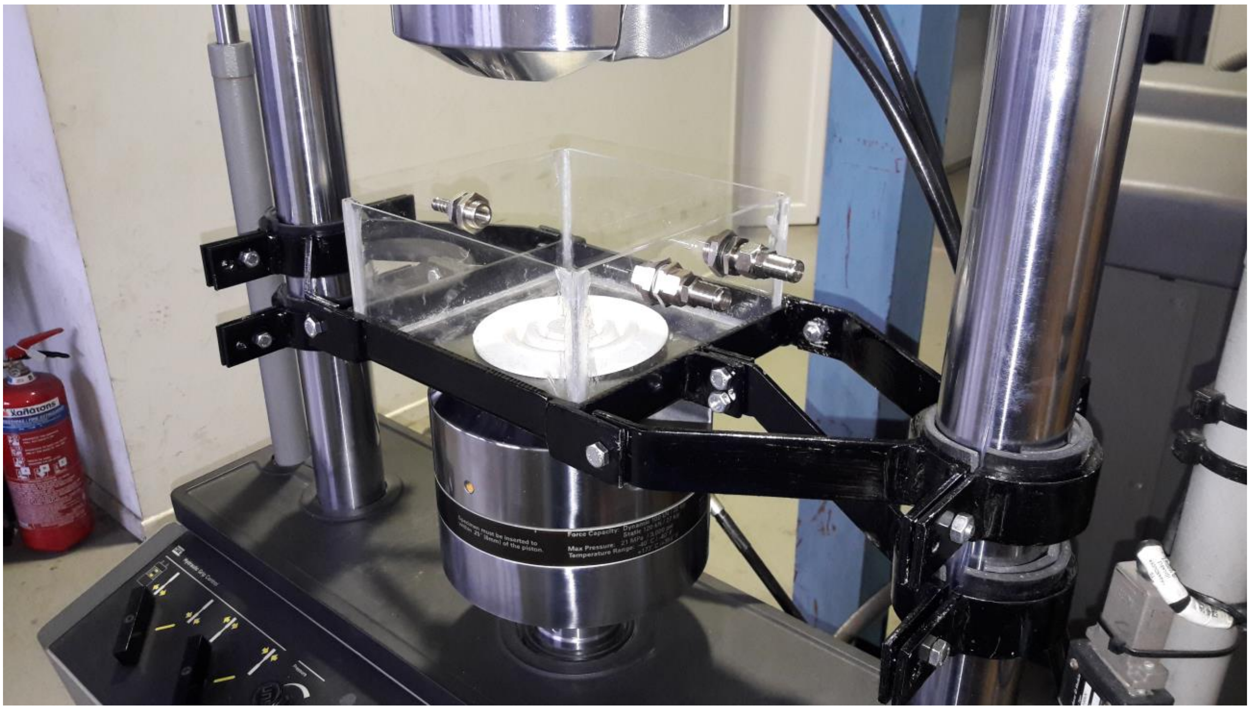


Figure 4.13After Drilling

After making the holes and tightening all screws, the structure became very stable and stiff. Positioning of all components was correct and at the same time there was room for small adjustments, by tightening different screws and adding more padding in different positions between the pillars and the rings.

4.3.2 **Acrylic Box and Bottom Insulation Improvements**

While running a small test for the pump and the recycling of water in the box, a high water level was observed.

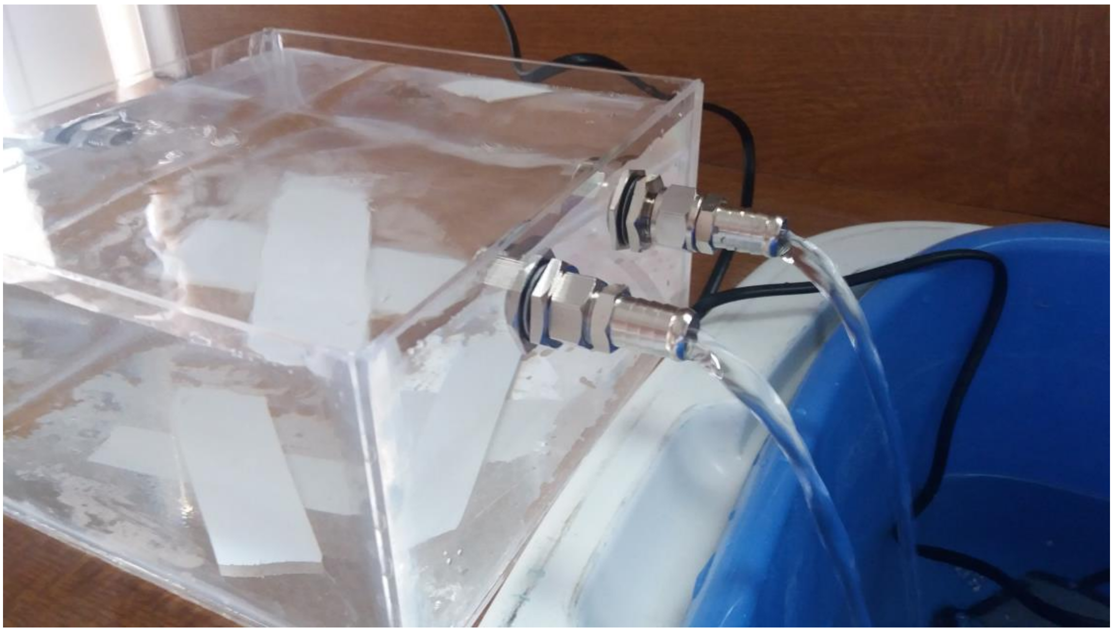


Figure 4.14

That was not anticipated during the design of the box, but could possibly cause a lot of damage to the equipment if water topped out during the experiment. That is the reason we constructed a second acrylic box, identical to the previous one, except the outlet holes were in the middle of its height, approximately at 5 cm from the bottom.

Furthermore, flattening and smoothing the edges with sandpapers before gluing was done more cautiously. More attention was given not to destroy the sharpness of the edges, as last time the edges were curved and less surface was left for gluing. All other features of the acrylic box remained the same as before.

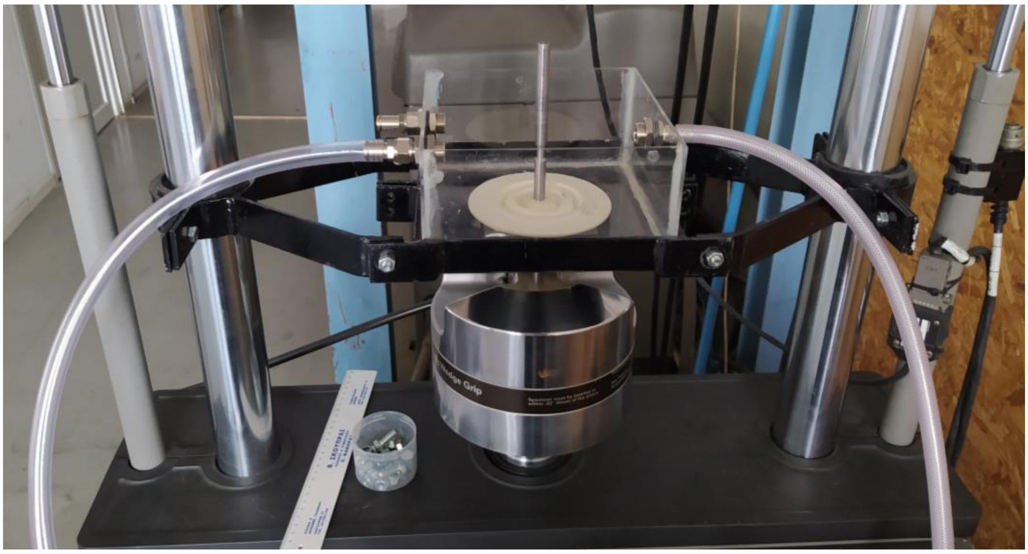


Figure 4.15

The bottom insulation had to be glued on the bottom surface of the box. In order to find the exact position, the specimen was placed in the test machine with the setup and through the 3D printed component. The location was marked on the box and later glued with the glue that was also used for the box.

Figure 4.16

The outer circle in the 3D printed component was filled with glue. Weight was used to press the component perimeter while the glue hardened. Later silicone was applied at the edges of the component connections with the box.

Unfortunately, after everything was ready for the experiment an unexpected setback happened. Although all connections were made properly, the box was dripping water at a fast pace, approximately 15 drops per second. Water penetrated and went through the 3D printed part. 3D printed components are made out of layers of material, these layers depending on the material and the settings of the printing machine may be thinner or thicker, but there are always small gaps between each layer. Apparently, in our case these gaps were big enough for water to pass through. It is also important to mention that water appeared to be dripping from the edges of the circles in our component, where there was less material due to the change in the geometry.

The solution to that was to fill the cavities in the component with silicone. After silicone was applied to the cavities in both sides, water stopped dripping so fast. Instead, one or two drops every second were dripping, which still was not acceptable but it was definitely an improvement. A sealing spray, special for water insulation applications, was applied to both sides in three layers. These layers formed a type of thick plastic, which was flexible and smooth. All gaps were filled and after a home test the box was completely insulated and no water was leaking.

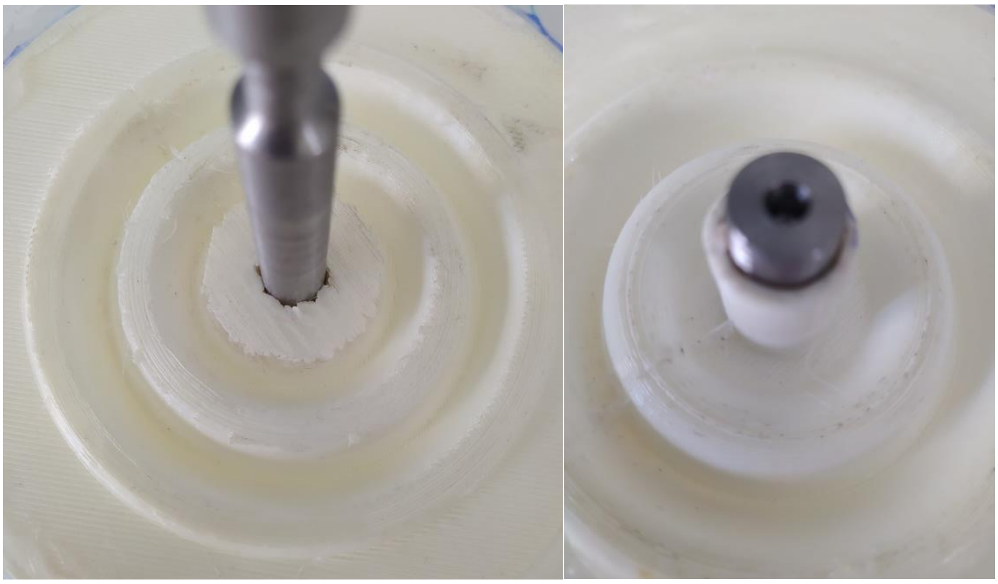


Figure 4.17 Before application of silicone

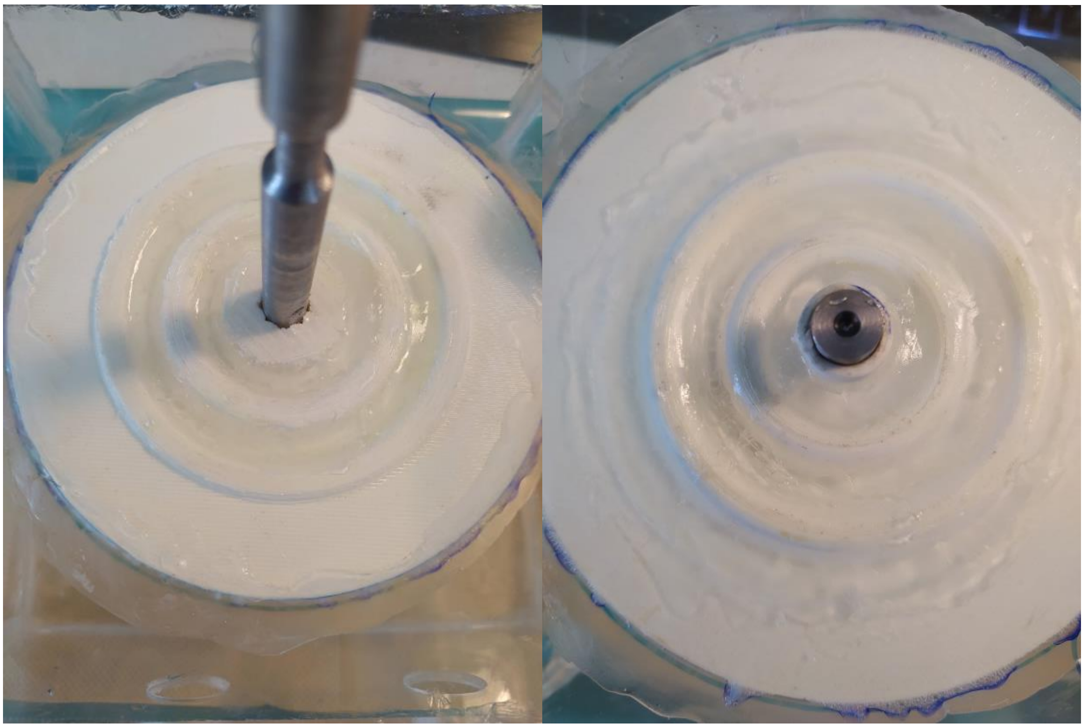


Figure 4.18 After application of silicone

The pictures below show the two sides of the box after three layers of sealing spray. The pictures were taken after the experiment took place, hence the orange color in the center that came from the corroded specimen.

Figure 4.19 Interior side

Figure 4.20 Exterior side

4.3.3 **Peripheral equipment setup**

Finally, the peripheral equipment was tested in order to make sure everything works properly. Teflon tape was applied to the connections of the water inlet and outlet to prevent leakage. A 15L basin was used as the main reservoir for the water. In that basin the pump was fully submerged in water. All hoses were secured in place on the basin and also stirring of salt added to the water took place in it.

The main issue was the height of the basin relative to the water container where the experiment took place. Since we used a small scale pump, its capacity to push water at an acceptable pace was not its nominal capacity. After a test at home, it was observed that maximum height of pumped water was around 1,5m. On the other hand, the setup could not operate properly if the pump was in the same height as the box because water in the outlet did not have enough pressure to exit the box, resulting in water topping out the box. An optimal height for the basin was around 0,8m below the box and that was followed during the experiment.

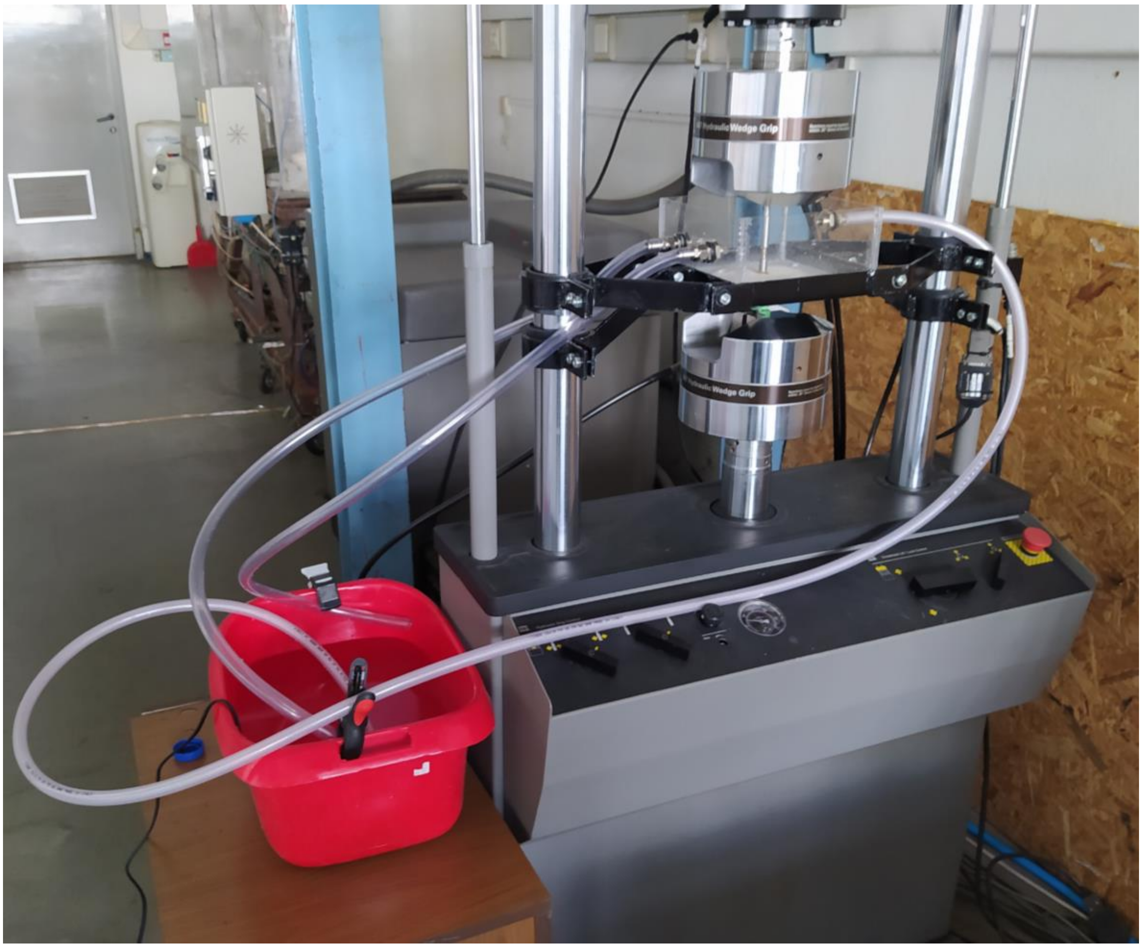
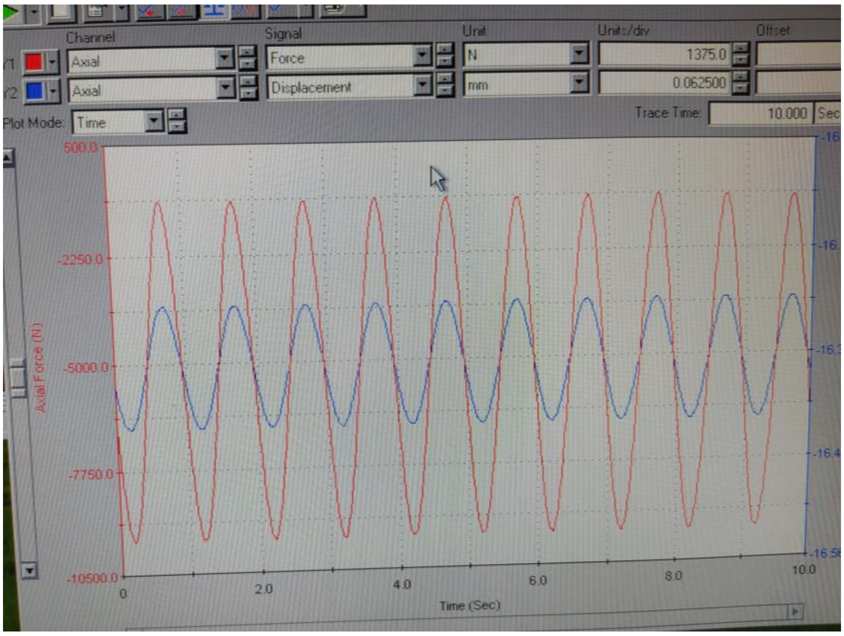


Figure 4.21 Corrosion Fatigue Experiment Setup

Forces and Frequency

According to mechanical properties data, st-37 metal yield strength is around 300Mpa. After confirming that value with a tensile stress on one of our specimens, the fatigue load was set at 250 Mpa. Unfortunately, there was no access to specific fatigue data about welded st-37 metal, so the fatigue load value was chosen a bit intuitively. The machine used for the tensile test was Instron 8801 with a 10mm extensometer, and the one for the fatigue test was MTS 810.

The load frequency was set to 1 Hz. This value is higher than real wave frequencies on offshore structures, which is 0.1 to 0.5 Hz, but it was chosen due to the difficulty and extremely long time required to complete an experiment with such low frequencies.



	Channel	Signal	Unit	Units/div	Offset
Y1 🟥	Axial	Force	N	1375.0	
Y2 🟦	Axial	Displacement	mm	0.062500	

Plot Mode: Time

Trace Time: 10.000 Sec

Figure 4.22 Load and Frequency

Water Circulation

The basin was filled with 10,5 L of deionized water and 4 grams of pure sodium chloride (NaCl) were added to it. The solution was agitated with a mixer until it became homogeneous with salinity 3,8%. Ph value was around 5.5 and the water flow rate was approximately 10L per minute. The water was renewed every two days to keep Ph stable and also remove debris from the corroded specimen.

Chapter 5 Results

When the experiment started everything operated normally. No leaks were detected, which was our main concern, water flow was steady and no rise in water level inside the box was observed. Due to the fact that this was an experiment to test the operation of the setup, the experiment was paused during the night or when no one was present. That was in order to prevent damages to the machine in case of a leak or if the specimen failed and the setup was damaged while unattended.

Figure 5.1 Total Setup

Figure 5.2

Figure 5.3

The experiment started 25.05.2021 and after seven days of experiments the operation was smooth and the specimen had experienced 93.471 load cycles. Unfortunately, in the morning of the 8th day of experiments we discovered that a small amount of water had leaked from the bottom of our box and therefore did not continue the operation. The initial plan was to perform the corrosion fatigue test until the specimen failed. Although, after the leak, this was no longer possible as we needed to fix the insulation of the acrylic container before continuing.

Instead, three other tests were performed to extract some useful about the remaining strength of our specimen. Since our corrosion fatigue experiment was not heavily monitored, the results could not be comparable and are used in a more qualitative way. Keeping that in mind, we decided to perform a fatigue test on another specimen until 93.500 cycles, same as the corroded one. Then, three tensile tests were performed, on the corroded specimen, on the fatigue specimen without corrosion and on a new specimen that had not experienced either corrosion or fatigue damage. That way a comparison between the remaining strength of the three specimens could be obtained and observe the effect of corrosion in fatigue life.

Figure 5.4 Corroded and new specimen tensile tests

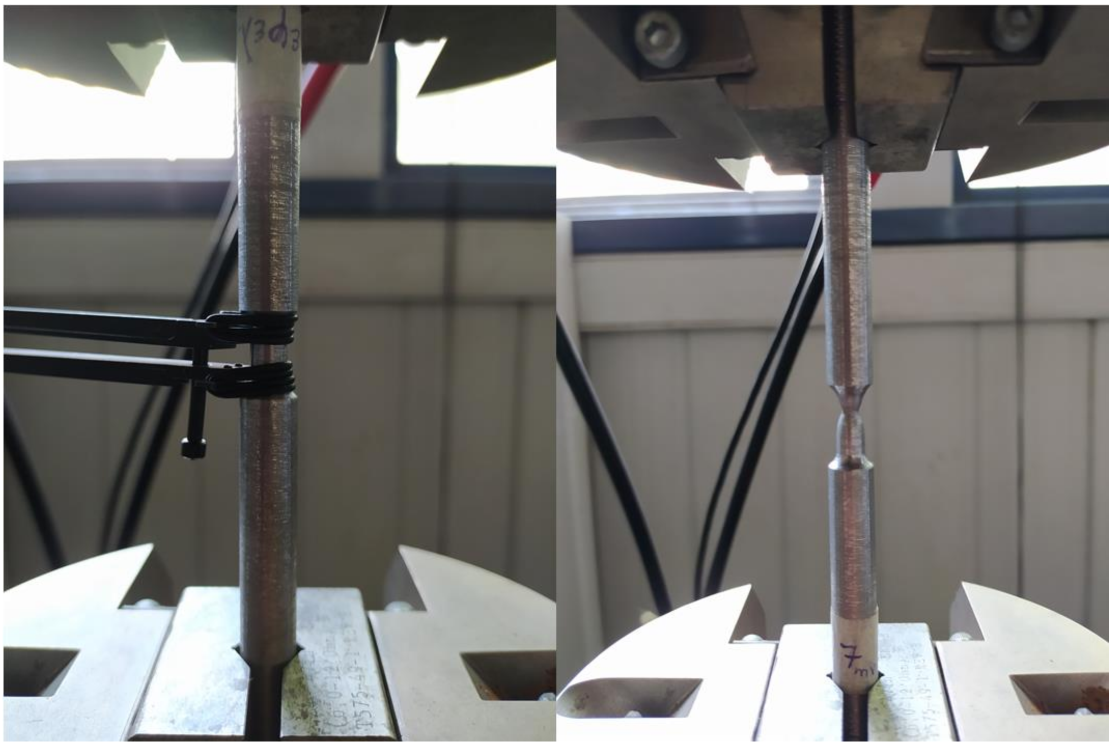


Figure 5.5 Extension-meter and neck formation before breaking

Results from Tensile Tests

- **Corrosion Fatigue Specimen:** 93.471 load cycles at 250 Mpa in salt water, **S**y (0,2%) = 350 Mpa, **S**uts = 507 Mpa

- **Fatigue Specimen:** 93.500 load cycles at 250 Mpa in air **S**y (0,2%) = 365 Mpa, **S**uts = 507 Mpa

- **Simple Tensile specimen:** no fatigue or corrosion damage **S**y (0,2%) = 378 Mpa, **S**uts = 519 Mpa

Yield stress values show a difference between the two specimens that experienced fatigue compared to the simple tensile specimen as their yield strength is decreased by 28 Mpa for the corrosion fatigue specimen and 13 Mpa for the fatigue specimen. This shows the fatigue damage taken by the two specimens but there is not a significant difference between the corrosion fatigue specimen and the fatigue specimen.

Below is shown the Stress/Strain diagram with the lines extracted from each tensile test.

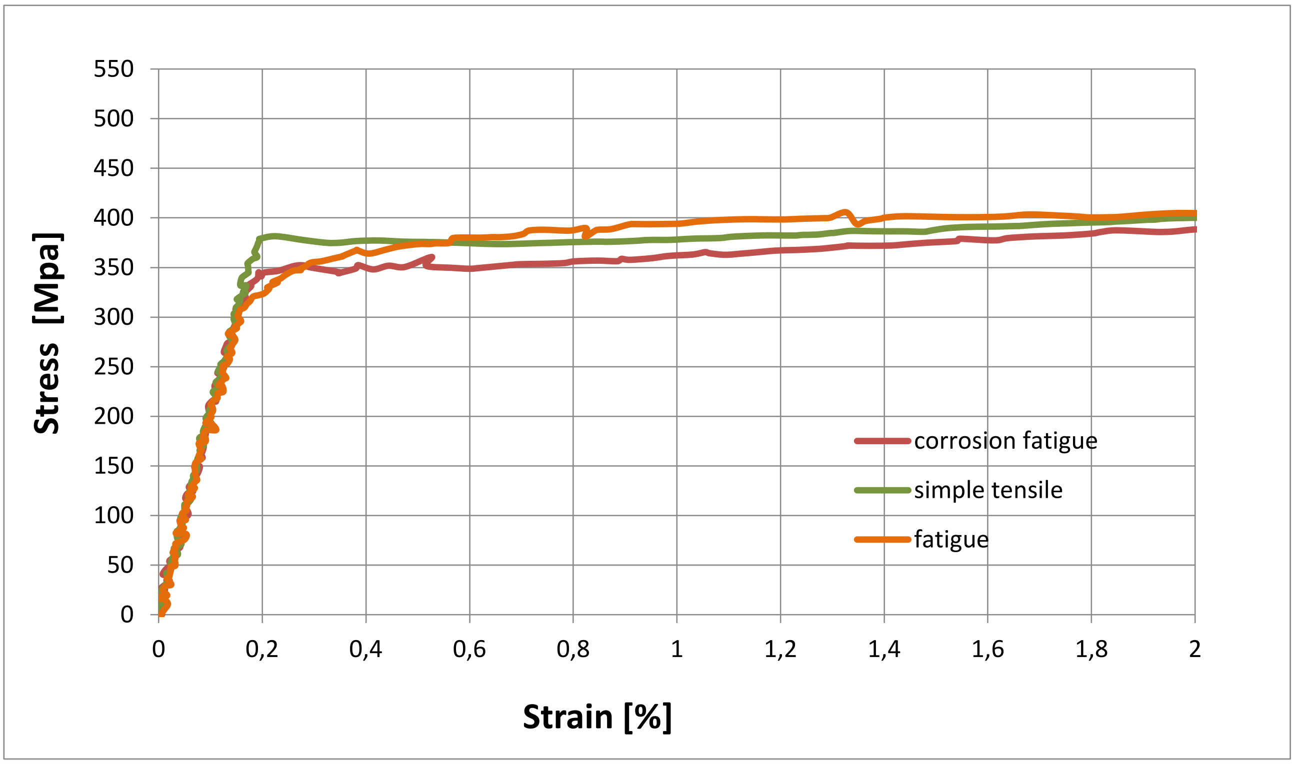


Figure 5.6 Tensile Test Results Diagram

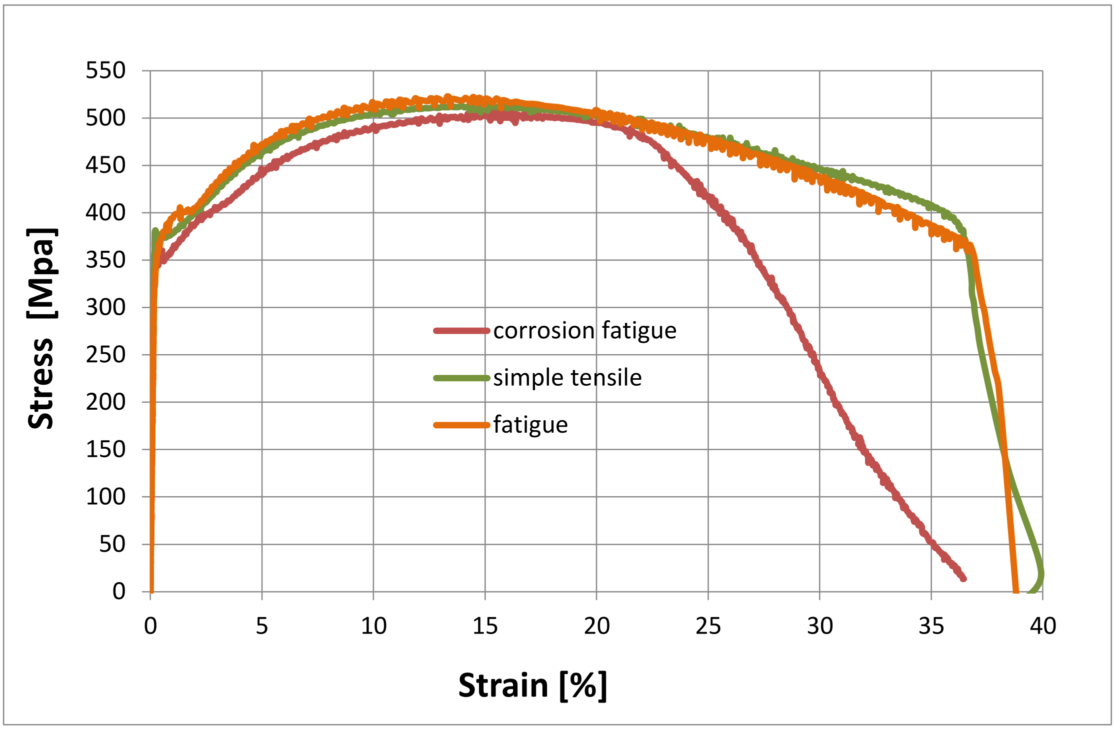


Figure 5.7 Tensile Test Results Diagram

The diagram shows that the corrosion fatigue specimen had a different behavior from the other two. Its line is clearly below the others and at 20% elongation the line dives fast, while the other two lines dive both after 35% elongation. The other two specimens dive for the same value of elongation and almost vertically while the corrosion fatigue specimen had a smoother slope. That means corrosion has affected severely the specimen making it much more ductile than the other two.

In any case, in order to extract valid results, a series of tests have to be performed in a more controlled environment. The test performed for this thesis is more of a trial test and cannot be considered a valid experiment producing comparable results.

Chapter 6 Conclusion

The goal of the thesis was the design and construction of a corrosion fatigue test setup. This goal was achieved with the setup shown in the previous chapters. Different design ideas were explored and the final design and construction of the setup worked quite well. All parts worked as they should and will be very useful in future endeavors as they are. Of course problems emerged along the way and most of them were faced effectively, making this thesis more interesting. Through these difficulties we provided details and solutions to problems that cannot be known beforehand.

Certainly, there is room for improvement, both in design and the manufacture of some components, but especially in the field of monitoring the test conditions. The next step for this research would be the implementation of devices to control and monitor the environmental conditions, such as temperature, water Ph, water salinity and other parameters. If that is achieved then totally valid experiments can be performed, providing very useful results, comparable to real life information about the fatigue life in offshore structures.

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