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STUDY AND ANALYSIS OF CORROSION PROTECTION PROCESS FOR PETROLEUM PIPELINES BY COMPOSITE COATING

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Master's Thesis

Supervisor

Asst. Prof. Dr. Yaser ALAIWI

İstanbul, 2024

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The thesis title STUDY AND ANALYSIS OF CORROSION PROTECTION PROCESS FOR PETROLEUM PIPELINES BY COMPOSITE COATING prepared by SAIF AYAD KAREEM AL-SAFI and submitted on 09/01/2024 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

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I hereby declare that this thesis meets all format and submission requirements of a Master’s thesis.

I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

Saif Ayad Kareem AL-SAFI

Signature

DEDICATION

My mother, thank you for being with me. Because with you I resist my stumbles. And my depression turns into laughter. Because with you I overcome the tired days. Because I fall into the depths of despair and all hands escape except yours, and every time I think it is my end. You make me rise again.

Do you see me as I see you in a dream every night? Great

To the soul most beloved to me, if I have any luck in the world, it is to have you with me. In you, I became certain that I have the most beautiful luck, and with you, I realized that you are the joy of life and I do not want anything from the world after you. I confess that I had my share of joy when I loved you and saw in you everything my soul desires.

To those who are my refuge and a symbol of my honor and pride, I am one of them and they are one of me. O Lord, do not bend your back for them, do not weaken in their affairs, facilitate their affairs wherever they are, and make them my firm shoulder and my strongest support.

What I wanted for myself, not if it actually happened to me, but I changed my plans a thousand times to be happy, a thousand times to endure, and a thousand times to live (Stand on the corner of the dream and fight).

If I say thank you, my thanks will not be enough for you, and if my ink dries up from expressing it, a heart with the purity of love will write you an expression. Oh Lord, you have blessed me with a family that fills all the gaps of life. Oh God, do not let me see anything wrong with them, and I seek refuge in You from their absence and loss. And protect them wherever their steps fall.

To the one who enlightens the mind of others with his knowledge or guides the confusion of those who ask him with the correct answer, so who demonstrates by his tolerance the humility of scholars and by his generosity the eminence of those who know.

ABSTRACT

STUDY AND ANALYSIS OF CORROSION PROTECTION PROCESS FOR PETROLEUM PIPELINES BY COMPOSITE COATING

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The aim of this research is to conduct a comprehensive study of the Petroleum pipeline in general, using composite coatings that prevent corrosion. A section of an oil pipeline in the city of Basra in Iraq was chosen with a length of 3 meters, and the rest of the specifications come standard depending on the type of material and the amount of test pressure. In the beginning, a test will be conducted without any compound paint, and this is what is known as Baseline Design. Then the study will be conducted by placing an internal and an external composite Coates on the surface. Two materials will be used, 3-Layer-Polyurethane (3LPE) and fusion-bonded epoxy (FBE). A study will be conducted on each material separately and their results will be extracted completely, as two tests will be conducted, the first is structure Integrity test is used to ensure the integrity of the structure when exposed to very high pressure which is a test pressure or hydrostatic pressure. The other test is thermo-static structural test and will be conducted over a period of 15 years using the design pressure and temperatures of the city of Basra recorded over a year. The study proved that the use of composite coatings completely prevents corrosion and collapse of pipes in the very long term by looking at the safety factor as well as the life of the oil pipe.

Keywords: Petroleum Pipeline, Composite Coating, Corrosion, FBE, 3LPE.

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ABBREVIATIONS

HDD	:	Horizontal Directional Drilling
FBE	:	Fusion Bonded Epoxy
DLS	:	Dynamic Light Scattering
SEM	:	Scanning Electron Microscopy
FRP	:	Fibre Reinforced Polymer
3LPE	:	3-Layer-Polyurethane
FEM	:	Finite Element Method
FEA	:	Finite Element Analysis
HPCC	:	High-Performance Composite Coating
CAD	:	Computer-Aided Design

LIST OF SYMBOLS

p	:	Pressure
n	:	Safety Factor
S	:	Ultimate Load or Strength
σ	:	Maximum Working Stress
ϵ	:	Normal Strain
δ	:	Total Elongation of The Bar
l	:	Original Length
P_h	:	Hydrostatic Pressure
P_{desing}	:	Design Pressure
A	:	Cross-Sectional Area

1. INTRODUCTION

1.1 BRIEF BACKGROUND

The need to move fluids from production sites to end-use areas has resulted in a notable increase in the number of pipelines that have been designed and built in recent years. These pipelines frequently cross highly sensitive environmental areas or are situated close to densely populated areas, and many of them are known to transport toxic or hazardous materials. Before a recent abrupt decline, the cost of producing oil rose sharply to more than $35 per barrel. Additionally, the cost of manufactured chemicals and industrial goods increased. Today, the pipeline industry is acknowledged as a multibillion-dollar worldwide business. New products, procedures, technologies, and standards are constantly being introduced with the goal of improving economy, safety, and dependability. Pipelines are anticipated to play a major part in the effective use and distribution of gas and liquid products in the future. They are expected to play a key role in transporting hydrogen, storing carbon dioxide, switching to cleaner burning fuels, and investigating previously unthinkable applications. It should be noted that tanks have special qualities, carrying frequently more hazardous, toxic, or flammable fluids than other pieces of equipment used in the chemical and oil industries. Because of the strict implementation of safety management systems and the pressure from the public and regulatory stakeholders, a safer industry has been established. The possibility of long-term product leaks—which frequently arise from contact between the bottom and soil where leaks go undetected—has led to contamination in practically all petroleum storage facilities that are several decades old [1].

1.2 PETRULIM PIPELINES ASSOCIATED PROBLEMS

a. Third-Party Damages

One of the most significant causes of pipeline failures. In European gas pipelines, third-party interference accounted for approximately 50% of all pipeline failures. Third-party damages can be due to construction activities, digging without proper clearances, or other external interferences [2].

Figure 1.1: Third-Party Interference Leads to Gas Pipeline Failure on the Shaanxi–Beijing Route [3].

b. Unintentional Release of Contents

This can be defined as a pipeline failure where the contents of the pipeline are unintentionally released. Causes can range from blockages, contamination, to equipment failures.

c. Failure to Perform Intended Function

A pipeline can fail if it doesn't meet its delivery requirements. This can occur due to blockages, contamination, equipment failure, and more. For instance, a pipeline meant for delivering a specific volume might fail to do so because of internal obstructions.

d. Earth Movements and Material Defects

Pipelines can fail due to natural causes like earthquakes or landslides. Material defects in the pipeline itself, such as manufacturing flaws, can also lead to failures.

Figure 1.2: Lateral Spreading-Induced Liquefaction Led to Pipeline Damage During the 1995 Kobe Earthquake [4].

e. Corrosion and Fatigue

Fatigue and corrosion are serious issues in the oil and gas sector that can have a negative impact on infrastructure and materials. A paper titled "Corrosion in the Oil and Gas Industry:

An Increasing Challenge for Materials" clarifies these problems. Materials used in the industry face significant challenges due to the presence of aggressive elements like CO_2 and H_2S, as well as high temperatures and pressures. The two main environmental deterioration issues that are highlighted are Sulfide Stress Cracking (SSC) and CO_2 corrosion. As hydrogen sulfide (H_2S) contamination grew in concern, SSC was first discovered in gas well tubing and casing in the 1950s. H_2S may have a biological or formation-dependent origin, with sulphate-reducing bacteria (SRB) primarily producing biogenic formation as the main cause of its rising concentration. Contrarily, CO_2 corrosion is complicated, and its mechanism is affected by several variables, such as the presence of other aggressive species, the surrounding environment, and the characteristics of the material. The study highlights that to address these issues, material selection is essential, and that additional research is necessary to fully comprehend these corrosion processes [5].

Figure 1.3: Corrosion in Petroleum Pipelines [6].

f. Offshore Challenges

Maritime activities and natural forces play a significant role in offshore pipeline failures. For instance, anchor damage from ships can cause leaks. Even though corrosion might lead to more leaks, anchor damage was found to cause most of the pollution in terms of the volume of spilled product.

g. Service Interruption

Pipelines can fail by not meeting their delivery requirements. This can be due to blockages, contamination, equipment failures, and more. Such interruptions can have significant economic and operational impacts, especially in critical sectors.

1.3 THESIS ORGANIZATION

In the current first chapter, general information about petroleum pipelines and their importance is presented. The most important problems that occur to these pipelines are also reviewed as an introduction to the work in this thesis.

In Chapter 2, previous studies related to this topic will be discussed in detail. The results of each study will be discussed and the most important points they have worked on will be discussed.

In Chapter 3, the importance of coatings for oil pipelines will be discussed first. Next, the most prominent types used in coatings will be addressed. Areas related to pipe analysis, such as mechanical design and finite element methods, will then be detailed. The pipe will be drawn and designed based on specific specifications from documented data. Subsequently, two analyses, one structural integrity and one thermostatic, will be conducted.

In Chapter 4, the most important results reached in the two analyses will be reviewed in detail, and then the results will be commented on and the great benefit of using composite coatings in the design of these pipes to increase their life will be explained. In the final chapter, the key takeaways are summarized, and recommendations for future investigations in this field are put forward.

In the last chapter, which is the last, the most prominent conclusions reached will be discussed, as well as the most important recommended future works well recommended.

1.4 THESIS AIMS

a. Studying petroleum pipelines in a specific manner in a specific area, which is Basra, which is an important oil city,
b. studying the importance of applying composite coatings on petroleum pipelines and showing the most important composite coatings that are used.
c. Another goal is to conduct more than one analysis using computer programs, and this shows the importance of a deep understanding of these programs.

2. LITERATURE REVIEW

A comprehensive review of corrosion problems and mitigation measures during oil and gas production has been provided by this preceding scientific paper. The chemistry of corrosion mechanisms, along with various types of corrosion and the correlating agents found in the oil and gas industry, has been thoroughly examined. The factors influencing each different form of corrosion have been systematically outlined. Furthermore, affordable current technology methods for combating this widespread issue have been discussed. A recognition has been made that an understanding of the principles of corrosion is essential for effective material selection and the design, fabrication, and utilization of metal structures to maximize the economic lifespan of facilities and ensure safety in oil and gas operations. In the examination, it was found that the durability of oil and gas materials is extended when the combined use of inhibitors and protective coatings is preferred over the use of batch inhibition alone. However, it has been suggested that consultations with process, operations, materials, and corrosion engineers are imperative to prevent billions of dollars from being squandered due to corrosion in the oil and gas industries [7].

A past manuscript at hand elucidates the corrosion protection mechanism employed in a section of a gas line located within a Horizontal Directional Drilling (HDD) in a landfall area. It delves into the amalgamation of the pipeline coating and cathodic protection systems, both specifically tailored to endure the pipeline's lifespan. A brief exploration of previously published studies concerning this topic is followed by a concentrated discussion on the design of the coating and cathodic protection, providing not just the principles, design data, and methodology leveraged, but also the resultant outcomes and installation difficulties. Computational modeling, coupled with suggested practices, were employed in ascertaining the optimal and most practical solution. The paper will culminate with the presentation of findings and suggestions aimed at aiding forthcoming projects that are faced with analogous challenges [8].

In this previous study conducted, fusion bonded epoxy (FBE) coatings were affixed onto chemically functionalized surfaces of carbon steel using organosilanes. This was done with the intent to explore potential uses in shielding against corrosion and degradation in severe marine environments. The carbon-steel API 5L X42 (a standard grade by the American Petroleum Institute) underwent chemical functionalization with two organosilanes, 3-

APTES(3-Aminopropyl) triethoxysilane and 3-GPTMS [(3-Glycidyloxypropyl) trimethoxy silane]. This was followed by the application of FBE composite coatings. A comprehensive characterization was conducted considering each component and the interface between the steel and the coating. The contact angle measurements and results of Fourier transform infrared spectroscopy (FTIR) revealed the steel surface's successful modification by the functional amine and glycidyl silane groups. This led to the formation of interfacial covalent bonds that exhibited increased hydrophobicity compared to uncoated steel surfaces. Additionally, the FBE's morphological and chemical characterizations were undertaken using scanning electron microscopy, atomic force microscopy, X-ray diffraction, and FTIR. These examinations confirmed that the FBE is comprised of an epoxy-based organic matrix of bisphenol-A diglycidyl ether (DGEBA), bolstered with evenly scattered inorganic phases of calcium silicates and TiO2 particles. Furthermore, the chemical functionalization of the steel surfaces using amino and glycidyl silanes brought about substantial changes in the interfacial forces with the FBE coatings. This resulted in a heightened adhesion strength for 3-APTES-modified steel compared to 3-GPTMS-steel. However, in both instances, the FBE component predominantly displayed a cohesive rupture mode [9].

The objective of an earlier study was to delineate and scrutinize corrosion-related challenges and their resolutions in the oil, gas, and refining sector. Discussions revolved around corrosion phenomena and the factors impacting them. Illustrations of corrosion control and monitoring techniques were provided. It was highlighted that the role of corrosion management was indispensable in addressing corrosion-related issues [10].

In a prior paper, an overview was provided of the various kinds of corrosion that affect buried steel pipelines. These were examined from two perspectives - internal and external corrosion. A comprehensive introduction was given to the primary detection technologies used for both internal and external corrosion. Moreover, protective strategies aimed at mitigating corrosion in buried steel pipelines were put forward. The research dedicated to corrosion protection for buried steel pipelines furnished the foundation for further studies on the corrosion protection of such pipelines [11].

The utilization of the extrusion technique to derive new compositions for the intermediate layer of the pipeline's three-layer rust protection coating was delineated in a prior study. Not only traditional low-density polyethylene and ethylene-vinyl acetate, but also various proportions of exfoliated vermiculite as mineral filler and gossypol resin, were incorporated into the layer composition. From the standpoint of enhancing adhesion, impact strength, rust resistance, and exfoliation, optimal component ratios for the layer were determined. The composed formulations, which fully conform to the contemporary technical standards in the field, were found to possess superior technical characteristics. These characteristics are attributed to the synergistic effect that occurs between the gossypol resin and the exfoliated vermiculite. The gossypol resin was identified as stabilizing polyethylene and enhancing the mechanical features of both the composition and the mineral filler. An enhancement of the interaction between the polymer matrix and the steel was brought about by the exfoliated vermiculite. A comparison was made to similar compositions, and it was discovered that the content of the costly component – ethylene-vinyl acetate – had been diminished from 62–90 wt% to 7–9%. Effective protection against high humidity conditions for pipelines is provided by the new composition. Economical local raw materials, inclusive of waste which negatively impacts the environment, are utilized in the developed composition, which was found to enhance the mechanical properties, rust resistance, and adhesion properties of the resulting coating [12].

Innovations for corrosion protection applicable to water industry components were classified in a previous review paper. The primary methodology examined was the creation and implementation of self-healing coatings, which can be applied internally to water components. These coatings, performing superiorly compared to contemporary epoxy-based coatings, can self-mend at the damage site, thereby restoring functionality and service quality to the component. The coating was found to contain micro/nanocapsules that encapsulate a polymerizable healing agent, which is discharged upon damage. The healing agent was observed to bind to the coating and fill any void, hence sealing the coating and the component from further damage. Superhydrophilicity, the heightened ability to repel water, was also examined as an enhancement to the already efficacious coatings. The induction of superhydrophobicity in both the coating and the healing agent allows the component to further resist corrosion, since water merely glides past the component, lessening the likelihood of corrosion. Furthermore, the manufacturing and characterization of these coatings, encompassing synthesis and processing parameters, were discussed by reviewing current studies and examples. Lastly, a summation was provided and suggestions for future work were proposed, addressing areas requiring refinement for the development of an optimally designed coating [13].

In a previous reaserch, a bilayer composite film was successfully manufactured utilizing a two-fold procedure that comprised of electroless plating and electrodeposition. The process involved overlaying a NieCueP film exhibiting hydrophobic traits on a NieP film. An examination was conducted to draw comparisons between the histological characteristics of both membrane strata. Evaluations were performed on the L360 pipeline steel, the NieP layer, and the NieCueP composite film employing electrochemical testing and the erosion corrosion method. Alterations in material properties under simulated seawater conditions before and after various service durations were noted. The experimental findings highlighted the potential of Cu to restrain the development of cellular structures on the layer's surface, heighten the nucleus formation points, and enhance the coating's microstructure during NieCueP film deposition. The NieP/NieCueP bilayer composite film displayed a structure akin to the contours of a pinecone, which significantly reduced the energy of the film layer's surface and imparted hydrophobic characteristics to it. This film was efficacious in deterring the adhesion of water and extraneous contaminants on its exterior, and exhibited commendable anti-contaminant properties. These attributes contributed to decelerating the corrosion of the surface and augmenting the resistance to corrosion. Moreover, copper's presence in the composite coating resulted in a passive, uniform, and compact coating structure, the primary reason for the amelioration of the composite coating's corrosion protective capabilities. The coating's defensive capacity significantly augmented the electrochemical and erosion resistance of L360. There was a noted reduction in the electrochemical corrosion rate of the substrate, dropping from 0.417mmpY to 0.025mmpY, because of the NieP/NieCueP bilayer composite film. Additionally, the abrasion weight loss rate of the film was reduced to 0.05% of the substrate [14].

A previous research focused on the development of new high-performance composite coatings by infusing nanoparticles into polymer resins for application on oil and gas pipelines. Different concentrations of graphene nanoplatelets were employed to produce the epoxy-based nanocomposites, which were subsequently evaluated using mechanical and electrical tests. To combat nanoparticle agglomeration, a dispersion technique was utilized, incorporating the use of high-speed disk and ultrasonication. Electron microscopy techniques were deployed to probe the agglomeration. The newly formed composites underwent both qualitative and quantitative assessment based on parameters such as contact angle, surface roughness, adherence to the substrate, resistance to corrosion, and resistance to abrasion. Findings indicated that a composite constituted with 0.5~1.0 wt.% of graphene nanofillers resulted in the most significant enhancement of both mechanical and electrochemical properties. The dispersion of nanoparticles within the matrix was inspected using scanning electron microscopy, while surface roughness was analyzed through atomic force microscopy. It was observed that a higher concentration led to substantial agglomeration, which in turn primarily caused a decrease in both corrosion and abrasion resistance [15].

Another study aimed to examine the corrosion protection behavior of Alumina-Titania (Al2O3-TiO2) oxide ceramic coatings applied on C45 carbon steel pipes via two distinct thermal spray coating processes. These processes, High velocity oxy-fuel (HVOF) and plasma thermal spraying techniques, could serve as alternatives to extensive, expensive chemical treatment to form coatings on pipelines and equipment. Their application was designed to enhance or restore the properties of a component's surface or dimensions and shield them from corrosion. Molten or semi-molten ceramic composite powders were sprayed onto the surface to form a dense layer of coating. Field Emission Scanning Electron Microscopy (FESEM) of the coated samples revealed that the high temperature utilized in the plasma coating method resulted in the melting of ceramic powders, leading to the formation of completely melted areas on the surface of the coated samples. This was in contrast to what was observed with the HVOF coating technique. Corrosion testing of the coated samples was performed in seawater (3.5% NaCl) over a duration of 30 days. The results from Electrochemical Impedance Spectroscopy (EIS) and potentiodynamic polarization tests demonstrated that the corrosion resistance offered by the plasma coating technique for this ceramic composite was superior to that of the HVOF coating technique. Nevertheless, it was noted that both coating techniques effectively protected the substrate against seawater [16].

A chapter in a book offers an analytical comparison of the currently used technologies for performing repairs on areas with volumetric surface defects, also known as local metal loss defects, of transmission pipelines intended for carrying hydrocarbons (petroleum, liquid petroleum products, natural gas, etc.) or other fluids. These repairs involve the use of reinforcing wraps or sleeves composed of polymeric composite materials. These technologies are juxtaposed with other pipeline repair methodologies, which involve the use of metallic components and potentially require welding operations, with the aim of emphasizing their advantages, particularly in situations where, for economic reasons, it's preferable to perform repair works on the pipeline while it remains in service (without halting fluid supply). Moreover, technologies used for applying coating systems that include polymeric composite materials for corrosion protection of transmission pipelines, or for repairing such protection systems, are also put under comparison and analysis [17].

In one of the past papers discussed before, the integration of FeTiO3 (ilmenite)/melamine formaldehyde composite (IMFC) particles at varying concentrations into epoxy coatings was meticulously examined for its potential to enhance corrosion resistance and chemical robustness. Micro-sized FeTiO3 particles, produced through a direct solid-phase milling process, acted as a bi-functional modifier within the composite. These particles were extensively characterized by employing methods such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and dynamic light scattering (DLS). The electrochemical behavior of the epoxy-coated films, as opposed to an uncoated carbon steel surface when exposed to high salinity formation water, was investigated using potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) techniques. Tests to determine cure durability and water resistance were rigorously performed in accordance with established standards to confirm the chemical resistance of the modified coating. Further comparative analysis of the corrosion protection efficacy of the IMFC-modified epoxy coated film versus a traditional unmodified coating on a carbon steel substrate was carried out in a high salinity formation water environment, utilizing scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX). The study's results highlighted the superior corrosion inhibition properties of the modified epoxy composite coating, marking a significant advancement in protective coating formulations [18].

In a prior scientific publication, various techniques have been outlined that are typically employed to prevent the formation of paraffin deposits. These include mechanical cleaning, coating the pipe to create a smooth surface that reduces paraffin adherence, electric heating, ultrasonic and microbial treatments, and the use of paraffin inhibitors. The benefits of pipeline coatings include not just the ease of preparation and wide application scope, but also their long-lasting effectiveness and stability. Recent years have witnessed noteworthy advancements in the research surrounding pipe coatings aimed at diminishing and warding off paraffin deposition. Bionic design has been successfully utilized to prepare several novel superhydrophilic organogel coatings with low surface energy. This manuscript provides a review of different types of coatings designed to inhibit wax deposition in the petroleum industry. A brief overview of the promising research opportunities and directions within this fast-paced field of study is also included [19].

In one of the past studies clarified before, the performance and essential attributes of filament wound fibre reinforced polymer (FRP) composite pipes were thoroughly scrutinized. Emphasis was placed on pivotal properties such as burst strength, buckling resistance, durability, and corrosion resistance. The influence of process parameters on the manufacturing methods' strengths and shortcomings was critically evaluated to foster enhanced performance. The analysis revealed that an optimal winding angle of ±55° significantly reduced failure mechanisms, including matrix cracking, whitening, leakage, and fracture. A reduction in buckling was observed when the hoop stress was lower in the hoop to axial stress ratio, compared to when axial stress, compression, and torsion were predominant. Hybrid composite pipes exhibited a marked improvement in energy absorption following thermal treatment. Nonetheless, alterations in the winding angle during the fabrication process were found to affect all the aforementioned properties. It was documented that a vast majority, nearly 90%, of the studies reviewed employed E-glass/epoxy materials for crafting composite pipes. The research suggested that by overcoming certain limitations—such as substituting synthetic materials with innovative material combinations and performing comprehensive cost-benefit analyses—the manufacturing expenses for lightweight FRP composite pipes could be reduced, thereby enhancing their viability for practical applications [20].

The primary focus of one of a previous article review is to underscore the diverse localized corrosion mitigation strategies applicable to oil and gas pipelines. Furthermore, potential obstacles and the trajectory of future research concerning localized corrosion, particularly in relation to oil and gas pipelines, are examined [21].

A previous review presents an overview of the latest developments in the domain of anticorrosive coatings, wherein graphene oxide nanostructures are utilized as active fillers. Due to its extraordinary attributes, this carbon-based material has been broadly exploited in recent years and has shown a significant contribution to composite materials. Aspects such as synthesis methods, protective features, anticorrosion mechanisms, potential challenges, and methods for enhancement of overall properties are emphasized in the context of graphene-based coatings. Special emphasis is given to various graphene oxide modification strategies and the cooperative effect observed when it is functionalized with other compounds, as these play a key role in improving the material's capacity [22].

A comprehensive and critical evaluation of the recently developed superhydrophobic coatings for steel pipelines, particularly for their use in the oil and gas sectors, is presented in another review paper. Initially, the fundamental principle of wettability is explained, with the derivation and explanation of the physical models that govern different wetting conditions. Subsequently, a discussion is held on the diverse methods employed for the synthesis of superhydrophobic coatings on steel substrates and recent insights from research concerning various methods of coating fabrication. Current applications of these developed superhydrophobic coatings, including corrosion prevention, deicing, anti-biofouling, and more, as well as future trends, are extensively examined over the past five years. As per the literature, spraying emerges as the most versatile and commonly used method for fabricating superhydrophobic coatings for steel pipelines. This technique offers a simple and cost-effective way of mass-producing coatings on a variety of steel substrates with desirable microstructures. It is reported that Silver nanoparticles (Ag NPs) display significant resistance to microorganisms when used in the fabrication of superhydrophobic surfaces. Recently, shape-memory polymers have also been integrated into the creation of superhydrophobic surfaces to imbue self-healing capabilities [22].

In one of the past research efforts, the corrosion resistance of an anticorrosion coating, which was enhanced by the incorporation of graphene, was assessed on the surface of an aluminum alloy. The application process of the graphene-modified anticorrosion coating, involving an epoxy resin primer and a polyurethane topcoat both amended with pre-dispersed reduced graphene oxide (rGO), was meticulously described. The microstructure of this innovative coating was examined using a Scanning Electron Microscope (SEM) and a Raman spectrometer, revealing that the rGO integration markedly improved the porosity issues commonly found in the epoxy resin primer. An electrochemical workstation facilitated the swift evaluation of the coating's corrosion resistance, with the electrochemical behavior monitored at five-hour intervals during immersion in a 3.5% NaCl solution. The patterns observed indicated that the corrosion resistance altered consistently with increased soaking time. The data indicated that the addition of 0.4% rGO content significantly reduced the porosity of the epoxy coating from 1.54% to 0.33%, a reduction by an order of magnitude. The self-corrosion potential was recorded at a relatively positive value (-0.72434 V), and the self-corrosion current density was notably low ($1.948 \times 10{-}6$ A/cm2), while the impedance modulus at low frequency was at its peak (10^3). Following the equivalent circuit fitting, a high dispersion index was noted, suggesting a minimal dispersion effect and a consequent increase in the coating's corrosion resistance. Initially, the presence of pores and other defects in the graphene-modified anticorrosion coating might amplify the dispersion effect, thereby reducing the corrosion resistance. However, during the intermediate stage of corrosion protection, as the pores became saturated with corrosive ions, the dispersion effect diminished, leading to a stabilization and a gradual decline in the loss of the coating's corrosion resistance [23].

In the study being discussed, the adoption of nanocomposite coating as an optimal strategy to enhance the corrosion resistance of steel is being scrutinized. Details on a variety of coating materials, along with the application techniques and the complications encountered in achieving an appropriate coating on steel, informed by recent research results, will be provided. Further, the specifications required for fillers to achieve high-performance nanocomposites will be elaborated upon[24].

One of the previous studies conducted before embarked on a series of erosion-corrosion tests on AISI 1018 steel, Ni-P, and Ni-P-Ti coatings. It was discovered that AISI 1018 steel exhibited the lowest resistance to erosion-corrosion. In contrast, the Ni-P-Ti coating, which comprised 15.2 wt% titanium, was shown to possess the most formidable erosion-corrosion resistance. The predominant mechanisms contributing to erosion-corrosion in AISI 1018 steel were identified as the removal of the oxide film due to abrasive particles and the occurrence of severe pitting corrosion. The Ni-P coating's degradation was primarily due to cracking and fracture. On the other hand, the Ni-P-Ti coatings were primarily affected by micro-cutting, micro-ploughing, and micro-indentation. Throughout the erosion-corrosion testing, titanium particles within the Ni-P-Ti coatings acted as protective barriers, significantly enhancing the erosion-corrosion resistance of these composite coatings [25].

One of the previous studies conducted before delved into the role of ceramic coatings in mitigating the corrosion of stainless steels within atmospheric crude oil distillation columns, with a particular focus on the effects of varying temperatures and exposure times. The weight loss method was employed as a means of assessment. The application of the coatings was executed via the thermal spray coating technique. It was observed that both an increase in temperature and prolonged exposure exacerbated the weight loss in the uncoated stainless steel samples; however, this effect was significantly curtailed when a ceramic coating was applied. The Al_2O_3 coating, in particular, was noted for achieving an optimal efficiency of 93.3% in protecting against corrosion. Surface morphology examinations conducted through atomic force microscopy, scanning electron microscopy, and energy-dispersive X-ray spectroscopy indicated a reduced corrosion impact when coatings were present, with the coating's thickness and porosity identified as vital factors. Mathematical and statistical methods were applied to articulate the findings, revealing that the weight loss as a function of time and temperature correlated well with second-order polynomial and exponential models, both exhibiting high correlation coefficients. Variations in the corrosion rate data with temperature conformed to the Arrhenius equation, with a lower activation energy noted in the absence of the coating, implying that the uncoated surfaces required less energy for the corrosion reaction to proceed. Further analysis of petroleum chemistry and local studies ascertained that sulphur content in the crude oil was the predominant factor influencing corrosion in the distillation columns, exerting a more significant impact than other contaminants present in the crude oil [26].

Extensive research and analysis have been performed on the factors leading to corrosion in oil gathering and transportation pipelines, a task that required considerable human effort, material assets, and financial investment. Consequently, it becomes necessary to examine and comprehend the elements that affect the corrosion of oil gathering and transportation pipelines. According to the specific circumstances, effectual anti-corrosion strategies should be devised to prolong the operational lifespan of these pipelines and facilitate sustained progress in oil field exploitation and operation [27].

The one of past papers explored before was dedicated to charting the trajectory of corrosion studies within the petrochemical sector, meticulously analyzing a vast array of research works. A significant number of scholarly articles, precisely 1,887, from 2000 to 2020, were extracted from databases like the Web of Science, scrutinized through informetric methods. These methods encompassed co-occurrence, keyword mutation, and co-citation analyses. The lion's share of contributions to the field was attributed to China, with the Universidade de Lisboa emerging as a central figure in this research arena. The study shone a light on pivotal subjects such as the investigation of anti-corrosive structures, models of corrosion loss, and particularly the corrosion affairs of steel in marine vessels. Leading periodicals in this scholarly discourse were recognized, including but not limited to, 'Engineering Failure Analysis' and 'Corrosion Science'. The corpus of knowledge on corrosion in petrochemical apparatus was found to be robust, with the research branching into innovative and avant-garde directions. Notably, three primary research pathways were uncovered: the dissection of corrosion mechanisms and their prevention, the study of microbially induced corrosion, and the progress in detection and monitoring of corrosion. The current and emerging trends signal a move towards the investigation of nano-materials for anti-corrosion, with simulation, biofuels, and composites marking the newest frontiers in this ever-evolving field.[28].

The one of past papers explored before delved into the innovative creation and utilization of composite coatings that comprised an electroactive epoxy thermoset enriched with aniline pentamer and infused with reduced graphene oxide platelets. Initiated by synthesizing aniline pentamer, the process progressed to its reaction with select fluorobenzoyl chloride and aminophenol, yielding a novel diamine monomer with an appended aniline pentamer structure. Comprehensive characterization of these compounds was achieved through the use of advanced spectroscopic and analytical techniques, including FTIR, NMR, and mass spectrometry. The ensuing composite coatings, produced by the reaction of this monomer with an epoxy matrix and integrating a specific ratio of graphene oxide derivatives, were subjected to meticulous analysis using transmission electron microscopy. The protective efficacy of these coatings against corrosion on steel substrates was rigorously assessed through electrochemical methods in saline environments. The hierarchy of corrosion protection efficacy was distinctly observed, with the graphene-oxide-infused coatings exhibiting paramount protection, followed by others in a descending order of effectiveness. The superior performance of these composite coatings was linked to a synergistic interplay between the graphene's barrier properties and the metal oxide layers induced by the aniline structures within the epoxy matrix. Furthermore, these coatings displayed exceptional mechanical resilience. This pioneering approach, embodying the integration of electroactive polymers into an epoxy matrix, potentially lays the groundwork for future advancements in efficient anti-corrosive materials [29].

In the preceding scientific paper, it was noted that during the transportation of natural gas via pipelines, components such as hydrogen sulfide within the natural gas can easily instigate corrosion of the pipelines. In severe cases, such corrosion can lead to leakage accidents, posing substantial risks to natural gas production. The scenario of corrosion and its mitigation during the transportation of natural gas via pipelines was examined with the aim of preventing various types of corrosion accidents and ensuring the safe operation of long-distance pipeline systems. Priority was given to preventing corrosion in metal pipelines according to various corrosion types. Following that, treatments for corrosion were implemented to prevent severe corrosion, enhancing the safety factor of the long-distance natural gas pipeline system and satisfying the technical demands of natural gas production [30].

One of the previous scientific papers conducted before embarked on a comprehensive investigation into the impact of different pulse frequencies on the properties of Ni-W/B4C composite coatings. Initially, a selection process was undertaken to identify an optimal electrolyte from various Ni-W coating bath compositions. This was followed by the characterization of the sourced boron carbide nanoparticles, ensuring their dispersion and suspension within the chosen bath electrolyte were satisfactory. The fabrication of Ni-W/B4C composite coatings was then executed at varying pulse frequencies, specifically 1, 10, 100, and 1000 Hz, with a detailed characterization of the resultant alloy coatings. The findings revealed that an increase in pulse frequency from 1 Hz to 1000 Hz led to a 40% reduction in the grain size of the coatings, a 3% reduction in nickel content, a 1.5% increase in tungsten content, an enhanced incorporation of B4C particles, and a marked decrease in the coatings' surface roughness. The mechanical attributes of the composite coatings were rigorously assessed through a series of tests, including micro-hardness, tensile strength, impact resistance, bending, and reciprocating wear tests. Surface characteristics were evaluated using water contact angle and porosity tests, and the coatings' corrosion resistance was predicted through electrochemical testing. It was concluded that the composite coating fabricated at a pulse frequency of 1000 Hz showcased the most enhanced mechanical properties, whereas the coating produced at 100 Hz pulse frequency was distinguished by its superior corrosion resistance [31].

This manuscript thoroughly reviews the evolution and application of various Fiber Reinforced Polymer (FRP) composites in pipeline systems. It scrutinizes the types of pipelines based on the fluid being transported, the advancements in composite pipelines, and the methods of repairing conventional pipelines using different FRP types to address issues like corrosion and leaks. Common practices of utilizing FRP composites in diverse pipeline applications are also encompassed in this review. A comparison and summarization of different designs and applications of FRP composites in pipelines, aimed at achieving improved properties, are presented. Moreover, future challenges along with comprehensive discussion on prospective research directions are also integrated into this study [32].

This prior review emphasizes the recent progress in the domain of innovative dyes and pigments, where Graphene Oxide (GO) is considered as a crucial ingredient or an essential cofactor. Interactions between graphene and other materials or compounds have been illuminated. The unique structure and exclusive properties of GO have been observed to significantly influence the performance of the created hybrid dyes and pigments. These include enhancing the colour yield of dyes, boosting the anti-corrosion attributes of pigments, and modifying the viscosity and rheology of inks, among others. This, in turn, broadens the application range of these dyes and pigments in sectors such as dyeing, optical components, solar-thermal energy storage, sensing, coatings, and microelectronic devices. In conclusion, this review discusses the challenges faced during the present developments, along with the future possibilities of GO-based dyes and pigments. It aims to serve as a reference point for further exploration in the field of innovative dyes and pigments [33].

In past scientific literature, the examination of natural compounds as alternatives to harmful organic and inorganic corrosion inhibitors has been carried out. The interest in these natural compounds is driven by their environmental friendliness, availability, and cost-effectiveness. In recent times, the role of nanoparticles as corrosion inhibitors has seen significant attention, given their broad industrial applicability and financial advantages. The management of corrosion rates in metals using nanomaterials underscores advancements in the field of nanotechnology. A variety of researchers have successfully explored the role of nanomaterials as corrosion deterrents. This review delves into the usage of nanoparticles for the protection against corrosion in diverse industrial metals, based on the reported experimental findings and their mechanism of inhibition. Moreover, the review brings to light various limitations, future directions, and potential enhancements in this field [34].

one of the past papers explored before has significantly contributed to the understanding of graphene's covalent modification, with a particular focus on the attachment of polymer brushes to graphene and its oxidized variant, graphene oxide (GO), for the enhancement of anticorrosive properties. This research distinguished itself by shedding light on a niche yet crucial aspect of anticorrosion applications that had not been extensively reviewed before — specifically, the covalent attachment of polymer brushes to graphene and GO. The study commenced with a detailed exposition of state-of-the-art methodologies tailored for the covalent attachment of polymer brushes to graphene and its derivatives. It then juxtaposed the utility of pristine graphene in anticorrosion applications with its inherent limitations, proposing that these could be surmounted through the use of graphene-based polymer composites. An insightful analysis of the latest advancements and innovative approaches in the field of polymer-modified graphene/GO for anticorrosion coatings was meticulously presented, based on research findings from the preceding three years. Concluding with a visionary outlook, the paper discussed the prospects of polymer composites with other two-dimensional (2D) materials for anticorrosive applications. It gave particular attention to hexagonal boron nitride — known as the most investigated 2D material after graphene — and the emergent Ti3C2Tx MXene, which is rapidly gaining recognition for its potential in 2D transition metal carbides/nitrides applications. This scholarly work, thus, not only provided a comprehensive review of current developments but also charted a course for future research directions in the innovative field of anticorrosion coatings [35].

One of the past papers conducted before embarked on a detailed 3D numerical analysis, utilizing the capabilities of COMSOL Multiphysics software, to dissect the multitude of factors affecting the corrosion process in underground pipelines. Grounded in actual geometric configurations and environmental conditions, a comparative study was meticulously carried out. This study included an examination of the pipeline's coating, specifically the application of high-density polyethylene (HDPE), the strategic placement of cathodic protection electrodes, and the varying conductivity of the soil in proximity to the pipeline. The findings from this analysis underscored the critical necessity of pipeline coating and provided a foundational basis for determining the optimal setup for cathodic protection systems, thereby contributing to the broader understanding and management of corrosion in subterranean pipeline infrastructures [36].

one of the past papers explored before has undertaken a comprehensive examination of the advancements in graphene oxide (GO)-based coatings applied to various metallic substrates, including steel and Cu-Ni alloys. The scholarly work highlighted several case studies, such as the application of a GO-based composite bilayer on Cu-Ni alloy specimens, the deployment of a chitosan-silver-GO ternary composite, the utilization of a polydimethylsiloxane layer interspersed with nano-SiO2 on carbon steel, and the introduction of a composite blend of GPTMS with GO on 316L stainless steel, each instance resulting in a notable enhancement of corrosion resistance. The discourse provided by the review initially cast light on coatings that employed graphene, graphene oxide, and reduced graphene oxide, considering their respective contributions to both passive and active corrosion protection strategies. In-depth analysis was dedicated to the progression of composite coatings that integrated a variety of substances such as epoxy, polyurethane, alkyd, polyetherimide, polyvinyl butyral, and polystyrene-graphene oxide, applied across a spectrum of metal and alloy surfaces, including the development of super-hydrophobic surfaces leveraging graphene oxide. A curated summary of the plethora of coatings developed, alongside their pivotal findings, was methodically cataloged, offering a concise reference to the significant progress achieved in this specialized domain. Furthermore, the paper expanded to include the practical implementation of GO-based coatings within industry, underscoring their relevance in diverse sectors that range from automotive to aerospace, and extending to critical components such as oil and gas pipelines, fuel cell parts, and battery cathodes, anodes, and separators. This review culminated in a forward-looking discussion, contemplating the empirical results, the breadth of potential applications, the challenges confronted, and the prospective trajectory for graphene-based composite coatings in the ongoing quest for corrosion protection solutions [37].

The one of past papers explored before probed into the synthesis of nickel-tungsten/zirconium phenylphosphonate (Ni–W/ZrPP) composite coatings on steel using pulsed electrodeposition. The inclusion of α-zirconium phosphate (αZrP) and ZrPP was scrutinized for their effectiveness in enhancing the coatings' surface quality, hardness, and resistance to wear and corrosion. It was observed that among the coatings tested, those with ZrPP exhibited the most uniform surfaces, free of defects like pinholes or cracks. These Ni–W/ZrPP coatings stood out for their superior wear resistance, shown by minimal track depths and widths during wear assessments, and an impressively low friction coefficient, measured at 0.312. Corrosion tests in saline environments revealed that these composite coatings also boasted the most impressive corrosion resistance, characterized by the highest corrosion potential and the lowest current density. The beneficial role of ZrPP in this context was attributed to its layered structure and hydrophobic qualities, which together acted as a robust barrier against corrosive elements [38].

One of the past papers conducted before was dedicated to examining the corrosion behavior of aluminum (Al)-based alloy sacrificial coatings, which are designed to protect pipelines in environments saturated with CO_2, specifically within a 3.5 wt.% NaCl aqueous electrolyte under a CO_2 partial pressure of 4 bar (3 barg) at 40°C. In this research, the corrosion resistance of Al-based alloys and thermal spray coatings was assessed inside an electrochemical reaction autoclave. This assessment was carried out using a suite of electrochemical techniques, including potentiodynamic polarization, linear polarization resistance, and electrochemical impedance spectroscopy. Following the corrosion tests, the surfaces were characterized using a scanning electron microscope that featured energy dispersive X-ray spectroscopy. The findings from this investigation indicated that Al-based alloy coatings are a promising candidate for CO_2 corrosion protection, showing no sudden degradation in the challenging conditions tested [39].

The one of past papers explored before delved into the innovative fabrication of Polyaniline (PANI) and Titanium dioxide (TiO_2) nanocomposites aimed at enhancing the corrosion resistance of mild steel. In this detailed study, the TiO_2 nanoparticles were synthesized employing the sol-gel technique, followed by the application of PANI/TiO_2 nanocomposites on mild steel through dip-coating methods. The treated steel samples underwent rigorous stability assessments in various environments over extended timeframes. A thorough examination of the anti-corrosive properties of the nanocomposite coatings was undertaken in differing industrial scenarios. Sophisticated characterization of both TiO_2 and the composite films involved techniques like Fourier Transform Infrared Spectroscopy (FTIR), Energy Dispersive X-Ray analysis (EDX), X-Ray Diffraction (XRD), and Dynamic Light Scattering (DLS), while Scanning Electron Microscopy (SEM) was employed to investigate the surface and microstructural features. Corrosion resistance was quantitatively gauged using an array of tests, including Potentiodynamic polarization, alongside Atmospheric and Wet/Dry cyclic tests. The findings revealed that the PANI-TiO_2 nanocomposite films, notable for their slender film thickness and prepared via dip-coating, constituted an effective corrosion mitigation approach. These films were particularly applicable to the oil industry's pipelines, demonstrating enhanced stability and endurance, and were recognized as a cost-efficient and eco-friendly alternative for combating corrosion [40].

A comprehensive review has been undertaken, building upon previous scholarly investigations, to methodically explore the diverse strategies for protecting metallic pipelines from corrosion. This review categorizes the techniques against external corrosion into passive, active, and hybrid approaches. Passive methods include the use of coatings, linings, barriers, material design innovations, electrical isolation, inhibitors, and the integration of various passive mechanisms. Active strategies involve sacrificial anodes and impressed current cathodic protection systems. When new causes of corrosion emerge or when coatings deteriorate, a combination of active and passive methods is often employed to create a more effective defense. For internal corrosion, the techniques range from internal coatings, linings, barriers, allowances for corrosion, the use of inhibitors and chemical treatments, dehydration, pigging, careful pipe material selection, and controlling the flow within the pipelines. The review thoroughly discusses the functionality, benefits, drawbacks, and limitations of these corrosion protection strategies, as well as the considerations influencing their adoption and effectiveness. This scholarly work is intended to guide researchers, industry practitioners, and the broader industrial sector in prioritizing strategies for corrosion protection. It aims to assist in selecting the most appropriate external and internal corrosion protection methods, bridging existing research gaps, and focusing on prospective research directions in this vital area [41].

In a prior study, the protective mechanism against corrosion, known as the "labyrinth effect" of composite coatings, was meticulously dissected. The genesis, structure, and attributes of graphene oxide (GO) were also comprehensively expounded upon. It was noted that a significant challenge in the application of coating fillers was the tendency of GO to exhibit poor dispersion within polymers and to aggregate as nanofillers in composite coatings. Furthermore, the discourse extended to cover the modification of GO surfaces and the enhancement of composite coatings through multifunctionalization based on GO. Despite the hurdles presently faced, such as the creation of eco-friendly modification techniques, the strategic arrangement of GO layers in composites, and the advancement of multifunctional coatings, these issues are expected to be at the forefront of future developments in GO-based anticorrosive coatings. This analytical review is deemed to be of substantial value for those in the research community who are delving into the design and utilization of GO for corrosion protection coatings[42].

In a past study, the synthesis of a self-healing coating based on polyaniline-modified epoxy resin through photopolymerization was demonstrated, which exhibited a notable resistance to water absorption, rendering it a potent anti-corrosion agent for carbon steel protection. Initially, graphene oxide (GO) was synthesized employing the modified Hummers' method and was then amalgamated with titanium dioxide (TiO2) to broaden its responsiveness to light. The structural nuances of the coating material were discerned through the application of scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FT-IR). The anti-corrosive behavior of both the innovative coating and the unadulterated resin layer was scrutinized using electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization curves (Tafel), revealing a shift in corrosion potential (Ecorr) towards more negative values in a saline environment, indicative of the photocathodic activity of TiO2. The integration of GO was shown to significantly bolster TiO2's capacity to harness light, and the presence of local anomalies or defects was observed to diminish the band gap energy, with the 2GO:1TiO2 composite manifesting a reduced Eg of 2.95 eV compared to 3.37 eV for sole TiO2. Upon irradiation with visible light, notable shifts in the Ecorr and Icorr values of the composite coatings were recorded, with the D-composite and V-composite coatings on composite substrates exhibiting protection efficiencies of approximately 73.5% and 83.3%, respectively. Subsequent analyses confirmed an enhancement in the coating's corrosion resistance when subjected to visible light, positioning this innovative material as a promising candidate for safeguarding carbon steel against corrosion [43].

In the field of materials science, a study was previously conducted where AISI 1018 steel substrates were subjected to a coating process with electroless Ni-P and Ni-P-NiTi composites of varying thicknesses, and a subsequent evaluation of their resistance to erosion, corrosion, and the combined effects of erosion-corrosion was meticulously performed. The methodology incorporated the use of slurry pot erosion-corrosion testing on the bare AISI 1018 steel, as well as on substrates coated with monolithic Ni-P and Ni-P-NiTi composites. It was discerned that the coating thickness played a pivotal role in influencing the erosion resistance, a phenomenon likely attributed to the interplay between the stress imparted by the erosive action and the inherent internal stress within the coating post-application. A marked improvement in erosion-corrosion resistance was observed with the incorporation of NiTi nanoparticles into the Ni-P matrix. The monolithic Ni-P coatings, when subjected to erosion-corrosion, predominantly exhibited pitting corrosion and cracking, whereas the Ni-P-NiTi composite coatings were characterized by a more uniform material loss. Among the tested specimens, the AISI 1018 steel substrate was identified as having the least resistance to erosion-corrosion, in stark contrast to the Ni-P-NiTi coating, which, at a thickness of 25 µm, exhibited superior resistance, underscoring the efficacy of NiTi nanoparticle addition in enhancing the durability of such coatings [44].

The aim of this past study was to evaluate the collapse pressure of steel pipelines exposed to non-uniform general corrosion and localized corrosion, where the randomness of the corrosion was a significant factor. In order to gauge the decrease in collapse pressure of offshore pipelines under external pressure, finite element analyses, accounting for non-linearities and large deformations, were utilized. Experimental results from published studies of corroded pipe samples were used to validate the numerical approach. Different degrees of corrosion deterioration on the pipeline's surface were incorporated in the finite element models. It was found that general corrosion causing an average thickness reduction of 10% led to a 10–13% decrease in the corroded pipe's collapse strength. Another scenario with general corrosion causing an average thickness reduction of 40% resulted in a significant 45% drop in the pipe's collapse strength. This demonstrates the importance of including general corrosion when estimating the residual strength of subsea pipelines. The study concluded that the pipe's ovality has a crucial role in the strength assessment, whereas eccentricity has minimal impact. The findings also demonstrated that distinct collapse modes can be triggered in pipe models with corrosion in various locations [45].

The initial review addressing the study and implementation of polyester-based coatings for steel corrosion protection is documented in this past article. It discusses the repercussions of corrosion, the challenges experienced to date, and the solutions discovered in the industrial sector. Additionally, it underscores the potential of polyesters as a viable alternative to current methodologies, such as phosphating, chromating, galvanization, and inhibitors. The categorization of polyesters and the composition of the network structure are vital factors in determining the polymer's overall applications and performance. Recent developments in green chemistry and smart, bio-based polyester coatings are presented in this review. Lastly, it covers the various applications of polyesters, with specific attention given to the use of polyesters in surface coatings and other industrial applications [46].

The outcomes of a piroir study conducted, aimed at assessing the design methodologies for contemporary composite material systems employed for the repair of hydrocarbon-transporting steel pipes exhibiting local metal loss defects (caused by corrosion and/or erosion processes), are documented in this paper. Repair technologies involving the use of composite material wraps, composed of a polymeric matrix and reinforcing fabric, are seen as beneficial alternatives to traditional techniques that necessitate welding in the corroded regions of the pipe. An examination was conducted on the efficacy and design approaches of these composite repair systems, particularly assessing the reinforcement impacts (the restoration degree of the damaged pipe's mechanical strength) that resulted from the composite wraps based on their geometrical and mechanical attributes. Finite element-based numerical models, previously devised and validated by the authors through comparison with various experimental programs executed within their university, were employed for this purpose. Different calculation methodologies, including a technique previously proposed by the authors and others suggested in the literature, for determining the dimensions (thickness and length) of the composite wrap suitable for a particular pipe were compared against numerical results. This comparison aimed to identify the most fitting solution for the design of the composite repair system. Additionally, the influence of the defect's orientation and width on the design process was also scrutinized [47].

3. METHODOLOGY

3.1 PETROLEUM PIPELINES COMPOSITE COATINGS

3.1.1 Introduction

In the petroleum pipeline sector, composite coatings have become essential for guaranteeing the durability and performance of pipelines. These carefully planned and applied coatings have two functions. First, they serve as a barrier, preserving the metal surface of the pipeline from the constant assault of corrosive substances found in the surrounding air. This is extremely important, especially considering the various and frequently difficult terrains that these pipelines cross. Second, by strengthening the pipeline's overall structural integrity, these coatings lessen the possibility of leaks or breaks that might cause environmental catastrophes. These coatings' underlying science is fascinating. For example, organic coatings cling to the metallic substrate by means of a mix of polar and mechanical bonding. The former is accomplished by using complex techniques for surface preparation. A mechanical grip or anchor is formed between the coating and the pipeline by generating an uneven surface profile, guaranteeing their unbreakable bond even in the most difficult circumstances. Conversely, polar bonding arises from the electrical attraction between the metallic surface and the polar molecules present in the coating formulations. This guarantees a tight seal, boosting the coating's protective qualities even more. Even though these coatings work incredibly well, they are not perfect. No coating, no matter how advanced, can provide a perfect defines against environmental factors like moisture. This inherent restriction highlights how crucial it is for the field to continue with research and innovation. This makes choosing the right coating system an extremely important task. To guarantee that the selected coating performs as best it can, factors including cost, exposure type, surface preparation, and operating conditions must be carefully considered. Moreover, the industry often emphasizes the value of meticulous surface preparation. Most coating failures can be traced back to hurried or insufficient surface preparation, highlighting the importance of being thorough and meticulous in this important step [48].

Figure 3.1: Plain End Coated Steel Pipe [49].

3.1.2 Materials Used in Composite Coating

Contemporary petroleum pipelines are commonly constructed using high-strength carbon steel materials to effectively endure both internal pressures and external forces. API 5L is the prevailing steel type employed for pipelines, wherein distinct designations such as X52, X60, or X70 are utilized to indicate the material's yield strength. The steel's composition is designed to provide durability against challenging environmental conditions and mechanical strains that the pipeline may encounter [50]. But these pipes need a coating to extend them life there are two famous composite coating used In these industries which are 3-Layer-Polyurethane (3LPE) and Fusion bonded epoxy (FBE) coatings.

a. 3-Layer-Polyurethane (3LPE)

The 3-layer polyethylene (3LPE) coating, which is a type of high-performance composite coating (HPCC), is a sophisticated protective solution for pipelines, particularly those in harsh northern environments. This coating system is comprised of a fusion-bonded epoxy (FBE) primer that adheres directly to the steel substrate, a chemically modified polyethylene adhesive tie layer, and a medium-density polyethylene outer layer. These three layers are meticulously bonded together to reduce the likelihood of interlayer delamination. The FBE layer, which is approximately 150 m thick, provides strong adhesion to the steel, while the polyethylene layer, which is approximately 500 m thick, provides compactness and resistance to environmental factors. The 100 m-thick intermediate polyolefin layer ensures a cohesive bond between the FBE and polyethylene layers. The combination of these layers' properties creates a coating that effectively resists water and chemical penetration, making 3LPE the material of choice for pipeline protection in demanding conditions [51].

Figure 3.2: Steel Pipe Coated by 3LPE [52].

b. Fusion bonded epoxy (FBE)

Fusion bonded epoxy (FBE) coatings have significantly transformed the pipe coating industry, offering corrosion protection for pipeline systems utilized in the production, transportation, and distribution of oil, gas, water, and petroleum products. Introduced by 3M Company in the late 1950s, the initial FBE product, Scotchkote 101, was based on a solid EPON1 resin cured with dihydrazone. While it provided exceptional corrosion resistance, its brittleness led to chipping during handling and cracking on bending, limiting its application to small-diameter pipes. However, advancements in the 1960s, particularly by Shell's Union Technical Service Laboratory, led to the development of more flexible, rapid-curing, and corrosion-resistant powder coatings based on EPON resin. By the late 1960s, a more user-friendly formulation was developed that could coat large-diameter pipes without requiring a post-cure. This balance of corrosion resistance and physical properties made FBE coatings, especially those modified with accelerators, additives, and improved pigments, the principal FBE pipe-coating systems by the 1990s [53].

Figure 3.3: Steel Pipe Coated by FBE [54].

3.2 MECHANICAL DESIGN

3.2.1 Introduction

Mechanical design is the methodical and iterative creation of a mechanical system, component, or structure that meets specified criteria and is constrained by imposed constraints. It encompasses a vast array of processes, including analysis, synthesis, and optimization. The objective of mechanical design is to produce a model that satisfies specified performance criteria, is safe and dependable, and can be manufactured at a reasonable cost [55].

3.2.2 Fundamental Concepts

a. Stress

The term "stress" refers to the quantification of the internal forces experienced by a material. This measurement quantifies the magnitude of force exerted per unit area. Within the realm of engineering, stresses are determined by considering the initial, unaltered geometric configuration. When a load is exerted, the cross-sectional area of the specimen decreases while its length increases, resulting in actual stresses that exceed the engineering stresses calculated [55].

$$\sigma = \frac{P}{A} \tag{3.1}$$

Where:

σ : True Stress

P : Applied Load

A : Cross-Sectional Area

b. Strain

Strain quantifies a material's deformation. Within a given length, the total elongation of a bar defines normal strain. Strain for a tensile specimen is calculated by dividing the length change by the initial length. When a material is subjected to a stress that is lower than its yield strength, it experiences elastic strain. Conversely, the amount of true strain is calculated by dividing the total of the incremental elongations by the gauge length that corresponds to the current load [55].

$$\epsilon = \frac{\delta}{l} \tag{3.2}$$

Where:

ϵ	:	Normal Strain
δ	:	Total Elongation of The Bar
l	:	Original Length

c. Safety Factor

The safety factor, commonly known as the factor of safety, is a quantitative parameter employed in the field of engineering to quantify the degree of strength that a system possesses beyond the minimum requirement for a given load. The inclusion of a margin in the design and analysis process allows for the accommodation of errors, uncertainties, and estimations. The factor of safety can be defined as the ratio between the allowable or ultimate load and the actual or design load. The purpose of its implementation is to ensure that the likelihood of a component experiencing failure under predetermined conditions is deemed to be within acceptable limits.

$$n = \frac{S}{\sigma} \tag{3.3}$$

Where:

n	:	Factor of Safety
S	:	Ultimate Load or Strength
σ	:	Maximum Working Stress

3.2.3 Pressure Testing Parameters

A pressure test or hydrostatic test is a method employed to assess the robustness of pipes or related components by subjecting them to pressures beyond their standard operational levels. This technique involves filling the pipe with water, elevating the water pressure for a set period, and subsequently releasing it. Commonly, this assessment is executed when the pipeline is initiated into service. However, it can also serve as a periodic check of the structure's durability following extended usage. Post-testing, it's crucial to eliminate all testing water and thoroughly dry the pipeline. Failure to do so may foster internal corrosion at water-retention sites. In some cases, nitrogen is opted for pressure testing to circumvent potential corrosion concerns [56].

The hydrostatic pressure could be found by specific tables depending on the material of pipeline or by equation below [57].

$$P_h = 1.25 \times P_{desing} \tag{3.4}$$

Where:

P_h : Hydrostatic Pressure

P_{desing} : Design Pressure

3.3 FINITE ELEMENT ANALYSIS

3.3.1 Introduction

The Finite Element Analysis (FEA) or (FEM) technique, initially introduced by Turner et al. in 1956, is a prominent computer approach that offers approximate answers for a wide range of practical engineering problems. These tasks frequently encompass complex domains characterized by precise boundary conditions. Finite Element Analysis (FEA) has emerged as an integral component of the design and modelling procedures across diverse engineering disciplines. Fundamentally, most physical phenomena occur within a continuous medium, which can manifest as either a solid, liquid, or gas state. These events encompass various field variables that exhibit positional dependence, resulting in a multitude of solutions within the given domain. Within the framework of this literary work, the term "domain" is employed to denote a continuum that possesses a clearly delineated border. Finite Element Analysis (FEA) functions by subdividing the given domain into multiple smaller components known as "elements." The solutions are subsequently estimated by employing mathematical techniques to these components. Finite Element Analysis (FEA) streamlines the computational task by dividing the domain into smaller segments and approximating the unknown field variable using predetermined functions within each segment. The functions are derived from the values of field variables that are associated with discrete locations referred to as nodes. The nodes, which are commonly located in the peripheries of the elements, serve to connect them. The indispensability of Finite Element Analysis (FEA) lies in its capability to partition and evaluate non-traditional regions, rendering it a crucial instrument for resolving boundary, initial value, and eigenvalue predicaments throughout diverse engineering domains. Since its inception, a multitude of scholarly publications and books have extensively explored the expansion and use of Finite Element Analysis (FEA). The contributions of Desai and Abel, Oden, Gallagher, Huebner, Bathe and Wilson, Ziekiewicz, Cook, and Bathe have had a significant impact on the development of contemporary Finite Element Analysis (FEA) [58].

Table 3.1: Engineering Applications of FEM [59].

Field of Study	**Engineering Applications Examples**
Structural and solid mechanics	Optimizing design of wind turbine blades, analyzing the integrity of nuclear reactor components, assessing the reliability of offshore structures, and simulating car crash scenarios represent advanced applications in engineering and safety assessment.
Heat transfer	Advanced computational simulations encompass modeling for electronics cooling, casting processes, and heat-transfer analyses within combustion engines.
Fluid flow	Advanced studies include the aerodynamic assessment of race car structures, airflow modeling within architectural designs, and analyzing seepage dynamics within porous materials.
Electrostatics/electromagnetics	Advanced computational analyses encompass field estimations in sensors and actuators, performance forecasting of antenna configurations, and evaluation of electromagnetic interference mitigation techniques.

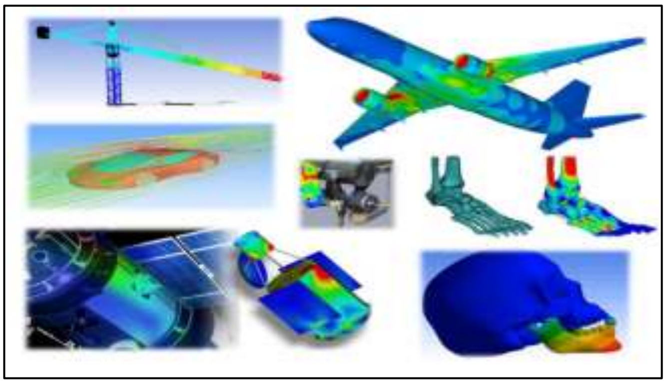

Figure 3.4: FEM Some Applications [60].

3.3.2 Finite Element Method General Steps

a. Specify and Choose the Element Types

In this phase, the structure or continuum is divided into discrete elements with associated nodes. The analyst must determine how to decompose the structure and which element type to employ for modeling. This decision is crucial because it affects the analysis's precision and efficacy. For instance, various elements may be used to model springs, bars, trusses, and so on. The element type is chosen based on the nature of the problem, the structure's geometry, and the intended level of precision [61].

b. Define Material Properties

After discretizing the structure, the next stage is to define the material properties of every element. Depending on the character of the problem, these include Young's modulus, Poisson's ratio, thermal conductivity, etc [61].

c. Use Boundary Conditions and Loads:

The model includes boundary conditions such as fixed supports, rollers, and custom constraints. These conditions determine how the structure interacts with its immediate environment. External loads such as forces, temperatures, and pressures are also exerted. These are the external factors affecting the structure [61].

d. Assemble the Element Equations

Each element's behavior is characterized by a set of equations. These equations are integrated into a larger system that represents the structure. Typically, this system of equations is expressed using matrix notation [61].

e. Find the Solutions:

Unknowns are determined by solving the resulting system of equations. Examples include displacements, stresses, and temperatures. To solve these equations, modern computational tools and software are utilized, particularly for complex models [61].

f. In post-processing:

After obtaining the solution, the outcomes are interpreted and represented graphically. This aids in comprehending the structure's behavior under the given conditions. It may entail observing contours of displacement, stress distributions, or any other pertinent result [61].

g. Validation and Modification:

If available, the obtained results are validated using experimental data or analytical solutions. If discrepancies are detected, the model may require modification. This may entail modifying the mesh, material properties, or boundary conditions [61].

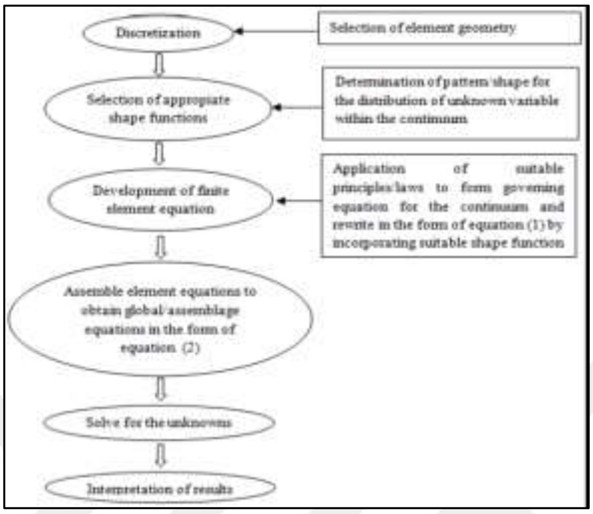

Figure 3.5: FEA Steps [62].

3.3.3 Software And Tools Used in Finite Element Analysis

Several well-established commercial and open-source software tools are available for FEA:

a. ANSYS is an advanced finite element software with a vast range of capabilities, encompassing over 100,000 lines of code. It can handle tasks ranging from static and dynamic analyses to heat transfer, fluid dynamics, and electromagnetism. Having led the FEA industry for more than four decades, ANSYS's latest version boasts a modern design featuring a user-friendly graphical interface, including dropdown menus, dialog prompts, and a streamlined toolbar. Professionals across sectors like aerospace, automotive, electronics, and nuclear commonly employ ANSYS. However, to effectively use ANSYS or any advanced FEA software, it's essential to first grasp the foundational principles and boundaries of finite element techniques. While ANSYS offers a robust platform for addressing numerous engineering challenges, using it without a clear understanding of finite element techniques is akin to a technician with an array of advanced tools but no knowledge of how a computer operates internally [63].

b. Abaqus, developed by Dassault Systems SIMULIA, stands out as a sophisticated finite element analysis software tailored for addressing complex nonlinear challenges, large-scale linear dynamics, and standard design simulations. It offers diverse capabilities, ranging from linear to nonlinear analyses, extensive deformation and interaction simulations, and a variety of analysis methods. Additionally, Abaqus is equipped with scripting options and GUI personalization features and supports an extensive array of nonlinear material models [64].

c. SOLIDWORKS Simulation: integrated into the well-known SOLIDWORKS CAD environment, is a Finite Element Analysis (FEA) tool. It offers design professionals the capacity to efficiently evaluate and refine their creations. With the backing of NAFEMS-certified FEA solvers, SOLIDWORKS Simulation delivers trustworthy and precise outcomes for various analyses, from straightforward linear static assessments to intricate nonlinear and dynamic studies. Enhance the pace of your design's refinement and prototype stages with SOLIDWORKS Simulation [65].

d. COMSOL Multiphysics is a prominent simulation software platform that analyzes data using the Finite Element Method (FEM). FEM is a numerical technique used to approximate boundary value problem solutions. COMSOL discretizes the domain of interest into a mesh of smaller, simpler shapes (often tetrahedra or hexahedra). Then, mathematical equations describing the underlying physical phenomena are applied to these tiny particles. By combining these elemental equations, COMSOL generates a system of algebraic equations that, when solved, provide an approximation of a solution over the entire domain. The software excels at handling Multiphysics problems and permits simultaneous FEM solution of coupled phenomena. The adaptability of the COMSOL method enables users to address a wide variety of engineering and scientific problems, ranging from

3.4 STRUCTURAL INTEGRITY ANALYSIS

3.4.1 Introduction

Evaluating the structural integrity of pipelines, especially under specified pressures like 1060 psi that will be used in this thesis, stands as a paramount element of petroleum engineering. This comprehensive examination dives deep into the mechanical resilience of the pipeline under such intense pressures. By scrutinizing the pipeline's behavior under these rigorous conditions, engineers can pinpoint regions that are susceptible to heightened stress or possible vulnerabilities. Such a meticulous approach serves dual purposes: not only does it unearth potential threats to the system's safety or efficacy, but it also sets the stage for proactive measures to reinforce and safeguard these potential weak zones. The overarching aim is not merely to meet industry standards but to surpass them, ensuring the pipeline's enduring performance and robustness. Rigorous structural assessments, bolstered by real-world data, play a pivotal role in averting potential financial setbacks, ecological implications, and safety risks.

3.4.2 Cad Desing Of Petroleum Pipelines

Because of the material of the pipe of study is API L5 X52, and from table in Appendix (A) the dimensions are as follows.

Table 3.2: API L5 X52 Data.

Parameter	Value
Length	3 m (section)
Size (pipe diameter	36 in or 0.914 m
Pipe wall thickness	0.406 in or 0.0103 m
Test Pressure	1060 psi or 7.3 Mpa

The hydrostatic pressure, often referred to as the test pressure, is quantified as 1.25 times the design pressure, as outlined in equation (3.4). The rationale behind this elevated pressure is to rigorously verify the structural safety of the pipeline.

Hence, the name of the test is derived from this purpose. It's important to note that the duration of this test is typically 4 hours [66].

3.4.2.1 CAD desing of petroleum pipeline without composite coating

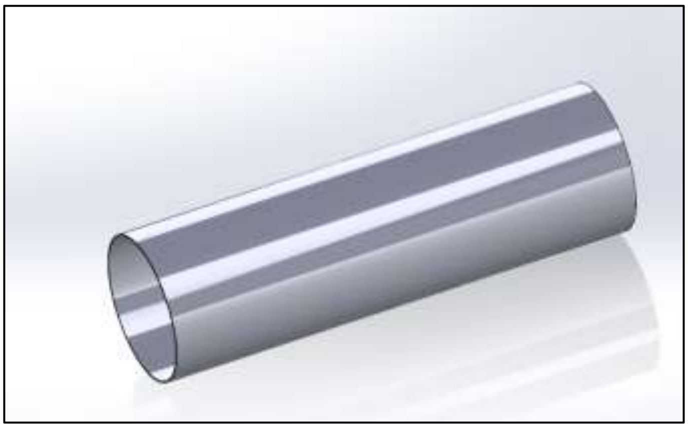

Figure 3.6: Petroleum Pipeline Model without Composite Coating.

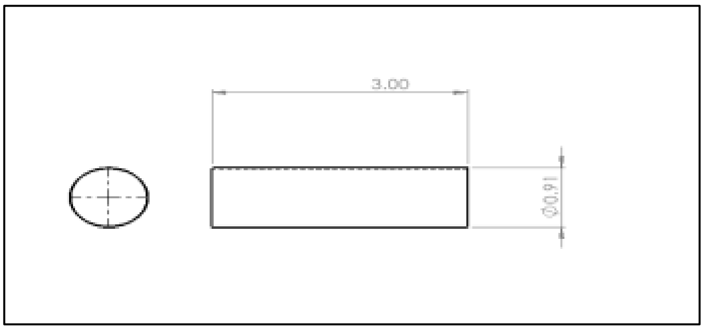

Figure 3.7: Petroleum Pipeline Drawing without Composite Coating.

3.4.2.2 CAD desing of petroleum pipeline with composite coating

Here two additional layers, each layer 5 mm thick, will be applied, one coating the inside of the tube and the other on the outside surface. These two layers will be used in both cases, with 3LPE in the first case. Then it will be changed to FBE, and the study will be conducted on each case separately. The green colour in the figure below represents the composite coating.

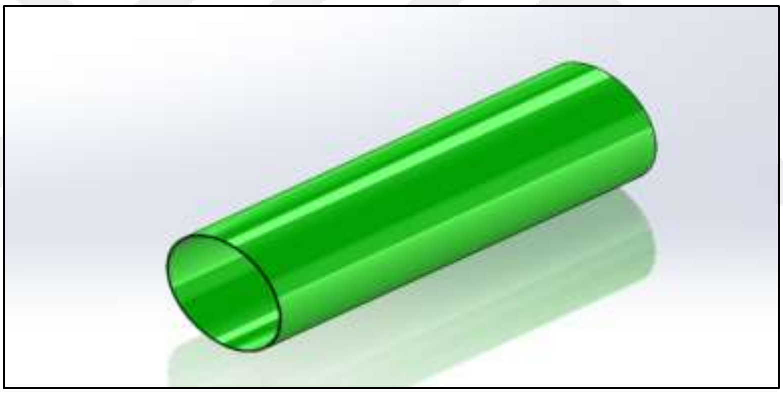

Figure 3.8: Petroleum Pipeline Model Without Composite Coating.

In the drawing below the 0.005 m represent the thickness of composite material for each surface (internal and external).

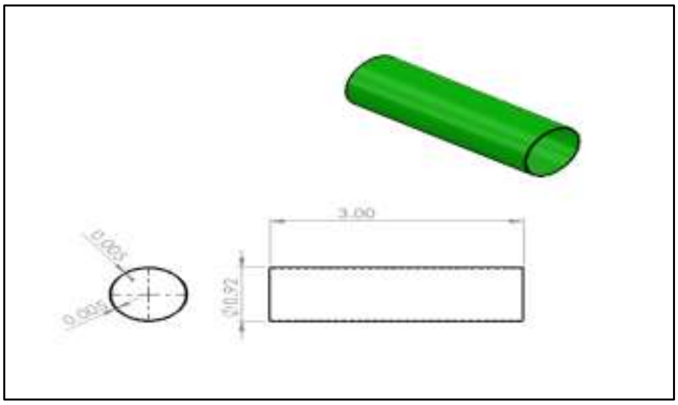

Figure 3.9: Petroleum Pipeline Drawing Without Composite Coating.

4.3.3 Analysis And Simulation

At the beginning, the three materials that will be used in this research will be defined, which are API L5 X52, Three-layer Polyethylene (3LPE), and Fusion Bonded Epoxy (FBE). Inside the Engineering Data in the ANSES materials library, where their full characteristics will be defined as in the tables below.

Table 3.3: API L5 X52 Mechanical Properties [67].

Parameter	**Value**
Yield Strength	360 Mpa
Tensile Ultimate strength	460 Mpa
Density	7850 kg/m^3
Thermal Expantion Coefficient	$12 \times 10^{-6}\ c^{-1}$
Young Modulus	200 Gpa
Poisson's Ratio	0.3

Table 3.4: Three-Layer Polyethylene Properties [68].

Parameter	**Value**
Yield Strength	25 Mpa
Tensile Ultimate strength	50 Mpa
Density	940 kg/m^3
Thermal Expantion Coefficient	$17.5 \times 10^{-5}\ c^{-1}$
Young Modulus	1.15 Gpa
Poisson's Ratio	0.45

Table 3.5: Fusion-Bonded Epoxy (FBE) Properties [69].

Parameter	**Value**
Yield Strength	50 Mpa
Tensile Ultimate strength	60 Mpa
Density	1350 kg/m^3
Thermal Expantion Coefficient	$65 \times 10^{-6}\ c^{-1}$
Young Modulus	4.2 Gpa
Poisson's Ratio	0.4

After that, the first analysis process was performed, which is the mesh process, and the results were as in the picture below.

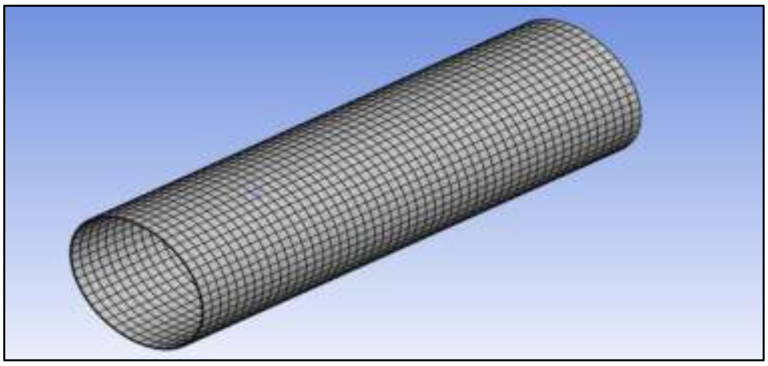

Figure 3.10: Petroleum Pipeline Mesh Result.

Mesh method: Automatic

Body sizing: 60 mm.

These settings were used for all analyzes because the tube dimensions are fixed.

For boundary conditions, Since a 3 m section was taken from the main pipeline, this means that the two ends of the pipe will be fixed supports as in figure below.

Figure 3.11: Petroleum Pipeline Supports.

As has been explained, the load here in this type of test is the hydrostatic pressure, which is equivalent to 1060 Psi.

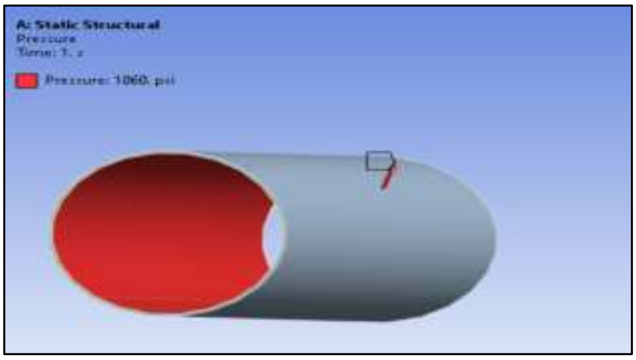

Figure 3.11: Test Pressure Inside Pipeline.

The same boundary conditions will be applied when using composite coatings, so there is no need to repeat the steps.

3.5 THERMO-STATIC STRUCTRAL ANALYSIS

3.5.1 Introduction

The transient thermal-structural analysis is a comprehensive methodology that examines the response of structures to temperature fluctuations over time, as well as the resulting stresses and deformations that occur, therefore. In contrast to steady-state or thermo-static analysis, transient analysis considers the dynamic implications of temperature variations over a period of time. For example, an aircraft wing may encounter fluctuating temperatures throughout ascent, cruising, and descent phases. It is essential to comprehend the impact of these temperature variations on the structural soundness of the wing. The study incorporates thermal parameters, including conductivity and heat capacity, in conjunction with structural variables such as modulus of elasticity and Poisson's ratio. By engaging in this practice, it offers a full perspective on probable deformations, stress concentrations, and fatigue life within the context of real-world temperature circumstances. The use of such studies is crucial in sectors such as aerospace, automotive, and energy since components are often exposed to dynamic temperature conditions.

3.5.2 Transient Thermal Analysis

In this research, in addition to the study that was conducted, which is a pressure test on the structure, which is a study that usually takes 4 hours, a long-term study will also be conducted on the design pressure in addition to the effects of temperature over a period of 15 years to examine the quality of the pipe in the presence of the composite coating, which has been explained with the previous analysis. In this analysis, the same method will be followed in terms of the mesh process, but in terms of analysis, the temperatures of the city of Basra will be added, which is the city from which this pipeline was taken, i.e., the place of study for this research, since it is a famous oil city. The city's temperatures were taken over a period of 12 months, i.e., a full year, from this site (climate-data.org) . It was assumed that temperatures in the next 15 years would be approximately the same value every month [70].

Table 3.6: Average Temperature at Al-Basra City in 2022 [70].

months	values
January	12.8°
February	15.5°
March	21°
April	27.1°
May	33.8°
June	38.3°
July	40.2°
August	40.1°
September	35.8°
October	29.6°
November	19.9°
December	14.2°

These temperatures will be entered as temperatures affecting the surface of the outer pipeline, and the type of analysis to begin with will be Transient Thermal due to temperature changes over time (Time Dependent). 180 steps will be taken, because there are 12 temperatures (1 year) and 15 years, meaning 180 steps for the software to read these steps. It is all months for 15 years.

In the figure below, the temperatures are shown for 24 months, i.e., two years. As was explained, they are 180 months (15 years), but due to the length of the list, 24 months were reviewed for clarification.

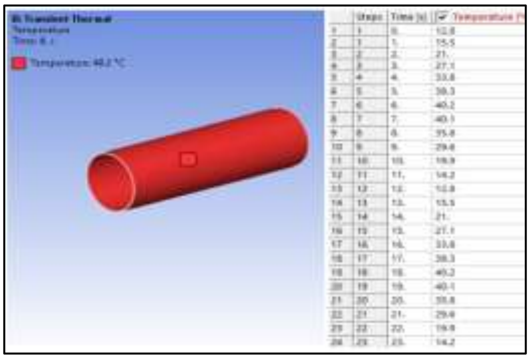

Figure 3.12: Temperature as Boundary Conditions on Petroleum Pipe Surface and Part of Steps Which are 24 Steps (Two Years).

3.5.3 Static Structural Analysis

As for the design pressure that will be used, since it is the normal pressure when making the pipe, it is calculated using the equation (3.4) that was explained previously. $1060 = 1.25 \times P_{desing}$, $P_{desing} = 848\ psi$

This value will be used in static structural analysis after getting the results of transient thermal.

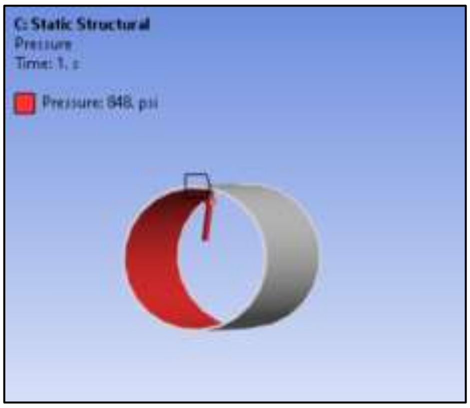

Figure 3.13: Desing Pressure Inside Pipeline.

The transient thermal analysis was linked, and the effect of temperature was transferred to the static structure, in addition to the effect of design pressure, as in the figure below.

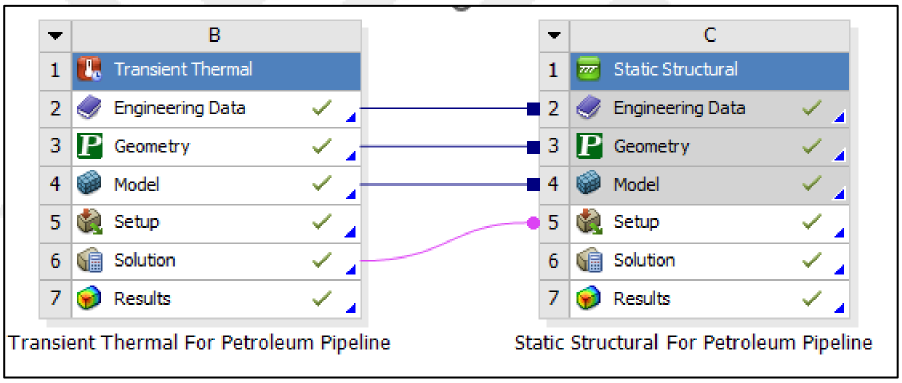

Figure 3.14: Schematic for Thermo-Static Structural Analysis.

4. RESULTS AND DISCUSSION

In this chapter, all the results related to the oil pipe will be reviewed. First, the results of the Structure integrity analysis will be reviewed in detail for the pipe in 3 cases. Then, the results of the Thermo-static Structure analysis will be reviewed in detail as well. All the results will be commented on in detail and the best tube will be chosen based on the coating material.

4.1 STRUCTURAL INTEGRITY ANALYSIS RESULTS

4.1.1 Pipeline Without Composite Coating

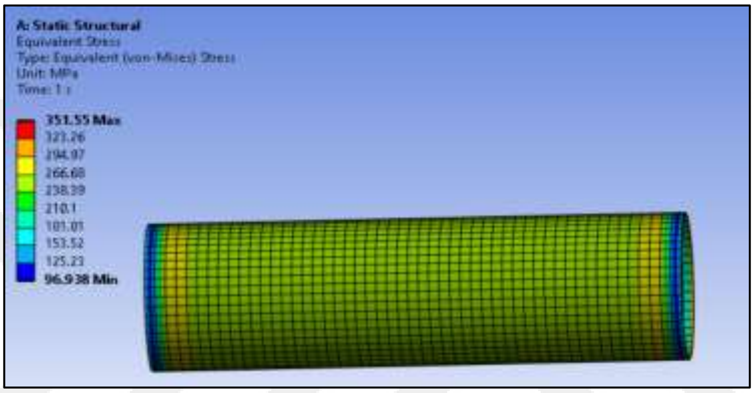

Figure 4.1: Maximum Stress on Pipeline Without Composite Coating.

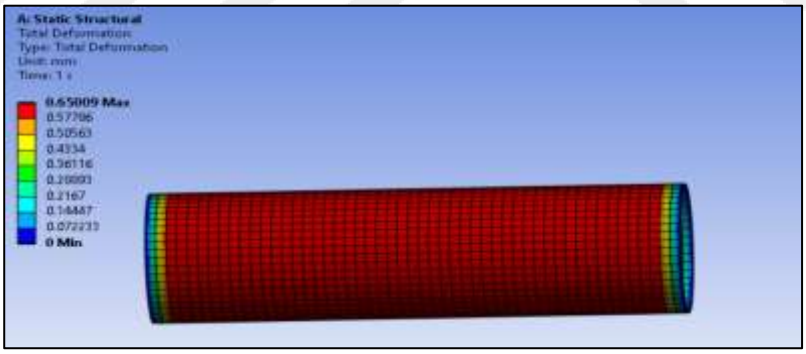

Figure 4.2: Total Deformation on Pipeline Without Composite Coating.

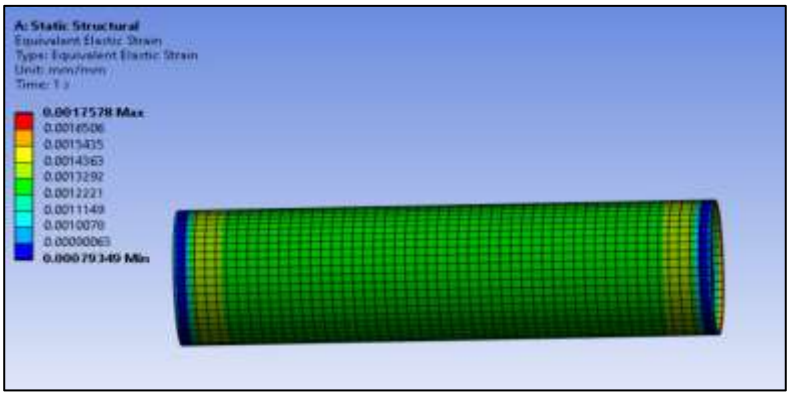

Figure 4.3: Equivelent Elastic Strain on Pipeline Without Composite Coating.

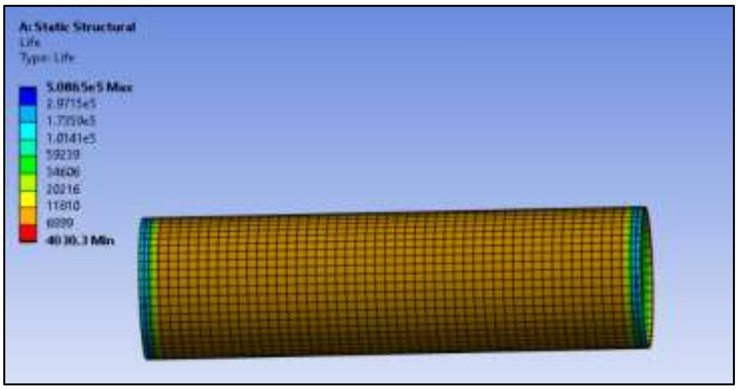

Figure 4.4: Life of Pipeline Without Composite Coating.

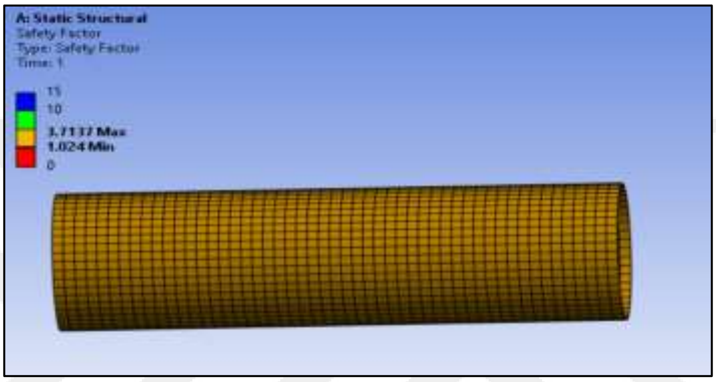

Figure 4.5: Safety Factor of Pipeline Without Composite Coating.

4.1.2 Pipeline With Fusion Bonded Epoxy (FBE) Composite Coating

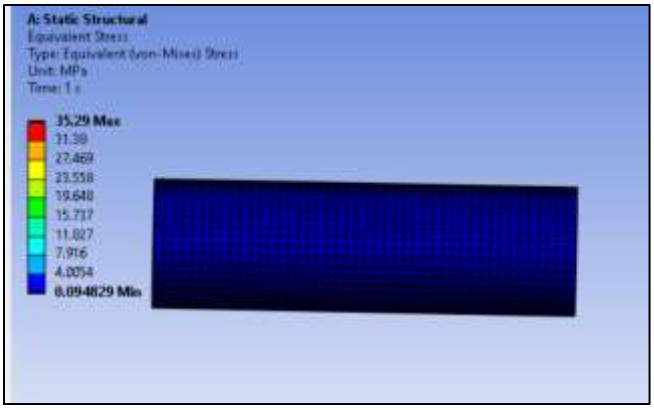

Figure 4.6: Maximum Stress on Pipeline with FBE Composite Coating.

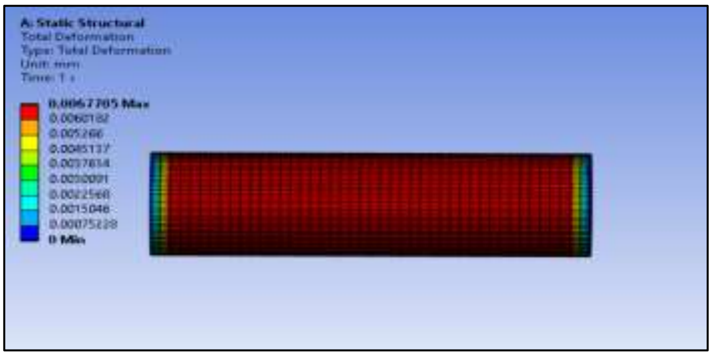

Figure 4.7: Total Deformation on Pipeline with FBE Composite Coating.

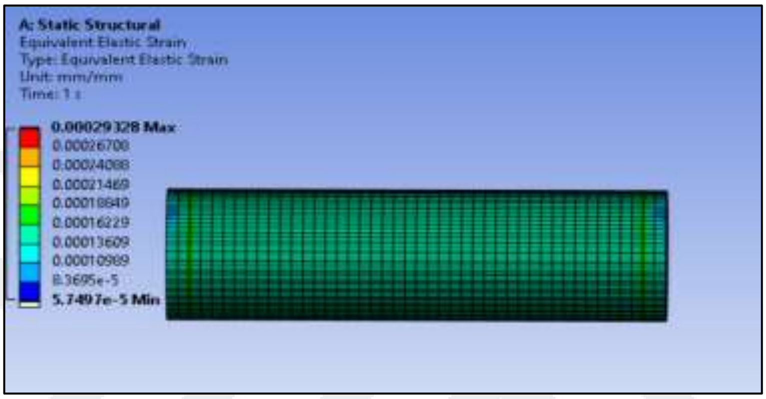

Figure 4.8: Euivelent Elastic Strain on Pipeline with FBE Composite Coating.

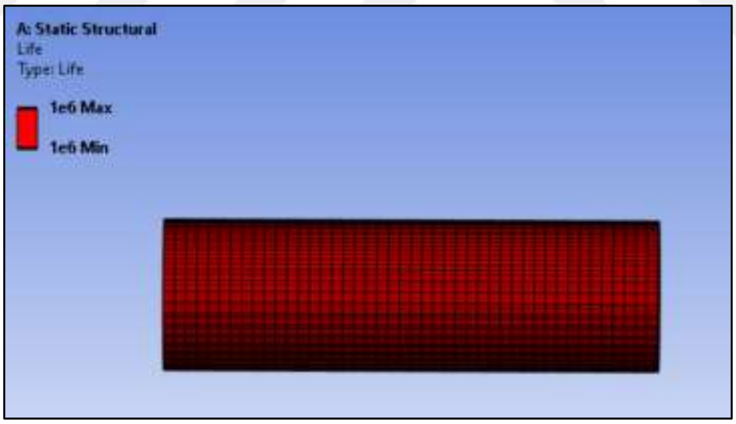

Figure 4.9: Life of Pipeline with FBE Composite Coating.

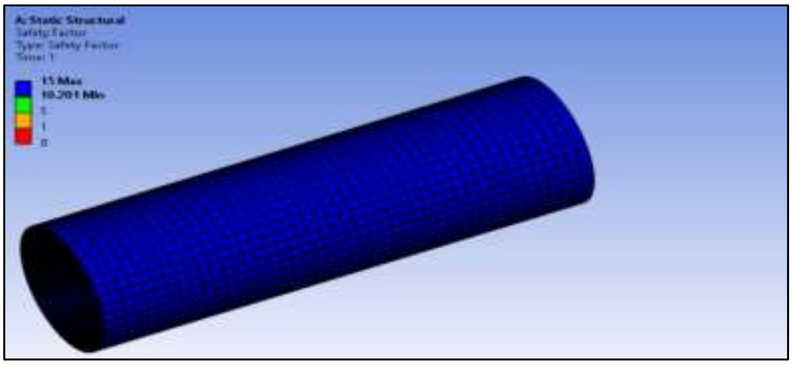

Figure 4.10: Safety Factor of Pipeline with FBE Composite Coating.

4.1.3 Pipeline With Three-layer Polyethylene (3LPE) Composite Coating

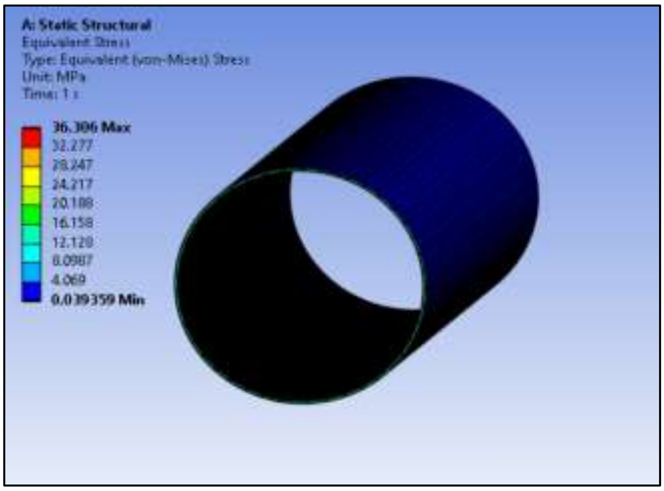

Figure 4.11: Maximum Stress on Pipeline with 3LPE Composite Coating.

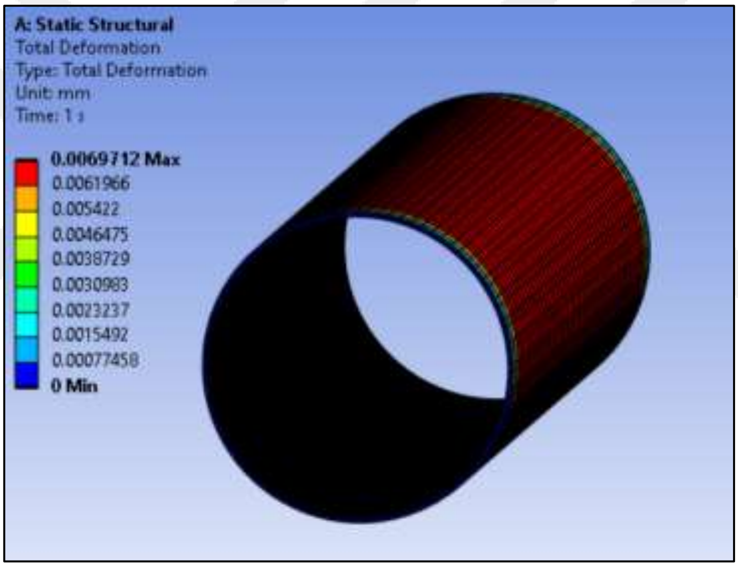

Figure 4.12: Total Deformation on Pipeline with 3LPE Composite Coating.

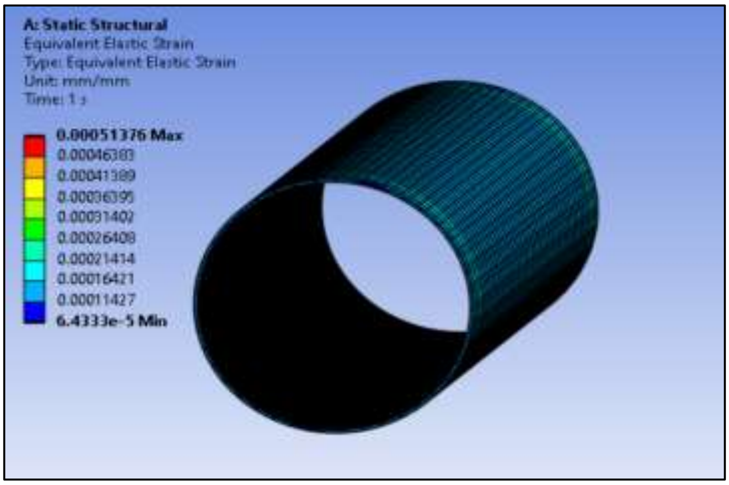

Figure 4.13: Equivelent Elastic Strain on Pipeline with 3LPE Composite Coating.

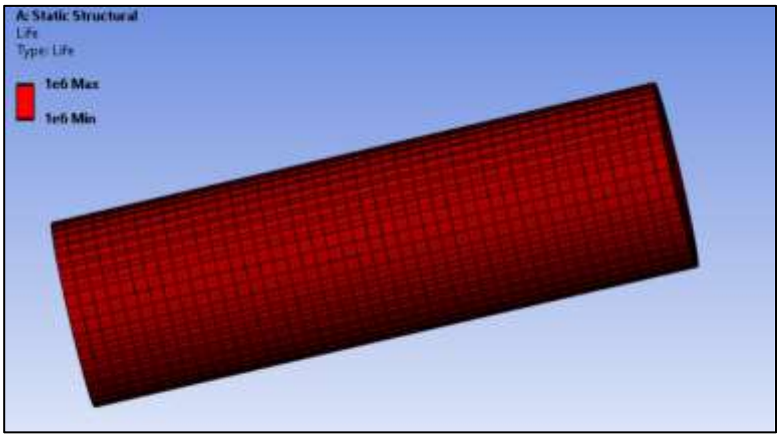

Figure 4.14: Life of Pipeline with 3LPE Composite Coating.

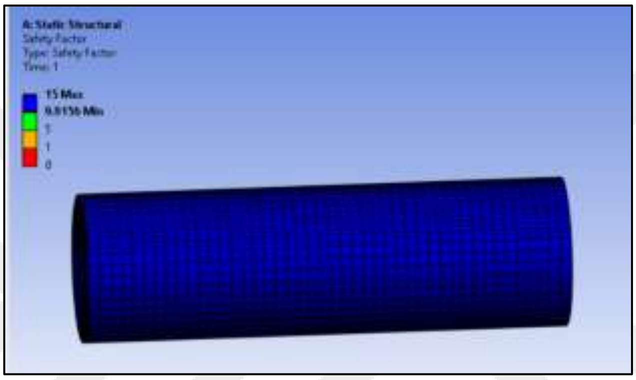

Figure 4.15: Safety factor of Pipeline with 3LPE Composite Coating.

4.2 THERMO-STATIC ANALYSIS RESULTS

4.2.1 Pipeline Without Composite Coating

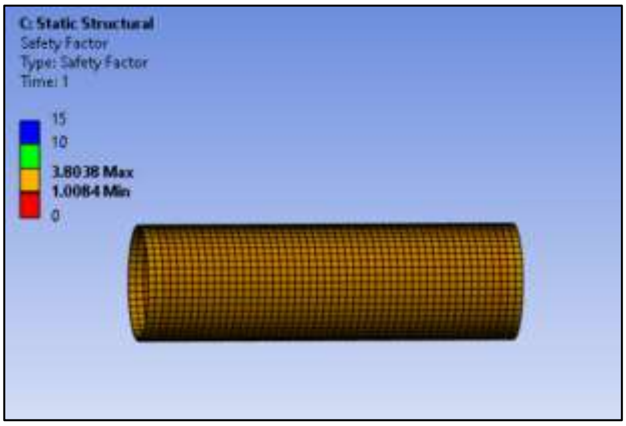

Figure 4.16: Long-Duration Safety Factor of Pipeline Without Composite Coating.

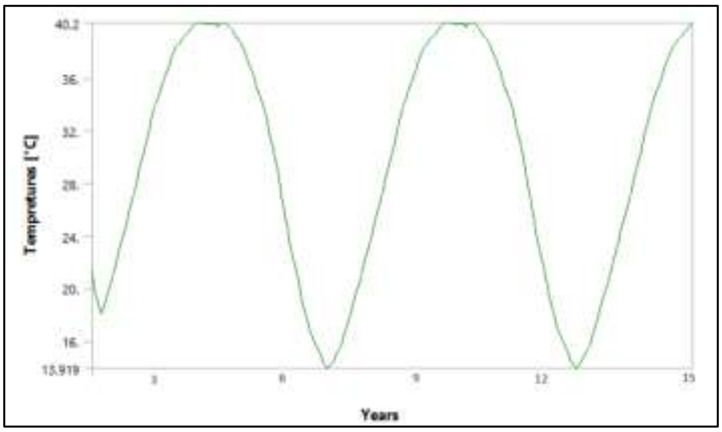

Figure 4.17: Tempreture of Pipe Surface Without Composite Coating.

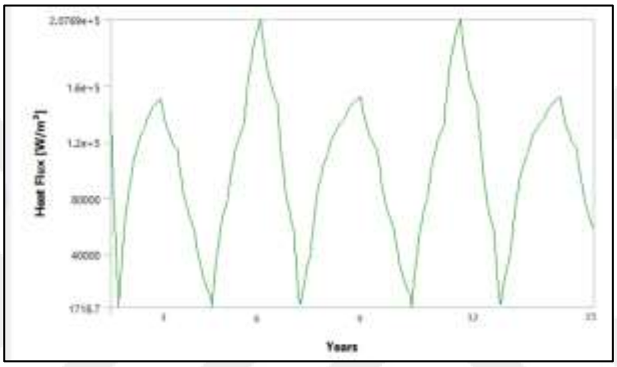

Figure 4.18: Heat Flux of Pipe Surface Without Composite Coating.

4.2.2 Pipeline With Three-layer Polyethylene (3LPE) Composite Coating

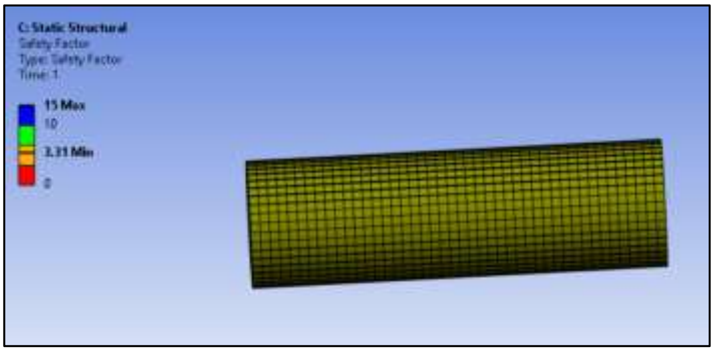

Figure 4.19: Long-Duration Safety Factor of Pipeline with 3LPE Composite Coating.

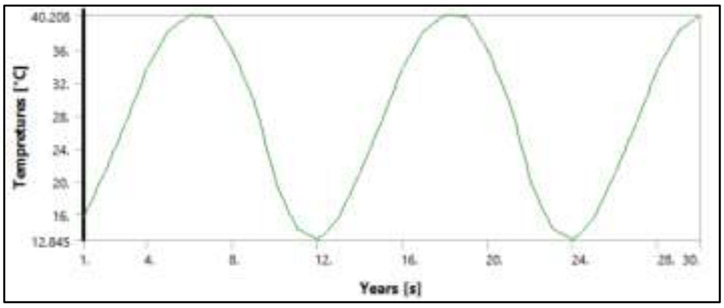

Figure 4.20: Tempreture of Pipe Surface with 3LPE Composite Coating.

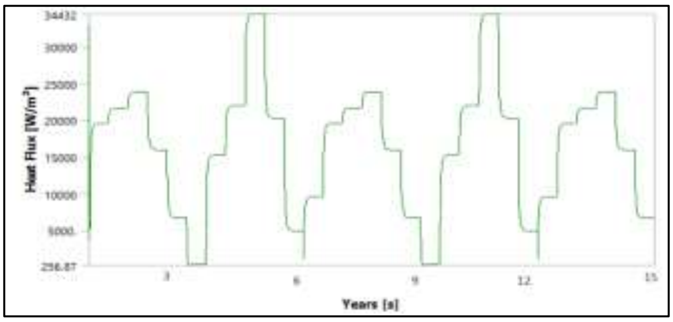

Figure 4.21: Heat Flux of Pipe Surface with 3LPE Composite Coating.

4.2.3 Pipeline With Fusion Bonded Epoxy (FBE) Composite Coating

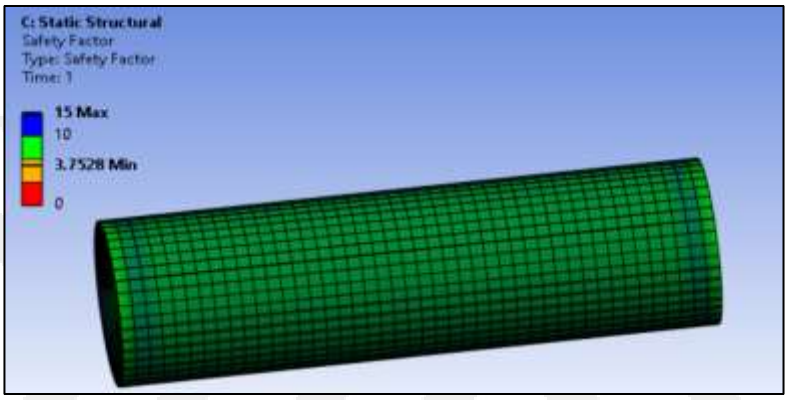

Figure 4.22: Long-Duration Safety Factor of Pipeline with FBE Composite Coating.

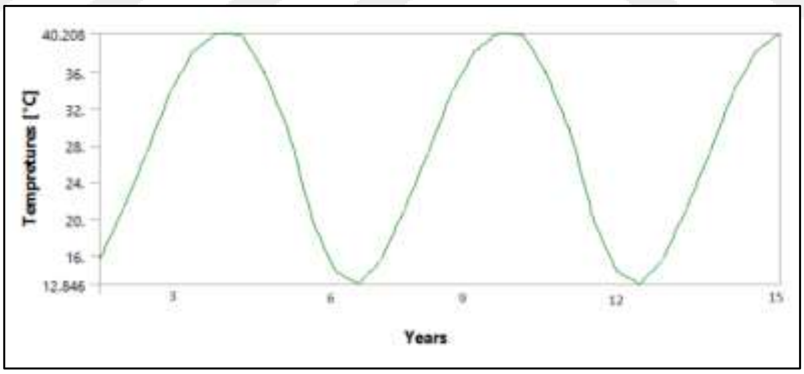

Figure 4.23: Tempreture of Pipe Surface with FBE Composite Coating.

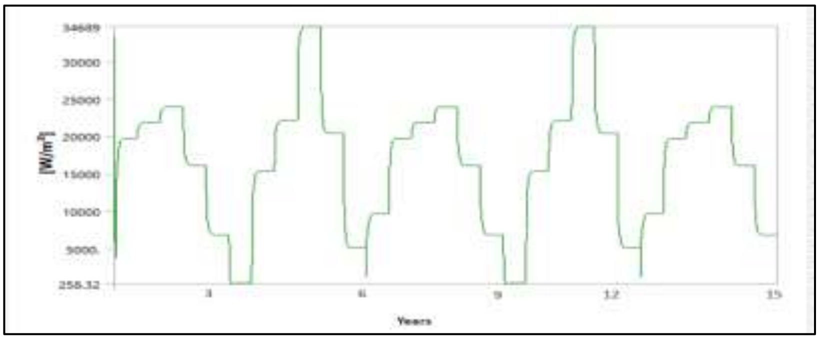

Figure 4.24: Heat Flux of Pipe Surface with FBE Composite Coating.

The performance of a petroleum pipeline is comprehensively assessed across different circumstances and coatings in the findings chapter. The Structural Integrity Analysis encompasses three separate scenarios: the pipeline in its uncoated state, the pipeline with a Fusion Bonded Epoxy (FBE) coating, and the pipeline with a Three-layer Polyethylene (3LPE) covering. In the absence of any composite covering, the pipeline demonstrates distinct degrees of stress (as seen in Figure 4.1), deformation, and strain. The analysis of the pipeline's life expectancy and safety factor, as shown in Figure 4.5, provides valuable information on its possible durability and ability to withstand unexpected pressures. Upon the application of fusion-bonded epoxy (FBE) coating to the pipeline, noticeable changes in stress (as seen in Figure 4.6), deformation, and strain measurements are observed. This implies that the FBE coating has a substantial impact on the longevity and safety margins of the pipeline, as shown by its safety factor (Figure 4.10). The 3LPE coating introduces a distinct range of performance measures, as seen in Figure 4.11, which highlights the possible benefits or obstacles associated with using 3LPE as a protective barrier. The safety factor associated with this coating is seen in Figure 4.15. The Thermo-Static Analysis involves the examination of the pipeline's response to fluctuations in temperature conditions. The long-term safety margin and surface temperature are of special importance, as they provide valuable insights into the performance and safety of the pipeline when subjected to extended periods of exposure to specified temperatures. The safety factor is consistently identified as a critical parameter in all contexts. The use of composite coatings, such as fusion-bonded epoxy (FBE) or three-layer polyethylene (3LPE) is seen to significantly contribute to the improvement of safety margins in pipelines. The significance of these coatings is further emphasized by the stress values, as they have the potential to substantially mitigate the stress encountered by the pipeline, thereby prolonging its lifespan and guaranteeing proper functionality. In summary, the findings underscore the essential significance of composite coatings in guaranteeing the longevity, security, and overall efficacy of petroleum pipelines.

5. CONCLUSION

It can be concluded from this thesis of the great importance of using composite coatings in the design of oil pipelines, as two coatings were made, one internal and one external, and two types were chosen, namely FBE and 3LPE. The fragility of these pipes was noted if no coating was used with them, even though they are made of materials designated for this purpose, but the use The composite coating increases the strength and durability of the pipe significantly and significantly. It has also been shown that using computer programs accurately and correctly leads to obtaining good results that are close to reality, but they cannot be 100% correct because they depend on finite element analysis, which is a science that gives approximate answers. However, upon observing the results and conclusions, they were largely logical, given that the life of the pipe increased after applying the composite coating.

It is recommended in the future to conduct the experiment on the ground by applying two paints, i.e. the same as what was done here, but by conducting the experiment on the ground with the same conditions and specifications that were specified in this research. Another recommendation is to use other composite coatings and reduce or increase the thickness of the coatings and conduct the same studies and explain the important conclusions.

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APPENDIX A

PIPE SPECFICATIONS

A.1 API L5 X52 DIMINSIONS AND SPECFICATIONS

Table 0.1: Plain-end Line Pipeline Specifications and Test Pressures for API L5 X52 [50].

Size	(in.)	(in.)	(lb/ft)	(in.)	Pressure test values
34	34.000	0.688	245.00	32.624	1890
34	34.000	0.750	266.58	32.500	2060
34	34.000	1.000	352.77	32.000	2750
34	34.000	1.062	373.94	31.876	2920
36	36.000	0.250	95.54	35.500	650
36	36.000	0.312	119.03	35.376	810
36	36.000	0.344	131.12	35.312	890
36	36.000	0.375	142.81	35.250	980
36	36.000	0.406	154.48	35.188	1060

APPENDIX B

Al-BASRA TEMPRETURES

B.1 AL-BASRA TEMPRETURES IN 2022

Table 0.1: AL-Basra City Temperatures in 2022 [70].

Month	Avg Temperature	Min Temperature	Max Temperature
January	12.8	7.5	18.4
February	15.5	9.4	21.6
March	21	13.9	27.7
April	27.1	19.5	33.8
May	33.8	25.8	40.6
June	38.3	30.5	45.2
July	40.2	32.6	47
August	40.1	32.3	47.2
September	35.8	28	43.2
October	29.6	22.5	36.6
November	19.9	14.3	25.7
December	14.2	9.1	19.7