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# Numerical Thermal and Structural Analysis for Enhanced Durability in Petroleum Pipelines Using Composite Coatings

Saif Al-Safi[1], Yaser Alaiwi[1], Hasan Mulki[2], Ahmad Jundi[3,*], Saleh Mahmoud[2], Ahmed Al-Hasan[4]

[1] Department of Mechanical Engineering, Altinbas University, Istanbul 34217, Turkey
[2] College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait
[3] Department of Mechanical Engineering, Istanbul University-Cerrahpaşa, Istanbul 34320, Turkey
[4] Department of Civil Engineering, Istanbul Gelişim University, Istanbul 34310, Turkey

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**ABSTRACT**

This research investigates the effectiveness of composite coatings in preventing corrosion in petroleum pipelines, focusing on computational methods for thermal and structural analysis. A 3-meter section of a Basra, Iraq pipeline was selected for evaluation. The study begins by establishing a baseline with an uncoated pipeline, followed by applying composite coatings both internally and externally. Finite Element Analysis (FEA) is used to assess structural integrity under high pressure and to perform a detailed numerical heat transfer analysis over a 15-year operational period. The thermal analysis evaluates the temperature distribution and thermal stresses that contribute to coating degradation and pipeline failure. By integrating Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE), this study demonstrates the critical role of advanced computational tools in modeling heat transfer phenomena and enhancing pipeline safety and durability. The findings provide actionable insights for optimizing coating technologies with a focus on thermal performance in real-world applications.

## 1. Introduction

The recent expansion of the global pipeline network, driven by the growing demand to transport fluids from extraction to end-use locations, has significantly increased the construction of pipelines that often traverse environmentally sensitive or densely populated areas while transporting hazardous materials. This expansion correlates with a sharp rise in oil production costs and the prices of chemicals and industrial goods, positioning the pipeline industry as a vital, multibillion-dollar global sector. Innovations in products, technologies, and standards continuously shape this industry, with a strong focus on improving economy, safety, and reliability, while also adapting to new roles, such as transporting hydrogen, storing carbon dioxide, and exploring alternative fuel options [1].

Despite these advancements, maintaining pipeline integrity remains a significant challenge, with third-party damages being a leading cause of failures, especially in European gas pipelines [2].

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[*] *Corresponding author.*
*E-mail address: ahmadt.a.jundi@ogr.iuc.edu.tr (Ahmad Jundi)*

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Unintentional release of content due to blockages, equipment failure, or failure to meet delivery requirements adds to the operational complexities faced by the industry. Natural phenomena such as earthquakes, landslides, and material defects also pose substantial risks to pipeline functionality [3]. The oil and gas sector also grapple with corrosion and fatigue issues, as pipeline materials are constantly exposed to harsh conditions, including the presence of CO2 and H2S, as well as elevated temperatures and pressures [4]. These conditions necessitate in-depth research and careful material selection to combat problems like Sulfide Stress Cracking (SSC) and CO2 corrosion, which are crucial to ensuring long-term pipeline integrity and safety.

Corrosion remains one of the most critical concerns in oil and gas pipeline systems, with various chemical mechanisms and numerous corrosion phenomena playing a significant role in pipeline degradation. A thorough examination of affordable contemporary technological solutions has determined that employing both corrosion inhibitors and protective coatings together significantly prolongs the lifespan of oil and gas infrastructure, compared to relying solely on batch inhibition. However, extensive consultations with process, operations, materials, and corrosion experts within the industry are advised to prevent massive financial losses due to corrosion [5].

Recent studies have explored integrating iron titanium oxide particles as nanoscale fillers in various concentrations into epoxy coatings to enhance corrosion resistance and chemical resilience. Electrochemical behavior of these modified epoxy films on steel, when subjected to high salinity fluids, has demonstrated superior protection compared to traditional coatings, marking an important advance in protective coatings technology [6]. Further research has examined graphene-modified anticorrosion coatings, which feature an epoxy primer, and a polyurethane top layer enriched with reduced graphene oxide, applied on aluminum alloy substrates. The inclusion of graphene oxide has shown positive results in mitigating coating porosity and enhancing corrosion resistance [7].

In addition, contemporary progress in graphene oxide-based composite coatings for corrosion defense in steel and copper-nickel alloys across diverse industrial settings has been extensively reviewed. Case studies demonstrate enhanced corrosion prevention across various compositions, highlighting their current and potential applications in key sectors [8]. The anti-corrosion mechanism of composite coatings, attributed to the so-called "labyrinth effect," has also been explored, with particular attention to graphene oxide-based coatings. However, current challenges related to processing and dispersion, alongside surface modification techniques, still impede progress. Further refinement is required to achieve well-organized and multifunctional composite configurations [9].

In petroleum pipeline engineering, significant advancements have been made with the use of composite coatings such as Three-Layer Polyethylene (3LPE) and Fusion Bonded Epoxy (FBE) to improve pipeline safety and durability. These coatings are essential for preventing corrosion and extending the service life of pipelines. However, despite these developments, a notable research gap exists in the application of computational modeling and numerical analysis to evaluate the long-term impact of these coatings on pipeline structures. Most studies to date have primarily focused on laboratory tests and theoretical analyses, without fully exploring the potential of specific software programs for in-depth modeling and simulation. This gap underscores the need for more detailed studies utilizing computational tools to better predict and enhance the safety and longevity of pipelines with composite coatings. Addressing this gap could lead to significant improvements in the selection and application of coatings for petroleum pipelines.

Addressing the critical need for enhanced pipeline durability, this research employs advanced computational modeling to evaluate the performance of two composite coatings—Fusion Bonded Epoxy (FBE) and Three-Layer Polyethylene (3LPE)—on a section of petroleum pipeline. The study assesses these coatings' ability to improve structural integrity, reduce stress concentrations, and enhance long-term durability under operational conditions that mirror real-world scenarios. By comparing coated and uncoated pipeline models under realistic thermal and mechanical loads, examining the effects of coating composition, thickness, and location on the pipeline's resilience and lifespan, and providing actionable insights through numerical simulations, the research supports optimal coating selection for industrial applications. These objectives are pursued using sophisticated computational tools, with further details on methodology, scenarios, and parameters discussed in the subsequent sections.

## 2. Methodology

This study uses computer simulations to evaluate composite coatings for corrosion protection in oil pipelines. Specifically, Finite Element Analysis (FEA) is applied to a 36-inch API 5L X52 pipeline model subjected to hydrostatic testing at 1060 psi. Various coating materials and configurations are tested to assess improvements in mechanical strength and safety factors. The simulation process examines stress, strain, and deformation in both uncoated and coated pipeline models under the applied pressure. This approach allows for the early identification of potential weaknesses and failure risks. The following sections provide detailed information on the coatings used, modelling parameters, boundary conditions, and the Multiphysics simulations performed. SOLIDWORKS will be used for the pipe design due to its ease of use and accuracy in design processes. As for the analyses, ANSYS will be utilized to conduct both the integrity analysis and the thermo-static analysis, as it provides the necessary tools for these purposes, making it an ideal choice for such applications [10,11].

### *2.1 Composite Coatings in Petroleum Pipelines: Materials and Applications*

Composite coatings are essential in the petroleum pipeline industry due to their ability to enhance durability and performance. These coatings serve two primary functions: preventing corrosion by protecting the metallic surface from external elements and improving structural integrity to prevent leaks [12]. The effectiveness of these coatings depends on the strong adhesion between the coating material and the pipeline surface [13]. However, a significant limitation is their inability to create an entirely impermeable barrier against moisture ingress. This challenge necessitates ongoing innovation to develop optimal coating systems that consider factors such as cost, exposure conditions, and surface preparation.

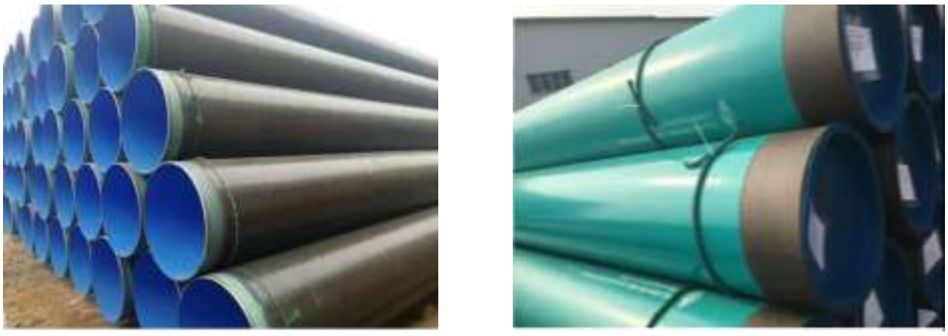
The two most widely used composite coatings for modern high-strength carbon steel pipelines, according to the API 5L standard, are Three-Layer Polyethylene (3LPE) and Fusion Bonded Epoxy (FBE) [14].

3LPE coatings consist of three layers:

i) FBE Primer Layer: A corrosion-resistant Fusion Bonded Epoxy layer that strongly adheres to the steel substrate.
ii) Polyethylene Adhesive Middle Layer: Provides additional bonding and flexibility.
iii) Polyethylene Top Layer: Resistant to chemicals and moisture ingress, offering superior protection against environmental factors [15].

FBE coatings have been transformative for pipeline protection due to their flexibility, rapid curing ability, and exceptional bonding with the steel substrate. These properties enable effective corrosion defense across a wide range of pipeline applications, enhancing both safety and longevity [16].

Ongoing advancements in composite coating technologies aim to address their current limitations by improving moisture resistance and adapting to diverse environmental conditions. This continuous improvement is crucial for maintaining the integrity and reliability of petroleum pipelines in increasingly challenging operational landscapes. Figure 1 below shows a steel pipe coated with 3LPE and a steel pipe coated with FBE.



(a) (b)

**Fig. 1.** (a) Steel Pipe Coated by 3LPE [17], (b) Steel Pipe Coated by FBE [18]

### 2.2 Mechanical Analysis of Pipeline

In this study, mechanical equations are critically analyzed using a passive voice structure, emphasizing their impact on pipeline coatings:

Stress is measured to understand how coatings withstand forces, crucial for maintaining structural integrity. It can be calculated by equation below [19]:

$$\sigma = \frac{\mathrm{P}}{\mathrm{A}} \tag{1}$$

Strain is assessed to evaluate coatings' deformation under stress, vital for their adaptability to pipeline dynamics. It can be calculated by equation below [19]:

$$\epsilon = \frac{\delta}{l} \tag{2}$$

Safety factor is calculated to ensure coatings exceed the minimum strength requirements, providing a safety margin. It can be calculated by equation below [19]:

$$n = \frac{S}{\sigma} \tag{3}$$

Hydrostatic pressure testing is conducted to validate the coating’s performance under elevated pressures. It can be calculated by the equation below [20].

$$P_h = 1.25 \times P_{\text{design}} \tag{4}$$

### 2.3 Structural Integrity Analysis

Assessing the structural integrity of petroleum pipelines under high-pressure conditions is crucial for identifying potential weak points susceptible to extreme stress and guiding reinforcement strategies. In this study, a 36-inch pipeline section was simulated under a pressure of 1060 psi to replicate real-world operational demands. Both composite-coated and uncoated pipelines were modeled to compare their performance under these conditions. Analyzing pipeline behavior under such stringent pressures is essential for enhancing safety margins, increasing durability, minimizing ecological impacts, and preventing financial losses due to pipeline failures. The primary objective of this research is to surpass existing industry standards by conducting rigorous computational assessments supported by empirical field data and evidence.

### *2.3.1 CAD Desing of Petroleum Pipelines*

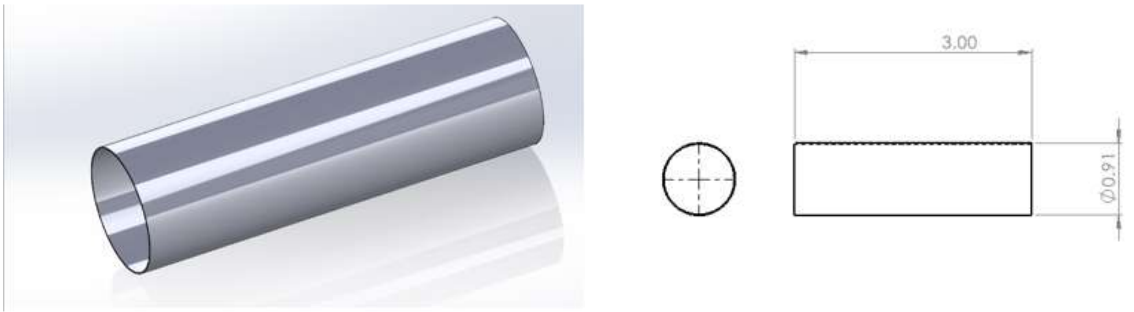
The study focuses on API L5 X52 material for pipeline construction. Detailed dimensions of this material are provided in the following reference [14]. Table 1 below shows the data of the API L5 X52 pipelines.

**Table 1**
API L5 X52 pipeline 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 test, set at 1.25 times the design pressure as per Equation (4), is conducted to assess the pipeline's structural integrity thoroughly. This test, typically lasting 4 hours, ensures the pipeline's robustness under elevated pressures [21].

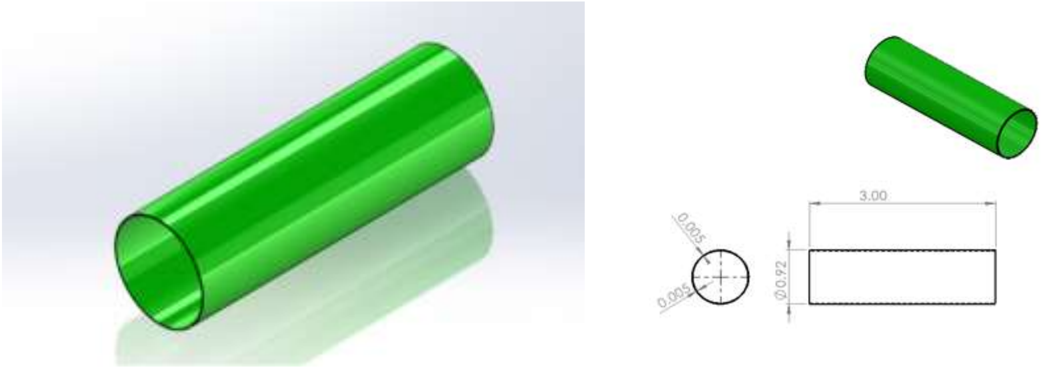
Figure 2 show the pipeline design and its dimensions without composite coating in the Figure 2(a) and with composite coating (green layer) in the Figure 2(b).



(a) (b)

**Fig. 2.** Petroleum pipeline model, (a) without composite coating model and (b) its dimensions

Figure 3 shows 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 color in the figure below represents the composite coating.



(a) (b)

**Fig. 3.** Petroleum Pipeline model with composite coating model and its dimensions

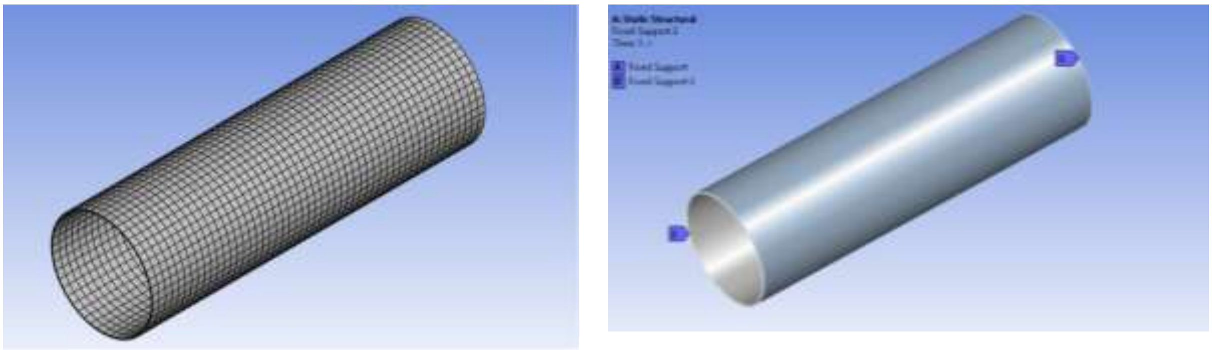
### 2.3.2 *Pipelines Analysis and Simulation*

The initial phase of the research involves defining the properties of three materials: API L5 X52, Three-layer Polyethylene (3LPE), and Fusion Bonded Epoxy (FBE). Their detailed characteristics will be outlined using the Engineering Data in the ANSES materials library, as indicated in the subsequent tables. Table 2 below shows the mechanical and physical characteristics of API L5 X52, 3LPE, and FBE.

**Table 2**
API L5 X52, 3LPE, and FBE properties [22-24]

| Property | API L5 X52 | 3LPE | FBE |
|---|---|---|---|
| Yield strength (mpa) | 360 | 25 | 50 |
| Tensile ultimate strength (mpa) | 460 | 50 | 60 |
| Density (kg/$m^3$) | 7850 | 940 | 1350 |
| Thermal expansion coefficient ($c^{-1}$) | $12 \times 10^{-6}$ | $17.5 \times 10^{-5}$ | $65 \times 10^{-6}$ |
| Young modulus (gpa) | 200 | 1.15 | 4.2 |
| Poisson's ratio | 0.3 | 0.45 | 0.4 |

The initial stage of analysis involved mesh processing, with the results illustrated in the Figure 4 below. This process utilized an automatic mesh method and a uniform body sizing of 60 mm, suitable for all analyses due to the fixed dimensions of the pipeline. The boundary conditions were established based on a 3-meter section of the main pipeline, with both ends supported as fixed, as shown in the Figure 4 and 5. This setup reflects the actual conditions and constraints of the pipeline section under study.



(a) (b)

**Fig. 4.** (a) Petroleum pipeline mesh result, (b) Petroleum pipeline supports

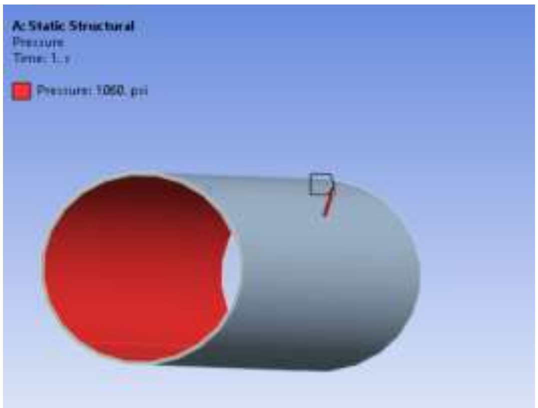


**Fig. 5.** Test pressure inside pipeline

### *2.4 Thermo-Static Structural Analysis*

This study performs a transient thermal-structural analysis to evaluate the pipeline's behavior under varying temperatures over time, focusing on the resulting stresses and deformations. Unlike steady-state analysis, which assumes constant temperature conditions, transient analysis accounts for temperature fluctuations, which are critical in real-world applications where components experience dynamic thermal environments. By integrating thermal properties with structural factors, this analysis provides detailed insights into deformations, stress concentrations, and material fatigue under realistic temperature conditions. This approach is essential for understanding and enhancing the pipeline's resilience in changing thermal scenarios.

In this research, a comprehensive transient thermal analysis is conducted over a 15-year period to assess the pipeline's structural integrity under both design pressure and the temperature variations typical of Basra City as in Table 3 below. Climate data is utilized to apply realistic temperature changes as external conditions, enabling the evaluation of the pipeline's long-term performance, especially when equipped with composite coatings. The analysis involves a 180-step transient thermal simulation to model the 15-year period, followed by a static structural analysis using the design pressure calculated from Eq. (5). This methodology combines the effects of temperature variations and design pressure to evaluate the pipeline's structural resilience over its intended service life.

$$P_{\text{design}} = \frac{P_h}{1.25} = 848\, psi \tag{5}$$

**Table 3**
Average temperature at Al-Basra City in 2022 [25]

| 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° |

Figure 6 below shows boundary conditions on the petroleum pipe surface for temperature (24 Steps, Two Years) and design pressure inside the pipeline.

| | Steps | Time [s] | ☑ Temperature [° |
|---|---|---|---|
| 1 | 1 | 0. | 12.8 |
| 2 | 1 | 1. | 15.5 |
| 3 | 2 | 2. | 21. |
| 4 | 3 | 3. | 27.1 |
| 5 | 4 | 4. | 33.8 |
| 6 | 5 | 5. | 38.3 |
| 7 | 6 | 6. | 40.2 |
| 8 | 7 | 7. | 40.1 |
| 9 | 8 | 8. | 35.8 |
| 10 | 9 | 9. | 29.6 |
| 11 | 10 | 10. | 19.9 |
| 12 | 11 | 11. | 14.2 |
| 13 | 12 | 12. | 12.8 |
| 14 | 13 | 13. | 15.5 |
| 15 | 14 | 14. | 21. |
| 16 | 15 | 15. | 27.1 |
| 17 | 16 | 16. | 33.8 |
| 18 | 17 | 17. | 38.3 |
| 19 | 18 | 18. | 40.2 |
| 20 | 19 | 19. | 40.1 |
| 21 | 20 | 20. | 35.8 |
| 22 | 21 | 21. | 29.6 |
| 23 | 22 | 22. | 19.9 |
| 24 | 23 | 23. | 14.2 |

(a) (b)

**Fig. 6.** (a) Boundary conditions on petroleum pipe surface for temperature (24 Steps, Two Years), (b) Design pressure inside pipeline

Figure 7 below shows Schematic of thermo-static structural analysis.

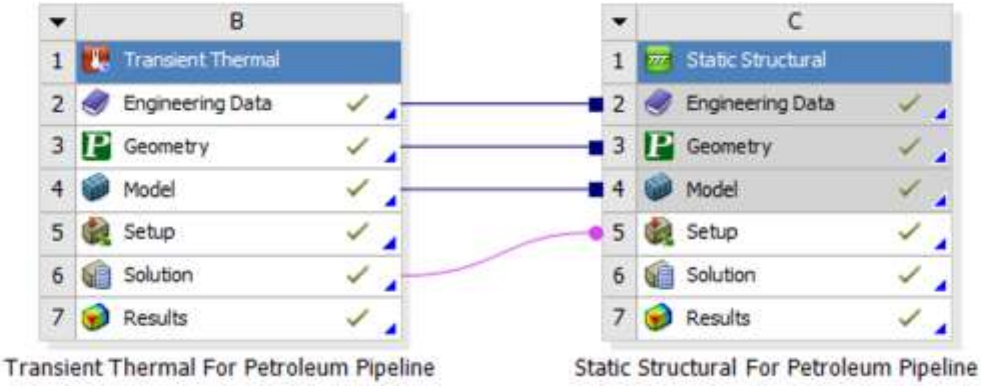


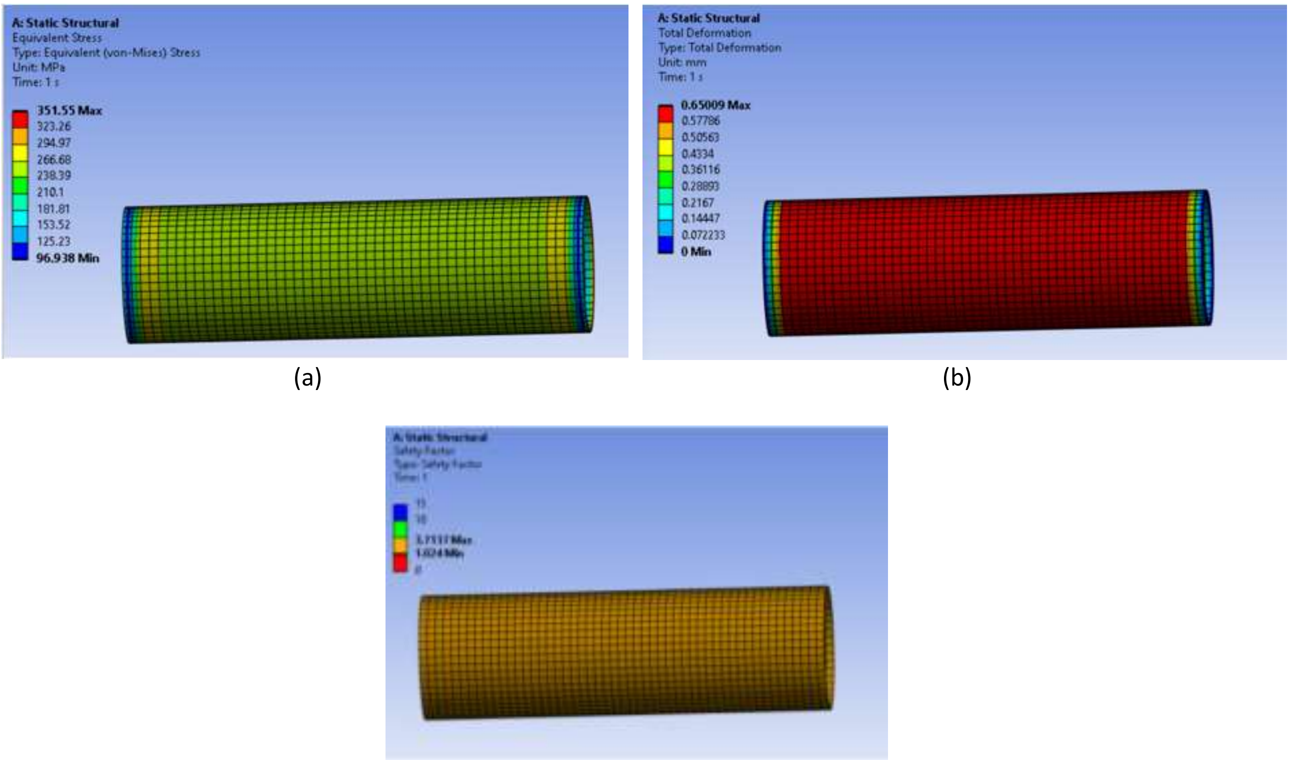
**Fig. 7.** Schematic of thermo-static structural analysis

## 3. Results

In this section, the results that have been achieved will be reviewed. First, the results of the CFD analysis will be reviewed, and then the results of the FSI will be fully reviewed and commented on.

### *3.1 Structural Integrity Analysis Results*

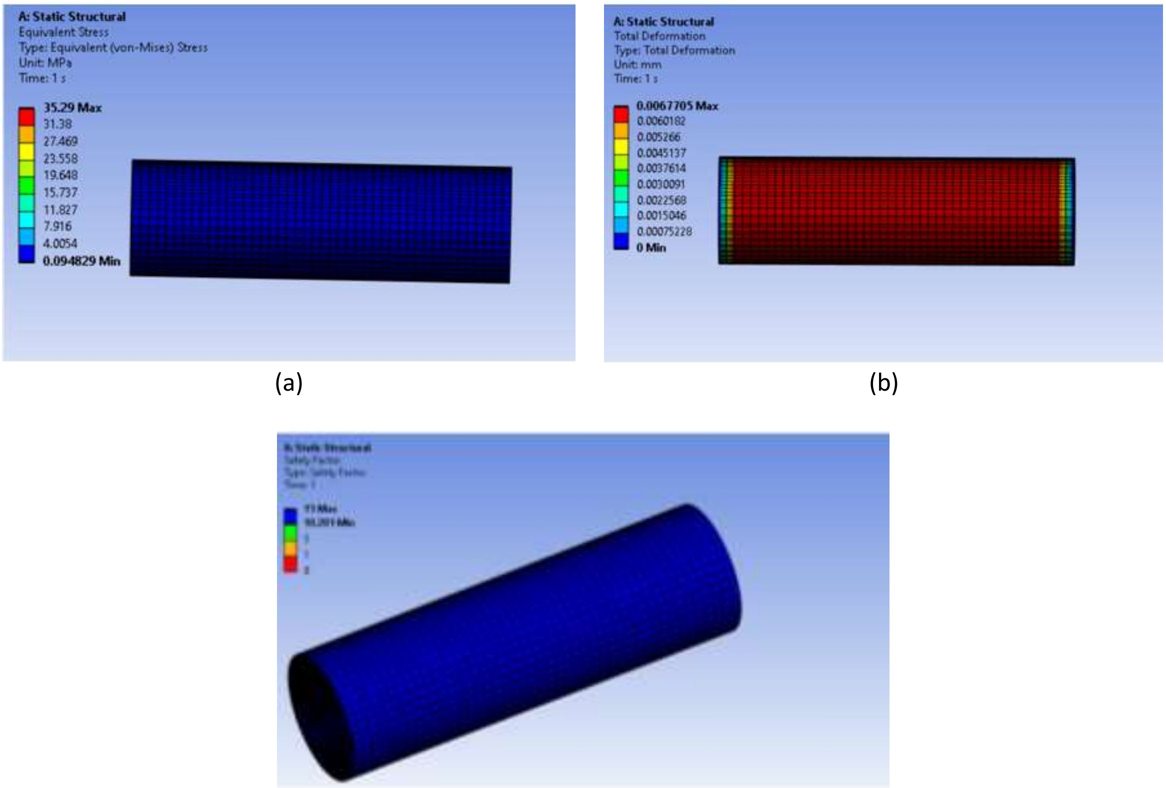
Figures 8, 9, and 10 below show the structural integrity analysis results for three case studies. Figure 8 presents the results for the pipeline without a composite coating, Figure 9 shows the results when using an FBE composite coating, and Figure 10 shows the results when using a 3LPE composite coating.



(a) (b)

(c)

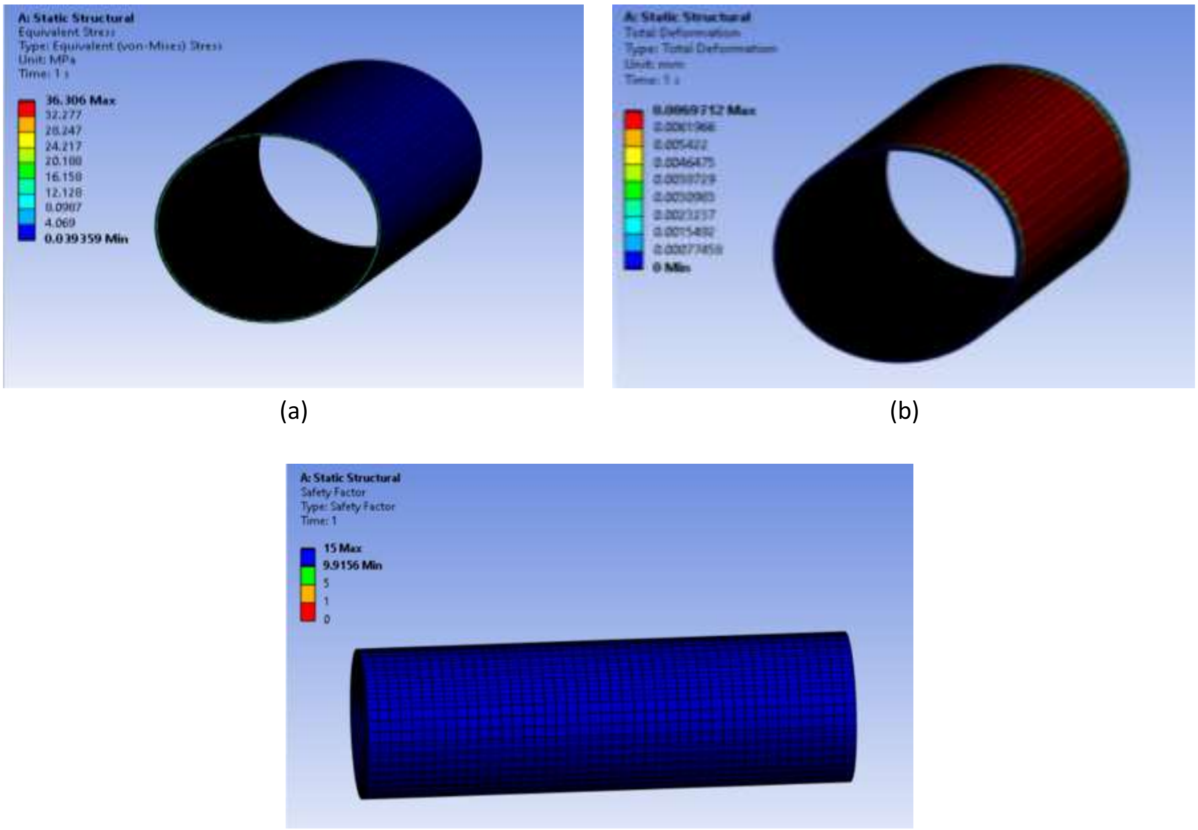
**Fig. 8.** Analysis of pipeline without composite coating - (a) Total deformation, (b) Maximum stress, (c) Safety factor



(a) (b)

(c)

**Fig. 9.** Analysis of pipeline with FBE composite coating - (a) Total deformation, (b) Maximum stress, (c) Safety factor



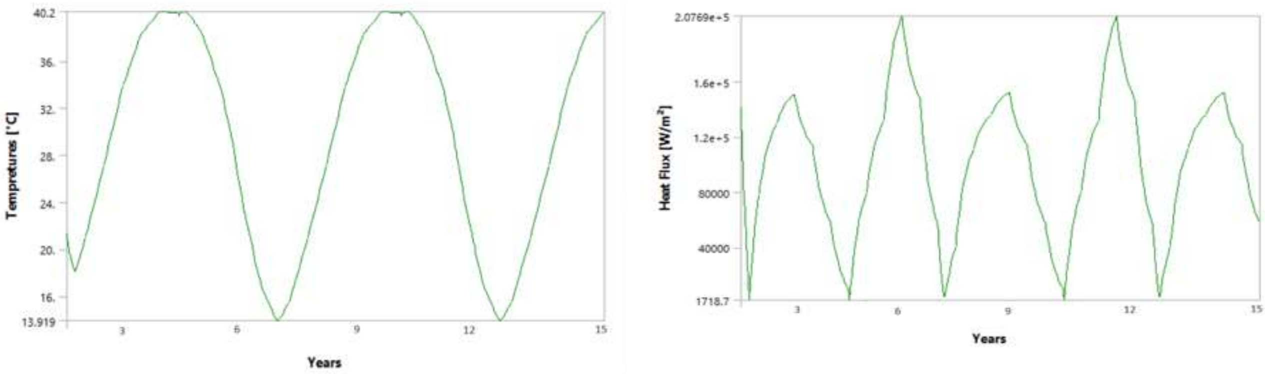
(a) (b)

(c)

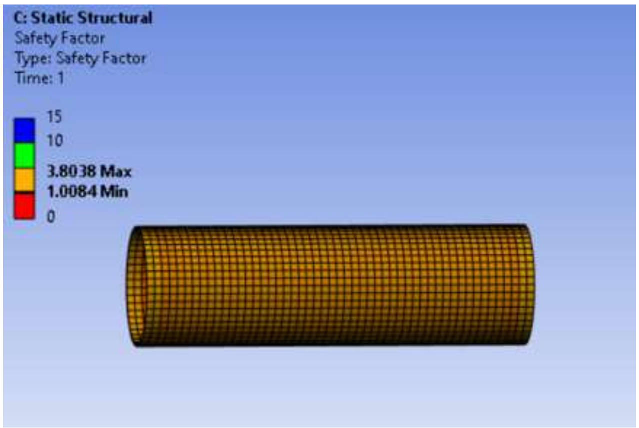
**Fig. 10.** Analysis of pipeline with 3LPE composite coating - (a) Total deformation, (b) Maximum stress, (c) Safety factor

### *3.2 Thermo-Static Analysis Results*

Figures 11, 12, and 13 below show thermo-static analysis results for three case studies. Figure 11 presents the results for the pipeline without a composite coating, Figure 12 shows the results when using an FBE composite coating, and Figure 13 shows the results when using a 3LPE composite coating.

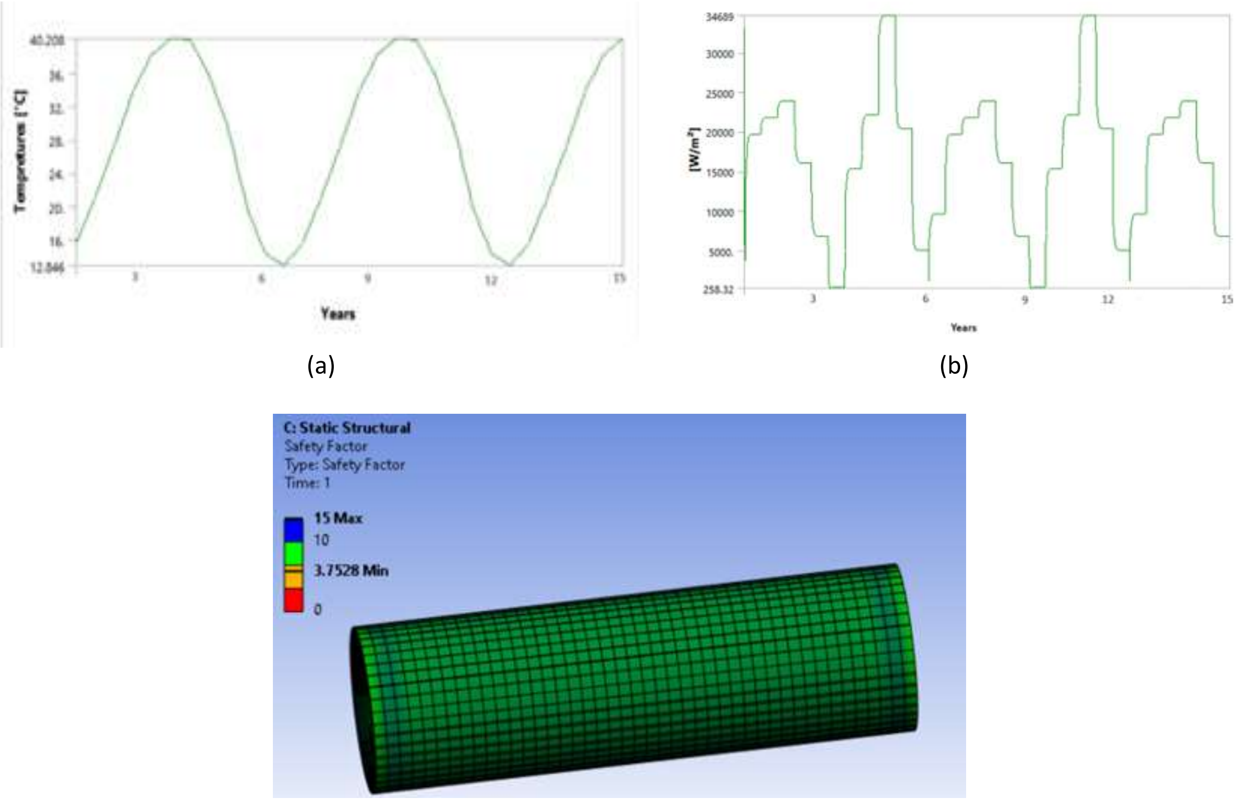


(a) (b)



(c)

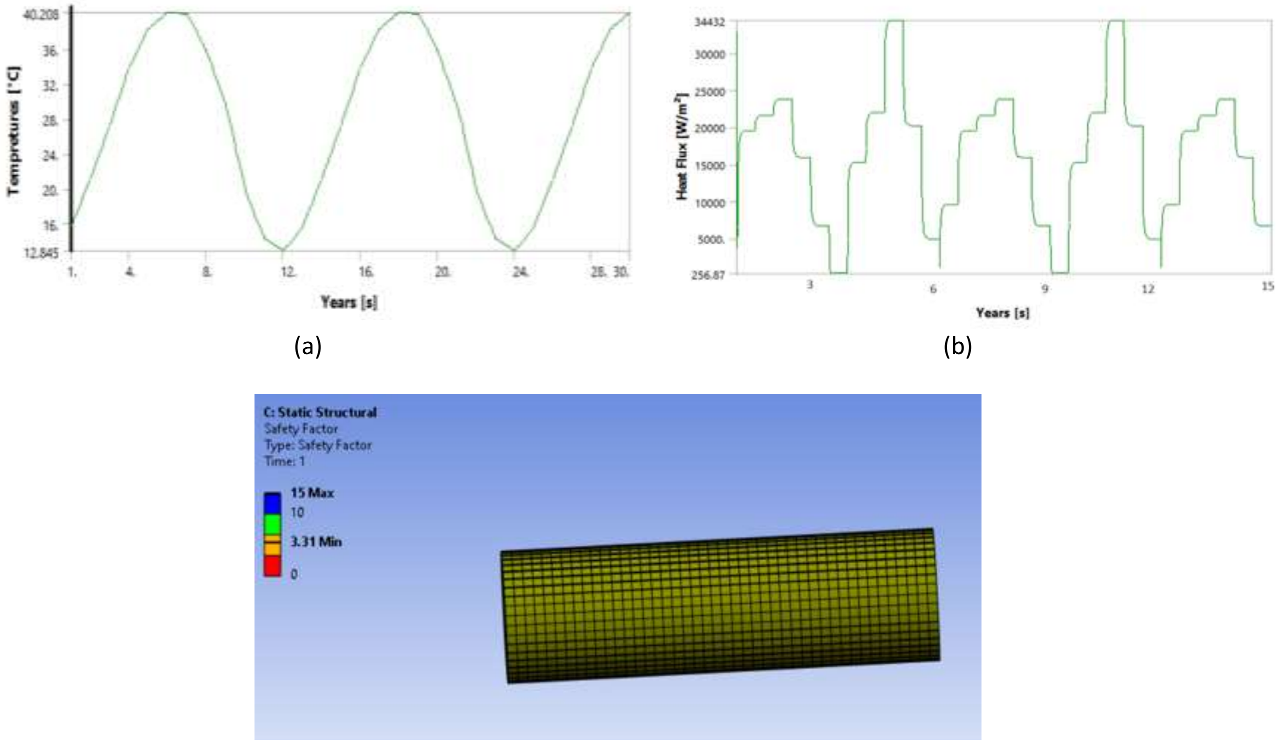
**Fig. 11.** Thermal and safety analysis of pipeline without composite coating - (a) Pipe surface temperature, (b) Heat flux, (c) Long-duration safety factor



(a) (b)

(c)

**Fig. 12.** Thermal and safety analysis of pipeline with FBE composite coating - (a) Pipe surface temperature, (b) Heat flux, (c) Long-duration safety factor



(a) (b)

(c)

**Fig. 13.** Thermal and safety analysis of pipeline with 3LPE composite coating - (a) Pipe surface temperature, (b) Heat flux, (c) Long-duration safety factor

The uncoated pipeline demonstrated heightened stress, deformation, and strain levels versus composite-coated models under stringent hydrostatic testing. FBE and 3LPE coatings markedly enhanced safety factors and projected lifespan, effectively shielding pipelines from failure despite intense pressures. Varied coating compositions directly impacted multiple performance parameters - the morphology, location and thickness being key optimization factors for specialized applications. Compared to an unprotected substrate, the composite coatings substantially mitigated experienced stresses, guaranteeing proper functionality over prolonged durations even in demanding conditions. Ultimately, advanced coatings proved indispensable for bolstering pipeline longevity, integrity and efficacy amid challenging operational and environmental loads. Further large-scale testing can validate optimal coatings tailored to niche specifications.

## 4. Conclusions

This study demonstrates the significant role of advanced composite coatings, specifically Fusion Bonded Epoxy (FBE) and three-layer polyethylene (3LPE), in improving the structural integrity and extending the operational lifespan of oil pipelines. Numerical simulations conducted over a 15-year period show that these coatings effectively reduce stress concentrations, enhance mechanical resilience, and maintain safety margins under challenging environmental and operational conditions. By utilizing real-world pipeline dimensions and environmental data, the findings offer valuable insights for optimizing coating performance and application strategies. To build upon these results, future research should include additional experimental validation and sensitivity analyses to address uncertainties in material properties and operational conditions. Incorporating detailed time-dependent material degradation models—such as variations in thermal conductivity, adhesion, and structural integrity—would enable more accurate predictions of long-term performance.

Additionally, integrating fluid-structure interaction (FSI) simulations could provide deeper insights into the dynamic interactions between the pipeline's internal fluid and its structure, capturing complex thermal and mechanical effects more comprehensively. Expanding the scope to consider external environmental factors like soil chemistry, humidity, and seismic loads, as well as analyzing stress concentrations in joint and weld regions, would further enhance the robustness and applicability of the models. Ongoing advancements in experimental work and computational modeling are essential for driving innovation in pipeline coating technologies. These efforts are crucial for achieving sustainable durability, improving safety margins, and raising industry standards for oil and gas infrastructure.

## Acknowledgement

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