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**Mechanical Properties of oil and gas transportation steel in the absence of inhibitors**

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## Dedication

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## **Abstact**

**This dissertation explores the mechanical properties of pipeline steels when used in oil and gas transportation pipelines subjected to harsh environmental conditions involving corrosion and fatigue.**

**The study starts with a review of pipelines systems, oil and gas transportation systems, material classifications, types of defects typically encountered within pipeline systems, and environmental stressors that may affect the mechanical properties of pipeline steel. A fatigue testing machine was designed for digital fabrication with SolidWorks, which simulated the behaviour using ANSYS to determine the fatigue life, damage accumulation, and safety factors of the pipeline steels under cyclic loading.**

**The results indicated that mechanical stress combined with environmental factors (i.e., corrosion) may significantly impact the structural integrity and lifespan of pipeline steel. It was concluded that material design, application of proper design safe factors, and maintenance of energy infrastructure is an important consideration.**

## **Résumé**

**Ce mémoire se porte spécifiquement sur l'analyse des propriétés mécaniques de l'acier utilisé dans le transport du pétrole et du gaz. Le contexte environnemental dans lequel ces aciers sont souvent utilisés est parfois difficile en raison des agressions mécaniques à répétition et de la corrosion.**

**Dans un premier temps, un tour d'horizon détaillé des systèmes de pipelines est proposé en prêtant attention aux matériaux, aux défauts typiques et aux mécanismes de dégradation. Une machine d'essai de fatigue a été conçue numériquement avec SolidWorks puis des simulations par l'intermédiaire d'ANSYS ont permis de déterminer la durée de vie, les dommages et les facteurs de sécurité de l'acier soumis à des chargements cycliques.**

**Les résultats montrent l'existence d'une interaction entre la mécanique et la corrosion qui participe à la dégradation du matériau, d'où l'importance du suivi structurel et de l'optimisation des matériaux dans le cadre du transport à risque énergétique.**

## ملخص

تستكشف هذه الأطروحة الخواص الميكانيكية لفولاذ الأنابيب عند استخدامه في أنابيب نقل النفط والغاز المعرضة لظروف بيئية قاسية تشمل التآكل والتعب. تبدأ الدراسة بمراجعة أنظمة الأنابيب، وأنظمة نقل النفط والغاز، وتصنيفات المواد، وأنواع العيوب الشائعة في هذه الأنظمة، والعوامل البيئية التي قد تؤثر على الخواص الميكانيكية لفولاذ الأنابيب. صُممت آلة اختبار التعب للتصنيع الرقمي باستخدام برنامج SolidWorks ، الذي يحاكي سلوك الفولاذ باستخدام برنامج ANSYS لتحديد عمر التعب، وتراكم الأضرار، وعوامل السلامة لفولاذ الأنابيب تحت الأحمال الدورية. أشارت النتائج إلى أن الإجهاد الميكانيكي، إلى جانب العوامل البيئية (مثل التآكل)، قد يؤثر بشكل كبير على سلامة هيكل فولاذ الأنابيب وعمره الافتراضي. وخلصت الدراسة إلى أن تصميم المواد، وتطبيق عوامل السلامة التصميمية المناسبة، وصيانة البنية التحتية للطاقة، كلها عوامل مهمة.

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## General Introduction

### GENERAL INTRODUCTION

The oil and gas industry plays a vital role in the global economy, relying heavily on extensive pipeline networks to ensure the safe and efficient transportation of hydrocarbons. These pipelines, typically constructed from carbon steel, are constantly exposed to harsh operational and environmental conditions, which can gradually compromise their structural and mechanical integrity.

One of the most significant challenges facing pipeline systems is material degradation due to corrosion. Corrosion not only deteriorates the mechanical properties of the steel but also poses serious safety risks and substantial economic losses. Therefore, understanding corrosion mechanisms and developing effective mitigation strategies are critical aspects of modern materials and structural engineering.

This dissertation focuses on the mechanical behavior of pipeline steel used in oil and gas transportation, particularly under conditions involving corrosion and fatigue. Special attention is given to the role of corrosion inhibitors, especially green inhibitors derived from environmentally friendly sources, as a sustainable solution to mitigate corrosion effects. Notably, this study does not include experimental laboratory testing. Instead, it relies on digital design and simulation tools.

The methodology adopted in this research includes:

- The digital assembly and design of a fatigue testing machine using SolidWorks, simulating the structure and function of physical testing equipment.
- The numerical simulation of corrosion and fatigue of steel behavior, where simulated by ANSYS, to evaluate performance under various loading and environmental conditions.
- A comprehensive literature review covering material degradation, corrosion control techniques, and the application of green inhibitors.

The structure of this dissertation is organized as follows:

- **Chapter 1:** provides a general overview of pipeline systems, including their design, and materials.

## General Introduction

- **Chapter 2:** explores the mechanisms of pipeline degradation, with a focus on corrosion and its consequences.
- **Chapter 3:** reviews different corrosion protection strategies, with emphasis on the potential of green inhibitors.
- **Chapter 4:** presents the digital design and assembly of a fatigue testing machine by SolidWorks, detailing the rotary bending process and its relevance to fatigue analysis.
- **Chapter 5:** discusses the simulation procedures and analyzes the results obtained through modeling using ANSYS.

**Chapter 01: General Information about Pipeline**

## I.1 Introduction

Most people associate ‘pipes’ with the hot and cold water they see in their houses. Also, most of us will have seen the plastic pipes laid under our streets and roads to locally distribute natural gas. But what many people do not know is that there are hundreds of thousands of kilometers of very large ‘pipelines’ crossing our nations and oceans delivering (transmitting’) huge quantities of crude oil, oil products, and gas. Most are underground or undersea: out of sight, out of mind! Crude oil is often transported between continents in large tankers, but oil and natural gas is transported across continents by pipelines. Transmission pipelines are the main ‘arteries’ of the oil and gas business, working 24 hours per day, seven days a week, continuously supplying our energy needs. [\[1\]](#).

This First chapter presents a comprehensive overview of pipeline systems, beginning with their definition and classification into various types. We’ll examine the key characteristics that define pipeline operations and identify common defects that can compromise their integrity. The chapter traces the historical development of pipeline systems and highlights their critical role in supporting global infrastructure, particularly in the oil and gas industries. In addition, we’ll explore essential technical specifications, including materials used in pipeline construction and their performance under different conditions. By the end of this chapter, readers will have a strong foundational understanding of pipeline systems, a framework essential for the technical analyses and simulations featured in the chapters that follow.

## I.2. History of pipeline

Transporting drinking water from water-rich regions to areas where it is scarce is the driving motivation behind the construction of long-distance water pipelines, which have a very long tradition [\[2\]](#). For thousands of years, pipelines have been constructed in various parts of the world to convey water for drinking, and irrigation for agriculture. Irrigation pipelines convey water from a supply source to a farm’s irrigation system, storage pond, or reservoir. As part of an irrigation system, this pipeline can be combined with other NRCS (stand for the Natural Resources Conservation Service) conservation practices [\[3\]](#). These pipes include baked clay and hollow bamboo: the ancient Chinese used bamboo pipes to transport water. While most people will say around a hundred years, the facts are actually quite mind-blowing. The very first pipelines recorded in history were constructed of bamboo. These hydrocarbon piping systems date back to 500 BC and were located in China. Of course, things have changed significantly over the years, but pipelines got their start over 2500 years ago. [\[4\]](#). Indeed, wood

(hollowed-out logs) was used as recently as about 100 years ago, to transport brine water in the developed world.

The earliest known example of copper piping was found in Ancient Egypt. Copper pipes are recorded in Mortuary Temple of King Sahura at Abusir dating from 2500BC [5]. There are references to the Egyptians using copper pipe to transport water in 3000BC. Gradually, people shifted to hollow tubes for the channels. Egypt used hollow palm trees [6], and the Greeks used earthenware, lead, bronze and stone pipes from 1600BC to 3000BC. The Ancient Greeks used conical pipes but they also used cylindrical ones. For instance, examples in the aqueduct at Naxos constructed in the late sixth century BC are jointed using sockets [5]. In that era, ‘blacksmiths’ connected the metal pipes together by simply hammering the red-hot ends together.

Ancient civilizations such as the Persians and Romans all used pipes of some type. for example, metal pipe was used as far back as 500 BC when the Romans used lead pipes to distribute water in highly developed towns. [1].



Figure I. 1:Wooden pipe[7]



Figure I. 2:Egyptien pipes [8]



Figure I. 3:Roman water pipe (stone pipeline) [5]



Figure I. 4: Pipeline irrigation for agriculture[9]



Figure I. 5:Water line pipe[10]



**Figure I. 6:**The ancient Chinese used bamboo pipes to transport water [\[11\]](#)

Bamboo pipelines aside, the actual history of pipelines as we know them starts in about 1815. Steel welded pipes were first used in piping systems in the early 1800s. A gentleman named William Murdock created the first pipeline by welding together the barrels of muskets to create a pipeline to bring coal gas from his well to his home. William started a great interest in how metal pipes could be formed and used to carry gas. By 1853, the Canadians got on board and constructed one of the first commercial pipelines. Pipelines also started to become more complex by adding things such as screwed fittings and pipe flanges. The fast-paced evolution of pipelines required some fast-paced legislation. By 1906, new laws were enacted in the United States that regulated pipelines. There have been many improvements since the first pipeline was designed, and there have been many new laws to accompany those improvements. [\[4\]](#).

The world's first oil and gas pipelines were built in the United States during the second half of the 19th Century (American Petroleum Institute, 2019). At that time, western Pennsylvania was the center of the early oil industry. In 1863 a group of oil producers built a 9-mile wooden pipeline to a nearby rail station in order to circumvent the regional monopoly position in local oil transportation held by the Teamsters. The first successful natural gas.

pipeline two inches in diameter and just over five miles long was built in 1872 to transport 'associated' gas to the Titusville, PA town center from a nearby oil well. The first long-distance oil trunkline was the Tidewater line, built by independent oilmen in 1879 to compete with aggressive oil baron John D. Rockefeller's stranglehold over oil transportation (soon thereafter Rockefeller purchased a half ownership stake in Tidewater). The first long-distance gas pipeline was built in 1891 to carry gas to Chicago from fields in Indiana. Today, most countries around the world have at least some types of pipeline system (or systems) for transporting oil, natural

gas, refined petroleum products, or simply water. The most extensive oil and gas pipeline systems in the world are located in the U.S and Russia. [\[12\]](#).

The idea of building a direct gas pipeline between Algeria and Europe arose in the 1970's. To study the feasibility of a subsea link, seismic surveys, geological tests, visual inspections of the seabed and oceanographical studies were all conducted.

However, at that time, technological constraints made it impossible to build and run an ultra-deepwater gas pipeline.

These limitations however had disappeared by august 2000, when CEPSA and Sonatrach signed a protocol agreement to resume the project to build an Algerian-European gas pipeline, which had been considered back in 1970's

In February 2001, the “Sociedad para El Estudio y Promoción del Gasoducto Argelia-Europa, via España S.A.” (“Company to Study and Build the Algerian-European Gas Pipeline via Spain, S.A.”) (MEDGAZ), was founded. At the beginning, several leading global energy companies expressed interest in joining the Project. At present, MEDGAZ is made up of two companies with renowned technical expertise and financial strength (Sonatrach & Medina Partnership).[\[13\]](#).

### I.3 Definition of pipeline

Pipelines, or pipeline systems, generally refer to an interconnected network of pipes and related facilities used for transporting gas or liquids, typically fuels such as natural gas or hydrocarbon liquids such as crude oil over long distances. Pipelines are a highly efficient means of inland fuel transport, connecting oil and/or gas producers at one end to refineries, retail gas distributors, or power plants at the other.[\[12\]](#).



Figure I. 7: pipeline for transportation of oil and gas [\[14\]](#)

## I.4 Types of pipelines

Pipelines play an indispensable role in the oil and gas industry, serving as the backbone for fluid transport. From crude oil to natural gas, pipe infrastructure ensures that these Industry essentials are securely conveyed from extraction sites to refineries and, finally, consumers. Each kind of pipe possesses certain qualities making it suitable for specific applications.

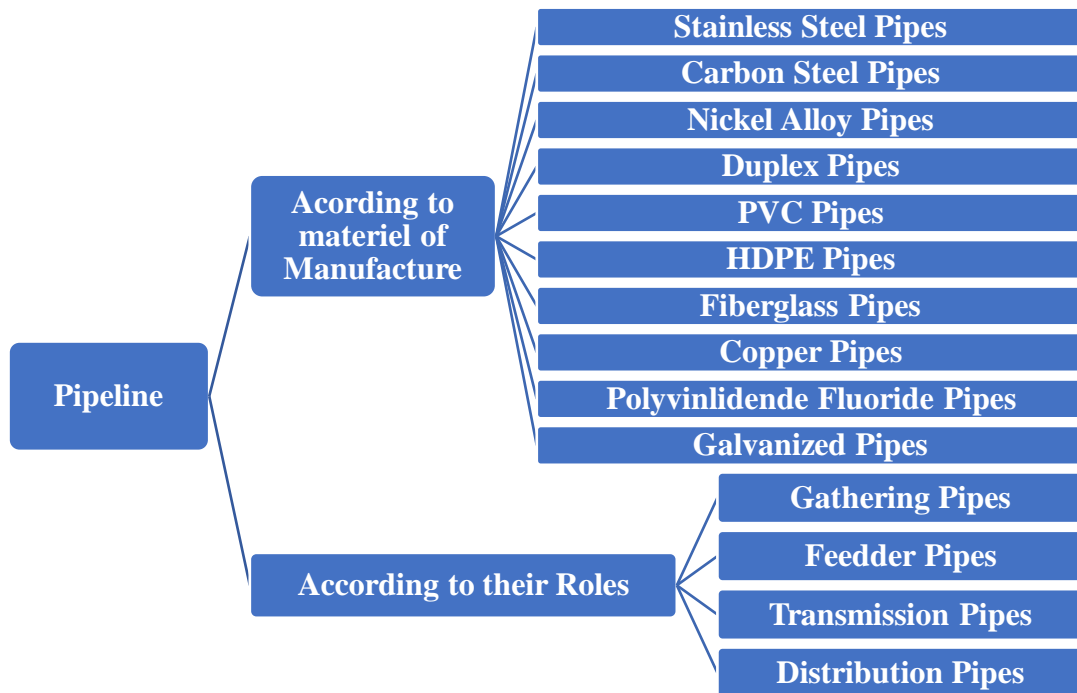


Figure I. 8: Classification of pipelines

### ➤ I.4.1. According to material of manufacture

#### I.4.1.1. Stainless Steel Pipes

Stainless Steel Pipe are of high use in the oil and gas industry due to their corrosion resistance ability. With the availability of different grades like 304, 310, 316, and 410, they cater to different use cases for instance, the 316 grade is ideal for high-temperature, high-pressure applications given its enhanced resistivity. Its structural integrity serves in applications like water transport and petroleum industries [\[15\]](#). Stainless steels possess broad resistance to a wide variety of corrosives from fresh water to strong nitric acid. This corrosion resistance generally allows the use of light-weight construction with Schedule 5S or 10S piping. [\[16\]](#)



Figure I. 9:Stainless Steel Pipes [17]

#### I.4.1.2. Carbon Steel Pipes

Carbon Steel Pipes, with their impressive durability and tensile strength, are perfect for transporting oil and gas within refineries or to consumer endpoints. Grades gauge the percentage of carbon from low to high carbon steel affecting flexibility and hardness. Their selection depends on the degree of stress they will endure. [15]

Carbon steel pipes & tubes are a long-lasting material made from carbon steel, a steel composite with carbon and iron, it is divided into hot-rolled and cold rolled steel pipes. Due to its strength and potential to resist stress. It is utilized in environmental conditions such as pressure or utmost weather.[18].



Figure I. 10:Carbon Steel Pipes [19]

#### I.4.1.2.1.API 5L pipes

API (American Petroleum Institute Standard) 5L is the international standard for steel pipe used in pipeline transportation systems.

API 5L covers steel pipe for a variety of applications for the transportation of natural gas, oil, and other liquids. [\[20\]](#)

API 5L are carbon steel pipes used for oil and gas transmissions. They include pipes manufactured in seamless and welded (ERW, SAW). The grades include API 5L Grade A and B (X42, X46, X52, X56, X60, X65, X70, X80 PSL1 & PSL2) onshore, offshore and sour services. API 5L is the implementation standard of steel pipe for pipeline transportation systems and specification for line pipe.

##### I.4.1.2.1.1.API 5L Grade A

API 5L Grade A is a base grade in the API 5L standard, and it is primarily used in relatively low-pressure application scenarios. Due to its relatively low strength, Grade A steel pipe is typically used in the following areas:

- **Urban and rural water supply piping:** piping systems used to transport potable water.
- **Irrigation systems:** Irrigation piping in the agricultural sector for the transportation of water.
- **Gas Distribution Networks:** Used in some low-pressure gas distribution systems to transport natural gas to residential and commercial customers.
- **Industrial Discharge:** Used for the discharge of treated wastewater from industrial sites in low-pressure environments.
- **Auxiliary Pipelines:** Pipelines used as auxiliary or maintenance pipelines at oil and gas extraction sites.[\[21\]](#)

##### I.4.1.2.1.2.API 5L Grade B

API 5L steel line pipe adopts different steel grades, which are Gr. B, X42, X46, X52, X60, X65, X80. Some manufacturers are capable of manufacturing steel grades up to X100 and X120. As steel line pipes grades go higher, they have stricter control on the carbon equivalent control and higher mechanical strength performance.

When API 5L grade B steel is subjected to powder-pack boriding, this can offer protection against erosion–corrosion mechanisms in oil-field-produced water environments with sand

particles, as long as they are not acidified by nitric acid. Boriding of API 5L grade steel offers satisfactory protection if the fluid contains acetic acid. Increasing the treatment temperature in the boriding process does not significantly improve the corrosion resistance of the studied steel. [\[22\]](#).

#### I.4.1.2.1.2.1.API 5L X52

The American Petroleum Institute specification API 5L X52 Pipe covers seamless and welded steel line pipe. This is steel pipe for pipeline transportation systems in the petroleum and natural gas industries. API 5L is suitable for conveying gas, water, and oil. Size range is limited only by manufacturer's capabilities.

API 5L X52 Pipes are specially designed to handle the transportation of oil and gas under high pressure and temperature conditions. The production of these pipes places a strong emphasis on toughness and impact resistance, particularly for sour service and other demanding applications. Due to the high levels of sulphur present in sour wells, these pipes are particularly susceptible to stress corrosion. To mitigate this, manufacturers often apply anti-corrosion coatings such as oil, varnish, or black paint to the surface of the pipes. This additional layer of protection helps to enhance the corrosion resistance of the pipes, ensuring their longevity and reliability in harsh environments. [\[23\]](#).



Figure I. 11:API 5L X52 [\[25\]](#)

#### I.4.1.2.1.2.2.API 5L X65

API 5L X65 pipe is also called ISO 3183 L450 pipe, it is a high-level grade pipe in API 5L (ISO 3183) specifications, used for oil and gas transmissions. The reason we call it X65 pipe or L415 pipe is because it's minimum yield strength required in 65000 Ksi or 450 Mpa. Though X65 pipe is a premium grade material, still it is carbon steel pipe not alloy pipe. It's specifications and performances comply to carbon steel scope.[\[26\]](#)



Figure 1.1: API 5L Grade X65 [\[27\]](#)

#### I.4.1.2.1.2.3.API 5L X70

pipe is a premium grade piping material in API 5L standard specifications. Also called L485 pipe, as its yield strength minimum in 485 Mpa (70,300 psi). API 5L X70 covers manufacturing types in seamless and welded (ERW, SAW) types, both applied for oil and gas transmissions.[\[28\]](#)

API 5L X70 (L485) is a type of steel pipe used in the oil and gas industry for pipeline transportation systems, named after its minimum yield strength of 70,300 psi (485 MPa), and consists of both seamless and welded pipe forms and is divided into two product specification levels, PSL1 and PSL2. In PSL1, X70 is the highest grade, while in PSL2 it is also one of the higher grades of steel pipe.

API 5L X70 steel pipe is particularly suited to the demands of long-distance, high-pressure transportation because of its high strength and pressure resistance. In order to withstand higher pressures, X70 steel pipe is often designed with thicker walls to ensure adequate strength and durability. [\[29\]](#)



Figure I. 12:API 5L Grade X70[29]

#### I.4.1.2.1.2.4.API 5L X80

API 5L X80 is a standard specification of pipes used to transport oil and natural gas. The API 5L X80 Pipe is mainly used in the rock oil and fossil fuel industry. The API 5L X80 Seamless Pipe comes with high mechanical strength and yield strength. The API 5L X 80 Carbon Steel Seamless Pipe can also be effectively used in onshore pipe applications. The X80 Carbon Steel Pipe is also used in polar regions where the high toughness of the pipe in low temperature is an essential requirement. The API 5L X80 SCH 40 DSAW Pipe offers a few benefits, like they are known for resisting cracking, which is a common occurrence in long pipelines. Also, the Grade X80 PSL2 Spiral Pipe is resistant to corrosion which means they are suitable for sour services. It is also to be noted that the Grade X80 PSL1 Pipe Line is quite durable, which means they have a long service life. The X80 Grade PSL2 Pipeline requires low maintenance and is indeed a cost-saving choice.[30]



Figure I. 13:X80 Carbon Steel Pipeline [30]

#### I.4.1.2.1.2.5.API 5L X120

API 5L X120 PSL2 Pipe is a steel pipe and is commonly used for pipeline transportation systems in the petroleum and natural gas industries. API 5L is suitable for oil and gas transmission, structural application, and mechanical components. [\[31\]](#)

These pipes are resistant to heat and provide Corrosion Resistance, Pressure Rating, Dimensions and Sizes, Material Properties.



Figure I. 14:API 5L X120 [\[31\]](#)

#### I.4.1.3. Nickel Alloy Pipes

Given the high-temperature operations intrinsic to the oil and gas industry, Nickel Alloy Pipes are the ideal choice. These pipes are resistant to heat and provide corrosion resistance, making them essential for extreme environments. [\[15\]](#)

Nickel alloy pipes have become integral components in various industrial sectors. They offer exceptional performance where ordinary materials fail. Understanding the nickel alloy pipe used for different applications is crucial for factories, channel distributors, and resellers seeking reliable piping solutions. These pipes are known for their strength, resistance to heat and corrosion, and durability. They play a vital role in industries that demand high-performance materials. [\[32\]](#)



Figure I. 15:Nickel Alloy Pipes [33]

#### I.4.1.4. Duplex Pipes

Duplex Pipes, a class of stainless steel, are well-suited for applications requiring high strength and good corrosion resistance, ideal for the oil and gas industries. chemical-laden environments. Grades like Duplex 2205 and Super Duplex 2507 are commonly used due to their resilience.[15]

Duplex steel pipes are used in various applications across various industries. They are commonly used in oil and gas extraction and chemical, petrochemical, and food processing industries. They are also used in marine applications, such as offshore drilling platforms and ships. Duplex steel pipes are known for their excellent durability and corrosion resistance, making them suitable for various applications.[34]



Figure I. 16:Duplex Pipes [35]

#### I.4.1.5.PVC Pipes

Lightweight, cost-effective, and easy to install, PVC Pipes are commonly used in oil and gas operations. Offering corrosion resistance and high strength, they prove ideal for low-pressure scenarios and are often used in saltwater disposal, chemical handling, and water flooding.[\[15\]](#)

PVC's strength, durability, easy installation, and low cost have made it one of the most widely used plastics in the world. PVC is a thermoplastic material that is melted into different shapes to create pipes, fittings, valves and other liquid handling supplies. It's the white plastic pipe commonly used for plumbing and drainage.[\[36\]](#)



Figure I. 17:PVC Pipes [\[37\]](#)

#### I.4.1.6. HDPE Pipes

**HDPE pipe** is a flexible plastic pipe made of thermoplastic high-density polyethylene widely used for low-temperature fluid and gas transfer. [\[38\]](#)

The High-Density Polyethylene (HDPE) Pipes provide excellent resistance to rugged terrains, corrosion, and chemicals - perfect for cross-country pipelines transporting natural gas. Their light weight and ductility make them advantageous for seismic-prone areas.[\[15\]](#)



Figure I. 18.HDPE Pipes [\[39\]](#)

#### I.4.1.7. Fiberglass Pipes

Fiberglass Pipes, owing to their lightweight, strength, and flexibility, are used extensively in oil field tubulars and casing for wells. Being resistant to corrosion and demanding less maintenance these pipes are used in application of oil and gas industry.[\[15\]](#)



Figure I. 19.Fiberglass Pipes [\[40\]](#)

#### I.4.1.8. Copper Pipes

The use case for Copper Pipes extends to handling gases like propane and natural gases needing a tight seal. Its corrosion resistance and ability to withstand heat make it a perfect fit for this domain.[\[15\]](#)



Figure I. 20: Copper Pipes [\[41\]](#)

#### I.4.1.9. Polyvinylidene Fluoride (PVDF) Pipes

The high purity application of oil and gas makes the PVDF Pipes a viable option, owing to their resistance to most minerals and aqueous solutions. These pipes also exhibit high abrasion resistance and mechanical strength.



Figure I. 21: Polyvinylidene Fluoride (PVDF) Pipes [42]

#### I.4.1.10. Galvanized Pipes

Galvanized Pipes, featuring a protective zinc coating preventing rusting, are effective in transportation of natural gas and other fluids. Once an industry standard, these pipes while still used, are gradually replaced by less corrosive materials. [43].



Figure I. 22: Galvanized Pipes [44]

#### ➤ I.4.2. According to their roles

From the moment oil or natural gas are removed from the ground pipelines are used to transport them. There are four main types of pipelines used in the process of delivering oil and gas products from the point of extraction to the end user:

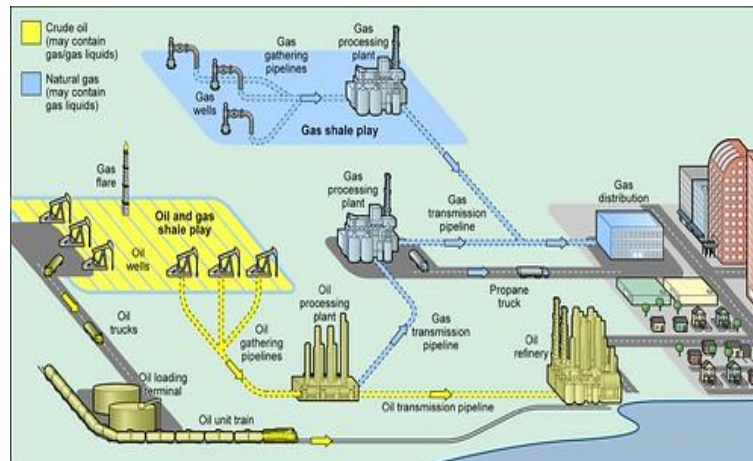


Figure I. 23: Different pipeline roles [45]

#### I.4.2.1-Gathering Pipelines

are used within oil and gas facilities to move unrefined product from wells to processing, refining or storage areas. These pipelines are owned and operated by the oil and gas exploration companies.

#### I.4.2.2-Feeder Pipelines

are also used primarily within oil and gas facilities. They transport oil and natural gas from processing, refining or storage facilities to the transmission lines. Like gathering lines, these are owned and operated by the oil and gas exploration companies.

#### I.4.2.3-Transmission Pipelines

are the larger diameter pipelines that are used to transport oil and natural gas larger distances; across provinces or across provincial/international borders. Transmission pipelines operate at high pressure, using compressor stations to keep the product moving. These lines are owned and operated by specialist transmission pipeline companies.

#### I.4.2.4-Distribution Pipelines

are smaller pipelines used to deliver energy products to the end user. For instance, they are the lines used to bring natural gas into homes and businesses for heating, cooking and other uses. Distribution lines are owned and operated by utility companies. [46].

### I.5. Mechanical Characteristics of Pipes

The development of long-distance transportation of large quantities of hydrocarbons has necessitated the use of large-diameter pipes, operated at higher pressures. To avoid reaching

thicknesses that are difficult to weld and to save on steel, new grades with improved mechanical properties have been adopted. This has led to the emergence of grades such as X60, X65, X70, X80, and even X100. The steels used for pipes can be divided into two groups: low-alloy carbon steels and low-carbon steels.

In the first group, we find ferritic-pearlitic steels such as X42 to X52 (according to API), containing up to 0.3% C, 1.6% Mn, and 0.7% Si. In the second group, we find low-alloy ferritic-pearlitic steels with low carbon content, such as X56, X60, X65, and X70, containing 0.12% C, 0.45% Si, 0.25% S, 1.9% Mn, 0.1% V, 0.1% Nb, and 0.015% Al. For pipelines with diameters greater than 1020 mm, intended to operate under high pressures, controlled-rolled steel pipes are generally used.[\[47\]](#).

### I.6. Types of Defects

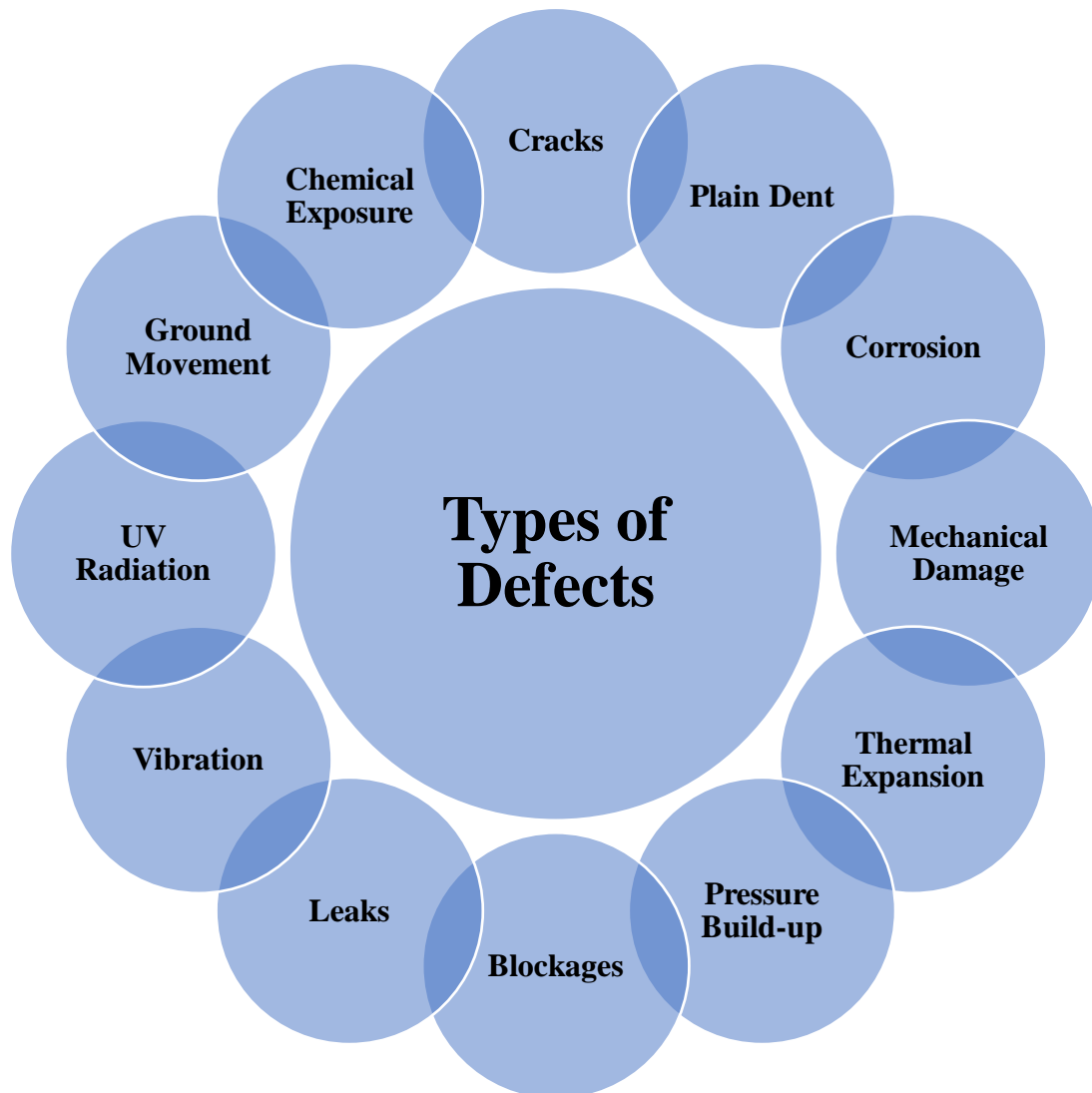


Figure I. 24:Types of Defects

### I.6.1-Cracks

Occur due to: \*Poor materiel properties -Manufacturing

\*Poor welding -construction

\*SCC -condition specific

Controlling the process and environment can limit the existence of these types of defects. [\[48\]](#)



Figure I. 25:Cracks [\[49\]](#)

### I.6.2-Plain dent

Occur due to: \*Installation /construction

\*Ground movement /settling Buckling

\*Some rock impingement

Plain dents are normally not harmful provided they are not extremely large. [\[48\]](#)



Figure I. 26:Plain dent [\[48\]](#)

### I.6.3-corrosion

we know the most about understand and can model

\*Behaviour – leak vs rupture

\*Growth mechanisms

\*Mitigation /Prevention. [\[48\]](#)



Figure I. 27:Corrosion [\[50\]](#)

### I.6.4-Mechanical damage

\*To effectively manage requires prevention

\*Difficult to mitigate due to random /time independent nature of the defect

\*Almost all fail immediately

\*Those that do not can remain latent for years

\*Most complex failure mechanism

\*Tendency to rupture rather than leak

Detection and sizing are key to analysis of latent defects.[\[48\]](#).



Figure I. 28: Mechanical damage [\[48\]](#)

### I.6.5-Thermal Expansion

Thermal expansion happens when pipeline materials expand due to high temperatures. This can cause pipes to warp, crack, or even burst. Be on the lookout for bulging pipes, unusual sounds, or pressure drops within your system. [.51\]](#)

### I.6.6-Pressure Build-up

With the need for more water in the summer, there's usually an increased demand on pipelines that can lead to pressure build-up. This can result in leaks, ruptures, and inefficient flow. Warning signs include unusual noises, vibrations, and pressure gauge fluctuations [.51\]](#)

### I.6.7-Blockages

Blockages can also increase the overall pressure within a pipeline system. These are typically caused by debris, sediment, or even biological growth within pipelines. Restricted flow can lead to reduced efficiency and potential damage. Keep an eye out for decreased flow rates, strange odors, and unusual water quality. [.51\]](#)



Figure I. 29:Blockages [\[52\]](#)

### I.6.8-Leaks

Leaks are one of the most recognizable pipeline problems. They are often the result of corrosion, pressure build-up, or physical damage. Signs of leaks include wet spots, drops in pressure, and increased utility bills.[\[51\]](#)



Figure I. 30:Leaks [\[53\]](#)

### I.6.9-Vibrations

Vibrations can be caused by machinery, seismic activity, or fluid flow within the pipeline and aren't always a bad thing. However, over time, excessive vibrations can weaken a pipeline's structure, leading to cracks and leaks. Listen for unusual noises and observe any abnormal movements in the pipeline.[\[51\]](#)

### I.6.10-UV Radiation

While many pipelines are underground, not all of them are. For those that aren't, prolonged exposure to sunlight can degrade pipeline materials. UV radiation is the main source of this degradation, causing fading, cracking, and brittleness. Look for discoloration, surface cracks, and changes in material texture..[\[51\]](#)

### I.6.11-Ground Movement

Ground movement can result from natural events like earthquakes or human activities such as construction. Shifting soil can stress pipelines, causing misalignment, cracks, or ruptures. Monitor for changes in pipeline alignment and soil conditions.[\[51\]](#)

### I.6.12-Chemical Exposure

While not as common, pipelines may come into contact with various chemicals, depending on where they're located. If exposed for too long, this can lead to erosion and degradation. This is particularly relevant in industrial settings where different substances are transported. Watch for signs of chemical exposure, such as discoloration, pitting, and unusual odors. [\[51\]](#).

### I.7 Conclusion

Chapter 1 provides a comprehensive overview of pipeline systems, detailing their history, types, materials, mechanical properties, and defects. Early pipeline use involved materials like bamboo and copper, which eventually evolved into the high-strength steel pipelines (API 5L grades X52–X120) commonly used today for transporting oil, gas, and water.

In countries like Algeria and the USA, private companies are increasingly prioritizing pipeline integrity, flow integrity, equipment selection, and regular preventive maintenance. These are crucial factors highlighted throughout the chapter. Safe and efficient pipeline operation hinges on a thorough understanding of different pipeline types, including gathering, feeder, transmission, and distribution systems, and their respective functions. Equally important is the ability to identify and manage common defects such as corrosion, mechanical damage, and pressure build-up.

**Chapter 02: Degradation Of Pipeline, Corrosion and Corrosion Control**

## II.1 Introduction

This second chapter provides a comprehensive analysis of pipeline corrosion, a critical form of degradation that presents substantial challenges to the safety, operational efficiency, and structural integrity of pipeline infrastructure. We begin with a historical perspective and establish a clear definition of corrosion as it pertains to metallic systems. This is followed by a detailed classification of corrosion types, complete with examples directly relevant to pipeline operations.

The discussion then extends to the profound global and economic ramifications of corrosion, highlighting its pervasive effects on industrial processes, escalating maintenance costs, and potential environmental hazards. Furthermore, the chapter systematically investigates the key factors that govern corrosion behavior, including temperature, fluid characteristics, flow dynamics, and the material composition of the pipelines. To mitigate these pervasive issues, various corrosion control strategies are subsequently explored, such as cathodic protection, the application of protective coatings, and the use of corrosion inhibitors.

## II.2 History of corrosion

The word corrosion is as old as the earth, but it has been known by different names. Corrosion is known commonly as rust, an undesirable phenomenon which destroys the luster and beauty of objects and shortens their life. A Roman philosopher, Pliny (AD 23–79) wrote about the destruction of iron in his essay ‘Ferrum Corrupter’. Corrosion since ancient times has affected not only the quality of daily lives of people, but also their technical progress. There is a historical record of observation of corrosion by several writers, philosophers and scientists, but there was little curiosity regarding the causes and mechanism of corrosion until Robert Boyle wrote his ‘Mechanical Origin of Corrosiveness’. Philosophers, writers and scientists observed corrosion and mentioned it in their writings:

- Pliny the elder (AD 23–79) wrote about spoiled iron.
- Herodotus (fifth century BC) suggested the use of tin for protection of iron.
- Lomonosov (1743–1756).
- Austin (1788) noticed that neutral water becomes alkaline when it acts on iron
- Thenard (1819) suggested that corrosion is an electrochemical phenomenon.
- Hall (1829) established that iron does not rust in the absence of oxygen.

- Davy (1824) proposed a method for sacrificial protection of iron by zinc.
- De la Rive (1830) suggested the existence of microcells on the surface of zinc.

The most important contributions were later made by Faraday (1791–1867) who established a quantitative relationship between chemical action and electric current. Faraday's first and second laws are the basis for calculation of corrosion rates of metals. Ideas on corrosion control started to be generated at the beginning of nineteenth century. Whitney (1903) provided a scientific basis for corrosion control based on electrochemical observation. As early as in eighteenth century it was observed that iron corrodes rapidly in dilute nitric acid but remains unattached in concentrated nitric acid.

Schönbein in 1836 showed that iron could be made passive. It was left to U. R. Evans to provide a modern understanding of the causes and control of corrosion based on his classical electrochemical theory in 1923. Considerable progress towards the modern understanding of corrosion was made by the contributions of Evans, Uhlig and Fontana. Corrosion laboratories established in M.I.T, USA and University of Cambridge, UK, contributed significantly to the growth and development of corrosion science and technology as a multidisciplinary subject. In recent years, corrosion science and engineering has become an integral part of engineering education globally.[\[54\]](#).

### **II.3 Definition of corrosion**

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment. "Rusting" applies to the corrosion of iron or iron-base alloys with formation of corrosion products consisting largely of hydrous ferric oxides. Nonferrous metals, therefore, corrode, but do not rust.[\[55\]](#).

Corrosion is the surface wastage that occurs when metals are exposed to reactive environments. It is the result of interaction between a metal and environments which results in its gradual destruction.[\[54\]](#).

## II.4. Classification of corrosion

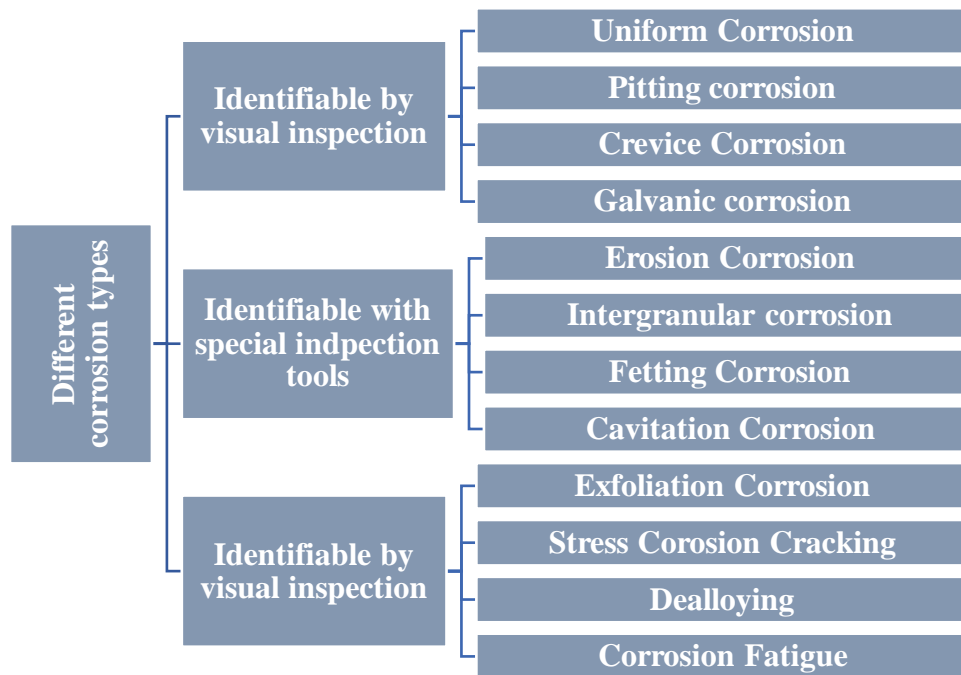


Figure II. 1 : Classification of corrosion

### II.4.1. Identifiable by visual inspection

#### II.4.1.1. General or Uniform Corrosion

Uniform corrosion is a phenomenon affecting all metallic materials depending on their standard potential. The effects on the mechanical stability of the implant are well controlled, but the release of ions and their hydrolyzed products can influence cell adhesion and metabolism.[\[56\]](#) This corrosion results from the continual shifting of anode and cathode regions of the surface of a metal in contact with the electrolyte and leads to a nearly uniform corrosive attack on the entire surface. it is characterized by the average surface loss.



Figure II. 2:Uniform corrosion [\[57\]](#)

### II.4.1.2. Pitting Corrosion

the pitting is just a special case of crevice corrosion. Pitting is an extremely localized attack that eventually results in holes in the metal. It is one of the most destructive and insidious forms of corrosion. Basically, the alloys subject to pitting are those that rely on an oxide film for protection, such as stainless steel. The initiation of a pit can be the result of any of the following: [\[58\]](#)

- a) Chemical damage to stainless steel from substances like ferrous chloride or aerated saltwater
- b) A Mechanical attack that eliminates tiny portions of the protective coating, such as an impact or scratch
- c) Crevice corrosion brought on by microscopic surface deposits, particularly in seawater that is stagnant

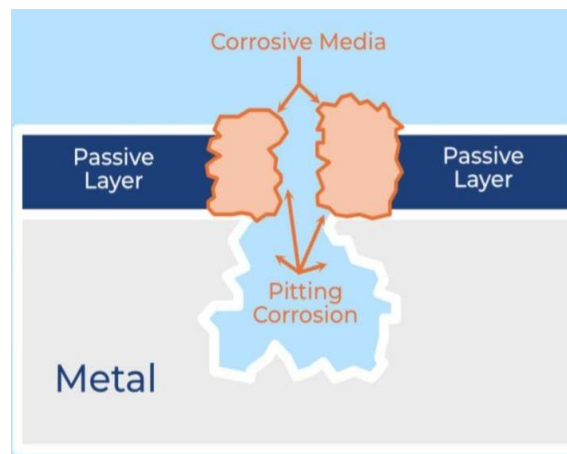


Figure II. 3:pitting corrosion [\[59\]](#)

### II.4.1.3. Crevice Corrosion

Crevice corrosion is a form of localized corrosion, similar to pitting, occurring at locations where easy access to the bulk environment is prevented, such as overlapping zones for riveting, bolting or welding, zones under joints, under deposits, etc. [\[60\]](#)

Crevice corrosion is a localized attack on a metal surface at, or immediately adjacent to, the gap or crevice between two joining surfaces when exposed to a stagnant electrolyte. This can occur

between two metals or a metal and nonmetal material, even if both materials would otherwise resist corrosion without the presence of a gap. [\[61\]](#)

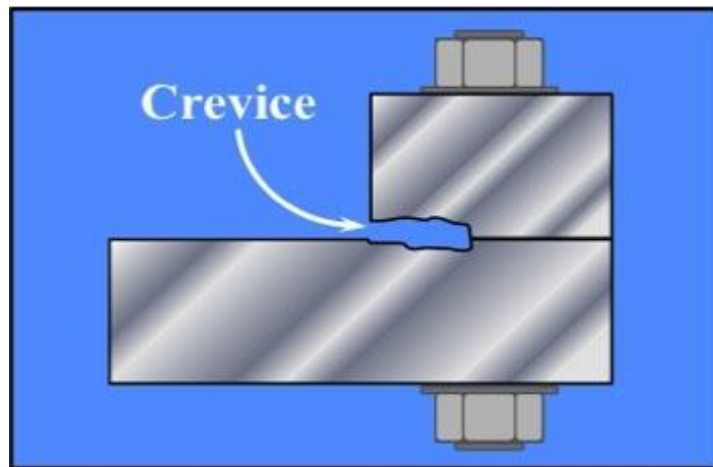


Figure II. 4: Crevice corrosion [\[62\]](#)

#### II.4.1.4. Galvanic Corrosion

When 2 different metals or alloys come in contact with each other, the less noble metal corrodes protecting the other cathodically. This phenomenon is called galvanic corrosion. Galvanic corrosion occurs when 2 different metals are electrically connected and are immersed in an electrolyte. Galvanic corrosion is often utilized in sacrificial anodes. For example, zinc is often used as a sacrificial anode for steel structure like pipelines. Factors such as relative size of anode, type of metal and operating conditions, affect galvanic corrosion. [\[58\]](#)



Figure II. 5: Galvanic Corrosion [\[63\]](#)

## II.4.2. Identifiable with special inspection tools

### II.4.2.1. Erosion Corrosion

Erosion-Corrosion results from a high velocity electrolyte flow whose abrasive action accelerates the corrosion. This corrosion is especially severe when the electrolyte contains solids in suspension. The effect is to remove a protective oxide from the film surface, thus exposing fresh alloy to corrode. Erosion-Corrosion could be thought of as pitting on a much larger scale. There is, in fact, a limit to what electrolyte velocities can be tolerated by specific metals. Copper- nickel alloys are selected for seawater service based on their resistance to erosion-corrosion (amongst other requirements). This table illustrates these limitations.[\[58\]](#)

Alloys	Maximum velocity, fps
Copper	3
90 Cu/10 Ni (with 1.25%Fe)	12
70 Cu/10 Ni (with 5%Fe)	15
85 Cu/10 Ni (with 5%Cr)	>15
Titanium	>15

**Tableau II. 1:Recommended Maximum Velocity to Reduce Impingement/Velocity Effects in Seawater**



**Figure II. 6:Erosion corrosion [\[64\]](#)**

Other types of attack associated with velocity effects, besides erosion, include:

- Cavitation, which is the degradation of a surface brought on by the abrupt emergence and collapse of voids and bubbles as a result of liquid turbulence. Usually, it is identified by a rough or pitted metal surface.
- Impingement attack: localized corrosion brought on by impinging flow or turbulence. In general, there is a threshold velocity above which attack grows quickly and below which impingement does not occur.

It should be noted that these three corrosion processes frequently take place at the same time.

#### II.4.2.2. Intergranular Corrosion

Intergranular corrosion occurs when metal on or adjacent to grain boundaries dissolves, or corrodes preferentially to grain interiors. The grain boundary region acts as an anode with the grain interior being a cathode, forming a galvanic cell with a large cathode and a small anode in which rapid corrosion occurs at the anode.[\[65\]](#)

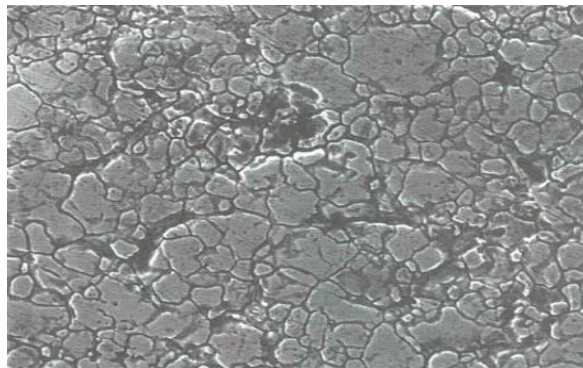


Figure II. 7: Intergranular corrosion [\[66\]](#)

#### II.4.2.3. Fretting Corrosion

Fretting corrosion occurs due to metal deterioration resulting from repetitive slip at the interface between two surfaces in contact.[\[67\]](#).

A rapid localized attack which occurs on mated surfaces under load when a small amount of slip is allowed to occur. It is often observed on bearings, shafts, and gears in mounted in vibrating machinery. Not only is mechanical damage of the surface possible but the protective

surface film of the metal is also removed. This in turn hastens electrochemical corrosion processes. [\[58\]](#)



Figure II. 8:Fetting Corrosion [\[68\]](#)

#### II.4.2.4. Cavitation corrosion

Cavitation corrosion is formed when the operational pressure is dropped below the vapor pressure of the fluid, causing the formation of gas bubbles that collapse at an increased velocity on the surface of the material, inducing initial cavitation. When this phenomenon happens, the pressure decreases as the velocity increases, called “vena contracta”. The fluid in the system is a corrosive driver, so where the cavity is formed, the part starts to corrode due to its environment. This cavity could then turn into pits, initiating cracking.



Figure II. 9:Cavitation corrosion [\[69\]](#)

### II.4.3. Identifiable by microscopic examination

#### II.4.3.1. Exfoliation corrosion

Exfoliation corrosion is a form of intergranular corrosion which involves selective attack of a metal at or adjacent to grain boundaries. In this process, corrosion products formed force metal to move away from the body of the material, giving rise to a layered appearance. Exfoliation corrosion is also known as layer corrosion or lamellar corrosion.[\[70\]](#)



Figure II. 10: Exfoliation corrosion [\[71\]](#)

#### II.4.3.2. Stress Corrosion Cracking (SCC)

Stress-corrosion-cracking occurs with specific alloys under the following threshold conditions:

- a) Specific corrosive environment solution composition
- b) Minimum tensile stress Levels
- c) Temperature
- d) Metal composition
- e) Metal structure

Some examples of SCC are the brass and stainless-steel alloys. The interplay of the conditions leading to SCC is not well understood. It is believed that the corrosion causes a pit or surface discontinuity to form on the metal which then functions to act as a stress concentrator. The presence of a minimum threshold tensile stress, coupled with the corrosion, causes the crack to propagate. Additionally, during the initial corrosion, the tensile stresses could cause the

protective films on the surface to rupture, thereby exposing the metal to the corrosive environment.[\[58\]](#)

Environmental variables or cyclic stresses may be the cause of this especially hazardous form of corrosion. The main categories of cracking attacks are as follows:

- Corrosion fatigue: When a metal is exposed to cyclic loading because it is in a corrosive environment, it fails more quickly.
- The corrosion-induced cracking that takes place in alloys under high tensile stress is known as stress corrosion cracking (SCC). The surface is where the cracks begin, and they move inward. It should be mentioned that external loading, forming, or cold working can all cause stress.



Figure II. 11: stress corrosion cracking [\[72\]](#)

#### II.4.3.3. Dealloying

Dealloying is a rare corrosion form usually found in gray cast iron, copper alloys, and other alloys. Usually, it occurs when alloy loses metal main components and maintains corrosion resistance on metal surface.[\[73\]](#)

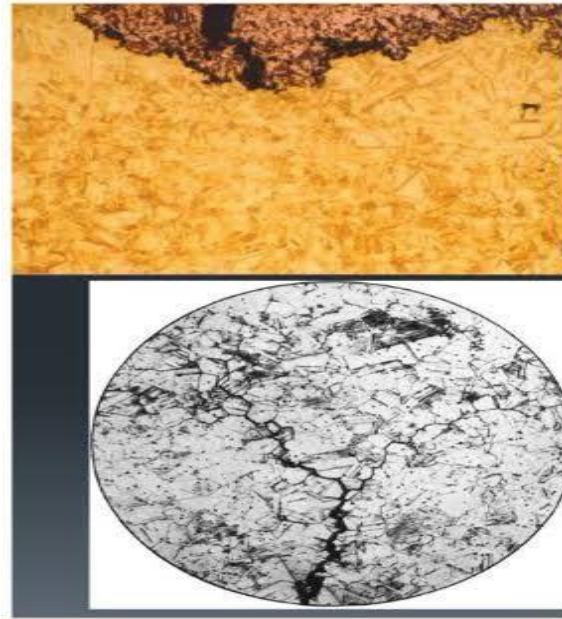


Figure II. 12:Dealloying [74]

#### II.4.3.4. Corrosion-fatigue

Corrosion-fatigue is the result of the combined action of an alternating or cycling stresses and a corrosive environment. The fatigue process is thought to cause rupture of the protective passive film, upon which corrosion is accelerated. If the metal is simultaneously exposed to a corrosive environment, the failure can take place at even lower loads and after shorter time. [75].

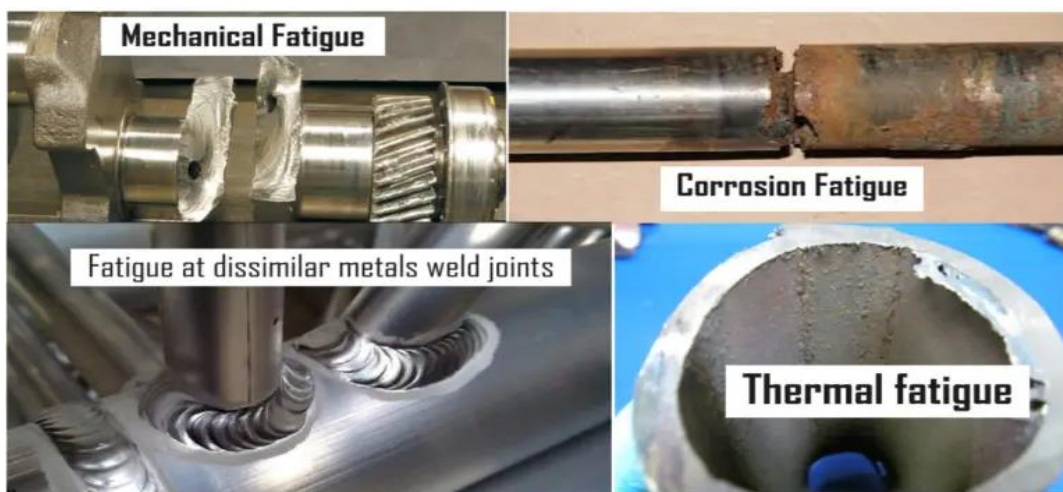


Figure II. 13:Corrosion fatigue [76]

### II.2.4. Global effects of Corrosion

The effects of corrosion shade our daily life both by direct and indirect means.[\[77\]](#)

How corrosion affects us from home to work is of much more severe consequence. The corrosion of steel reinforcing bars in concrete can occur without being noticed. It can cause the failure of a section of highway, damage to buildings, bridges, parking structures, and the collapse of electrical towers, etc., resulting in significant economic loss and jeopardizing public safety. Corrosion that occurs in major industrial plants, such as chemical processing plants or electrical power plants, is perhaps the most dangerous of all. Such type of corrosion could result in plant shutdowns.

- Some corrosion consequences are economical and result in the following:
  - Replacing the corroded equipment
  - Taking preventive measures, such as painting
  - Equipment shut down due to corrosion failure Overdesigning to allow for corrosion
  - Efficiency loss
  - Damage of equipment adjacent to one in which corrosion failure occurs.
    - Some consequences are social and can cause the following issues:
      - Health, for instance, an escaping product from corroded equipment or corrosion product itself can cause pollution
      - Safety, as an example, sudden failure can cause an explosion, fire, release of a toxic product, and/or construction collapse
      - Unpleasant appearance of the corroded materials to the eye
      - Depletion of natural resources, including the metals and fuels used to manufacture them.[\[78\]](#)

### II.2.5. Economic effects of corrosion

The cost of repairs of the structure that has been destroyed due to the effect of corrosion has been analysed recently to make up to three percent of the GDP of developed countries. Although some countries with more terrible climate changes such as the Middle East where the temperature and humidity are on the high part of the scale and they also encounter air borne chlorides have a GDP of about 5%.[\[79\]](#)

It is a general belief that corrosion is a universal enemy that should be accepted as a process that is inevitable. As products and production processes become more complex and the penalties

for corrosion failures have become more expensive and increased awareness has been generated.[\[80\]](#)

underscores the above assertion and further argues that corrosion is like corruption, when both are left uncontrolled, they eat deep into the fabrics of a nation's economy in an irreversible manner that recovery most often becomes an unrealizable mirage. Moreover, an average of 10 percent of the total metal output in the world is estimated to be lost in corrosion. This affects the economy of a nation and her assets: infrastructures, transportation, utilities, nuclear and military facilities, and production and manufacturing plants. According to the cost of corrosion in industrialized nations is about 3-4% of their GDP. Deductively, third world countries spend ten times the above estimate to fight corrosion.[\[81\]](#)

- classified the economic costs of corrosion into two:
- **Direct Cost/Losses:** Those that can be quantitatively accounted for. Such as replacement cost, protection cost, corrosion inhibition, research and development.
- **Indirect Cost/ Losses:** These cannot be quantitatively evaluated. Examples are loss of products to spill and fire, loss of revenue due to downtime, loss of efficiency of equipment, contamination of products, environmental pollution, etc...[\[82\]](#)

## II.6. FACTORS AFFECTING CORROSION

Many factors are responsible for the corrosion of metals. These are relative velocity, presence of impurities, nature of firm, and oxidizing agent.

### II.6.1. RELATIVE VELOCITY

An increase in velocity of relatively movement between a corrosive solution and a metallic surface tends to accelerate corrosion of metals. This effect may be due to the rate of which might otherwise accumulate and retard corrosion are carried away.

### II.6.2. PRESENCE OF IMPURITIES

Impurities can exhibit or lead effect from the corrosion start point, impurities in a stream may act as a catalyst and actually accelerate corrosion.

### II.6.3. OXIDIZING AGENTS

Majority of the metallic corrosion observed in practice proceed under conditions where the oxidation of hydrogen by oxygen to form water is a necessary part of the corrosion process. For this reason, oxidizing agents are often powerful corrosion accelerations. [83]

### II.7. Corrosion control methods

The corrosion control starts with studying the system components, fluids, and operating conditions, followed by proper material selection, and then developing and implementing a corrosion control (prevention, mitigation) program and rigorously following up and monitoring for corrosion signs during operations. Depending on the validity of the applied corrosion control plan, changes can be done to improve it or to switch to a more effective plan. [84]

Methods of combating corrosion (protection of metals against corrosion) The following methods are used to protect metals against corrosion:

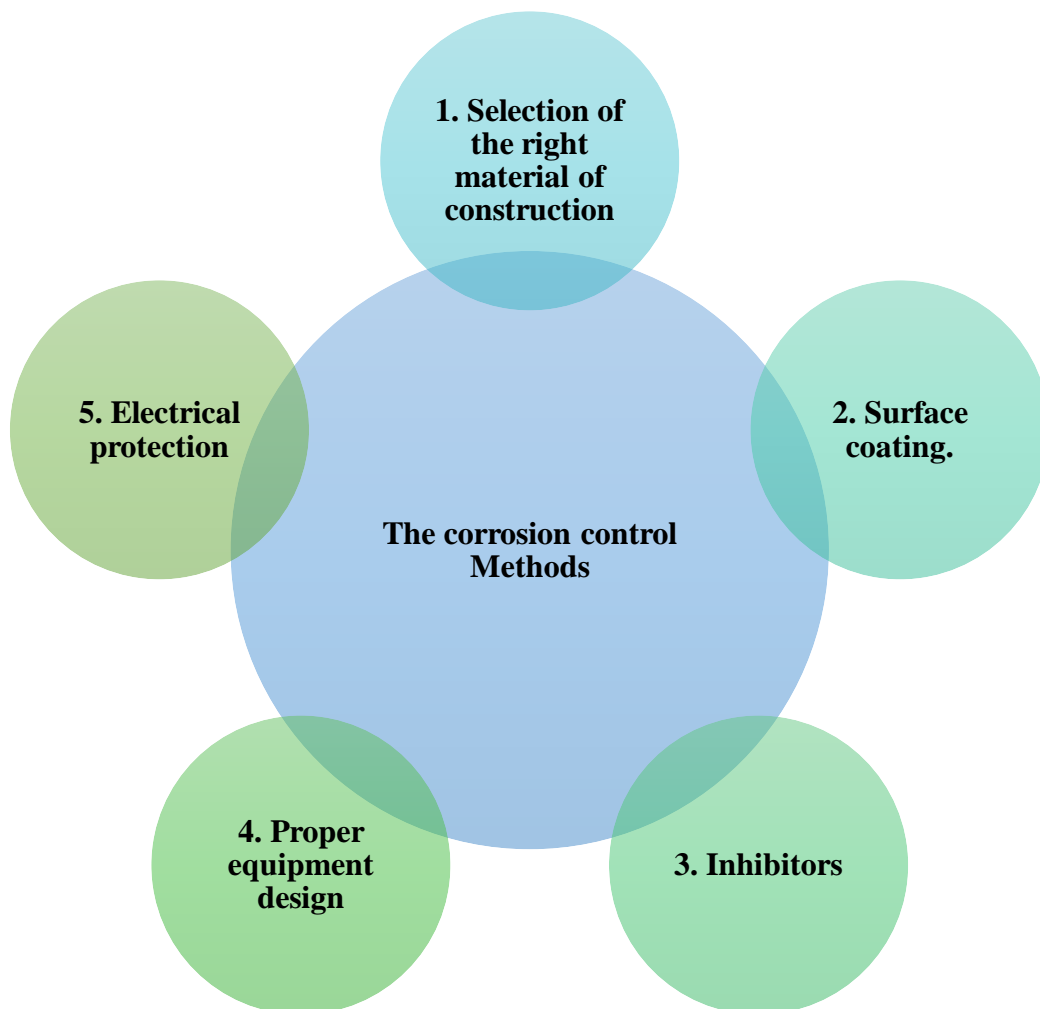


Figure II. 14:Corrosion Control Methods

### II.7.1. Selection of the right material of construction

The right material of construction should have the following properties:

- (1) high mechanical strength      (2) high corrosion resistance      (3) low cost. [\[85\]](#)

### II.7.2. Surface coating

Surface coating can be utilized on nanomaterials for modifying or diminishing the adverse effects associated with them. Surface coatings can also be used to modify properties like stabilization of particles, agglomeration and arrest dissolution and discharge of noxious ions.

[\[86\]](#)

Surface coating is a promising membrane modification approach where the modifiers are adhered or settled on the membrane surface through a non-specific interaction. [\[87\]](#)

### II.7.3. inhibitors

Corrosion inhibitors are substances used to prevent or reduce metal surface corrosion in corrosive environments. There are two types of corrosion inhibitors: natural and synthetic

- **Natural inhibitors**, derived from plants and minerals, are eco-friendly, biodegradable, and low in toxicity, natural inhibitors that can be used in various applications, such as in the oil and gas industry
- **Synthetic inhibitors** are chemically manufactured to provide high efficacy in a range of corrosive environments. Synthetic inhibitors are more effective, have a wider range of applications, are reliable, and have a longer shelf life than natural inhibitors. [\[88\]](#)

### II.7.4. Minimizing corrosion by proper design

Avoid dissimilar metal contact in the presence of an electrolyte especially when the cathode/anode ratio is high.

If the use of dissimilar metals is unavoidable in building the structure they should be separated by an insulator such as plastic or rubber.

Dissimilar metals are sometimes used intelligently to design structures which are corrosion resistant and less expensive. [\[85\]](#)

### **II.7.5. Electrical Protection**

Electrical Corrosion Protection has a high dielectric constant and also stops corrosion on battery terminals and grounding wires. It provides easy applications to junction boxes and motor windings. Designed to penetrate, it spreads and soaks into hard-to-reach areas. [\[89\]](#)

### **II.8. Conclusion**

This chapter meticulously explored the complexities of pipeline corrosion, dissecting its various forms, underlying causes, and far-reaching consequences. This foundational understanding is crucial for what comes next.

Building on this, the subsequent chapter will pivot to corrosion protection methods, placing a special emphasis on green inhibitors. These innovative, plant-based compounds offer a promising path for effective corrosion mitigation while championing environmental responsibility and industrial safety. Our aim is to seamlessly transition from understanding the problem of corrosion to presenting the technical rationale and potential of sustainable solutions in the ongoing discussion.

**Chapter 03: Protection Methods (Green Inhibitor)**

### III.1 Introduction

Corrosion is the deterioration of metal by chemical attack or reaction with its environment. It is a constant and continuous problem, often difficult to eliminate completely. Prevention would be more practical and achievable than complete elimination. Corrosion processes develop fast after disruption of the protective barrier and are accompanied by a number of reactions that change the composition and properties of both the metal surface and the local environment, require the use of corrosion inhibitors in order to restrain their corrosion attack on metallic materials.[\[90\]](#)

To protect metal from corrosion reactions, one of the most practical methods is to apply corrosion inhibitors. Corrosion reduction is typically achieved through cathodic protection, process control, metal impurity reduction, surface treatment techniques, and alloy incorporation. Phytochemicals, active plant ingredients, have been proven to inhibit the corrosion of mild steel and aluminium in various corrosive environments.[\[91\]](#)

Inhibitors are used in the oil and gas sector to stop or lessen problems like scale buildup and corrosion in pipelines and associated infrastructure. In the context of oil and gas pipelines, these inhibitors are essential for preserving the effectiveness and integrity of oil and gas operation inhibition. The protective methods chapter dedicated to green inhibitor describes the green and environmentally friendly ways to prevent corrosion. It emphasizes the increasing necessity for reducing dependence on natural toxic materials as potential replacements for traditional chemical inhibitors. Focusing on greener alternatives, this chapter covers the technical efficiency, as well as the environmental footprint of corrosion protection strategies, in line with worldwide trends in Green Chemistry and sustainable engineering.

### III.2 History

Early uses of corrosion inhibitors, such as lime in water systems in the early 1900s, were made to stop protective layers from forming. Inhibitors were widely utilized in a variety of industries by the middle of the 1940s, including oil refineries, boilers, engines, aluminum equipment, and airplanes. Since then, studies have concentrated on comprehending the mechanics underlying corrosion inhibition, investigating eco-friendly substitutes, and creating novel inhibitor kinds.

Initial Uses and Developments:

In the early 1900s, plumbing in potable water systems was protected with calcareous deposits made of lime.

Midway through the 1940s, inhibitors were widely utilized in a variety of industries, such as oil refineries, aluminum equipment, and airplanes.

1950s: The emphasis switched to comprehending the workings of inhibitors of the oxidation and adsorption types.

1970s: Studies started concentrating on inhibitors that are safe for the environment and how they work.

2000s: Because of its toxicity, the use of Cr (VI) (chromate) in aquatic environments was prohibited, which prompted the creation of substitute inhibitors.

### III.3 Definition of Corrosion inhibitor

Inhibitors are antibodies. [93]. An inhibitor is a substance that minimizes metal loss, reduces hydrogen embrittlement, protects against pitting, and reduces acid fumes. It acts as a barrier, reducing the oxidation rate of metals, and is easy to apply without significant disruption, making it an effective method for corrosion prevention. [94]. In general this is the definition of an inhibitor, but we specialize corrosion inhibitor.

**So, Corrosion inhibitors** are substances used to prevent or reduce metal surface corrosion in corrosive environments. There are two types of corrosion inhibitors: natural and synthetic

- Natural inhibitors, derived from plants and minerals, are eco-friendly, biodegradable, and low in toxicity.
- Synthetic inhibitors are ideal for applications such as offshore platforms, pipelines, and nuclear power plants where maintenance is challenging or costly. Nevertheless, synthetic inhibitors are more expensive than natural inhibitors and require proper selection and dosing to prevent environmental damage and interference with other chemical processes in the system [95]



Figure III. 1: Corrosion Inhibitor [96]

### III.4 The role of Corrosion inhibitors

The role of inhibitors is to form a barrier of one or several molecular layers against acid attack. This protective action is often associated with chemical and/or physical adsorption. [\[96\]](#)

### III.5 the mechanism of the Corrosion inhibitor

Generally, the mechanism of the inhibitor is one or more of three that are cited below:

- the inhibitor is chemically adsorbed (chemisorption) on the surface of the metal and forms a protective thin film with inhibitor effect or by combination between inhibitor ions and metallic surface.
- the inhibitor leads a formation of a film by oxide protection of the base metal.
- the inhibitor reacts with a potential corrosive component present in aqueous media and the product is a complex. [\[90\]](#)

Green corrosion inhibitors function by forming a protective layer on the metal surface, which prevents corrosive agents from interacting with the metal. [\[97\]](#)

The mechanism of the inhibition process of the corrosion inhibitors under consideration is mainly due to the adsorption. The phenomenon of adsorption is influenced by the nature and surface charge of the metal and by chemical structure of inhibitors. The surface charge of the metal is due to the electrical field which emerges at the interface on immersion in the electrolyte. [\[98\]](#)

### III.6 Classification of inhibitor

Corrosion Inhibitor can be classified as shown in the following diagram:

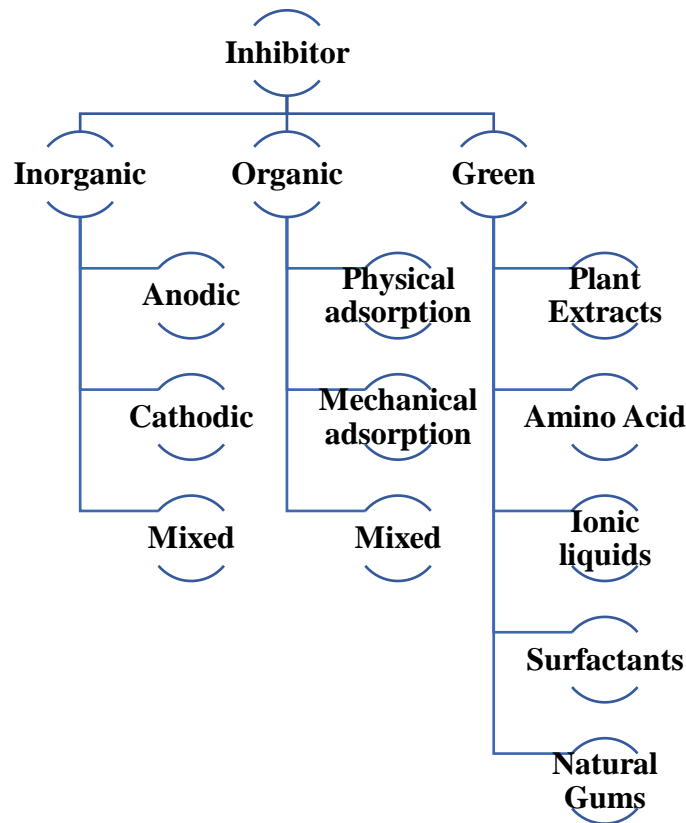


Figure III. 2: Classification of Inhibitor

### III.6.1 Inorganic inhibitor

Inorganic corrosion inhibitors are compounds that are added to a corrosive environment to slow down or prevent the corrosion process. These inhibitors are widely used in various industries such as oil and gas, chemical, petrochemical, and construction.[\[100\]](#) Inorganic corrosion inhibitors can be classified into 3 Parts: Anodic, Cathodic and Mixed inhibitor.

They work by forming a protective film on the metal surface, which prevents the formation of corrosion cells.[\[95\]](#)

#### III.6.1.1 Cathodic Inhibitor

The cathodic inhibitors are precipitation inhibitors.[\[101\]](#) Cathodic inhibitors reduce corrosion by slowing the reduction reaction rate of the electrochemical corrosion cell. This is done by blocking the cathodic sites by precipitation. Cathodic inhibitors are effective when they slow down the cathodic reaction.[\[99\]](#)

Cathodic inhibitors work by decreasing the rate of the cathodic reaction, which typically involves the reduction of oxygen or hydrogen ions in a corrosive environment. These inhibitors can either form a barrier on the metal surface or react with corrosive species to neutralize them,

effectively reducing the metal's tendency to lose electrons. Examples of cathodic inhibitors include polyphosphates, zinc, and various metal salts, which create protective coatings that are particularly useful in protecting pipelines and industrial equipment.[\[102\]](#)

Cathodic inhibitors can work to slow the cathodic reaction down or they can work to selectively precipitate on the cathodic regions of the metal in order to restrict the diffusion to the metal surface of the elements that are eroded. Examples for Cathodic Inhibitors include sulfite and bisulfite ions which can react with oxygen to form sulphates. Another example of a cathodic inhibitor is a catalyzed redox reaction by nickel.[\[103\]](#)

Cathodic inhibitors act by either slowing the cathodic reaction itself or selectively precipitating on cathodic areas to limit the diffusion of reducing species to the surface. The rates of the cathodic reactions can be reduced by the use of cathodic poisons.[\[104\]](#)

### III.6.1.2 Anodic Inhibitor

An anodic inhibitor increases the anodic polarization and hence moves the corrosion potential to the cathodic direction and hence also called as passivating inhibitors. [\[99\]](#)

Anodic inhibitors usually act by forming a protective oxide film on the surface of the metal causing a large anodic shift of the corrosion potential. This shift forces the metallic surface into the passivation region. They are also sometimes referred to as passivators. [\[104\]](#)

These types of corrosion inhibitors form a thin preventive oxide layer on the surface of the metal. This reaction leads to a big anodic shift, turning the metallic surface into a passivation area. This passivation area helps in reducing the corrosion of the metal. Examples for anodic inhibitors include chromates, nitrites, orthophosphates, and molybdates.[\[103\]](#)

Anodic inhibitors, also referred to as passivating inhibitors, function by blocking the anodic reaction in corrosion, where metals lose electrons. They achieve this by forming a protective oxide layer on the metal surface, which reduces oxidation and protects against corrosive substances. Common anodic inhibitors include chromates, nitrites, and molybdates, which are widely utilized in industries such as water treatment and oil and gas pipelines.[\[102\]](#)

### III.6.1.3 Mixed inhibitors

Mixed inhibitors provide the highest protection because they affect both cathodic and anodic reactions.[\[105\]](#). Mixed inhibitors combine the properties of both anodic and cathodic inhibitors, offering comprehensive protection against corrosion. They form a film on the metal surface that

hinders both oxidation and reduction processes, effectively addressing multiple corrosion mechanisms. Common mixed inhibitors include amine-based compounds and imidazolines, which are particularly effective in various environments encountered in oilfield applications.[\[102\]](#)

Examples for Mixed inhibitors include silicates and phosphates which are used as water softeners to stop the rusting of water.[\[103\]](#)

### III.6.2 Organic inhibitor

Organic inhibitors adsorb inhibitor molecules onto the electrolyte/metal interface, preventing both cathodic and anodic reactions. This process can be either chemical or physical, depending on factors such as chemical structure, concentration, electrolyte type, external charge, and molecule circulation. Physisorption and chemisorption are two primary methods through which organic inhibitors function.[\[94\]](#)

#### III.6.2.1 Physical adsorption

Physical adsorption involves electrostatic interactions at the interface, while chemical adsorption involves chemical bonding between the inhibitor molecules and the metal substrate.[\[94\]](#)

The physisorption occurs through an electrostatic interaction between the metal surface and inhibitor's charged molecule. [\[104\]](#)

#### III.6.2.2 Chemical adsorption

The chemical adsorption involves chemical bonding between the inhibitor molecules and the metal substrate.[\[103\]](#)

The chemisorption mechanism occurs through charge transfer share between the adsorbed inhibitor molecules and the metal surface.[\[104\]](#)

#### III.6.2.3 Mixed

Mixed organic corrosion inhibitors are substances that protect metal surfaces against corrosion by exploiting both physical and chemical adsorption mechanisms.

### III.6.3 Green Corrosion Inhibitor

Green Corrosion Inhibitor are Environmentally, Natural, Friendly, Non-Toxic and Biodegradable.

Green corrosion inhibitors function by forming a protective layer on the metal surface, which prevents corrosive agents from interacting with the metal.[\[105\]](#) Green corrosion inhibitors are biodegradable and do not contain heavy metals or other toxic compounds.[\[94\]](#)

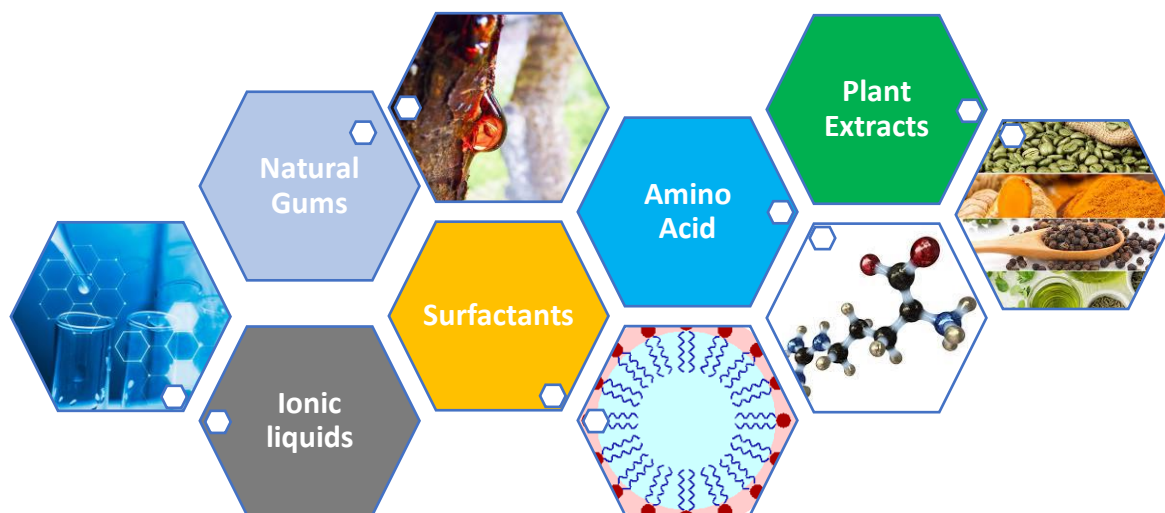


Figure III. 3:Types of green corrosion inhibitor

### III.6.3.1 Plant Extracts

Plant extracts and essential oils have shown significant potential as green corrosion inhibitors.[\[105\]](#) Plant Extract is a diverse collection of compounds.

This type of inhibitor is quite renewable, and for this reason, they were mentioned as affordable resources. Biocompatibility and eco-friendliness can pass the environmental issues as well, while the ionic liquids and amino acids require advanced facilities for production and they are valueless for industrial applications. In recent days, the plant extracts were introduced as common green inhibitors sources due to their green nature, high accessibility, ease of production, and renewability. Assessments have displayed that the plant leaves are the most favorable part for extraction and provide significant performance also. Recent investigations have evidenced that the plant extract phytochemicals contain a great number of heteroatoms in their own structures which mean considerable performance achievement after. [\[98\]](#)

For several reasons, plant-based extracts have gained significant attention recently. These plants are abundant in many countries, and, due to the simplicity of the extraction process, they have become increasingly valuable.[\[93\]](#)

### III.6.3.2 Amino Acid

Amino acids are considered as green corrosion inhibitors because they are non-toxic, biodegradable, inexpensive, soluble in aqueous media, and easy to produce purities higher than 99%.[\[90\]](#). Amino acids are organic molecules that are the basic building blocks of proteins.

Amino acids and their derivatives have made significant progress in corrosion prevention due to their favorable environmental effects and their ability to form effective chelating complexes with metallic substrates.[\[93\]](#). Amino acids are one of the most popular inhibitors and have been used to inhibit corrosion in many metals such as iron, steel, aluminum, copper, and nickel. Amino Acids is due to their reversibility, non-toxicity, easy to make, biodegradability, environmentally friendly, solubility in water, and low cost.[\[109\]](#)

### III.6.3.3 Ionic liquids

Ionic liquids as corrosion inhibitors have been widely evaluated. And their unique properties are high thermal and chemical stability, non-flammability, very low toxicity, low volatility, and the ability to absorb metal surfaces have made them popular.[\[92\]](#)

### III.6.3.4 Surfactants

Typically, surfactants are used in applications like shampoos, detergents, paints, coatings, and concrete, but they also have other uses, in fact, they are also used as corrosion inhibitors. Their advantages include cheapness, easy preparation methods, non-toxicity, and high performance.[\[109\]](#)

### III.6.3.5 Natural Gums

The last member of the category of green corrosion inhibitors is natural gums. Gums are generally classified as a pathological response to plant damage and are exudated from the stem or root of the tree.[\[109\]](#)

## III.7 Effects of inhibitors on corrosion processes

In acid solutions the anodic process of corrosion is the passage of metal ions from the oxide-free metal surface into the solution, and the principal cathodic process is the discharge of

hydrogen ions to produce hydrogen gas. In air-saturated acid solutions, cathodic reduction of dissolved oxygen also occurs, but for iron the rate does not become significant compared to the rate of hydrogen ion discharge until the pH exceeds a value of 3. An inhibitor may decrease the rate of the anodic process, the cathodic process, or both processes. The change in the corrosion potential on addition of the inhibitor is often a useful indication of which process is retarded. Displacement of the corrosion potential in the positive direction indicates mainly retardation of the anodic process (anodic control), whereas displacement in the negative direction indicates mainly retardation of the cathodic process (cathodic control). Little change in the corrosion potential suggests that both anodic and cathodic processes are retarded.[\[110\]](#)

### III.8 Inhibitor efficiency

Inhibition efficiency is a crucial metric for evaluating the effectiveness of corrosion inhibitors. It quantifies how well a substance reduces metal corrosion rates, typically measured through weight loss comparisons with and without the inhibitor. This efficiency is often expressed as a percentage reduction in corrosion rate, highlighting the inhibitor's performance. Various methods, such as weight loss and polarization studies, are employed to calculate this efficiency, providing a standardized way to assess the protective capabilities of corrosion inhibitors. Also, it quantifies a corrosion inhibitor's effectiveness in minimizing corrosion rates, typically assessed through weight loss and polarization studies, reflecting its role in preserving metal integrity against corrosive environments.[\[111\]](#)

A corrosion inhibitor is a chemical substance that, when added in small concentration to an environment, effectively decreases the corrosion rate. The efficiency of an inhibitor can be expressed by a measure of this improvement:

$$\text{Inhibitor efficiency } 100\% = \frac{CR_{\text{uninhibited}} - CR_{\text{inhibited}}}{CR_{\text{uninhibited}}}$$

where

$CR_{\text{inhibited}}$ : corrosion rate of the inhibited system

$CR_{\text{uninhibited}}$ : corrosion rate of the uninhibited system

In general, the efficiency of an inhibitor increases with an increase in inhibitor concentration (e.g., a typically good inhibitor would give 95% inhibition at a concentration of 0.008% and 90% at a concentration of 0.004%). A synergism, or cooperation, is often present between

different inhibitors and the environment being controlled, and mixtures are the usual choice in commercial formulations.[\[112\]](#)

### III.9 Benefits of Green Corrosion Inhibitors

- **Environmental Benefits:** Green inhibitors reduce environmental pollution and help conserve natural resources by being biodegradable and non-toxic.
- **Health and Safety Benefits:** Using non-toxic inhibitors enhances the safety of workers and communities, reducing health risks associated with exposure to hazardous chemicals.
- **Regulatory Compliance and Sustainability:** Adopting green inhibitors helps industries meet stringent environmental regulations and promotes sustainable practices.
- **Cost-Effectiveness and Long-Term Benefits:** While the initial cost of green inhibitors may be higher, their long-term benefits include reduced maintenance costs, extended equipment lifespan, and improved operational efficiency.[\[98\]](#)

### III.10 Challenges and Future Directions

- **Current Limitations and Challenges in Adopting Green Inhibitors**

Despite their benefits, green inhibitors face challenges such as:

- Limited availability and higher cost compared to traditional inhibitors.
- Variability in effectiveness depending on environmental conditions and application methods.

- **Research and Development in Green Corrosion Inhibition**

Ongoing research aims to overcome these challenges by:

- Developing new and more effective green inhibitors.
- Improving the scalability and cost-efficiency of green inhibitors.[\[98\]](#)

### III.11 Conclusion

Inhibitors are a great method of preventing corrosion and are easy to apply. Has application in a wide range of sectors. The knowledge of the method of the action, facilitates the choice of the inhibitors, improves efficiency, avoids the process is impaired and side effects. It is important in the choice of inhibitor, ascertain the subsequent effects of this towards the environment.[\[108\]](#)

Green corrosion inhibitors are substances obtained from natural sources that are biodegradable in many settings, giving a promising alternative to their traditional equivalents. The use of green inhibitors is essential for the new world and industries.[\[110\]](#)

Finally, green inhibitors are emerging as a new development in corrosion inhibition technology, contributing to sustainability while fulfilling their purpose. The chapter shows that such sustainable processes can indeed be widely effective here with sensible choice and use, (other)wise involving relatively little environmental damage. Further study and development in this direction are also required for wider use of green inhibitors in practice. Continued research and development in this area is essential for the wider adoption of green inhibitors in future industrial and environmental applications.

**Chapter 04: Fatigue Testing Machine & Rotating Banding**

## IV.1 Introduction

Fatigue analysis is a critical aspect of designing and analyzing structures and components subjected to cyclic loading. Fatigue occurs when a material is subjected to repeated loading and unloading cycles, leading to the formation and propagation of cracks.[\[1\]](#)

Fatigue is a crucial aspect of materials science and mechanical engineering which constitutes progressively localized structural damage resulting from cyclic loading. Although the applied stresses may be below the materials yield strength, if a material is subjected to sufficient cyclic loading, initiation, and therefore propagation of cracks can lead to eventual failure. This chapter features a comprehensive discussion on Fatigue and provides the principles and operation of a fatigue testing machine, with specific emphasis on the method of rotating bending.

The fatigue testing machine will be a useful tool for assessing the durability and life expectancy for materials utilized in engineering components. The mechanics of the design and assembly for the fatigue testing machine, including the testing process, several types of fatigue machines, and the various advantages and disadvantages with fatigue testing are discussed in this chapter. Special attention is given to the S-N curve (Wöhler curve) which describes the relationship between stress amplitude and cycles to failure, as this curve is the basis of fatigue analysis for engineering design

## IV.2 Definition

Fatigue Testing is a non-destructive test.[\[2\]](#) Fatigue testing machines are used to determine the durability of a material, component or product, and are suitable for tensile, compression, and alternating load tests.[\[3\]](#) Therefore, fatigue testing is a dynamic testing mode, which can be used to simulate the behavior of a material under real life loading conditions.[\[4\]](#) Fatigue testing machine is used for the test the fatigue strength of material by various material manufacturer, institute and laboratories.[\[5\]](#) Fatigue testing machines are essential tools used to evaluate the durability and longevity of materials and components under repeated stress.[\[6\]](#)

## IV.3 The Fatigue Testing Process

- **Setting Up the Sample:** The sample material is secured in the machine.
- **Applying Load Cycles:** Load is applied repeatedly in cycles to simulate real-world conditions.
- **Recording Data:** As the cycles continue, data on stress, strain, and deformation are collected to determine the sample's endurance.[\[7\]](#)

Fatigue is often a silent but destructive process in materials. It occurs when materials are exposed to cyclic forces, think of bending a paperclip back and forth until it snaps. Causes of fatigue can range from repeated pressure, vibration, to temperature changes, leading to cracks, fractures, and eventually complete failure.[\[7\]](#)

#### IV.4 The Wöhler curve

Fatigue testing plays a critical role in understanding how materials behave under cyclic loading, which is vital for industries such as aerospace, automotive, and construction. One of the most widely used tools to represent fatigue data is the S-N curve, also known as the Wöhler curve.[\[7\]](#)

On this basis we can plot the S-N diagram for that particular material. Basically, this is rotating beam type machine in which load is applied in reverse bending direction.[\[5\]](#)

An S-N curve represents the relationship between the stress amplitude (S) applied to a material and the number of cycles to failure (N) it can endure under cyclic loading. The curve provides insights into a material's fatigue life and is commonly used to design components that experience repeated loads over time.

- **Stress Amplitude (S):** The maximum stress a material experiences during a single cycle.
- **Number of Cycles (N):** The total number of cycles a material can withstand before failing.

The S-N curve typically has two distinct regions:

1. **High-Stress, Low-Cycle Region:** At high stress levels, materials fail quickly after a small number of cycles.
2. **Low-Stress, High-Cycle Region:** At lower stress levels, materials can withstand millions of cycles before failure, reaching what is often called the endurance limit.[\[6\]](#)

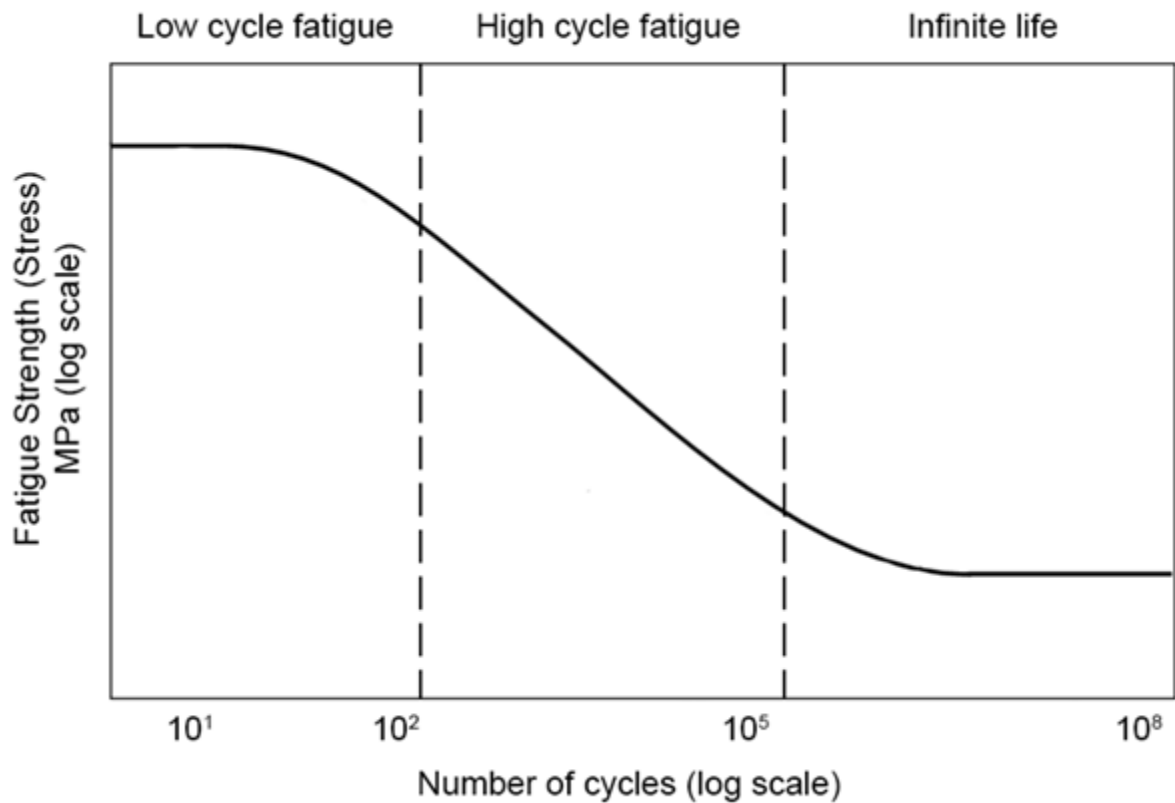


Figure IV. 1 : S-N Curve [7]

#### IV.5 Types of Fatigue Testing Machine

There are several common types of fatigue testing as well as two common forms: load controlled high cycle and strain controlled low cycle fatigue. A high cycle test tends to be associated with loads in the elastic regime and low cycle fatigue tests generally involve plastic deformations. [3]

Fatigue testing machines are designed to simulate different types of repetitive stress. Here are the main types:

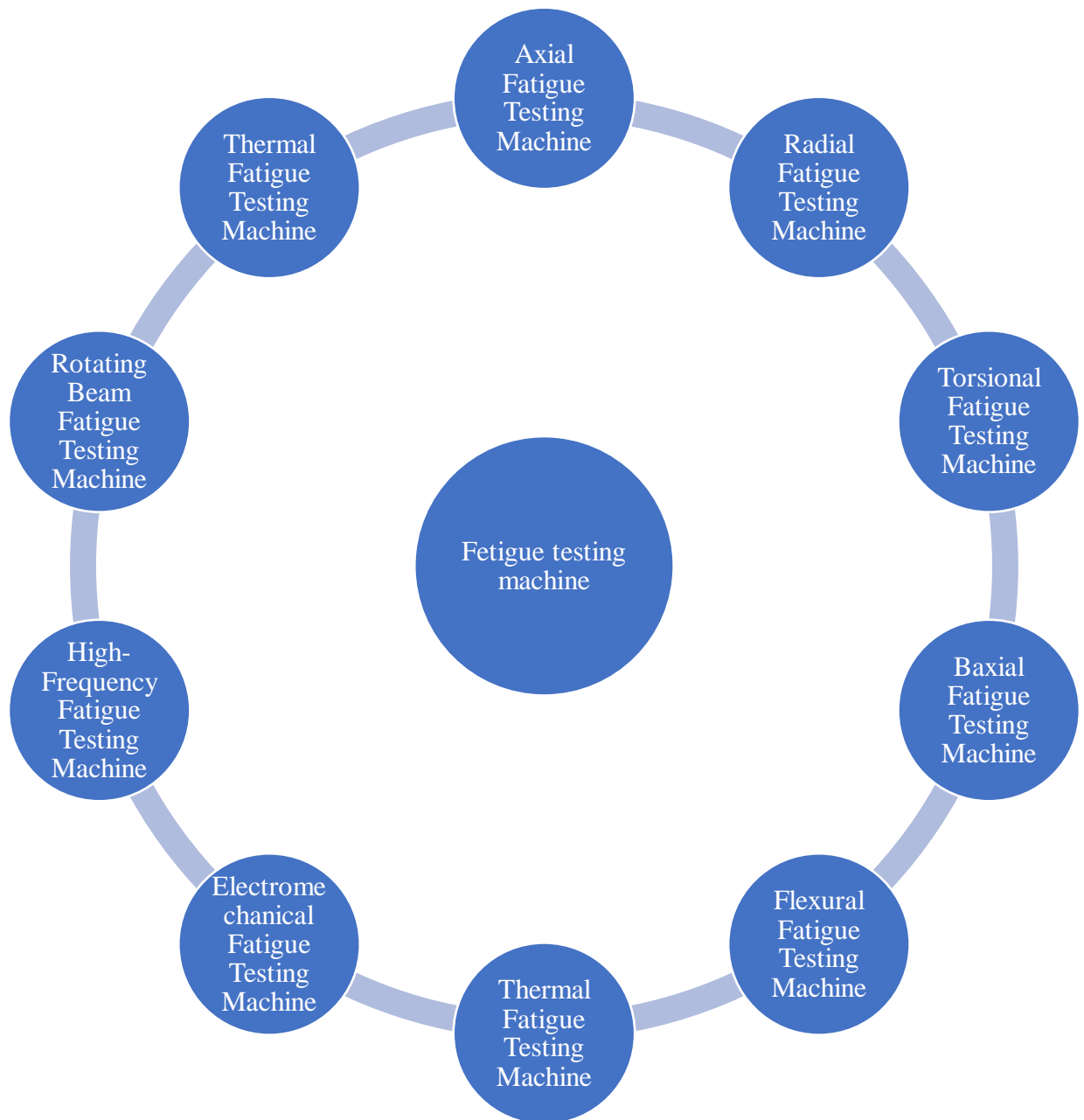


Figure IV. 2:Types of Fatigue Testing Machine

#### IV.5.1. Axial Fatigue Testing Machines:

These apply a direct compressive or tensile load on the material.[\[7\]](#)

Axial fatigue testing machine helps determine the fatigue strength of materials. In this test, the load that applies along the sample axis then compares results to similar samples subjected to various levels of cyclic loading (i.e., a known number of cycles). It tests the durability and strength of machine. That have metal on metal contact. It also tests the ability of a material to withstand repeated stress in the same plane.[\[2\]](#)

This machine tests the component by stretching and compressing it. It applies the load in the axial direction, and the constant load is applied repeatedly. So, the material faces consistent stretching and compression. Engineers fit the part that is under testing on the frame of these machines. The actuator, which is the main component, stretches and compresses the part. This stretching is not sudden. It is gradual over time. This way, the machine tests how many cycles a material can handle before it fails. If the product does not break in the first cycle, it undergoes many repeated cycles.[\[9\]](#)



Figure IV. 3: Axial Fatigue Testing Machine [\[10\]](#)

#### IV.5.2. Radial Fatigue Testing Machine

Radial fatigue testing is crucial because of its stress due to rotation motion. [\[9\]](#). Radial fatigue testing is a non-destructive technology that effectively evaluates the material's mechanical properties under test. Results are a reflection of the inner and outer structure and surface conditions. It is an electrically driven fatigue testing machine that simulates the load forces that a wheel experiences while cornering on the road. It uses a horizontally moving carriage to create radial and tangential stress, replicating stresses during use.[\[2\]](#)



Figure IV. 4: Radial Fatigue Testing Machine [\[11\]](#)

### IV.5.3. Torsional Fatigue Testing Machines

These machines twist the material to simulate shear stresses.[\[8\]](#) Torsional fatigue testing machines are valuable in prompting real-life service requirements and checking product grade for products. It can avoid the influence of other factors on testing and obtain a more accurate result. The main feature is that it can test two sides of the same sample simultaneously by using a high-precision electric system and control system, which greatly shortens the time for loading and unloading samples and reduces labor intensity. It performs a torsion test on a material sample after being subjected to a specified level of cyclic loading.[\[3\]](#)

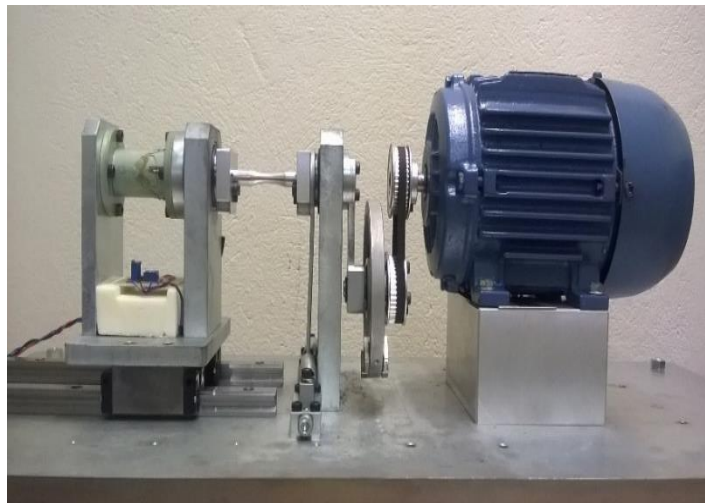


Figure IV. 5: Torsional Fatigue Testing Machine [\[12\]](#)

### IV.5.4. Biaxial Fatigue Testing Machines

Biaxial test systems measure both force and torque simultaneously, enabling them to test the mechanical properties of twist-and-push devices.[\[13\]](#) In the above section, we discussed axial fatigue testing machines. However, this biaxial machine is different as it applies force in two directions. This machine is suitable for parts and components that undergo high pressure in the real world. So, they are tested in these machines at very high pressure. So, the engineers know how a component will behave under high pressure. This machine lets the material undergo different levels of stress. Those include axial, torsional (twisting), and bending loads. The operator of the machine applies the stress in periodic cycles. If a product passes one cycle, it undergoes a second and the process goes on. Many believe a biaxial fatigue testing machine is better than a uniaxial one. The reason is that it puts stress on every side of the component. Remember that a component face loads and pressure from each side when used in the real world. Furthermore, the machine can test multiple materials at once.[\[9\]](#)

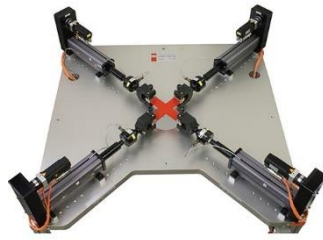


Figure IV. 6: Biaxial Fatigue Testing Machine [14]

#### IV.5.5. Flexural Fatigue Testing Machines

Designed for bending forces, these are ideal for materials used in beams or similar structures. [7]

The flexural fatigue test is performed by placing a beam of HMA in repetitive four-point loading at a specified strain level. During the test, the beam is held in place by four clamps and a repeated haversine (sinusoidal) load is applied to the two inner clamps with the outer clamps providing a reaction load. The load rate is variable but is normally set at 1 to 10 Hz. This setup produces a constant bending moment over the center portion of the beam (between the two inside clamps). The deflection caused by the loading is measured at the center of the beam. The number of loading cycles to failure can then give an estimate of a particular HMA mixture's fatigue life. Another important value that can be obtained from the beam fatigue test is the dissipated energy of the specimen. Dissipated energy is a measure of the energy that is lost to the material or altered through mechanical work, heat generation, or damage to the sample. [15]



Figure IV. 7: Flexural Fatigue Testing Machine [15]

### IV.5.6. Thermal Fatigue Testing Machines

The fatigue behavior of materials and components undergoing thermal cycling is assessed using thermal fatigue testing devices. In the real world, a component can face different loads and stresses. The stress can be simple load, pressure, or high temperature. This machine checks the material by exposing it to high and low temperatures. The product behaves differently when undergoing such temperature changes. Keep in mind that this temperature change simulates real-world conditions. Under such extreme temperatures, components can either crack or deform. Sensors in these high-quality fatigue testing machines detect the component's behavior. If it cracks, it indicates it is unsuitable for use, and vice versa. [9]



Figure IV. 8: Thermal Fatigue Testing Machine [16]

### IV.5.7. Electromechanical Fatigue Testing Machines

Electromechanical Testing Machines: These machines use electric motors to drive the crosshead, providing precise control over the speed and displacement during testing. Electromechanical testing machines are highly accurate and suitable for tests that require precise control over the testing parameters. [17]. This type of fatigue testing machine is different from other types. An electric motor applies the load to the component. What makes this machine stand out is its control. The operator can apply the load with precise control. This machine is typically used in metal and composite components. The servo-hydraulic system made the testing easy and precise. The load checks the durability of the metal. You might wonder if this load breaks the component or not. The machine contains a sensor. This sensor detects the conditions of the component when it passes the load. These sensors detect if the component is deformed or not. [9]



Figure IV. 9: Electomechanical Fatigue Testing Machine [18]

**IV.5.8. High-Frequency Fatigue Testing Machines**

These fatigue-testing machines are very efficient. The reason is that they apply loads at high frequency. Usually, the material faces hundreds to thousands of cycles of loads per minute. Such high frequencies make the test reliable. It checks how a component will behave when it faces high-frequency stress. These machines are expensive as opposed to simple fatigue testing machines. The reason is that they require more complex and precise sensors. Small lags of error can affect the reliability of these testing machines. More sophisticated and high-quality sensors are used in these machines. These sensors track the behavior of the material and check for fatigue. The aerospace industry uses this type of machine, and its primary reason for its usage is its quick speed. Reliability and quick speed are the significant features of this fatigue testing machine.[19]

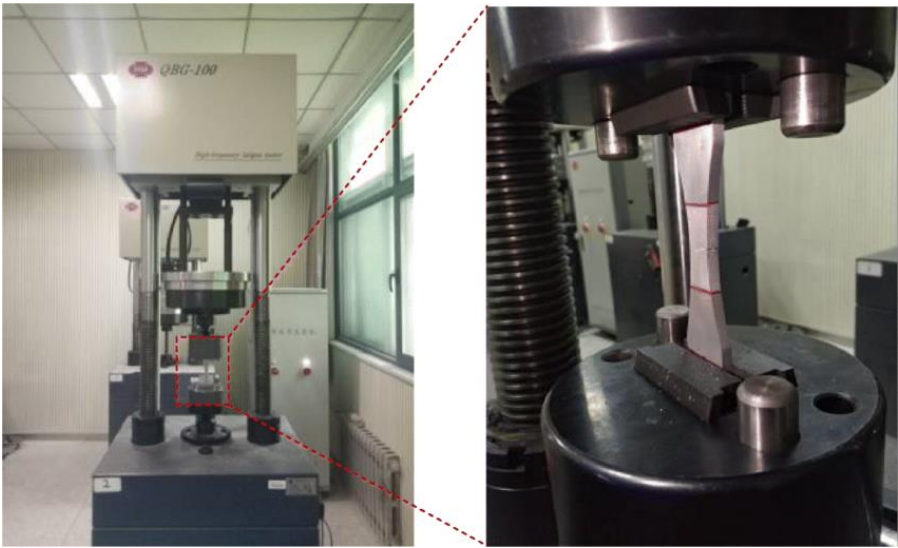


Figure IV. 10: Hight Fatigue Testing Machine [19]

### IV.5.9. Corrosion Fatigue Testing Machines

These machines are very costly as well. The reason is that they have dedicated corrosion chambers. The component under test goes in these chambers. The operator analyzes how a product will behave when it goes to a rusty environment. It is not just about corrosion testing. Instead, the component also faces high mechanical stress. The sensor detects how the product behaves when it faces a load with a rusty environment. Usually, marine products or components undergo this type of testing. The reason is that those parts remain in such conditions in real life. For example, some components of vessels and boats. They remain in salty water. The chances of rust are high. So, such testing tells how long a component will last without getting rusty.[\[9\]](#)

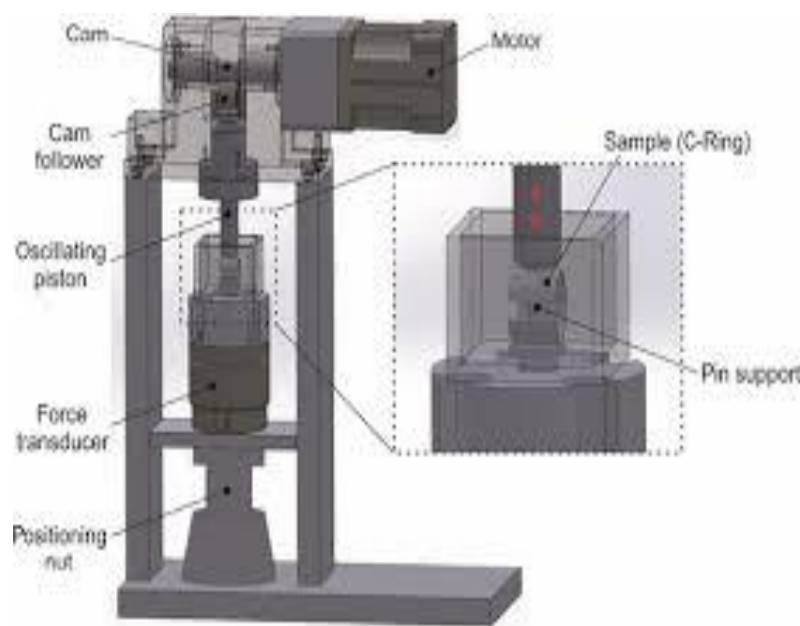


Figure IV. 11:Corrosion Fatigue Testing Machine [\[20\]](#)

### IV.5.10. Rotating Beam Fatigue Testing Machine

A rotating-beam fatigue testing machine facilitates testing of materials to generate the S-N curve from which one can determine endurance limit. It uses beams to conduct stress tests and other types of mechanical testing. These beams rotate several times and attach shafts at opposing ends with a clamped workpiece placed in the center. The rotating beam fatigue testing machine is a similar apparatus but serves a different purpose. The beam or equivalent device turns until one end inevitably fails due to excessive vibration, stress, or other damaging force. [\[2\]](#)



Figure IV. 12:Rotating bending Fatigue Testing Machine

#### IV.6. Advantages and Challenges of Fatigue Testing

##### Advantages :

- Provides a comprehensive understanding of material behavior under real-world conditions.
- Helps improve safety and reliability in critical applications.
- Supports cost-effective material selection and design optimization.

##### Challenges :

- Time-intensive for high-cycle tests that require millions of cycles.
- Variability in results due to factors like surface finish, temperature, and environmental conditions.
- Testing non-metallic materials, such as composites, requires specialized equipment and methods.[\[21\]](#)

#### IV.5 Mechanical Assembly Report

**Project Title:** Mechanical Assembly of Fatigue Testing Machine

**Full Name:** CHAABANE Djihad / Khedimi Abderrahmane

**Department:** Mechanical Engineering

**Academic Year:** second Year Master's

**Institution:** University of Hassiba Ben Bouali Hassania Chlef

**Date :** 15/06/ 2025

## 1. Introduction

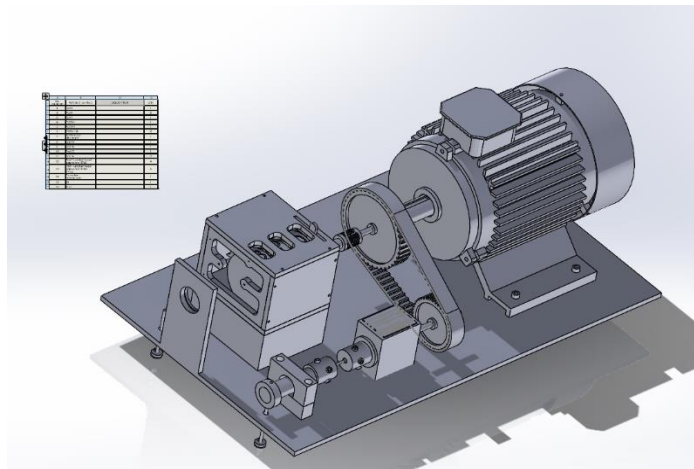
This report presents the stages of design and assembly of the project "Fatigue Testing Machine " using SolidWorks. It includes illustrations, a bill of materials (BOM), and a brief analysis of mechanical components.

### 1. Assembly Overview

The mechanical system comprises several components that were modeled and assembled in SolidWorks. The aim was to ensure fit, function, and ease of manufacturing. The following sections provide detailed views of the assembly.

This report provides an overview of the design and assembly of a fatigue testing machine. It includes structural analysis, bill of materials, and key mechanical properties. The purpose of this project is to integrate it as part of the graduation thesis.

### 2. Isometric View of the Assembly (Assembly Image)



**Figure IV. 13:Assembly of Rotating Bensing HI-TECH (Fatigue Testing Machine)**

### 3. Bill of Materials (BOM)

S	NUMERO DE PIECE	QTE
1	Part2	1
2	Part3	2
3	Part4	1

4	Part5-1	1
5	Part5-2	1
6	Disk	2
7	electric motor	1
8	part10	1
9	Part12	1
10	Part13	1
11	Part15	2
12	socket head cap screw 4762	4
13	socket head cap screw 4762 - Copy	6
14	Mechanical counter	1
15	Pull with a belt (assembly)	1
16	Part1	1

Table IV. 1:Bill of Material (BOM)

Some Part of Machine

- mechanical counter

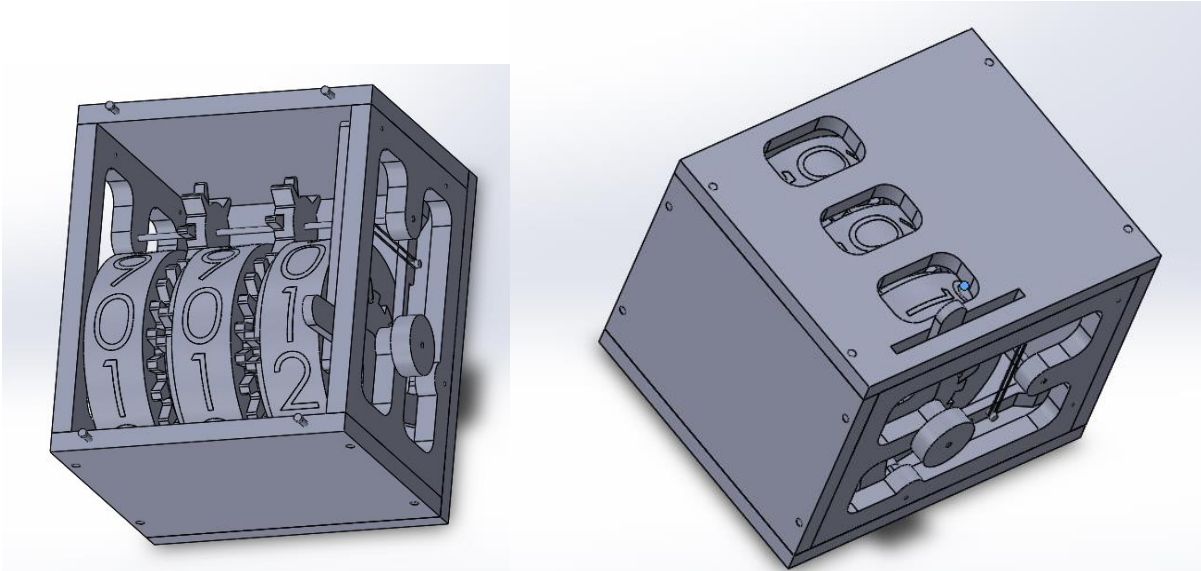


Figure IV. 14:Mechanical Counter

- Electric motor

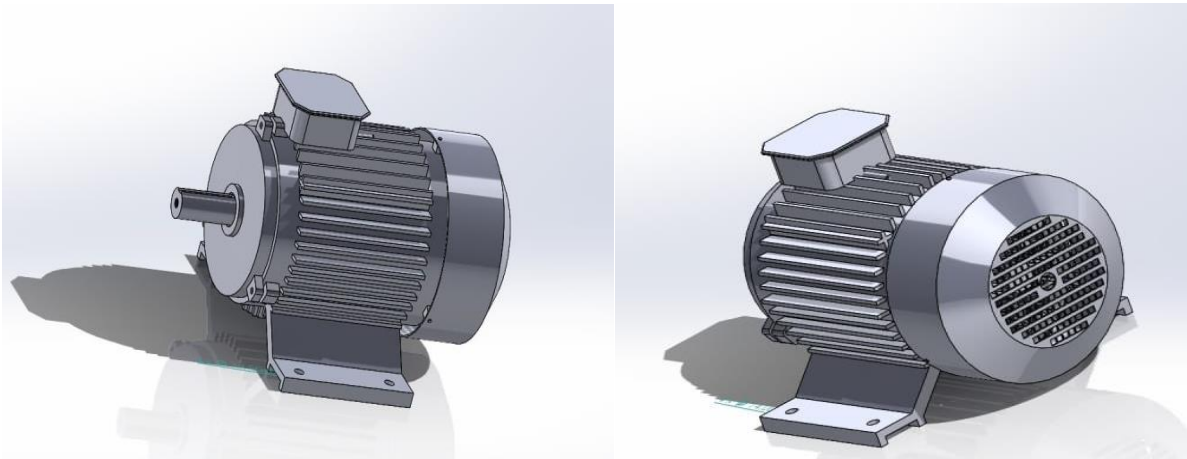


Figure IV. 15:Electric Motor

- Pulley



Figure IV. 16:Pulley and Belt

- Sample

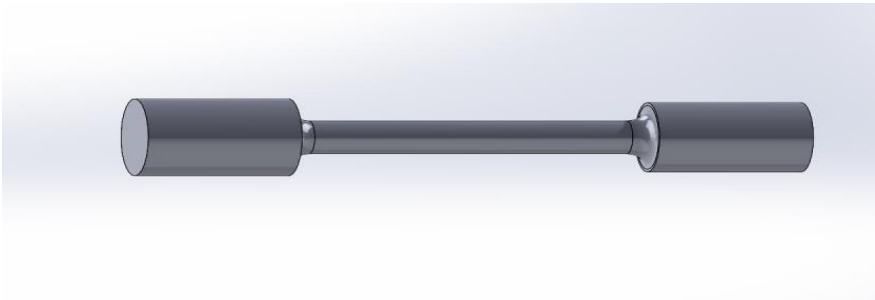


Figure IV. 17:Sample (Test Specimen)

- Socket head cap screw 4762

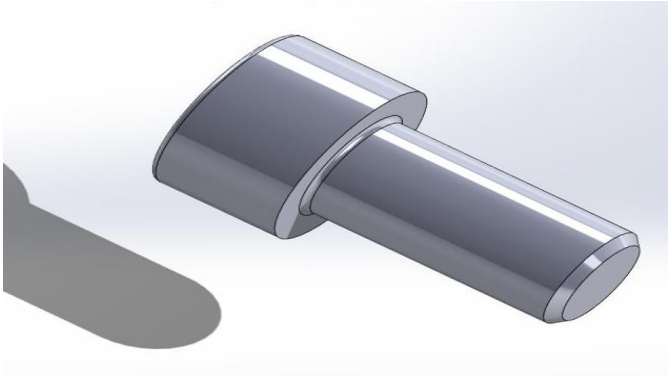


Figure IV. 18:Socket head cap screw 4762

- Table

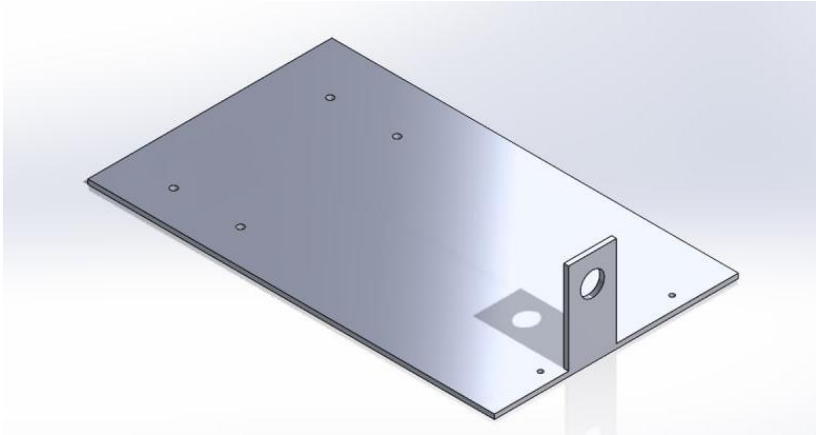


Figure IV. 19:Table (Base Frame)

- Disk

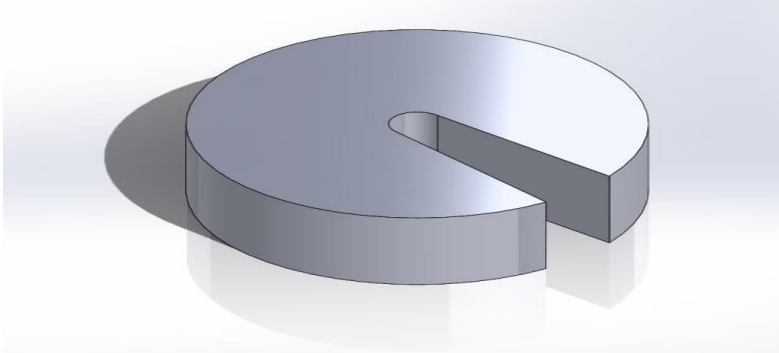


Figure IV. 20:Disk

#### 4. Materials and Physical Properties

##### Material used : Steel

The main structural and functional components of the fatigue testing machine are primarily made from Steel. Steel is selected for its mechanical robustness, resistance to cycle loading, and ease of machining, which are essential characteristics for fatigue testing equipment

- **Physical and mechanical Properties of steel**

Property	Typical Value
Density	7850 Kg/m <sup>3</sup>
Young's modulus	210 GPA
Poisson's Ratio	0.3
Yield Strength	250MPA (mild steel)
Ultimate Tensile Strength	400-500 MPA
Fatigue Strength (approx.)	50% of UTS
Hardness (Brinell)	120-180 HB
Thermal Conductivity	45-60 W/m. K
Melting Point	1425-1540 °C

**Table IV. 2:Physical & Mechanical Properties**

#### 5. Assembly Steps

##### Assembly Steps of the Fatigue Testing Machine HI-TECH

The following steps describe the sequential assembly process of the fatigue testing machine, integrating mechanical and electrical components to create a functional testing system:

##### 1. Mounting the Support Table (Base Frame)

Begin by placing the fabricated steel table on a leveled working surface.

##### 2. Installing the Electric Motor

Position the electric motor on the designated mounting plate on the table.

Align the motor shaft with the axis of the pulley system.

Fix the motor using DIN 4762 socket head cap screws for reliable and strong attachment.

##### 3. Pulley and Belt System Setup

Attach the first pulley to the motor shaft.

Fix the second pulley on the shaft of the driven component (e.g., rotating support for the specimen).

Loop the belt around both pulleys, adjusting tension as necessary to avoid slippage.

#### **4. Sample (Test Specimen) Mounting**

Position the sample (specimen) horizontally or vertically depending on design.

Ensure alignment along the load axis to prevent bending stress.

#### **5. Installing the Mechanical Counter**

Fix the mechanical counter to the frame near the rotating part.

Connect it mechanically to the rotating shaft or the pulley system to count cycles.

Test for correct engagement and reset capability.

#### **6. Final Assembly and Fastening**

Double-check all joints and fasteners, especially those holding:

Motor base, Pulleys, Frame elements, Specimen holders, all screws and bolts should follow DIN 4762 specifications, ensuring torque-tightened fitting.

The machine was successfully designed and assembled using SolidWorks. This process enables understanding of the mechanical interactions between components and validation. This mechanical assembly project improved understanding of 3D modeling, component interfacing, and assembly documentation. Further improvements can be made by integrating simulation and material optimization.

The fatigue testing machine assembly provides an effective representation of mechanical integration and component interaction. Further testing and optimization may be performed in the future to improve its performance and validate its accuracy.

Relevance to Fatigue Testing Application:

Fatigue testing machines are used to simulate cyclic loads on specimens to evaluate their resistance to material fatigue, which is a major cause of failure in mechanical parts. Steel's ability to withstand high-cycle loading, combined with its consistent elastic behavior, makes it a suitable choice for the frame, load arms, and test fixtures.

#### **Interpretation**

The Assembly Process in SolidWorks was successfully completed, and all components were properly constrained and positioned. However, when attempting to perform a motion simulation or test the assembly's movement, the system was unable to handle the computational load. This likely stems from hardware limitations, such as insufficient RAM or Processing power, which prevented the full assembly from moving smoothly.

Despite this issue, each component was tested individually and responded correctly to motion commands. This confirms that the problem isn't related to the assembly constraint or design errors, but to the performance capabilities of the computer used.

**Note: that my computer is too weak (My Computer is core i7 8<sup>th</sup> Gen)**

#### **IV.6 Conclusion**

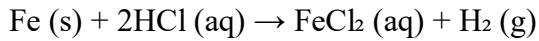
In conclusion, fatigue testing is an essential part of mechanical engineering since it establishes whether a structural and mechanical component can withstand repeated, cyclic loads safely and reliably. By employing fatigue testing machines, particularly the rotating bending type, engineers can replicate the real-world types of loading and acquire useful data on material endurance.

This chapter has emphasized the importance of understanding fatigue behavior, the working principles of fatigue machines, and the relationship of S-N curves to predict material life.

**Chapter 05: Simulation & Results**

## Introduction

In corrosive industrial environments, steel is frequently exposed to reactive substances that threaten its structural integrity. One such aggressive interaction involves liquid hydrogen chloride (HCl), which reacts chemically with steel as follows:



This reaction leads to the formation of ferrous chloride and hydrogen gas, initiating localized corrosion that compromises the steel surface over time.

In this study, the material's response to mechanical fatigue under rotational stress was also investigated. A steel specimen was mounted on a rotational stress testing machine, where a constant load was applied via a suspended weight. The specimen was then rotated at 2870 revolutions per minute (RPM), inducing cyclic torsional deformation. With continued rotation, the material experienced progressive fatigue and eventually fractured. The machine automatically recorded the number of stress cycles until failure, enabling direct insight into the fatigue resistance of the corroded material.

This combined chemical and mechanical analysis aims to explore how corrosion due to HCl exposure deteriorates the mechanical performance of steel structures. As corrosion progresses, it leads to a measurable reduction in strength, ductility, and fatigue life, which are all critical for maintaining structural reliability. To further assess this degradation, we employed ANSYS Fluent 2021 R1 to simulate the flow, heat transfer, and chemical reactions occurring near the steel surface. The simulation helps pinpoint regions of intensified degradation and provides a predictive understanding of material failure in real-world conditions.

- **Rapport 1 :**

### System Information

<b>Application</b>	<b>Fluent</b>
<b>Setting</b>	<b>3d, double precision, Pressure-based, species, SST K-omega</b>
<b>Version</b>	<b>21.1.0-10179</b>
<b>Source Revision</b>	<b>49a2c352da</b>
<b>Build Time</b>	<b>Nov 20 2020 15:49:32 EST</b>

<b>CPU</b>	<b>Intel(R) Core (TM) i7-78665U</b>
<b>OS</b>	<b>Windows</b>

Table V. 1: System Information

- Geometry and Mesh
- Mesh Size

<b>Cells</b>	<b>Faces</b>	<b>Nodes</b>
<b>38096</b>	<b>121441</b>	<b>23935</b>

Table V. 2: Mesh Size

- Mesh Quality

<b>Name</b>	<b>Type</b>	<b>Min Orthogonal Quality</b>	<b>Max Aspect Ratio</b>
<b>Fluid-zone</b>	<b>Mixed cell</b>	<b>0.0010565092</b>	<b>2058.9063</b>
<b>Solid-zone</b>	<b>Mixed Cell</b>	<b>0.16005915</b>	<b>37.110682</b>

Table V. 3: Mesh Quality

- Orthogonal Quality

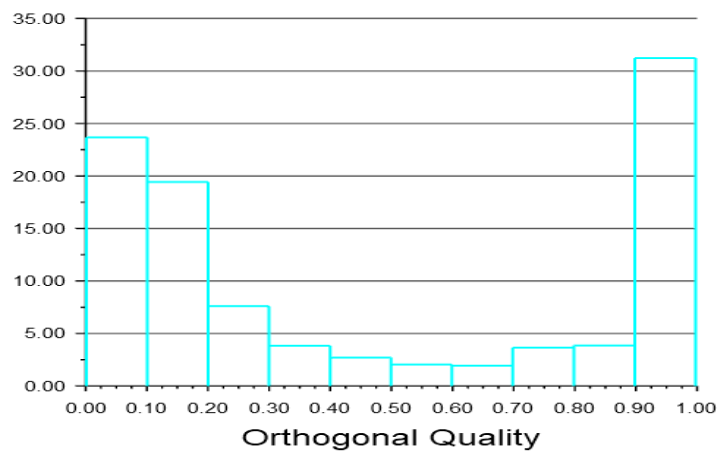


Figure V. 1: Orthogonal Quality

### Interpretation (Mesh Quality Analysis – Orthogonal Quality)

The graph above represents the distribution of Orthogonal Quality for the mesh elements used in the simulation. Orthogonal quality is a critical indicator of mesh health, with values ranging between 0 (poor quality) and 1 (excellent quality)

#### From the histogram:

A large number of elements fall within the 0.0–0.2 range, which indicates very poor mesh quality. This can negatively impact the accuracy and convergence of the numerical simulation. A smaller portion of elements have orthogonal quality in the range of 0.9–1.0, representing very high-quality cells, which is a positive aspect. However, the dominance of low-quality elements (<0.3) is a concern and suggests that the mesh needs significant improvement.

- **Simulation Setup**
- **Physics**
- **Models**

<b>Model</b>	<b>Setting</b>
<b>Space</b>	<b>3D</b>
<b>Time</b>	<b>Steady</b>
<b>Viscous</b>	<b>SST K-Omega turbulence model</b>
<b>Heat Transfer</b>	<b>Enabled</b>
<b>Species</b>	<b>Reacting</b>

**Table V. 4:Model**

- **Material Properties**

Fluid	
water-liquid	

Density	998.2 kg/m <sup>3</sup>
Cp (Specific Heat)	4182 J/(kg K)
Thermal Conductivity	0.6 W/(m K)
Viscosity	0.001003 kg/(m s)
Molecular Weight	18.0152 kg/kmol
Standard State Enthalpy	-2.8584122e+08 J/kgmol
Standard State Entropy	69902.211 J/(kgmol K)
Reference Temperature	298 K
Thermal Expansion Coefficient	0
Speed of Sound	None
ferro-chloride	
Density	3160 kg/m <sup>3</sup>
Cp (Specific Heat)	600 J/(kg K)
Thermal Conductivity	1.2 W/(m K)
Viscosity	0.0001 kg/(m s)
Molecular Weight	126.75 kg/kmol
Standard State Enthalpy	-340000 J/kgmol

Standard State Entropy	123 J/(kgmol K)
Reference Temperature	298 K
Thermal Expansion Coefficient	0
Speed of Sound	None
hydrogen-chloride	
Density	1 kg/m <sup>3</sup>
Cp (Specific Heat)	Polynomial
Thermal Conductivity	0.0454 W/(m K)
Viscosity	1.72e-05 kg/(m s)
Molecular Weight	36.46097 kg/kmol
Standard State Enthalpy	-92320736 J/kgmol
Standard State Entropy	186797.8 J/(kgmol K)
Reference Temperature	298 K
Thermal Expansion Coefficient	0
Speed of Sound	None
— hydrogen	
Density	0.08189 kg/m <sup>3</sup>

Cp (Specific Heat)	Polynomial
Thermal Conductivity	0.1672 W/(m K)
Viscosity	8.411e-06 kg/(m s)
Molecular Weight	2.01594 kg/kmol
Standard State Enthalpy	0
Standard State Entropy	130579.06 J/(kgmol K)
Reference Temperature	298.15 K
Thermal Expansion Coefficient	0
Speed of Sound	none
— Solid	
— steel	
Density	8030 kg/m <sup>3</sup>
Cp (Specific Heat)	502.48 J/(kg K)
Thermal Conductivity	16.27 W/(m K)
— Mixture	
— mixture-template	
Mixture Species	names

Reaction	finite rate
Mechanism	reaction mechs
Density	incompressible ideal gas
Cp (Specific Heat)	mixing law
Thermal Conductivity	0.0454 W/(m K)
Viscosity	1.72e-05 kg/(m s)
Mass Diffusivity	Constant dilute appx
Speed of Sound	None

Table V. 5:Material Proprieties

- Plot



Figure V. 2:Plot

## Overview of the Graph

This graph shows **residual values** (the numerical differences between two successive iterations) for key variables across **16 iterations**. It's on a **logarithmic scale** ranging from  $10^{-6}$  to  $10^{12}$  which magnifies the huge dynamic range in convergence behavior.

## Key Observations and Interpretation

### 1. Species: $H_2$ , $HCl$ , and $FeCl_2$ – Varied Convergence

- **Trend :**
  - $H_2$  drops to around  $10^{-6}$  → **converged well.**
  - $HCl$  and  $FeCl_2$  stabilize higher  $10^{-3}$  to  $10^{-1}$  → **converged well.**
  -
- **Cause :**
  - $H_2$  is a lighter molecule and possibly more uniformly distributed.
  - $HCl$  and  $FeCl_2$  are directly tied to the **corrosion reaction** on the surface.
- **Interpretation:**  $H_2$ /  $HCl$ / $FeCl_2$  predictions are reliable

- **Contour**

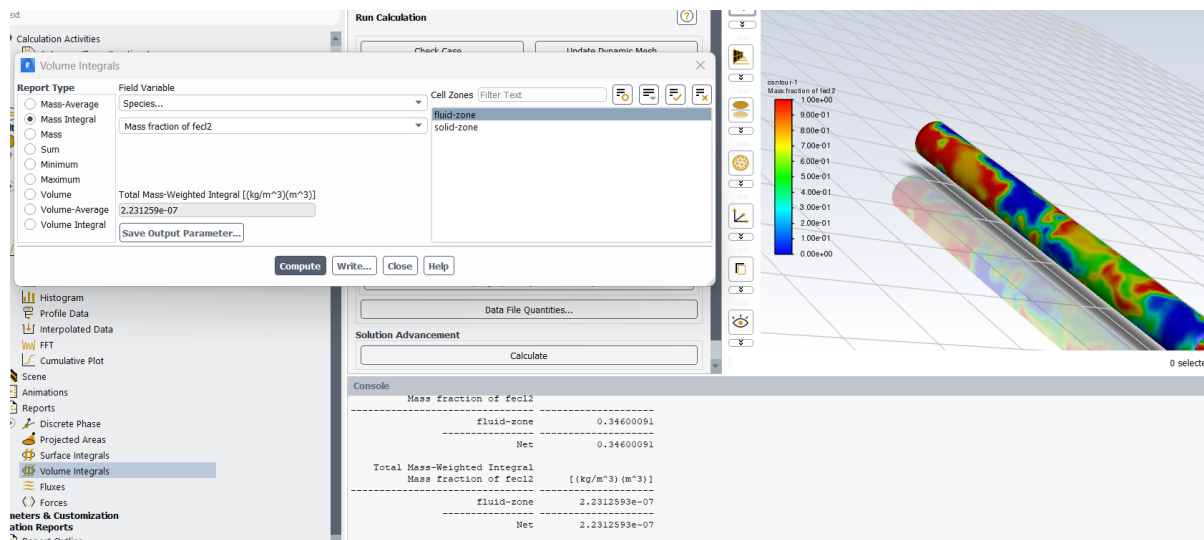


Figure V. 3:Contour

- Interpretation contour

The figure presents the results of a corrosion simulation in ANSYS Fluent, focusing on the formation and distribution of ferrous chloride ( $\text{FeCl}_2$ ) as a product of the chemical interaction between hydrochloric acid (HCl) and a steel surface. A volume integral was performed over the solid zone to calculate the total mass of  $\text{FeCl}_2$  accumulated within the steel, yielding a mass-weighted integral value of approximately  $2.22 \times 10^{-7}$  kg. This value quantifies the extent of corrosion product retained inside the solid domain. Additionally, a surface integral was carried out over the fluid zone to determine the average mass fraction of  $\text{FeCl}_2$ , which was found to be around 0.0172. This indicates that approximately 1.72% of the fluid composition consists of  $\text{FeCl}_2$ , suggesting the diffusion of corrosion products into the surrounding medium. The contour plot on the right visualizes the spatial distribution of  $\text{FeCl}_2$  across the cylindrical geometry or reaction surface, with red regions highlighting areas of higher concentration and thus more severe localized corrosion, while blue areas correspond to regions with minimal concentration of  $\text{FeCl}_2$ . These results collectively demonstrate the non-uniform nature of the corrosion process and provide insights into the zones most affected by chemical degradation.

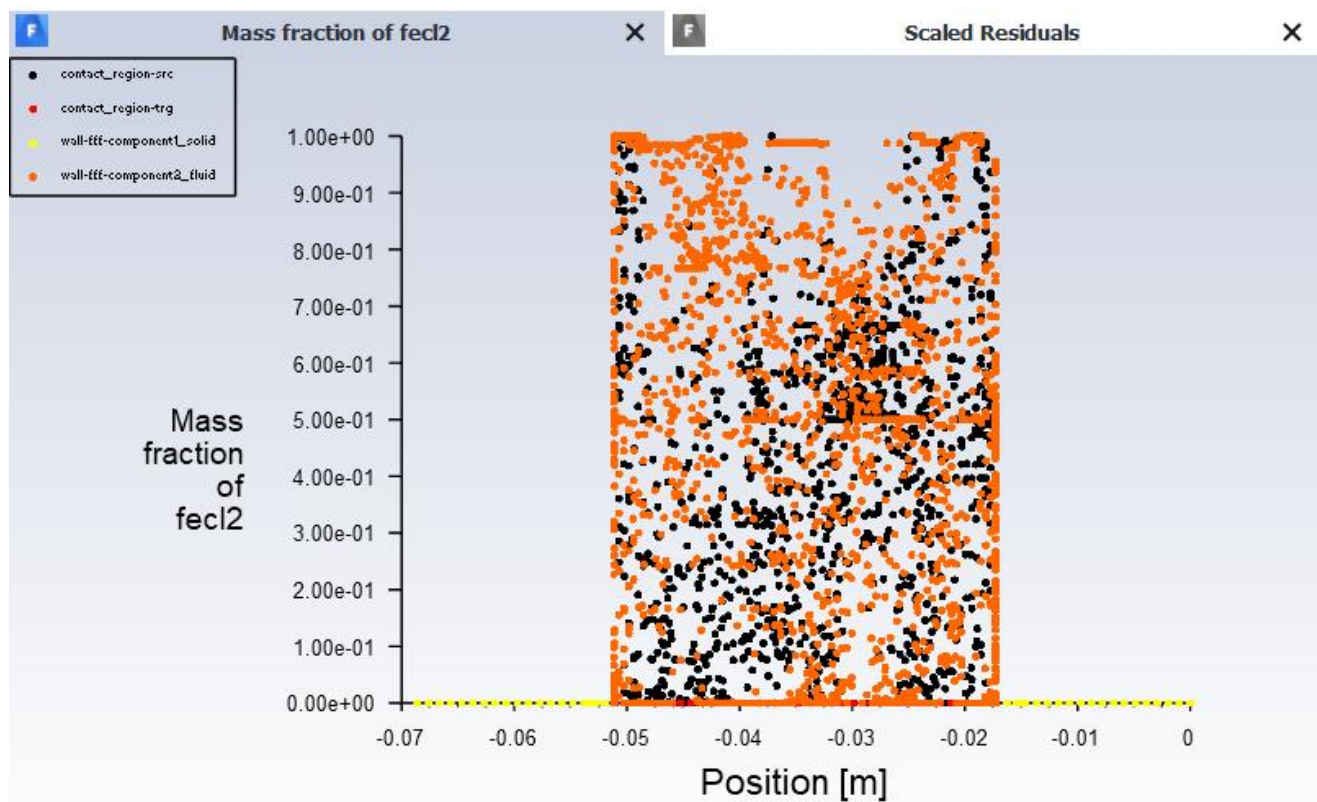


Figure V. 4: Mass fraction of  $\text{FeCl}_2$

## Interpretation

The graph illustrates the mass fraction distribution of  $\text{FeCl}_2$  as a function of position along the surface of a corroded structure. Multiple wall and contact regions are represented, including contact region-arc

contact region-trig,

component1\_solid,

component2\_fluid.

The x-axis denotes the position in meters, while the y-axis quantifies the mass fraction of  $\text{FeCl}_2$ , ranging from 0 to 1.

The data reveal significant spatial variation in  $\text{FeCl}_2$  concentration across the surface. High mass fraction values (close to 1.0) are observed in certain localized regions, indicating intense corrosion and accumulation of  $\text{FeCl}_2$  in those areas. These peaks are more prominent in both the contact\_region-arc and contact\_region-trig zones, suggesting that geometrical or contact conditions strongly influence the corrosion behavior. Meanwhile, lower mass fractions are scattered throughout other regions, particularly near the edges, where corrosion appears minimal or absent.

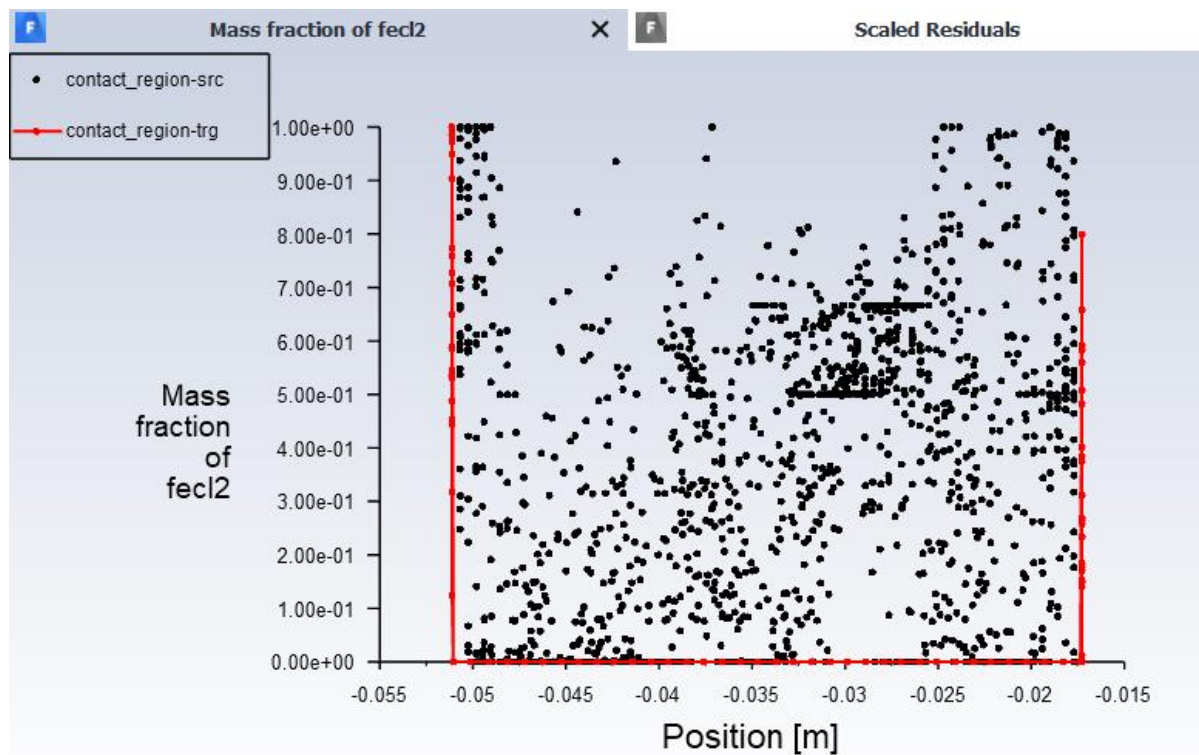


Figure V. 5: Mass Fraction of  $\text{FeCl}_2$

This one here its only for the contact region

### Interpretation

The figure displays the mass fraction of  $\text{FeCl}_2$  as a function of spatial position along two designated contact regions: `contact_region-src` and `contact_region-trg`. The x-axis represents the position in meters, while the y-axis indicates the mass fraction of  $\text{FeCl}_2$ , ranging from 0 to 1.0. The data correspond to corrosion product formation along the interface between two components, possibly steel in contact with a reactive fluid.

The black data points represent the `contact_region-src`, while the red curve outlines the boundary of `contact_region-trg`. The plot reveals a non-uniform distribution of  $\text{FeCl}_2$  mass fraction along the interface. The values show considerable scattering, with localized peaks reaching up to 0.9 or higher. These peaks are evidence of intense localized corrosion activity in certain areas of the contact surface.

In contrast, large regions along the position axis show very low or near-zero mass fractions, suggesting areas that experienced minimal reaction or were less exposed to the corrosive agent. The asymmetry and irregularity in the distribution imply that corrosion is strongly dependent on local geometry, contact behavior, or possibly flow and concentration gradients of the reactive species (HCl).

This plot supports the observation that corrosion is highly localized and likely governed by complex surface interactions, rather than uniform chemical exposure across the interface.

- **Interpretation Rapport 01**
- Why use a mixture-template?

It allows multi-species interactions and reactions. Fluent blends species based on mole/mass fractions for mixed-phase behavior.

#### 4. Cell Zones & Rotation

- Why define motion (300.54 rad/s) in both fluid and solid zones?

The system involves a rotating frame (like a spinning reactor). Specifying motion replicates centrifugal and Coriolis effects that alter flow paths and enhance mixing or surface interaction.

- Why use relative reference frames?

This simplifies rotating machinery modeling it removes the need to solve full transient motion and focuses on behavior in the rotating space.

### 5. Boundary Conditions

- Why apply "heat flux0" (adiabatic) walls?

These simplify the problem by assuming no external heat transfer. It's common when testing internal effects only, though you might replace this with convective losses in future studies.

- Why assign "coupled" thermal interfaces between steel and fluid?

These allow heat exchange across solid-fluid boundaries, reflecting physical reality-important if heat generated by reaction affects steel temperature.

- Why activate surface reactions wall-fff-component2\_fluid?

To model corrosion at that steel surface-this simulates chemical degradation ( $\text{Fe} + \text{HCl} \rightarrow \text{FeCl}_2 + \text{H}_2$ ) realistically.

### 6. Solver Configuration

- Used the SIMPLE algorithm for pressure-velocity coupling
- Discretization schemes were set to second-order upwind, improving accuracy for transport equations.
- Appropriate under-relaxation factors were applied to stabilize convergence.

### 7. Results Summary

Simulation converged in approximately 16 iterations, though initial residuals were high ( $\sim 10^{-10}$ ), indicating strong initial imbalances.

Final residuals reached acceptable thresholds (Reaction rate contours showed intensities up to 7.02  $10 \text{ kgmol/m}^3$  suggesting high localized activity potentially tied to boundary layer effects or turbulence-induced mixing

## Rapport 02:

- Units

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Table V. 6:Model (B3)

- Geometry

Object Name	<i>Geometry</i>
State	Fully Defined
<b>Definition</b>	
Source	C:\Users\djiha\Downloads\flexural test algeria\fluxrual test algeria_files\dp0\FFF\DM\FFF.scdoc
Type	SpaceClaim
Length Unit	Meters
<b>Bounding Box</b>	
Length X	6,86e-002 m
Length Y	8,7e-003 m
Length Z	8,7e-003 m
<b>Properties</b>	
Volume	2,1322e-006 m <sup>3</sup>
Scale Factor Value	1,
<b>Statistics</b>	
Bodies	2
Active Bodies	2
Nodes	109866
Elements	38096
Mesh Metric	None
<b>Update Options</b>	

Assign Default Material	No
<b>Basic Geometry Options</b>	
Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	Yes
Parameters	Independent
Parameter Key	
Attributes	Yes
Attribute Key	
Named Selections	Yes
Named Selection Key	
Material Properties	Yes
<b>Advanced Geometry Options</b>	
Use Associativity	Yes
Coordinate Systems	Yes
Coordinate System Key	
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Analysis Type	3-D
Mixed Import Resolution	None
Import Facet Quality	Source
Clean Bodies On Import	No
Stitch Surfaces On Import	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	No

Table V. 7:Model (B3) &gt; Geometry

Object Name	<i>FFF</i>
State	Meshed
<b>Graphics Properties</b>	
Visible	Yes
<b>Definition</b>	
Suppressed	No
Assignment	
Coordinate System	Default Coordinate System
<b>Bounding Box</b>	
Length X	6,86e-002 m
Length Y	8,7e-003 m
Length Z	8,7e-003 m
<b>Properties</b>	
Volume	2,1322e-006 m <sup>3</sup>
<b>Statistics</b>	
Nodes	109866
Elements	38096
Mesh Metric	None
<b>CAD Attributes</b>	
Part Tolerance:	0,00000001
Color:143.175.143	

**Table V. 8:Model (B3) > Geometry > Body Groups**

Object Name	<i>Component2\Flu id</i>	<i>Component1\Sol id</i>
State	Meshed	
<b>Graphics Properties</b>		
Visible	Yes	
Transparency	1	
<b>Definition</b>		
Suppressed	No	
Coordinate System	Default Coordinate System	
Treatment	None	
Reference Frame	Lagrangian	
<b>Material</b>		
Assignment		
Fluid/Solid	Defined By Geometry (Solid)	
<b>Bounding Box</b>		
Length X	3,384e-002 m	6,86e-002 m
Length Y	3,34e-003 m	8,7e-003 m
Length Z	3,34e-003 m	8,7e-003 m
<b>Properties</b>		
Volume	2,4028e-008 m <sup>3</sup>	2,1082e-006 m <sup>3</sup>
Centroid X	-3,42e-002 m	-3,4393e-002 m
Centroid Y	4,35e-003 m	
Centroid Z	1,5019e-019 m	-1,6302e-019 m
<b>Statistics</b>		
Nodes	62925	47045
Elements	27000	11096
Mesh Metric	None	

Table V. 9:Model (B3) &gt; Geometry &gt; FFF &gt;

Object Name	<i>Materials</i>
State	Fully Defined
<b>Statistics</b>	

Materials	0
Material Assignments	0

Table V. 10: Coordinate Systems

Object Name	<i>Connections</i>
State	Fully Defined
<b>Auto Detection</b>	
Generate Automatic Connection On Refresh	Yes
<b>Transparency</b>	
Enabled	Yes

Table V. 11: Model (B3) &gt; Connections

Object Name	<i>Contacts</i>
State	Fully Defined
<b>Definition</b>	
Connection Type	Contact
<b>Scope</b>	
Scoping Method	Geometry Selection
Geometry	All Bodies
<b>Auto Detection</b>	
Tolerance Type	Slider
Tolerance Slider	0,
Tolerance Value	1,7424e-004 m
Use Range	No
Face/Face	Yes
Face-Face Angle	75, °
Tolerance	
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No

Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
<b>Statistics</b>	
Connections	1
Active Connections	1

Table V. 12:Model (B3) &gt; Connections &gt; Contacts

Object Name	<i>Contact Region</i>
State	Fully Defined
<b>Scope</b>	
Scoping Method	Geometry Selection
Contact	1 Face
Target	3 Faces
Contact Bodies	Component2\Fluid
Target Bodies	Component1\Solid
Protected	No
<b>Advanced</b>	
Small Sliding	Program Controlled

Table V. 13:Model (B3) &gt; Connections &gt; Contacts &gt; Contact Regions

Object Name	<i>Mesh</i>
State	Solved
<b>Display</b>	
Display Style	Use Geometry Setting
<b>Defaults</b>	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Quadratic
Element Size	1,e-003 m
Export Format	Standard
Export Preview Surface Mesh	No

<b>Sizing</b>	
Use Adaptive Sizing	No
Growth Rate	Default (1,2)
Max Size	Default (2,e-003 m)
Mesh Defeaturing	Yes
Defeature Size	Default (5,e-006 m)
Capture Curvature	Yes
Curvature Min Size	Default (1,e-005 m)
Curvature Normal Angle	Default (18,°)
Capture Proximity	No
Bounding Box Diagonal	6,9695e-002 m
Average Surface Area	1,6088e-004 m <sup>2</sup>
Minimum Edge Length	1,0053e-002 m
<b>Quality</b>	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
<b>Inflation</b>	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
View Advanced Options	No
<b>Advanced</b>	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled

Topology Checking	Yes
Pinch Tolerance	Default (9,e-006 m)
Generate Pinch on Refresh	No
<b>Statistics</b>	
Nodes	109866
Elements	38096

Table V. 14:Model (B3) &gt; Mesh

Object Name	<i>Inflation</i>	
State	Fully Defined	
<b>Scope</b>		
Scoping Method	Geometry Selection	
Geometry	1 Body	
<b>Definition</b>		
Suppressed	No	
Boundary Scoping Method	Geometry Selection	
Boundary	1 Face	
Inflation Option	Smooth Transition	
Transition Ratio	Default (0,272)	
Maximum Layers	5	
Growth Rate	1,2	
Inflation Algorithm	Pre	

Table V. 15:Model (B3) &gt; Mesh &gt; Mesh Control

### The interpretation rapport 02

This ANSYS Mechanical report provides a detailed pre-processing overview of a numerical simulation model prepared using version 2021 R1 of the software. The unit system is set to Metric (meters, kilograms, seconds, Celsius), with angles in degrees and rotational velocity in radians per second. The geometry consists of two solid bodies modeled in 3D using SpaceClaim. The imported file has a bounding box of approximately 68.6 mm in the X-direction and 8.7 mm in both Y and Z, with a total volume of  $2.1322 \times 10^{-6} \text{ m}^3$ . The model comprises two components: a solid domain

(Component1) and a fluid domain (Component2). The solid domain occupies a volume of approximately  $2.1082 \times 10^{-6} \text{ m}^3$  and contains 47,045 nodes and 11,096 elements, while the fluid domain has a much smaller volume of  $2.4028 \times 10^{-8} \text{ m}^3$ , with 62,925 nodes and 27,000 elements. Both domains are fully meshed and visible in the model.

The coordinate system used is Cartesian, originating at (0, 0, 0), with standard directional vectors. Contact interactions have been automatically generated between the two components using face-to-face contact with a small sliding setting enabled, which indicates potential preparation for a fluid-structure interaction (FSI) simulation. The mesh setup uses a quadratic element order, a default growth rate of 1.2, and a minimum edge length of about 0.01 m. Curvature is captured in the mesh, and inflation layers (five layers with a smooth transition) are applied to one face, typically used to better resolve near-wall flow or stress gradients. Despite the detailed meshing and contact definition, no materials have been assigned to the components, and no loads or boundary conditions are defined, which are critical for performing any physical simulation.

Overall, this report reflects a well-prepared geometric and mesh configuration, suitable for future structural or CFD-based simulation. However, it remains incomplete from a physics standpoint due to the absence of material properties and solver settings. The project appears to be in the setup phase, likely for a simulation involving either a flexural test or a fluid-structure interaction scenario, as suggested by the combination of solid and fluid domains and the use of inflation layers in the mesh

**Rapport 03 :**

- Units

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

**Table V. 16:Model A4 / Unit**

- Geometry

Object Name	<i>Geometry</i>		
State	Fully Defined		
<b>Definition</b>			
Source	C:\Users\djiha\Downloads\flexural	test	algeria\fluxrual test

	algeria_files\dp0\SYS\DM\SYS.sdoc
Type	SpaceClaim
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
<b>Bounding Box</b>	
Length X	6,86e-002 m
Length Y	8,7e-003 m
Length Z	8,7e-003 m
<b>Properties</b>	
Volume	2,1322e-006 m <sup>3</sup>
Mass	1,6738e-002 kg
Scale Factor Value	1,
<b>Statistics</b>	
Bodies	2
Active Bodies	2
Nodes	91293
Elements	17782
Mesh Metric	None
<b>Update Options</b>	
Assign Default Material	No
<b>Basic Geometry Options</b>	
Solid Bodies	Yes
Surface Bodies	Yes
Line Bodies	Yes
Parameters	Independent
Parameter Key	

Attributes	Yes
Attribute Key	
Named Selections	Yes
Named Selection Key	
Material Properties	Yes
<b>Advanced Geometry Options</b>	
Use Associativity	Yes
Coordinate Systems	Yes
Coordinate System Key	
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	Yes
Compare Parts On Update	No
Analysis Type	3-D
Mixed Import Resolution	None
Import Facet Quality	Source
Clean Bodies On Import	No
Stitch Surfaces On Import	None
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

Table V. 17:Model (A4) &gt; Geometr

Object Name	<i>Component1\Solid</i>	
State	Meshed	
<b>Graphics Properties</b>		
Visible	Yes	
Transparency	1	
<b>Definition</b>		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default	Coordinate System
Reference Temperature	By Environment	
Treatment	None	
<b>Material</b>		
Assignment	Structural Steel	
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
<b>Bounding Box</b>		
Length X	6,86e-002 m	
Length Y	8,7e-003 m	
Length Z	8,7e-003 m	
<b>Properties</b>		
Volume	2,1082e-006 m <sup>3</sup>	
Mass	1,6549e-002 kg	
Centroid X	-3,4399e-002 m	
Centroid Y	4,3497e-003 m	
Centroid Z	-2,565e-007 m	
Moment of Inertia Ip1	1,3438e-007 kg·m <sup>2</sup>	
Moment of Inertia Ip2	1,0694e-005 kg·m <sup>2</sup>	
Moment of Inertia Ip3	1,0694e-005 kg·m <sup>2</sup>	
<b>Statistics</b>		

Nodes	48819
Elements	11388
Mesh Metric	None

Table V. 18:Model (A4) &gt; Geometry &gt; Component1 &gt; Part

Object Name	<i>Component1</i>	
State	Meshed	
<b>Graphics Properties</b>		
Visible	Yes	
<b>Definition</b>		
Suppressed	No	
Assignment	Structural Steel	
Coordinate System	Default	Coordinate System
<b>Bounding Box</b>		
Length X	6,86e-002 m	
Length Y	8,7e-003 m	
Length Z	8,7e-003 m	
<b>Properties</b>		
Volume	2,1082e-006 m <sup>3</sup>	
Mass	1,6549e-002 kg	
Centroid X	-3,4399e-002 m	
Centroid Y	4,3497e-003 m	
Centroid Z	-2,565e-007 m	
Moment of Inertia Ip1	1,3438e-007 kg·m <sup>2</sup>	
Moment of Inertia Ip2	1,0694e-005 kg·m <sup>2</sup>	
Moment of Inertia Ip3	1,0694e-005 kg·m <sup>2</sup>	
<b>Statistics</b>		
Nodes	48819	

Elements	11388
Mesh Metric	None
<b>CAD Attributes</b>	
PartTolerance:	0,00000001
Color:143.175.143	

Table V. 19:Model (A4) &gt; Geometry &gt; Body Group

Object Name	<i>Component2\Fluid</i>	
State	Meshed	
<b>Graphics Properties</b>		
Visible	Yes	
Transparency	1	
<b>Definition</b>		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default	Coordinate System
Reference Temperature	By Environment	
Treatment	None	
<b>Material</b>		
Assignment	Structural Steel	
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
<b>Bounding Box</b>		
Length X	3,384e-002 m	
Length Y	3,34e-003 m	
Length Z	3,34e-003 m	
<b>Properties</b>		
Volume	2,4028e-008 m <sup>3</sup>	

Mass	1,8862e-004 kg
Centroid X	-3,42e-002 m
Centroid Y	4,35e-003 m
Centroid Z	7,7716e-019 m
Moment of Inertia Ip1	4,9963e-010 kg·m <sup>2</sup>
Moment of Inertia Ip2	1,8159e-008 kg·m <sup>2</sup>
Moment of Inertia Ip3	1,8159e-008 kg·m <sup>2</sup>
<b>Statistics</b>	
Nodes	42474
Elements	6394
Mesh Metric	None
<b>CAD Attributes</b>	
PartTolerance:	0,00000001
Color:143.175.143	

**Table V. 20:Model (A4) > Geometry > Parts**

Object Name	<i>Materials</i>
State	Fully Defined
<b>Statistics</b>	
Materials	2
Material Assignments	1

**Table V. 21:Model (A4) > Material**

Object Name	<i>Structural Steel Assignment</i>
State	Fully Defined
<b>General</b>	
Scoping Method	Geometry Selection
Geometry	2 Bodies
<b>Definition</b>	
Material Name	Structural Steel
Nonlinear Effects	Yes
Thermal Strain Effects	Yes
Reference Temperature	By Environment
Suppressed	No

Table V. 22:Model (A4) &gt; Materials &gt; Structural Steel Assignment

- Coordinate Systems

Object Name	<i>Global Coordinate System</i>
State	Fully Defined
<b>Definition</b>	
Type	Cartesian
Coordinate System ID	0,
<b>Origin</b>	
Origin X	0, m
Origin Y	0, m
Origin Z	0, m
<b>Directional Vectors</b>	
X Axis Data	[ 1, 0, 0, ]
Y Axis Data	[ 0, 1, 0, ]
Z Axis Data	[ 0, 0, 1, ]

Table V. 23:Model (A4) &gt; Coordinate Systems &gt; Coordinate System

- Connections

Object Name	<i>Connections</i>
State	Fully Defined
<b>Auto Detection</b>	
Generate Automatic Connection On Refresh	Yes
<b>Transparency</b>	
Enabled	Yes

**Table V. 24:Model (A4) > Connections**

Object Name	<i>Contacts</i>
State	Fully Defined
<b>Definition</b>	
Connection Type	Contact

<b>Scope</b>	
Scoping Method	Geometry Selection
Geometry	All Bodies
<b>Auto Detection</b>	
Tolerance Type	Slider
Tolerance Slider	0,
Tolerance Value	1,7424e-004 m
Use Range	No
Face/Face	Yes
Face-Face Angle Tolerance	75, °
Face Overlap Tolerance	Off
Cylindrical Faces	Include
Face/Edge	No

Edge/Edge	No
Priority	Include All
Group By	Bodies
Search Across	Bodies
<b>Statistics</b>	
Connections	1
Active Connections	1

**Table V. 25:Model (A4) > Connections > Contacts**

Object Name	<i>Contact Region</i>
State	Fully Defined
<b>Scope</b>	
Scoping Method	Geometry Selection
Contact	3 Faces
Target	1 Face
Contact Bodies	Component1\Solid
Target Bodies	Component2\Fluid
Protected	No
<b>Definition</b>	
Type	Bonded
Scope Mode	Automatic
Behavior	Program Controlled
Trim Contact	Program Controlled
Trim Tolerance	1,7424e-004 m
Suppressed	No
<b>Advanced</b>	
Formulation	Program Controlled
Small Sliding	Program Controlled
Detection Method	Program Controlled
Penetration Tolerance	Program Controlled

Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Program Controlled
Update Stiffness	Program Controlled
Pinball Region	Program Controlled
<b>Geometric Modification</b>	
Contact Geometry Correction	None
Target Geometry Correction	None

**Table V. 26:Model (A4) > Connections > Contacts > Contact Regions**

- Mesh

Object Name	<i>Mesh</i>
State	Solved
<b>Display</b>	
Display Style	Use Geometry Setting
<b>Defaults</b>	
Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	1,e-003 m
<b>Sizing</b>	
Use Adaptive Sizing	No
Growth Rate	Default (1,85)
Max Size	Default (2,e-003 m)
Mesh Defeaturing	Yes
Defeature Size	Default (5,e-006 m)
Capture Curvature	Yes
Curvature Min Size	Default (1,e-005 m)
Curvature Normal Angle	Default (70,395°)
Capture Proximity	No
Bounding Box Diagonal	6,9695e-002 m
Average Surface Area	1,906e-004 m <sup>2</sup>
Minimum Edge Length	1,0053e-002 m
<b>Quality</b>	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None
<b>Inflation</b>	
Use Automatic Inflation	None
Inflation Option	Smooth Transition

Transition Ratio	0,272
Maximum Layers	5
Growth Rate	1,2
Inflation Algorithm	Pre
View Advanced Options	No
<b>Advanced</b>	
Number of CPUs for Parallel Part Meshing	Program Controlled
Straight Sided Elements	No
Rigid Body Behavior	Dimensionally Reduced
Triangle Surface Mesher	Program Controlled
Topology Checking	Yes
Pinch Tolerance	Default (9,e-006 m)
Generate Pinch on Refresh	No
<b>Statistics</b>	
Nodes	91293
Elements	17782

**Table V. 27:Model (A4) > Mesh**

Object Name	<i>Edge Sizing</i>	<i>Face Sizing</i>	<i>Automatic Method</i>
State	Fully Defined		
<b>Scope</b>			
Scoping Method	Geometry Selection		
Geometry	2 Edges	1 Face	1 Body
<b>Definition</b>			
Suppressed	No		
Type	Number of Divisions	Element Size	
Number of Divisions	50		
Element Size		Default (1,e-003 m)	
Method			Automatic
Element Order			Use Global Setting
<b>Advanced</b>			
Behavior	Soft		
Growth Rate	Default (1,85)		
Capture Curvature	No		
Capture Proximity	No		
Bias Type	No Bias		
Defeature Size		Default (5,e-006 m)	
Influence Volume		No	

Table V. 28:Model (A4) &gt; Mesh &gt; Mesh Controls

- Static Structural (A5)

Object Name	<i>Static Structural</i> (A5)
State	Solved
<b>Definition</b>	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
<b>Options</b>	
Environment	25, °C
Temperature	
Generate Input Only	No

**Table V. 29:Model (A4) > Analysis**

Object Name	<i>Analysis Settings</i>
State	Fully Defined
<b>Step Controls</b>	
Number Of Steps	1,
Current Step Number	1,
Step End Time	1, s
Auto Time Stepping	On
Define By	Time
Initial Time Step	0,1 s
Minimum Time Step	1,e-003 s
Maximum Time Step	1, s
<b>Solver Controls</b>	
Solver Type	Program Controlled
Weak Springs	Off

Solver Pivot Checking	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Quasi-Static Solution	Off
<b>Rotordynamics Controls</b>	
Coriolis Effect	Off
<b>Restart Controls</b>	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Combine Restart Files	Program Controlled
<b>Nonlinear Controls</b>	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
<b>Advanced</b>	
Inverse Option	No
Contact Split (DMP)	Off
<b>Output Controls</b>	
Stress	Yes
Surface Stress	Yes
Back Stress	Yes
Strain	Yes
Contact Data	Yes
Nonlinear Data	Yes
Nodal Forces	No
Volume and Energy	Yes
Euler Angles	Yes

General Miscellaneous	No
Contact Miscellaneous	No
Store Results At	All Time Points
Result File Compression	Program Controlled
<b>Analysis Data Management</b>	
Solver Files Directory	C:\Users\djiha\Downloads\flexural test algeria\fluxrual test algeria_files\dp0 \SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Contact Summary	Program Controlled
Delete Unneeded Files	Yes
Nonlinear Solution	No
Solver Units	Active System
Solver Unit System	Mks

Table V. 30:Model (A4) > Static Structural (A5) > Analysis Setting

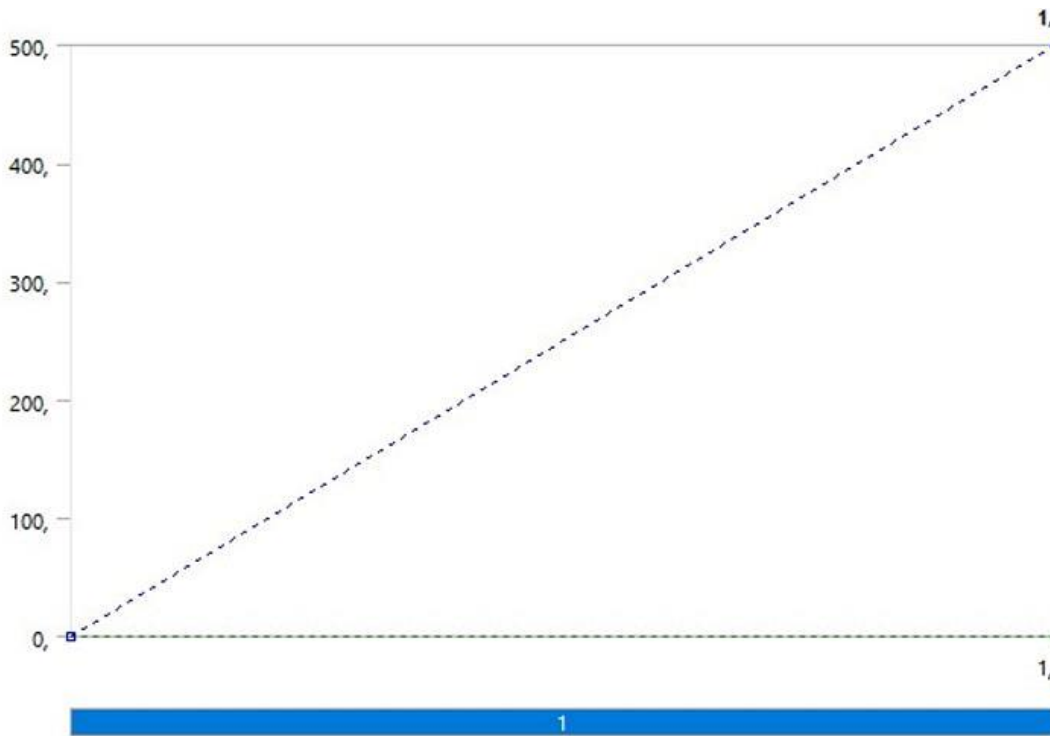


Figure V. 6:Mode(A4) > Static Structural (A5)>Force

X-axis: The x-axis ranges from 0 to 1. It's common in simulation plots for this axis in the context of a bending test, it represents the progression of the test from start to finish, or the application of the load from zero to maximum.

Y-axis: The y-axis is labeled "Force" and ranges from 0 to approximately 500N

This represents the magnitude of the applied force.

The Blue Line/Bar at the Bottom: There's a solid blue horizontal bar near the bottom of the graph. This typically indicates the "Load Application" or "Time Step" over which the force is being applied.

The Dotted Line: This is the most significant part of the plot. It shows a linear increase in force from approximately 0 at the beginning of the load application ( $x=0$ ) to roughly 500 at the end ( $x=1$ ). This indicates that the load was applied progressively and linearly.

Interpretation in the Context of a Bending Test:

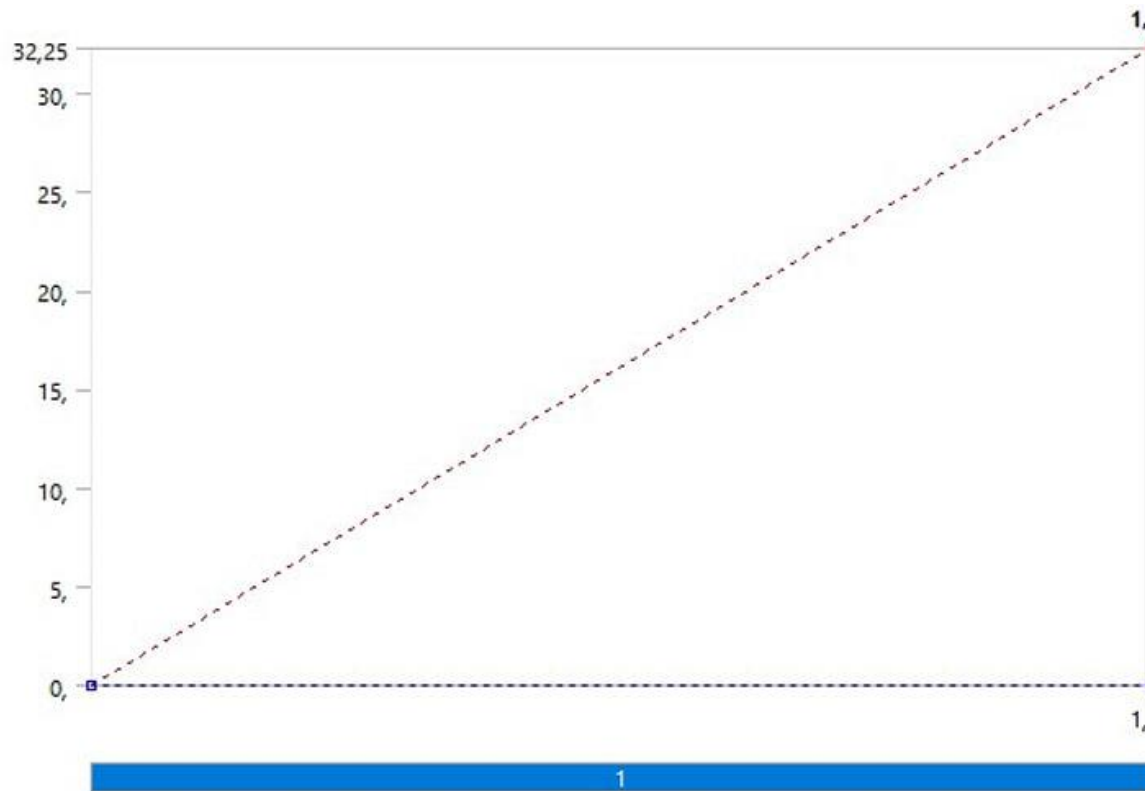
In a bending test, this graph would represent the controlled application of force to a specimen.

Loading Profile: The graph shows a ramped loading profile. The force starts at zero and increases linearly up to a maximum value of around 500N. This is a common way to apply load in a static bending test, where the force is gradually increased until a certain deflection or failure is observed.

Static Structural Analysis: The title "Static Structural (A5)" confirms that this force is part of a static structural analysis. This means the analysis is concerned with the behavior of the material under steady (non-time-varying, or very slowly varying) loads, rather than dynamic or impact loads.

Maximum Load: The maximum load applied in this specific analysis/test was approximately 500 N. This value is crucial for determining the material's bending strength, stiffness, and ultimate load-bearing capacity.

In summary, this graph illustrates that a linearly increasing force, reaching a maximum of about 5000N, was applied during a static structural analysis, likely as part of a bending test setup. To fully interpret the results of the bending test, this force-time/load-step data would typically be correlated with corresponding displacement data or stress/strain results.



**Figure V. 7:Model (A4) > Static Structural (A5) > Momen**

**Solution** The graph labeled "**FIGURE 7**" which represents "Model (A4) > Static Structural (A5) > Moment".

Overall Impression:

The graph illustrates a linear relationship.

representing the distribution or variation of "Moment" within a "Static Structural" analysis of a "Model". The x-axis appears to represent a normalized or relative position (ranging from 0 to 1), while the y-axis shows the magnitude of the moment, scaling up to approximately 32.35 N\*m.

Key Observations and Interpretation:

**Linear Progression:** The most prominent feature is the dashed diagonal line, which indicates a direct linear increase in moment as the x-axis value progresses from 0 to 1. This suggests a uniform change in moment across the analyzed element or structure.

**Moment Range:** The moment starts near zero at the beginning of the x-axis (0) and increases steadily to a maximum value of approximately 32.35 N\*m. at the end of the x-axis (1). This range (0 N\*m. to 32.35 N\*m.) represents the full extent of the moment's variation.

**Boundary Conditions/Starting Point:**

At  $x=0$ , the moment is essentially zero, indicated by the dashed line originating from the origin. It represents a fixed support.

There's also a horizontal dashed line along the x-axis, suggesting a baseline or reference point for zero moment.

**End Point/Maximum Moment:** At  $x=1$ : the moment reaches its peak value of 32.35 N\*m. The solid vertical line at  $x=1$  reinforces this as a defined endpoint or boundary where the maximum moment is observed. This corresponds to a point of maximum bending.

**Application Context (Inferred from Labels):**

- "Static Structural": This implies the analysis is dealing with forces and moments on a non-moving (static) structure.
- "Moment": This refers to bending moment, a crucial parameter in structural engineering that indicates the internal rotational forces within a structure due to applied loads. High moments can lead to significant stress and potential failure.
- "Model (A4) > Static Structural (A5)": These refer to specific analysis steps or components within a larger simulation software (Ansys), where A4 is the model definition and A5 the static structural analysis setup.

In summary, this graph provides a clear visual representation of a linearly increasing moment within a static structural model, reaching a maximum value of 32.35 N\*m.

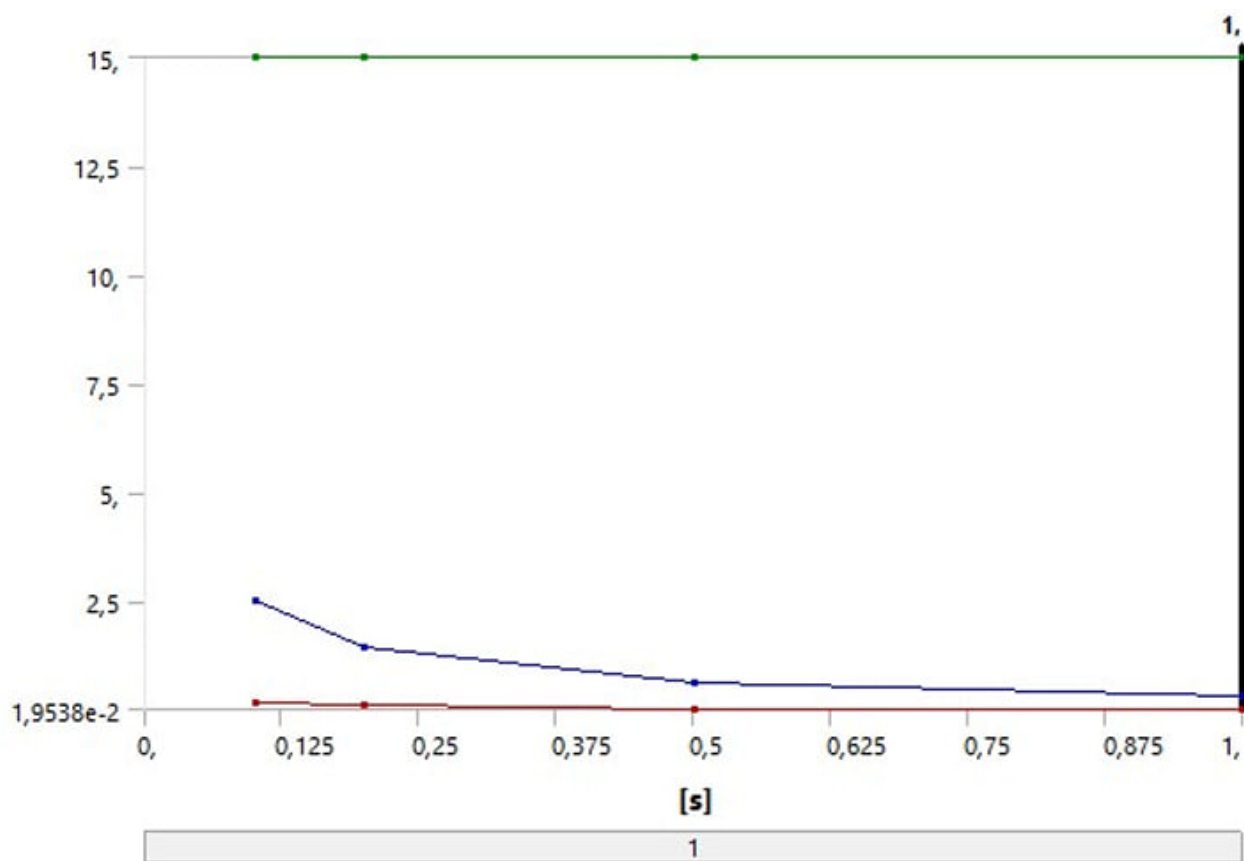


Figure V. 8:the transient response of a physical system over a period of 1 second

### Interpretation

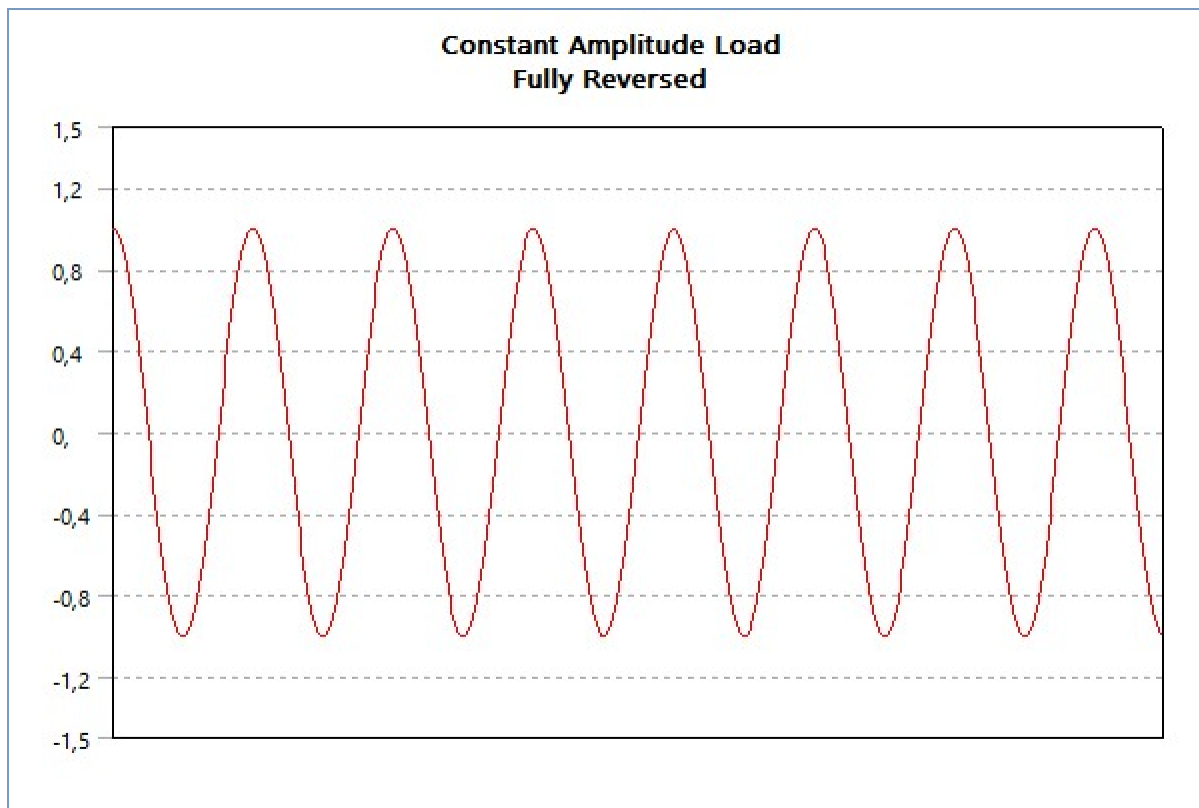
This graph represents the transient response of a physical system over a period of 1 second. The x-axis indicates time [s], and the y-axis represents the response variable (possibly displacement, stress, or energy).

The blue curve shows a rapid decrease in value over time, suggesting that the system experienced an initial disturbance (such as an applied load or force), followed by a damped response. This behavior is typical of mechanical systems with damping, where the response reduces and stabilizes after the initial excitation.

The green line remains constant at a high value ( $\sim 15$ ), possibly representing an applied load or boundary condition that does not change with time.

The red line, located near the bottom, stays nearly constant and close to zero, which may represent a variable or degree of freedom with no significant response.

By around 0.5 seconds, the system reaches a steady state, with very minimal changes afterward. This indicates that the damping is effective, and the system does not experience sustained oscillations or instability.



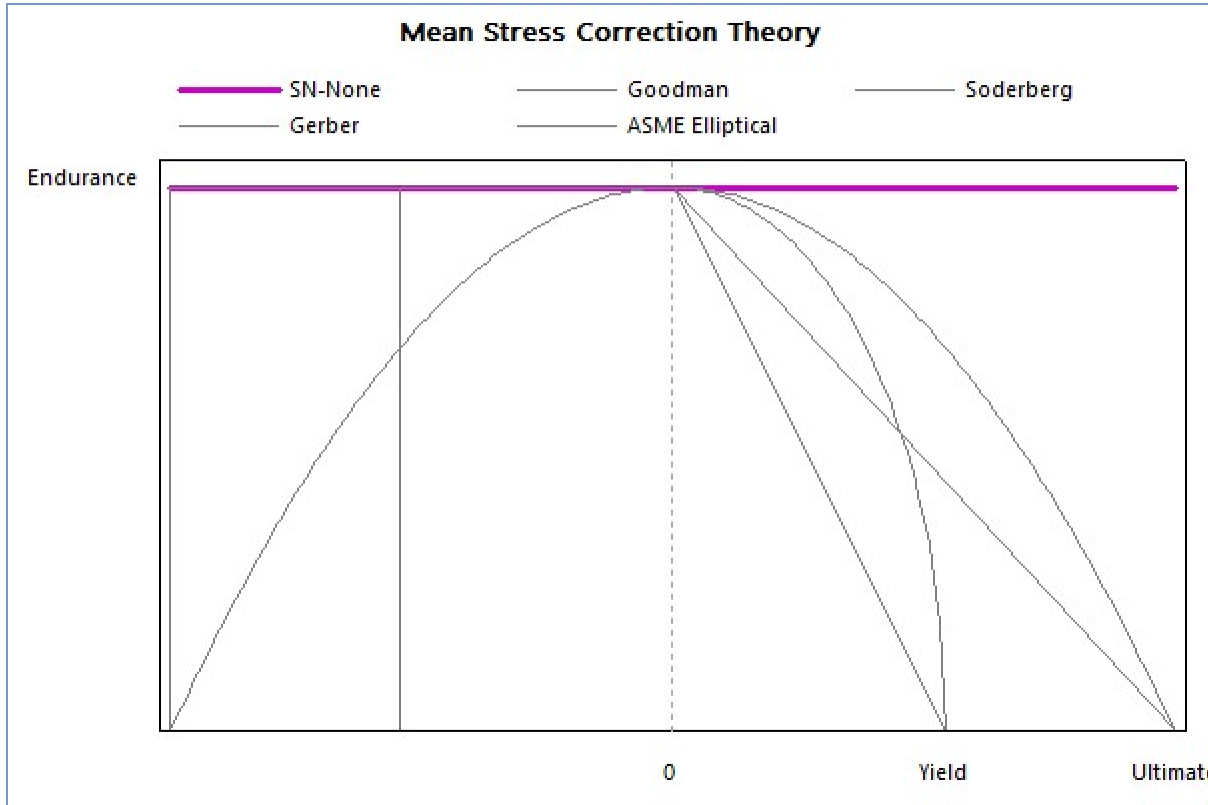
**Figure V. 9:Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool**

**Figure 9** represents a fully reversed cyclic loading condition with constant amplitude, generated using the Fatigue Tool in ANSYS. The graph displays a symmetric sinusoidal waveform, which alternates between equal positive and negative values. This type of loading is characterized by a zero mean stress and is known as a fully reversed load.

The waveform indicates that the material is subjected to repeated and alternating tensile and compressive stresses. This loading condition is commonly used in fatigue analysis to evaluate the structural behavior of components under high-cycle or low-cycle fatigue regimes.

The amplitude remains constant throughout all cycles, ensuring that each stress cycle imposes the same magnitude of loading. Such a scenario is ideal for assessing material fatigue life, as it allows the direct application of S-N (Stress vs. Number of Cycles) curves to determine the number of cycles a material can endure before failure.

Fully reversed constant amplitude loading represents a critical fatigue loading case, as it maximizes damage potential by stressing the material alternately in tension and compression. This condition accelerates crack initiation and propagation, making it a conservative and widely accepted approach in fatigue design and testing.



**Figure V. 10:Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool**

**Figure 10** illustrates the application of various mean stress correction theories within the context of fatigue analysis, generated using the Fatigue Tool in ANSYS. This plot evaluates the effect of mean stress on fatigue strength by comparing multiple widely used theoretical models.

The graph compares five correction methods:

- **None (SN Curve without mean stress correction):** flat horizontal line representing baseline endurance limit.
- **Goodman:** a linear relationship connecting the endurance limit to the ultimate tensile strength.
- **Soderberg:** a more conservative linear model linking the endurance limit to the yield strength.
- **Gerber:** a parabolic relation offering a less conservative correction.
- **ASME Elliptical:** a balanced elliptical approach, typically used in design standards.

Each model adjusts the allowable alternating stress depending on the presence of a non-zero mean stress. This is essential because real-world components rarely operate under fully reversed loading, and the presence of tensile mean stress can significantly reduce fatigue life.

This figure highlights how different correction models predict fatigue limits under mean stress conditions. The Soderberg line is the most conservative, ensuring maximum safety, while the Gerber and Goodman models offer higher predicted strength but with increased risk. The ASME Elliptical method provides a middle ground, often preferred in practical engineering applications.

Selecting the appropriate correction model depends on the application, material properties, and safety requirements. This analysis is crucial in high-cycle fatigue design, where accuracy in predicting endurance under complex stress states determines structural reliability and safety.

Object Name	<i>Life</i>	<i>Damage</i>	<i>Safety Factor</i>
State	Solved		
<b>Scope</b>			
Scoping Method	Geometry Selection		
Geometry	All Bodies		
<b>Definition</b>			
Type	Life	Damage	Safety Factor
Identifier			
Suppressed	No		
Design Life		1,e+009 cycles	
<b>Results</b>			
Minimum	0, cycles		6,7264e-004
Minimum Occurs On	Component1\Solid		Component2\Fluid
Maximum		1,e+032	
Maximum Occurs On		Component1\Solid	

**Table V. 31:Model (A4) > Static Structural (A5) > Solution (A6) > Fatigue Tool > Results**

- **Material Data**
- **Structural Steel**

Density	7850, kg m <sup>-3</sup>
Isotropic Secant Coefficient of Thermal Expansion	1,2e-005 C <sup>-1</sup>
Specific Heat Constant Pressure	434, J kg <sup>-1</sup> C <sup>-1</sup>
Isotropic Thermal Conductivity	60,5 W m <sup>-1</sup> C <sup>-1</sup>
Isotropic Resistivity	1,7e-007 ohm m

**Table V. 32:Structural Steel > Constants**

Red	Green	Blue
132,	139,	179,

**Table V. 33:Structural Steel > Color**

Compressive Ultimate Strength Pa
0,

**Table V. 34:tructural Steel > Compressive Ultimate Strength**

Compressive Ultimate Strength Pa
2,5 e+008

**Table V. 35:Structural Steel > Compressive Yield Strength**

Tensile Yield Strength Pa
2,5 e+008

**Table V. 36:Structural Steel > Tensile Yield Strength**

Tensile Ultimate Strength Pa
4,6e+008

**Table V. 37:Structural Steel > Tensile Ultimate Strength**

Zero-Thermal Reference Temperature C
22,

Table V. 38:Structural Steel &gt; Isotropic Secant Coefficient of Thermal Expansion

Alternating Stress Pa	Cycles	Mean Stress Pa
3,999e+009	10,	0,
2,827e+009	20,	0,
1,896e+009	50,	0,
1,413e+009	100,	0,
1,069e+009	200,	0,
4,41e+008	2000,	0,
2,62e+008	10000	0,
2,14e+008	20000	0,
1,38e+008	1,e+005	0,
1,14e+008	2,e+005	0,
8,62e+007	1,e+006	0,

Table V. 39:Structural Steel &gt; S-N Curve

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9,2e+008	-0,106	0,213	-0,47	1,e+009	0,2

Table V. 40:Structural Steel &gt; Strain-Life Parameters

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa	Temperature C
2,e+011	0,3	1,6667e+011	7,6923e+010	

Table V. 41:Structural Steel &gt; Isotropic Elasticity

Relative Permeability
-----------------------

10000

Table V. 42: Structural Steel > Isotropic Relative Permeability

Geometrical result

About fatigue tool

1/Life

- T=0s

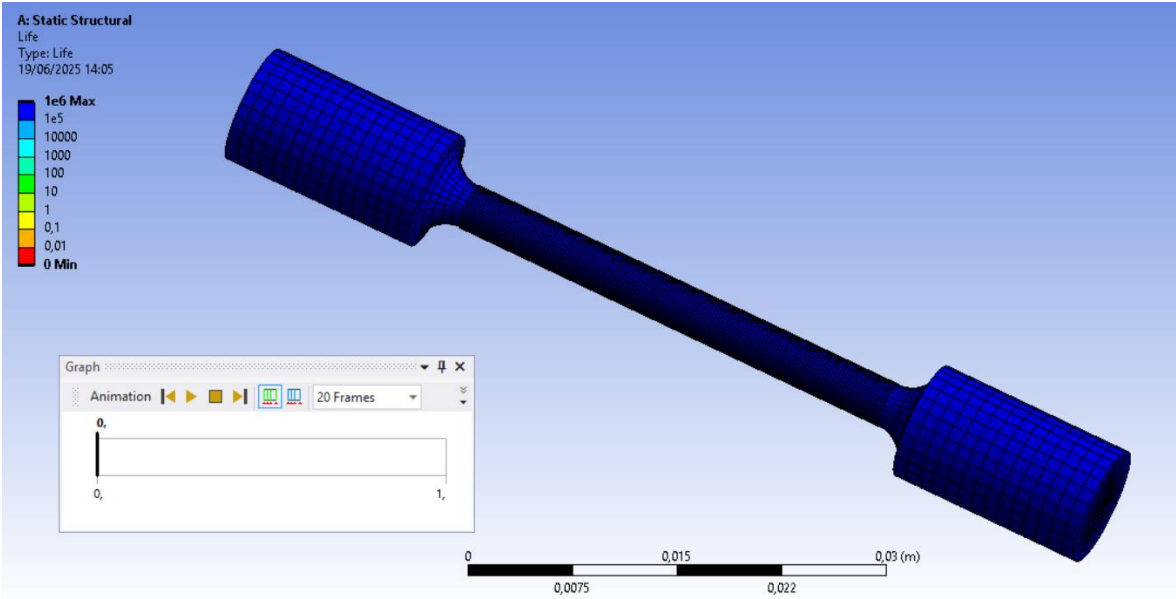


Figure V. 11: Life T=0s

- T=0.5s

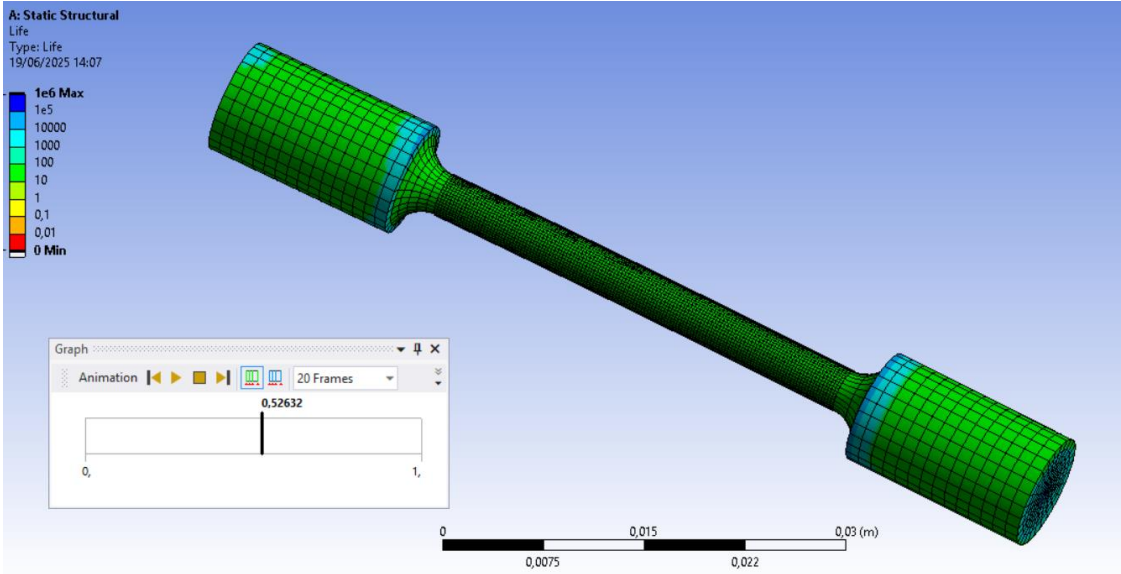


Figure V. 12: Life T=0.5s



- $T=0.8s$

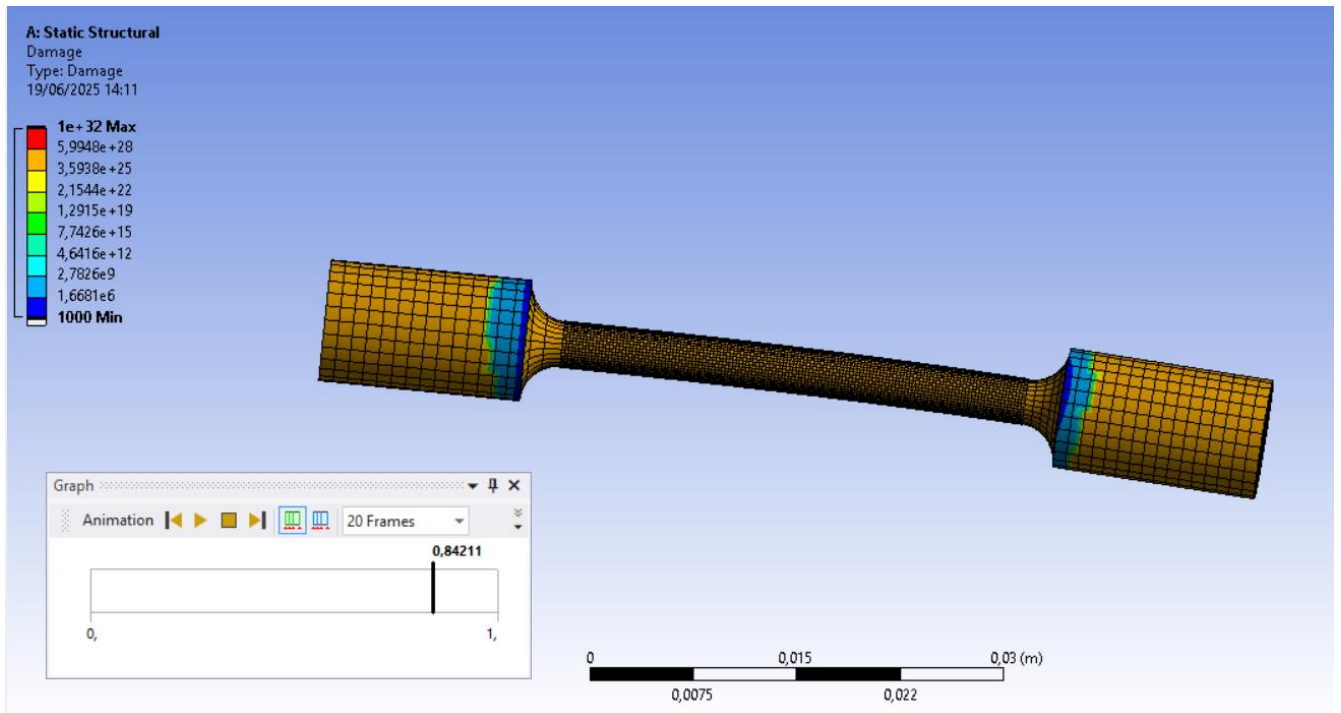


Figure V. 15: damage  $T=0.8s$

- $T=1s$

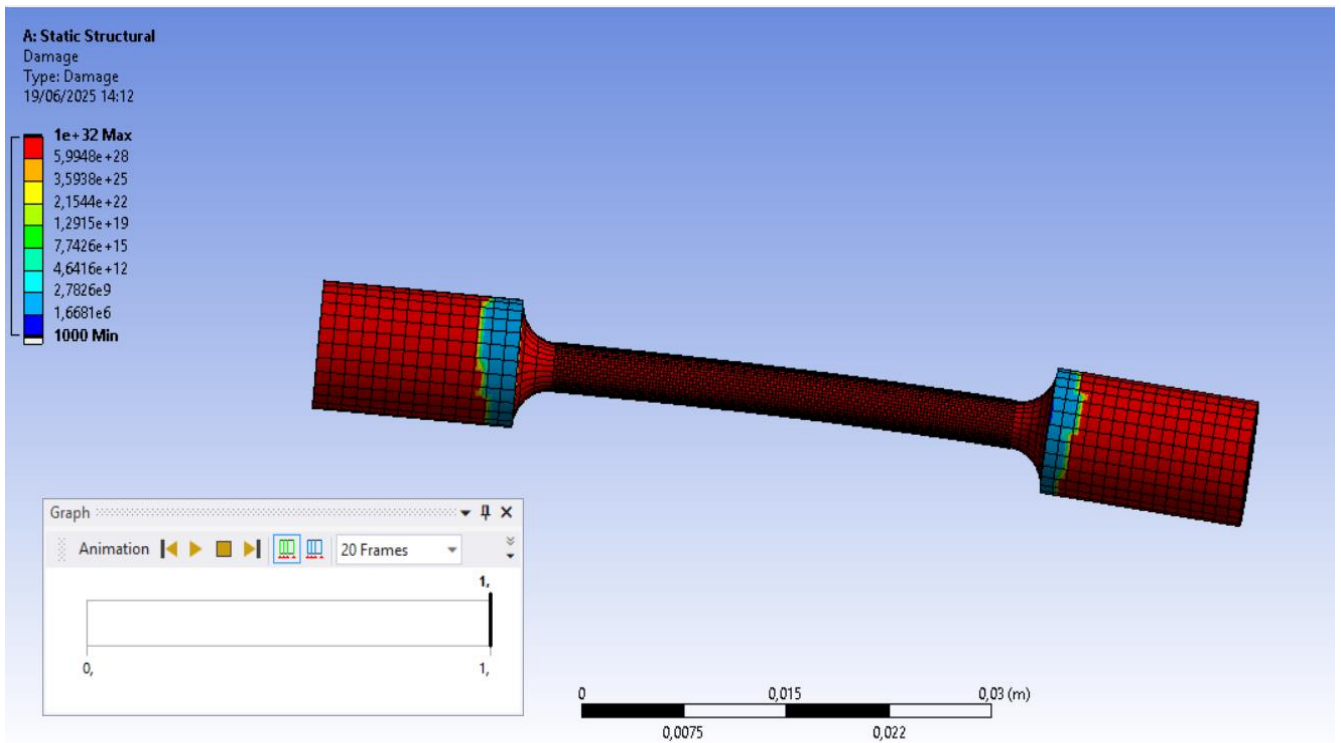


Figure V. 16: damage  $T=1s$

3/ safety factors

- T=0s

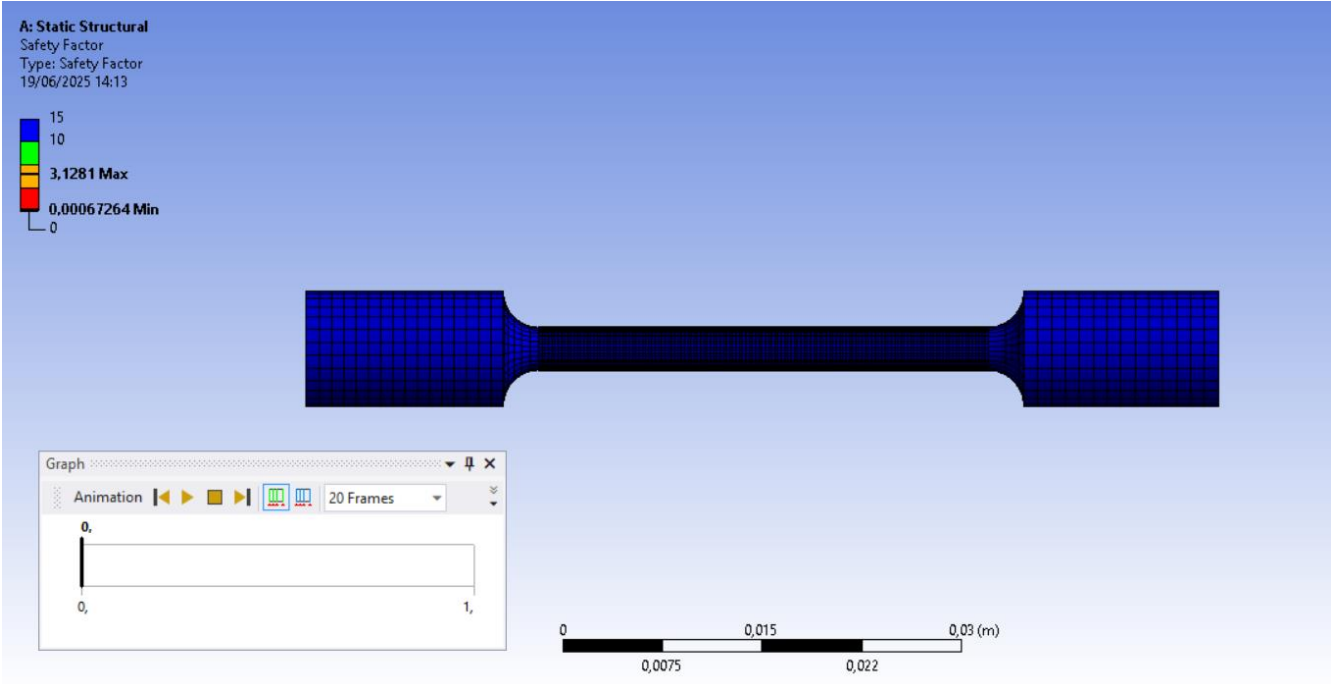


Figure V. 17:safety factors T=0s

- T=0.4s

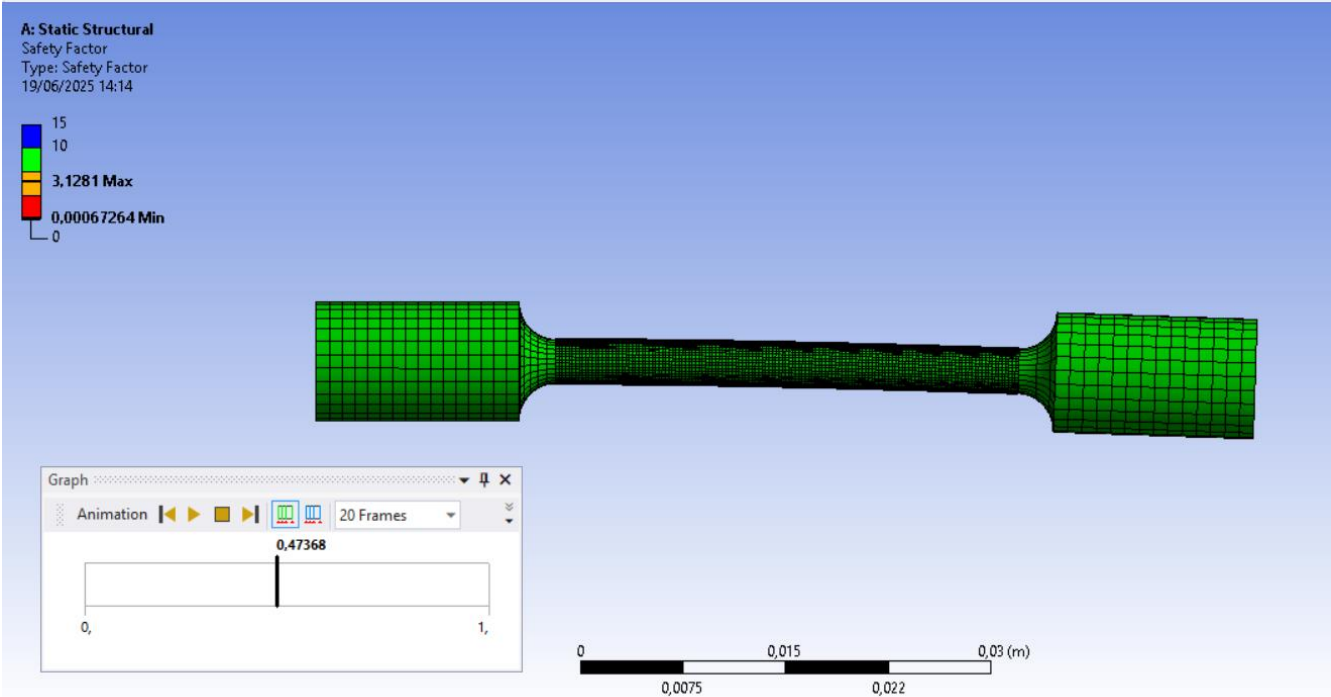


Figure V. 18:safety factors T=0.4s

- T=1s

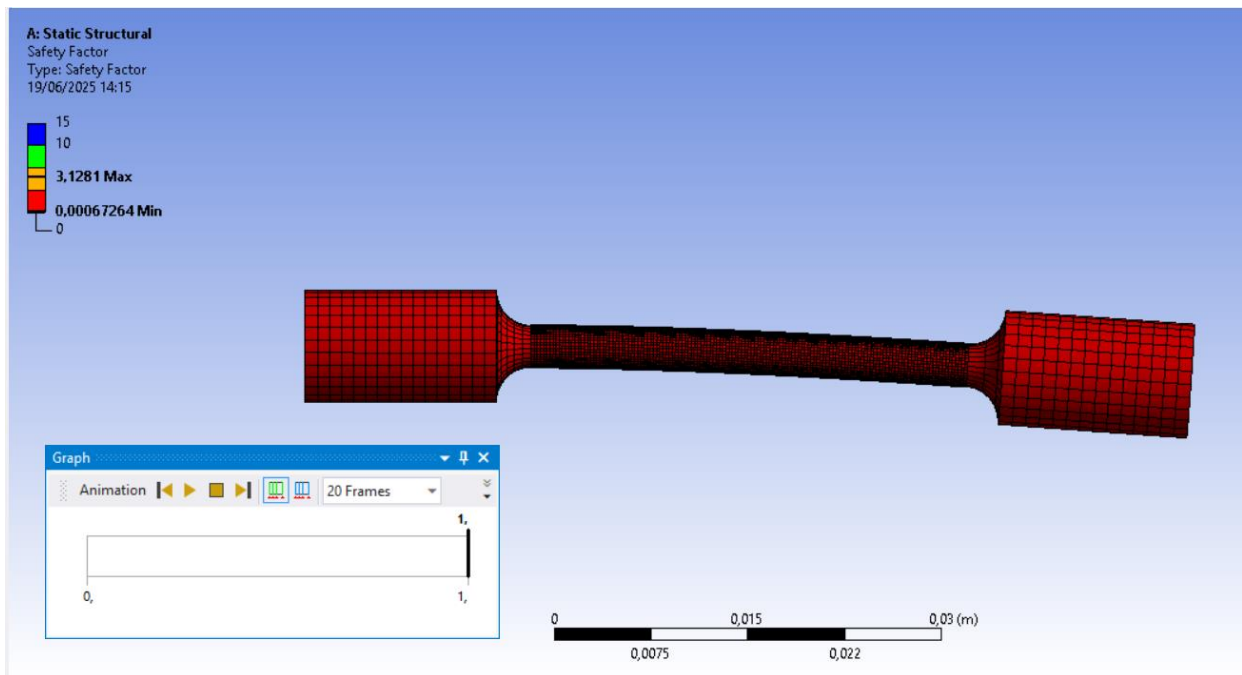


Figure V. 19:safety factors T=1s

- Comparative Structural Assessment: Corroded vs. Uncorroded Steel

### 1. Deformation Behavior

- **Uncorroded Steel:** The maximum *total deformation* under static structural load reached **2.60 cm**. Given that the material retains its full tensile yield strength ( $2.5 \times 10^8$  Pa), this deformation is within manageable elastic-plastic behavior.
- **Corroded Steel:** An equivalent deformation value was recorded; however, due to a significantly reduced yield strength ( $1.8 \times 10^8$  Pa), the same deformation now indicates material overstrain and potential failure.

**Implication:** While the displacement appears unchanged, the *mechanical resilience* is not. In the corroded condition, the structure enters plastic deformation sooner, elevating the risk of structural compromise.

### 2. Fatigue Performance

- **Maximum Life** (non-critical zones): Both models exhibit an upper fatigue life around  $1 \times 10^7$  cycles, which corresponds to low-stress zones away from loading effects.
- **Average Life** (performance across the structure):

- **Uncorroded Steel:** Exhibits significantly higher average life, implying greater fatigue resistance under cyclic loads.
- **Corroded Steel:** Shows a marked decrease in average fatigue life, indicating widespread susceptibility to early fatigue failure due to material degradation.

**Implication:** The corroded steel is more vulnerable across the full structure—even before critical stress thresholds are reached—due to compromised endurance properties.

This comparison provides clear evidence that **corrosion measurably degrades the mechanical performance of structural steel**. The HCl-induced corrosion reduces both the yield strength and fatigue endurance, despite similar deformation patterns. This is substantiated by:

- Increased stress-to-strength ratios in the corroded case.
- Lower fatigue safety margins and average life values.
- Greater likelihood of premature failure under equivalent loading scenarios.

**3. Total Deformation**

The total deformation increased significantly in the steel sample exposed to HCl corrosion, indicating a loss in stiffness and strength.

Condition	Maximum Total Deformation
Without Corrosion	2.5967e-2 m
With Corrosion (HCl)	4.0494e-2 m

**Table V. 43 : Total Deformation**

**4. Fatigue Tool-Average Life**

The average fatigue life decreased in the corroded sample, showing a reduction in durability under cyclic loading.

Condition	Average Fatigue Life
Without Corrosion	20,748 cycles
With Corrosion	17,455 cycles

**Table V. 44: Fatigue Tool-Average Life**

### 5. Fatigue Tool-Maximum Life

The maximum fatigue life dropped drastically after corrosion, indicating compromised material durability.

Condition	Maximum Fatigue Life
Without Corrosion	1e+7 cycles
With Corrosion	1e+5 cycles

**Table V. 45: Fatigue Tool-Maximum Life**

### 6. Mechanical properties Comparison

Mechanical properties such as yield strength, tensile strength, and Young's modulus showed significant reduction in the corroded steel.

Property	Steel (No Corrosion)	Corroded Steel
Tensile Yield Strength	2.5e+8 Pa	1.8e+8 Pa
Tensile Ultimate Strength	4.6e+8 Pa	3.25e+8 Pa
Young's Modulus	2e+11 Pa	1.5e+11 Pa
Poisson's Ratio	0.3	0.19

**Table V. 46: Mechanical properties Comparison**

### Conclusion

After comparing the simulation results of non-corroded and HCl-corroded steel in ANSYS, it is evident that corrosion has a negative impact on the mechanical properties. The corroded material showed higher total deformation, lower fatigue resistance, and reduced mechanical constants. Therefore, corrosion significantly reduces the structural integrity and service life of steel components.

### GENERAL CONCLUSION

This study explored several aspects of materials science, with a particular focus on fatigue behavior under corrosive conditions. One of the main components investigated was a flange-shaped sample subjected to the Rotating Bending Test. The sample was mounted on a rotating bending machine; however, the experimental process could not be completed due to a number of technical challenges.

These challenges included:

- The rupture of the machine's belt and the lack of available replacements,
- The damage or loss of most of the sample-holding fixtures
- A sudden stoppage of the machine
- The malfunction of the classical mechanical counter used to record the number of cycles.

Despite these obstacles, the test setup was successfully simulated using SolidWorks, allowing for a virtual analysis of the machine's operation. Subsequently, a fatigue simulation was conducted using ANSYS, and results showed that the flange sample could endure between 10 million and 100 million cycles under standard conditions.

In a further stage, the surface of the same sample was exposed to an acidic solution to simulate the effects of corrosion. The corroded surface was then reintroduced into the simulation to assess its updated mechanical properties. By comparing the results before and after corrosion, a significant reduction in fatigue resistance was observed. This highlights how surface degradation due to corrosion directly impacts the mechanical behavior of steel.

Ultimately, the study confirms that corrosion is a critical factor in reducing the structural integrity and service life of metallic materials.

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