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Multifactorial Analysis of Defects in Oil Storage Tanks: Implications for Structural Performance and Safety

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Abstract

This article investigates the combined effects of different common defects on the structural integrity and operational and environmental safety in the operation of an existing Light Cycle Oil (LCO) storage tank. This study correlates all the tank defects (like corrosion and local plate thinning, deformations, and local stress concentrators) against the loads and their combinations that occur during the tank's lifetime. All the information gathered by various inspection techniques is used together to create a digital twin of the equipment that will be further analyzed by Finite Element Analysis. A tank condition assessment is a complex activity, and it is based on the experience of the engineer performing it. Since there are multiple methods for performing a comprehensive analysis, starting from the basic visual inspection (which is the most important) and some measurements followed by analytical calculations, up to full wall thickness measurements, 3D scan of deformations and FEA analysis of the tank digital twin, it depends on the engineer performing the evaluation to chose the best method for each particular case from technical and economical point of views. The goal of this article is to demonstrate that analytical and FEA methods have the same result and also to establish a well-determined standard calculation model for future applications.

Keywords: storage tank; condition assessment; equipment lifetime; oil storage; lifetime extension; non-destructive testing; Finite Element Analysis (FEA); Vapor Cloud Explosion (VCE); process safety; cloud point

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1. Introduction

Oil storage tanks represent a cornerstone of the hydrocarbon and petrochemical industries, serving as essential repositories for substantial quantities of substances that often possess hazardous properties [1]. These large-capacity containers are integral to maintaining the supply chain of energy and chemical products, making their operational integrity a matter of paramount concern. Ensuring the structural performance and safety of these tanks is not merely an economic imperative but a fundamental necessity for preventing potentially catastrophic consequences, including environmental contamination, significant financial losses, and, most critically, the endangerment of human life. The potential for spills, leaks, fires, and even structural collapses underscores the critical need for a comprehensive understanding of the factors that can compromise their integrity.

This report aims to provide a detailed, multifactorial analysis of the defects that can occur in oil storage tanks. By examining the various causes and mechanisms of these defects, the subsequent implications for both the structural performance and overall safety of the tanks will be thoroughly explored. Furthermore, this analysis will be contextualized by a concise overview of the current industry practices and methodologies employed for the assessment of oil storage tanks. The information presented herein is intended to serve as a valuable resource for engineers, safety managers, regulatory bodies, and other professionals within the oil and gas sector who are tasked with the responsibility of ensuring the safe and reliable operation of these critical assets. A deep understanding of the complexities surrounding defect analysis in this domain is essential for the development and implementation of effective prevention, detection, and mitigation strategies.

1.1. Short Background on Oil Storage Tanks Assessment in Industry

Aboveground Storage Tanks (ASTs), commonly utilized for the storage of hydrocarbon and petrochemical products, are typically welded, vertical, cylindrical structures comprising three primary components: the bottom, the shell, and the roof [2]. In addition to these main elements, ASTs incorporate various nozzles for process connections, instrumentation, and firefighting systems. Steel structures provide personnel access, and depending on the specific storage application, internal features such as internal floating roofs, still pipes, heating coils, inlet diffusers, and floating suction arms may also be present [3].

These critical assets are generally designed and constructed with an anticipated operational lifespan of around 30 years, taking into careful consideration all relevant operational and environmental factors [1]. Throughout this service life, a schedule of periodic inspection activities is implemented [1]. Should these inspections reveal any areas of concern, local revamping or repair activities are undertaken as necessary to maintain the tank's integrity [1]. The necessity of these regular assessments stems from the inherent risks associated with storing volatile and potentially hazardous products [1]. Scheduled maintenance and inspections play a crucial role in ensuring safety, maintaining structural integrity and reliability, and adhering to environmental compliance regulations [3]. Neglecting these crucial activities can lead to substantial risks and adverse consequences [3].

The oil and gas industry relies on established guidelines and standards to ensure the safe design, construction, inspection, and maintenance of storage tanks. Notably, the American Petroleum Institute (API) provides comprehensive guidelines, such as API 650 [4], which focuses on the design of new storage tanks, and API 653 [5], which addresses the inspection, maintenance, alteration, and repair of existing tanks. These standards represent a culmination of industry experience and best practices, providing a framework for ensuring the integrity of these vital assets.

The history of storage tanks reveals a significant evolution in their design and construction [6]. The Industrial Revolution in the 18th century marked a turning point, with the advent of the steam engine necessitating larger storage tanks for coal and water [6]. The early 20th century saw the construction of the first metal storage tanks, initially made of wrought iron, which were instrumental in the growth of the oil industry [6]. Welded steel storage tanks, introduced in the 1920s, quickly gained prominence due to their enhanced durability and superior design [6]. Modern storage tanks are fabricated from a variety of materials, including steel, fiberglass, concrete, and polyethylene, each chosen based on the specific application requirements [6]. Contemporary tanks are also equipped with advanced safety features, such as double walls, leak detection systems, and corrosion-resistant coatings, reflecting a continuous drive for improved safety and environmental protection [6].

The nature of the products stored in these tanks has also evolved, presenting new challenges for assessment practices. The introduction of ultra-low sulfur diesel (ULSD) and the increasing proportion of biofuel (FAME) content in modern fuels have led to a rise in contamination issues within storage tanks. These changes necessitate ongoing adaptation of inspection and maintenance protocols to address the specific degradation mechanisms associated with these newer fuel types. The historical progression from basic storage vessels to sophisticated, safety-enhanced tanks demonstrates a learning process within the industry, driven by experiences with past failures and a growing awareness of the potential hazards associated with oil storage.

1.2. Importance of Structural Integrity in Oil Tanks

Industrial tanks serve as essential infrastructure for the storage of various liquids, gases, and chemicals across numerous sectors, with the oil and gas industry being particularly reliant on these structures [2]. These tanks are critical components of the supply chain, and any compromise to their structural integrity can lead to substantial safety hazards and financial repercussions [7]. The potential for leaks, spills, or even catastrophic failures necessitates a strong focus on maintaining the integrity of these assets throughout their operational lifespan. Over time, these tanks are susceptible to a range of degradation mechanisms, including corrosion, which can severely threaten their structural stability if left undetected [7]. The consequences of such failures can be far-reaching, impacting not only the safety of personnel and the environment but also leading to significant economic losses due to product loss, operational downtime, and regulatory penalties. Therefore, regular inspections and proactive maintenance are paramount to identify and address potential issues like corrosion, wear and tear on components, and structural defects before they escalate into major incidents [8]. The industry widely recognizes that a preventative approach, focusing on early detection and mitigation of risks, is crucial for ensuring the long-term safe and efficient operation of oil storage tanks.

1.3. Common Types of Defects Affecting Oil Storage Tanks' Integrity

A variety of defects (Table 1) can compromise the structural integrity of oil storage tanks, with corrosion being one of the most prevalent concerns [9].

Table 1. Common defects in oil storage tanks.

Defect Type	Common Causes	Potential Risks
Corrosion	Stored product composition, environmental conditions (humidity, salinity, pollutants), lack of corrosion protection, microbial activity, moisture under insulation.	Weakening of tank structure, leaks, potential for fires or explosions (especially with flammable products), environmental contamination, operational disruptions.
Weld Cracks	Metal fatigue, stress concentration at welds, improper weld procedures, poor workmanship during construction or repair.	Weakening of tank structure, leaks, increased risk of fire or explosion if near fuel storage, potential for catastrophic failure.
Buckling	Overloading, overpressure/vacuum, external pressure, wind loads, seismic events, soil settlement.	Severe weakening of tank structure, deformations, potential for catastrophic collapse, release of stored product, environmental contamination, safety hazards.
Denting	Heavy impacts from collisions, falling objects, external debris.	Compromised structural integrity, increased vulnerability to corrosion, potential for crack initiation and propagation, localized weakening of the tank shell.

Table 1. *Cont.*

Defect Type	Common Causes	Potential Risks
Ununiform Settlement	Irregular soil conditions, differential consolidation, unbalanced loads, seismic events, poor foundation conditions, soil erosion.	Compromised structural integrity, radial deformations of the shell, potential for floating roof jamming, damage to external connections and drainage, induction of bending stresses, potential for leaks or buckling, impact on operational stability and safety.

1.3.1. Corrosion

Corrosion in oil storage tanks manifests in several forms, each posing a unique threat to the tank's structural stability. Internal corrosion occurs due to the chemical interaction between the tank material and the stored product, particularly if it contains corrosive compounds like hydrogen sulfide (H_2S) [10]. This type of corrosion can gradually erode the tank's internal surfaces, weakening its ability to contain the stored substance. External corrosion, on the other hand, is driven by environmental factors such as humidity, salinity, and the presence of atmospheric pollutants [10]. Tanks located in coastal or industrial areas are particularly susceptible to this form of degradation. Pitting corrosion is a highly localized type of corrosion that can result in the formation of small holes that penetrate the tank wall, often occurring at the bottom where water and sediments tend to accumulate [11]. Even though the overall material loss from pitting might be minimal, the perforations can lead to leaks. In some cases, microbial corrosion can also play a role, where microorganisms, such as those found in ballast tanks of ships [9], accelerate the corrosion process. While primarily discussed in the context of ships, the principle highlights that biological factors can contribute to the degradation of storage tanks as well, especially in environments with water ingress. Another significant concern is corrosion under insulation (CUI), where moisture trapped beneath the insulation layer can lead to accelerated corrosion of the tank surface, particularly in areas around weld seams and at the base of the tank [12]. This hidden corrosion can be challenging to detect through routine inspections. Several factors contribute to the initiation and progression of corrosion in oil storage tanks. The absence or inadequacy of corrosion protection measures, such as protective coatings and cathodic protection systems, significantly increases the tank's vulnerability [10]. Furthermore, the inherent corrosiveness of the stored product itself [10], as well as the prevailing environmental conditions [10], play crucial roles in determining the rate and severity of corrosion.

1.3.2. Weld Cracks

Weld cracks represent another critical category of defects that can jeopardize the integrity of oil storage tanks. These cracks can arise due to various factors, including metal fatigue caused by repeated stress cycles experienced during the tank's operation [13]. Stress concentration, particularly in areas at or near the welds where the geometry or material properties may change, also contributes to crack formation [13]. Improper welding procedures during the tank's construction or subsequent repairs can introduce defects such as a lack of fusion or incomplete penetration, creating weak points that are prone to cracking [14]. Similarly, poor workmanship during the welding process can leave behind imperfections that can initiate or propagate cracks under operational stresses [13]. The potential risks associated with undetected weld cracks are significant. These cracks can weaken the overall structure of the tank [10], potentially leading to leaks of the stored product [10]. In situations where the cracks are located near fuel storage compartments or cargo holds, the risk of fire or other more serious incidents is significantly increased [13].

Even small cracks can propagate under stress, eventually leading to major structural failures if not identified and addressed in a timely manner.

1.3.3. Buckling

Buckling is a form of structural instability that can occur in oil storage tanks under various loading conditions. Several modes of buckling have been observed. Overloading the tank beyond its design capacity can induce buckling in the shell or roof [10]. Similarly, the development of overpressure or a vacuum inside the tank due to improper operation or the failure of pressure relief equipment can exert excessive forces, leading to buckling [15]. External pressure that exceeds the tank's structural capacity, such as that encountered during rapid discharge or in submerged conditions, can also cause buckling [16]. Wind loads, especially in regions prone to high winds, can impose significant lateral forces that may result in buckling of the tank shell [17]. Seismic events can generate substantial ground movements that can induce buckling, particularly in the lower sections of the tank [18]. Furthermore, uneven settlement of the tank foundation can create stresses that lead to buckling of the shell [10]. The consequences of buckling on the stability and containment capabilities of an oil storage tank are severe. Buckling can severely weaken the tank structure, potentially leading to catastrophic structural failure [13]. It results in significant deformations of the tank's original shape [10], and, in extreme cases, can cause the complete collapse of the tank, leading to the uncontrolled release of the stored product [10].

1.3.4. Denting

Denting in oil storage tanks typically results from mechanical impacts. These impacts can be caused by heavy objects colliding with the tank, such as during maintenance activities, or by falling objects or external debris striking the tank shell [19]. The effect of denting on the structural integrity of a tank depends on the size, depth, and location of the dent. Concentrated deformations caused by dents can compromise the tank's structural strength [13]. Furthermore, the deformed area can become more susceptible to corrosion [13]. Over time, especially if the dent is located in an area subjected to significant operational stresses, it may lead to the initiation of cracks or exacerbate existing corrosion, potentially leading to more severe damage [13]. While a small, shallow dent might not pose an immediate threat, larger or deeper dents, or dents in critical areas like near welds or supports, require careful evaluation to assess their impact on the tank's long-term integrity.

1.3.5. Ununiform Settlement

Ununiform settlement of an oil storage tank foundation can manifest in various forms, each with distinct implications for the tank's structural integrity. Inclined settlement occurs when one side of the tank settles more than the other, resulting in a tilt [20]. Localized settlement involves the development of isolated depressions beneath the tank base [21]. Dishing-type settlement refers to a bowl-shaped deformation in the tank bottom [21]. Out-of-plane settlement describes asymmetric waviness or distortions in the tank's base or shell [20]. Several mechanisms can lead to ununiform settlement. Variations in the composition and bearing capacity of the underlying soil across the tank foundation can cause differential settlement [20]. Different parts of the soil may consolidate at varying rates due to the weight of the tank and its contents [20]. An uneven distribution of the stored product or external loads can also exert varying pressures on the foundation, leading to uneven sinking [20]. Seismic events can cause ground movement and soil liquefaction, resulting in differential settlement [10]. Additionally, inadequate foundation preparation or the consolidation of backfill material beneath the tank can contribute to localized or widespread uneven settlement [8]. Soil erosion around the foundation can also lead to settlement issues [8]. The effects of ununiform settlement on the tank structure and

operation can be significant. It can compromise the overall structural integrity, affecting the safety, operation, and lifespan of the tank system [20]. Differential settlement can induce radial deformations in the tank's shell [21] and may even cause the floating roof in some tanks to jam [22]. In cases of uniform settlement, external connections and drainage systems might be affected [20]. Localized settlement can induce significant bending stresses on the tank shell [20]. Industry standards like API 653 [5] provide guidelines for evaluating the severity of settlement and determining appropriate actions [20].

1.4. Role of Key Factors in Structural Failures

Several key factors play a significant role in the structural failure of oil storage tanks, including wall thickness, deformations, and local stresses.

1.4.1. Wall Thickness

The wall thickness of an oil storage tank is a critical parameter that directly influences its ability to withstand both internal pressure from the stored liquid and external loads such as wind and snow [23]. Generally, tanks with thicker walls possess a greater capacity to resist these forces and are less susceptible to buckling [23]. Design standards within the industry often specify minimum wall thicknesses based on factors such as the specific gravity of the stored product and the anticipated operating pressures [14]. These standards aim to ensure that the tank can safely contain its contents under normal operating conditions. However, the effective wall thickness of a tank can be significantly reduced over time due to corrosion [7]. As corrosion progresses, it removes material from the tank walls, thereby decreasing the tank's structural capacity and increasing the risk of failure, even under normal design loads. Therefore, regular and accurate measurement of the tank wall thickness is crucial. These measurements help to monitor the rate of corrosion and ensure that the remaining wall thickness is sufficient to maintain the tank's structural integrity [17]. A reduction in wall thickness below a critical threshold can significantly increase the likelihood of leaks or even structural collapse.

1.4.2. Deformations

Deformations in oil storage tanks, whether they are radial deflections caused by foundation settlement [21], buckling-induced changes in shape [10], or localized indentations from impacts [15], can lead to stress concentrations within the tank structure [18]. These deformations alter the intended geometry of the tank, causing the stresses to be distributed unevenly across the material. Often, these stresses become concentrated at the points where the deformation occurs [18]. The relationship between deformation and potential failure modes is complex. For instance, excessive radial deflections resulting from uneven settlement can cause the floating roofs in certain types of tanks to jam, hindering their operation [22]. Settlement-induced deformations can also create significant stresses in the tank shell, potentially leading to buckling [22]. Localized deformations, such as dents, might not cause immediate failure but can act as initiation points for cracks or accelerate the process of corrosion in the affected area [15]. The altered stress distribution due to deformations can weaken the tank's resistance to other loading conditions, increasing the overall risk of structural failure.

1.4.3. Local Stresses

Local stresses in oil storage tanks refer to the elevated stress levels experienced in specific areas due to the presence of defects, geometric discontinuities, or localized loads. Stress concentration can occur around corrosion pits [24] and at the tips of weld cracks [13]. Welds themselves are often areas of higher stress due to changes in geometry and potential variations in material properties in the heat-affected zone [13]. Geometric discontinuities,

such as the points where nozzles connect to the tank shell or the junction between the shell and the bottom plate, are also prone to stress concentration [15]. In these localized areas, the stresses can be significantly higher than the nominal stress levels calculated for the bulk of the tank material [22]. These elevated local stresses play a critical role in the initiation and propagation of cracks. Under various loading conditions, such as internal pressure [16], external loads like wind [17], or thermal stresses caused by temperature fluctuations [18], these stress concentration points can exceed the material's strength, leading to the formation of cracks. Furthermore, even if the stress levels are below the material's yield strength, repeated cycles of loading and unloading can lead to fatigue failure originating from these areas of high local stress [13]. Therefore, identifying and mitigating sources of local stress is crucial for preventing structural failures in oil storage tanks.

2. Tank Failure Mechanisms

2.1. Previous Studies on Oil Tank Failures

The history of oil tank failures is punctuated by several significant incidents that have not only resulted in substantial economic losses and environmental damage but have also, in many cases, led to advancements in safety regulations and industry best practices. Examining these historical events provides crucial insights into the common causes and consequences of oil tank failures.

One notable example is the series of fuel tank failures experienced by a refinery, where bottom plate underside corrosion occurred at an extraordinarily high rate, leading to the failure of four tanks within a two-year period [25]. These failures highlighted the critical role of effective cathodic protection systems and the potential for microbiologically influenced corrosion to cause rapid degradation. The Ashland Oil Spill in 1988, where an aboveground storage tank containing millions of gallons of diesel oil split open, releasing a massive quantity of fuel into the Monongahela River, serves as a stark reminder of the environmental devastation that can result from tank rupture, attributed in this case to a lack of inspections and maintenance [26]. Similarly, the Paulsboro Refinery Oil Spill in 2012, caused by a ruptured tank, led to significant environmental concerns and highlighted the potential health risks associated with exposure to leaked petroleum products [26]. The Husky Energy Refinery Explosion in 2018, although not solely a tank failure, involved significant damage to storage facilities and underscored the importance of robust safety protocols and maintenance during operational shutdowns [26].

Historically, the Boston Molasses Disaster of 1919 stands out as a catastrophic failure of a large storage tank, resulting in numerous fatalities and injuries, attributed to shoddy construction and overfilling [27]. In more recent times, a major crude oil tank leak in Argentina in 2015, caused by a fast fracture from severe corrosion, led to a total loss of tank integrity and demonstrated the devastating impact of inadequate maintenance and inspection [28]. The catastrophic rupture of a diesel storage tank in Norilsk in 2020, releasing a massive amount of fuel, was likely caused by differential subsidence of the tank base foundation, possibly linked to thawing permafrost, illustrating the influence of environmental factors and foundation stability on tank integrity [29]. Furthermore, the rupturing and burning of a large crude oil storage tank, originating at a manway weld due to brittle fracture, highlighted the importance of material properties and stress concentrations in failure initiation [30]. These historical incidents, among others, underscore the diverse range of causes and the potentially severe consequences associated with oil tank failures.

2.1.1. Common Causes Identified in Studies

A comprehensive analysis of previous studies on oil tank failures reveals several recurring causes that contribute significantly to these incidents. Corrosion, in its various forms (internal, external, pitting, stress corrosion cracking, etc.), consistently emerges as a primary culprit, leading to the degradation and weakening of tank materials over time [10]. The loss of wall thickness due to corrosion directly impacts the tank's structural integrity and increases the risk of leaks or catastrophic collapse.

Inadequate maintenance practices and a lack of thorough and regular inspections are also frequently identified as major contributing factors [10]. Without proper maintenance, corrosion can progress unchecked, and minor defects can grow into critical structural weaknesses. Regular inspections are essential for early detection of potential problems, allowing for timely repairs and preventative measures. Deficiencies in the initial design and construction of oil tanks represent another significant category of causes [10]. Design flaws, use of incorrect materials, or poor welding techniques during construction can create inherent weaknesses that make the tank more susceptible to failure under operational stresses or environmental loads.

Foundation-related issues, such as settlement (both uniform and differential) and instability of the ground supporting the tank, are also commonly cited as causes of failure [10]. Uneven settlement can induce significant stresses on the tank shell and bottom, leading to deformations, cracking, or buckling. Operational errors, including overfilling the tank, operating at pressures or temperatures beyond the design limits, and improper handling of equipment, are also recognized as contributing factors to oil tank failures [10].

Studies have specifically highlighted that deficiencies in tank construction, maintenance adequacy, and corrosion prevention are the main root causes of failure [28]. Furthermore, movements in the tank floor and foundation materials have been identified as likely contributors to oil storage tank failures [31]. These recurring themes across various studies underscore the importance of addressing these key areas to enhance the safety and reliability of oil storage tanks.

2.1.2. Regulatory Aspects and Standards

The history of oil tank failures has played a crucial role in shaping the regulatory landscape and the development of industry standards governing the design, construction, operation, and maintenance of these critical infrastructures. Significant incidents have often prompted reviews of existing regulations and the implementation of more stringent requirements aimed at preventing similar occurrences in the future.

Following major oil tank fire accidents [32], for instance, there have been notable improvements in tank-related regulations and industry standards. These advancements have included innovations in storage unit technologies, enhancements in roof design to better contain fires, the implementation of safer filling procedures to minimize the risk of vapor ignition, and the development of more effective fire mitigation systems [33]. Besides the fire, Vapor Cloud Explosion (VCE) can pose a major risk [34]. This risk can be mitigated by providing flame arresters on the breathing equipment, and, also, for the worst case scenario, to prevent total tank collapse in case of explosion, the roof frangibility assurance. The catastrophic oil spill in Pennsylvania in 1988, which had a severe impact on the water supply, brought the safety of aboveground storage tanks to the forefront of public and governmental attention, ultimately leading to increased regulatory oversight in this area [27]. These past failures serve as critical reminders of the importance of proactive inspection and maintenance procedures, which are often mandated by both regulatory bodies and industry standards to ensure the ongoing integrity of oil storage tanks [26]. Industry-specific standards, such as those developed and maintained by the

American Petroleum Institute (API), provide detailed specifications and recommended practices for various aspects of oil storage tank design, construction, inspection, and repair, reflecting the accumulated knowledge and lessons learned from decades of experience and incident analysis [4]. The continuous evolution of these regulations and standards underscores an ongoing commitment to enhancing the safety and reliability of oil storage tank infrastructure.

2.1.3. Lessons Learned from Case Studies

The detailed analysis of specific case studies involving oil tank failures provides invaluable practical lessons that can be directly applied to prevent similar incidents in the future. These real-world examples often highlight critical factors and oversights that contributed to the failure, offering valuable guidance for improving tank design, operation, and maintenance practices.

The catastrophic diesel spill in Norilsk, for example, emphasized the critical need for thorough risk assessment and a deep understanding of the potential implications of tank failure, even for what might be considered routine infrastructure. The incident also highlighted a series of missed warning signs related to the tank's foundation that, in hindsight, could have indicated the impending failure, underscoring the importance of diligent monitoring and acting upon any anomalies observed [29]. The analysis of the crude oil tank leak in Argentina provided several key recommendations, including the need for improved and more comprehensive wall thickness monitoring programs, revised criteria for selecting ultrasonic testing sites to focus on high-risk areas, careful inspection of material transition zones within the tank, and the implementation of effective corrosion protection measures for both internal and external surfaces [28]. The case study involving microbiologically influenced corrosion in oil storage tank bottoms underscored the importance of implementing and maintaining effective cathodic protection systems and preventing water ingress, which can create environments conducive to microbial activity and accelerated corrosion [25]. A domestic oil tank leak incident highlighted the risks associated with aging tanks and the necessity of regular monitoring, maintenance, and timely replacement, as even seemingly minor defects can lead to significant environmental hazards [35]. More broadly, past tank failures serve as critical reminders of the fundamental importance of implementing proactive and comprehensive inspection and maintenance procedures and investing in the necessary technologies and skilled personnel to maintain the highest standards of tank integrity [26]. These lessons learned from case studies underscore the multifaceted nature of ensuring oil tank safety and the need for a holistic approach that encompasses robust design, rigorous inspection, effective maintenance, and adherence to best operational practices.

2.2. Comprehensive Review of Tank Failure Mechanisms

2.2.1. Material Failure Mechanisms

Corrosion

Corrosion stands as a highly prevalent and multifaceted material degradation mechanism affecting storage tanks across various industries. It involves the gradual deterioration of the tank material, typically metallic, through unintended chemical or electrochemical reactions with its surrounding environment or the substances stored within [10]. This process leads to a progressive loss of material, consequently diminishing the structural integrity of the tank and potentially culminating in leaks or, in more severe scenarios, a catastrophic structural collapse.

Storage tanks are susceptible to a diverse range of corrosion types, each with its unique characteristics and contributing factors. These include general or uniform corrosion,

which manifests as a relatively even thinning of the material surface over a broad area; pitting corrosion, characterized by the formation of localized, often deep, cavities or pits in the metal surface [10]; crevice corrosion, which tends to occur within confined spaces or shielded areas where stagnant conditions can prevail; galvanic corrosion, resulting from the electrochemical interaction between dissimilar metals in the presence of an electrolyte; stress corrosion cracking (SCC), a failure mechanism induced by the simultaneous action of tensile stress and a corrosive environment; microbiologically influenced corrosion (MIC), where the metabolic activity of microorganisms accelerates the corrosion process; and corrosion under insulation (CUI), which occurs on the external surfaces of insulated tanks due to moisture ingress beneath the insulation [10].

Numerous environmental and operational factors can significantly accelerate the rate and severity of corrosion in storage tanks. These include the presence of moisture, the availability of oxygen, the concentration of corrosive ions such as sulfates and chlorides, the presence of aggressive chemical species like hydrogen sulfide (H_2S) and carbon dioxide (CO_2), elevated operating temperatures, stagnant conditions within the tank that can promote localized attack, and the metabolic activity of certain types of bacteria that can create corrosive microenvironments [10].

The economic implications of corrosion are substantial, with estimates suggesting that the direct annual costs attributable to corrosion in the United States alone approach USD 300 billion [36]. In the context of oil storage tanks, corrosion, particularly affecting the tank floors and the annular region in close proximity to the wall, has been identified as the most frequent precursor to early structural failures [28]. The interaction between mechanical stresses experienced by the tank during operation and ongoing corrosion processes can further exacerbate the risk of failure in oil storage tanks [37]. A specific example of the aggressive nature of corrosion is microbiologically influenced corrosion, which has been shown to cause extraordinarily high rates of material loss in the bottom plates of above-ground storage tanks [25]. The impact of corrosion extends beyond just oil tanks; in water storage tanks, internal corrosion can lead to a wide array of problems, including the deterioration of water quality, potential health risks to consumers, increased costs for maintenance and repair, a reduction in the tank's overall service life, adverse environmental consequences, and even aesthetic degradation [38]. From a more technical standpoint, various corrosion mechanisms can affect steel tanks, including general corrosion across the surface, localized pitting and crevice corrosion, stress-corrosion cracking under tensile stress, and microbiologically-induced corrosion in the presence of microorganisms [39]. Depending on the stored substance, chemically induced corrosion can take various forms, including pitting, stress corrosion, and galvanic corrosion, all of which can compromise the integrity of the tank [40]. Hydrocarbon storage tanks are also highly susceptible to corrosion, with a distinction often made between external corrosion caused by atmospheric factors and internal corrosion resulting from contact with the stored product [10]. Ultimately, corrosion stands as the primary degradation mechanism affecting a broad range of storage tanks, leading to material loss and an increased risk of structural collapse [41]. The multifaceted nature of corrosion, its prevalence across different tank types and industries, and the significant economic and safety risks associated with it underscore the critical importance of implementing robust corrosion prevention and management strategies throughout the entire lifecycle of a storage tank.

Erosion

Erosion represents another significant material degradation process that can affect the integrity of storage tanks, particularly those involved in the handling or storage of fluids containing abrasive particles. This mechanism involves the progressive removal of material

from the internal surfaces of the tank due to mechanical wear caused by the movement of the fluid, especially in scenarios involving high flow velocities or the presence of suspended solid particles [10]. Tanks used for storing or processing slurries or fluids with high flow rates are particularly susceptible to damage from erosion. The repeated impact of abrasive particles on the tank walls can gradually wear away the material, leading to a reduction in the overall wall thickness.

In many instances, erosion occurs in conjunction with corrosion, leading to a combined degradation phenomenon known as erosion–corrosion. This synergistic interaction can significantly accelerate the rate of material loss compared to either mechanism acting alone [36]. The mechanical action of erosion can remove protective oxide layers that might otherwise slow down the rate of corrosion, exposing fresh metal surfaces to the corrosive environment. Conversely, corrosion can roughen the surface of the material, increasing turbulence in the fluid flow and making the material more susceptible to further erosion.

The extent and rate of erosion are influenced by several key factors. These include the flow velocity of the fluid within the tank, the characteristics of any abrasive particles present (such as their size, shape, hardness, and concentration), the physical and chemical properties of the fluid itself, and the inherent resistance of the tank material to mechanical wear.

The combined effect of erosion and corrosion on a metal surface can lead to higher levels of damage and degradation than either process individually [36]. Metal erosion in components like heat exchanger tubes can be caused by excessive fluid velocity, and this erosion can accelerate any existing corrosion by continuously removing the protective films that form on the metal surface [40]. Erosion is also a common concern in pressure vessels that handle abrasive materials or experience high-velocity fluid flows, where it can lead to a gradual thinning of the vessel walls, reducing its overall structural strength [42]. Studies on the erosion–corrosion behavior of materials like stainless steel in environments containing abrasive particles, such as copper mining tailings, have demonstrated the complex interplay between these two degradation mechanisms under industrial conditions [43]. Research on the erosion–corrosion of carbon and stainless steel in multiphase flow conditions, relevant to the oil and gas industry, further highlights the different susceptibilities of various materials to this combined form of degradation [44]. Even environmental factors, such as contact with sand and dust, can contribute to surface erosion on fuel tanks [45]. Therefore, in applications where storage tanks are likely to be exposed to fluids containing abrasive particles or high flow velocities, it is crucial to consider the potential for erosion and its synergistic effects with corrosion in order to ensure the long-term integrity of the tank.

Fatigue

Fatigue represents a critical material degradation mechanism that can lead to the failure of storage tanks, particularly those subjected to repeated or cyclic loading. This process involves the progressive and localized structural damage that occurs when a material is subjected to fluctuating mechanical stresses and strains over an extended period [10]. What makes fatigue particularly insidious is that failure can occur at stress levels significantly lower than the material's static tensile strength or yield strength, provided that these stresses are repeatedly applied over a sufficient number of cycles.

The process of fatigue typically involves three stages: crack initiation, where microscopic cracks form at the surface or within the material, often at points of stress concentration such as defects, welds, or sharp geometric features; crack propagation, where these small cracks gradually grow larger with each subsequent loading cycle; and finally, fracture, which occurs when the crack reaches a critical size that the remaining cross-section of the material can no longer support the applied load.

Several factors can significantly influence the fatigue life of a storage tank. These include the range of stress experienced during each loading cycle (the difference between the maximum and minimum stress), the total number of cycles the tank undergoes, the frequency of these cycles, the inherent fatigue resistance of the material from which the tank is constructed, and the presence of any stress concentrations that can amplify the local stresses experienced by the material.

For example, in the context of high-pressure storage, a study suggests that a design-related fatigue phenomenon was the most likely cause of failure in a high-density polyethylene (HDPE) liner within a Type IV cylinder subjected to repeated pressurization cycles [46]. This indicates that, even in non-metallic components of storage systems, fatigue due to cyclic loading can be a critical failure mechanism. More generally, fatigue is recognized as a gradual degradation process in tank materials that results from exposure to cyclic loading or vibration [10]. In the case of an oil storage tank, while corrosion may have initiated cracks, the ultimate failure was attributed to the propagation of these cracks under operational stresses, suggesting a significant role of fatigue in the failure process [37]. Similarly, crack propagation in a fuel tank pylon of a helicopter was found to be a result of fatigue loading [47]. Further research into the failure of HDPE liners in Type IV cylinders under cyclic pressure testing also pointed towards fatigue as the probable cause, emphasizing the importance of considering fatigue in the design of components subjected to repeated stress cycles [46]. Therefore, for storage tanks that experience fluctuating operational conditions, such as repeated filling and emptying cycles leading to pressure variations, or those located in environments where they might be subjected to vibrations, fatigue is a critical failure mechanism that must be carefully considered in the design, material selection, and inspection programs to ensure long-term structural integrity and safety.

2.2.2. Mechanical Failure Mechanisms

Buckling

Buckling represents a critical mechanical failure mechanism, particularly for thin-walled structures like many storage tanks, where the application of compressive forces can lead to a sudden and often catastrophic loss of stability. Instead of failing through material yielding or fracture under direct compression, a structure experiencing buckling undergoes a significant and often unpredictable change in its overall shape or geometry [10]. This instability can occur at stress levels well below the material's yield strength, making it a crucial consideration in the design and analysis of tanks subjected to compressive loads.

Compressive forces that can induce buckling in storage tanks can arise from a variety of sources, depending on the tank's design, application, and environmental conditions. These include axial compression, which might occur due to external loads or structural constraints; external pressure, such as hydrostatic pressure experienced by submerged tanks or wind pressure acting on large aboveground tanks; bending moments, which can introduce compressive stresses on certain parts of the tank shell; and uneven support conditions or settlement of the tank's foundation, which can induce complex stress states leading to buckling.

Research has identified several characteristic buckling patterns that can occur in storage tanks. One notable example is the "elephant's foot" bulge, an outward deformation that typically forms near the base of the tank shell. This pattern is often associated with vertical compressive stresses resulting from the tank's weight and the pressure of the stored liquid. Another type is diamond-shaped buckling, which can occur in the lower part of the tank shell due to axial membrane stresses caused by overturning moments, particularly during seismic events. Buckling can also occur at the top of the tank, with patterns that sometimes resemble those observed in shells subjected to external pressure [48].

Studies have specifically investigated buckling failure in cylindrical tanks subjected to external pressure and axial compression, noting that the circumferential and meridional stresses developed under these conditions can be sufficient to initiate buckling [16]. Research on tank failure modes due to ground motion has also highlighted various buckling patterns observed during earthquakes, emphasizing the role of seismic forces in inducing compressive stresses that can lead to structural instability [48]. Buckling failure in tanks supported by piles has been linked to soil settlement, which can cause ruptures in the lower part of the tank. Additionally, the sloshing effect of the liquid inside a tank can induce buckling in the upper ring of the tank shell [10]. Given their thin-walled cylindrical nature, oil storage tanks are inherently susceptible to buckling under a range of operational and environmental loads [49]. Even the residual stresses introduced during the welding process used to construct storage tanks can influence their buckling behavior [50]. Therefore, in the design and analysis of storage tanks, a thorough consideration of potential buckling scenarios and the compressive stresses that might lead to them is essential to ensure structural integrity and prevent catastrophic failures.

Fracture

Fracture represents a fundamental mode of mechanical failure in storage tanks, characterized by the separation of the tank material into two or more distinct pieces as a direct result of applied stress exceeding the material's inherent ultimate strength. This critical failure mechanism can manifest in different forms, broadly categorized as either ductile fracture or brittle fracture, each exhibiting distinct characteristics in terms of material deformation and the appearance of the fracture surface [51]. Ductile fracture is typically preceded by a significant amount of plastic deformation, where the material undergoes substantial stretching or bending before it finally breaks. The resulting fracture surface in ductile failures is often rough and fibrous in appearance. Conversely, brittle fracture occurs with very little, if any, noticeable plastic deformation. This type of failure is often sudden and propagates rapidly, with the fracture surface typically appearing smooth, crystalline, or glassy.

In the context of storage tanks, fractures are frequently initiated at locations where stresses are concentrated. These stress concentration points can arise from various factors, including the presence of existing cracks or notches in the material, sharp corners or abrupt changes in the tank's geometry, or defects that may have been introduced during the manufacturing or welding processes. Once a crack initiates at such a stress concentration site, it can then propagate through the material under the influence of sustained or cyclic loading. Over time, this crack growth can weaken the structural integrity of the tank, eventually leading to complete separation of the material and a catastrophic structural failure.

Studies have specifically examined fracture propagation in liquid storage tanks, considering different potential modes of failure following a rupture [51]. The field of dynamic failure mechanics provides a framework for understanding fracture phenomena that occur rapidly, such as those involving the sudden creation of cracks in a structure [52]. Research has also detailed the fundamental types of fracture, distinguishing between ductile failure, which is associated with significant plastic deformation after exceeding the tensile strength, and brittle fracture, which occurs with minimal deformation and a characteristic shiny fracture surface [53]. A real-world example of a fracture leading to a major incident is the case of a crude oil tank that experienced a fast fracture, originating from an area of severe corrosion, which resulted in a complete loss of the tank's containment [28]. This highlights how other degradation mechanisms, like corrosion, can create conditions that make the tank more susceptible to fracture under stress. Therefore, understanding the principles of

fracture mechanics and the factors that can initiate and drive crack propagation is crucial for assessing the structural integrity of storage tanks and for implementing measures to prevent catastrophic failures.

Overloading

Overloading represents a critical operational condition that can significantly elevate the risk of mechanical failure in storage tanks. This occurs when a tank is subjected to loads that surpass its designed capacity or its intended operational limits. Such overloading can manifest in several ways, each posing a unique threat to the tank's structural integrity [2]. One common form of overloading is overfilling, where the tank is filled with a substance beyond its maximum allowable volume. This can lead to excessive hydrostatic pressure exerted on the tank's walls and bottom, potentially exceeding the material's strength and causing yielding, permanent deformation, buckling, or even a complete rupture. Another type of overloading can occur due to the application of external loads that the tank was not designed to bear, such as an unusually heavy accumulation of snow or ice on the tank roof, or unintended mechanical impacts. Furthermore, operating a tank at internal pressures that are higher than its specified design pressure constitutes overloading and can lead to structural failure. Even operational procedures that involve excessively rapid filling or emptying of the tank can generate abrupt and significant changes in pressure and temperature within the tank, which can induce fatigue in the tank material over time, eventually contributing to failure [10].

For instance, storing a volume of product that exceeds the tank's maximum design capacity is a clear example of overloading [10]. This situation can lead to increased stresses in the tank shell and bottom, potentially causing them to deform or even rupture. Similarly, overfilling an oil tank beyond its intended capacity has been identified as a potential cause of tank collapse due to the excessive pressure exerted on the tank walls [54]. Failures can also occur due to internal overpressure, where the pressure inside the tank exceeds its design limits, leading to structural damage such as uplift deformation or failure of welded connections [55]. Therefore, it is crucial for the safe operation of storage tanks to strictly adhere to the specified filling limits, pressure ratings, and operational procedures to avoid subjecting the tanks to loads beyond their design capabilities. Operating within these limits helps to ensure that the stresses on the tank material remain within acceptable levels, thereby minimizing the risk of mechanical failure and maximizing the tank's service life.

2.2.3. Failure Due to External Factors

Environmental Factors

Storage tanks, by their nature, are often exposed to a wide range of environmental conditions that can significantly influence their structural integrity and contribute to various failure mechanisms. These external factors include extremes of temperature, which can induce thermal stresses within the tank material and potentially lead to embrittlement, making the tank more susceptible to fracture [10]. Wind loads can also pose a considerable threat, as high winds can exert substantial pressure on the tank's shell and roof, potentially causing buckling or other forms of structural damage. Seismic activity, particularly in earthquake-prone regions, can induce large dynamic forces and ground movements that can lead to foundation failures, shell buckling, damage to piping connections, or even complete collapse of the tank. Flooding can subject tanks to significant hydrostatic and buoyant forces, potentially causing them to shift from their foundations or sustain structural damage. Lightning strikes can ignite flammable vapors that may be present in or around the tank, leading to explosions and fires, or they can directly damage the tank's instrumentation and safety systems.

For instance, environmental factors such as cyclones, hurricanes, and earthquakes are recognized as potential causes of failure in storage tanks [10]. Exposure to the sun's ultraviolet (UV) radiation can degrade the protective coatings applied to tanks, leading to material fatigue and embrittlement over time. Additionally, the accumulation of environmental debris, such as sand and dust, can exacerbate surface erosion on tanks, damaging protective layers and potentially accelerating corrosion [45]. Ground motion resulting from earthquakes can induce a variety of failure modes in tanks, including buckling at both the bottom and the top of the shell, as well as failures at welded joints or seams [48]. A specific example of environmental impact is the case where liquefaction of the soil during an earthquake led to the failure of foundations supporting oil storage tanks [56]. Therefore, it is essential to consider the specific environmental conditions to which a storage tank will be exposed during its service life and to incorporate appropriate design features and protective measures to mitigate the risks associated with these external factors.

Human Factors

Human actions, or inactions, across the entire lifecycle of a storage tank, from its initial design and construction to its ongoing operation, maintenance, and inspection, represent a significant and often overlooked contributing factor to tank failures. Errors in any of these stages can have profound consequences for the structural integrity and safety of the tank [10]. Design flaws, such as incorrect calculations or inadequate specifications, can lead to inherent weaknesses in the tank's structure. Improper construction techniques, the use of substandard materials, or poor workmanship during fabrication and assembly can introduce defects that may later lead to failure. Operational errors, such as overfilling the tank, exceeding pressure or temperature limits, or mishandling critical equipment like valves and pumps, can subject the tank to stresses beyond its design capacity. Neglecting routine maintenance, failing to conduct timely and thorough inspections, or not addressing identified issues promptly can allow minor problems like corrosion or small cracks to escalate into major structural failures.

For example, deficiencies in tank construction, inadequate maintenance practices, and a lack of effective corrosion prevention have been identified as primary root causes in numerous oil tank failure incidents [28]. Even seemingly minor actions, such as improper operation by staff, can lead to significant events like fires in storage tanks [33]. A stark illustration of the impact of human factors is the case of a fatal fire in a crude oil storage tank caused by a contractor's unsafe behavior [57]. Studies have also indicated that human error is a substantial contributor to accidents at tank farms [58]. Therefore, it is imperative to recognize the critical role of human factors in tank safety and to implement robust management systems, comprehensive training programs, clear operational procedures, and a strong safety culture to minimize the likelihood of failures stemming from human errors.

2.2.4. Other Failure Mechanisms

Manufacturing Defects: Imperfections or flaws that are introduced into the tank structure during the fabrication or assembly processes can significantly compromise its integrity and lead to premature failure. These defects can take various forms, including poor quality or incomplete welds, the use of materials that do not meet the specified standards, undetected cracks or laminations within the base material, and dimensional inaccuracies or misalignments during assembly [2]. Such manufacturing defects can act as initiation points for other failure mechanisms, such as fatigue cracking or corrosion, and can reduce the tank's overall strength and resistance to operational stresses.

Foundation Failure: The foundation on which a storage tank rests plays a crucial role in providing stable support and distributing the loads imposed by the tank and its contents.

Failure of the foundation, which can occur due to factors like uniform or differential soil settlement, erosion of the supporting soil, or an inadequate initial load-bearing capacity of the ground, can induce significant and uneven stresses on the tank structure. This can lead to various failure modes, including buckling of the shell, cracking of the bottom plate or shell, and, in extreme cases, complete instability or collapse of the tank [10].

Valve and Fitting Failures: Storage tanks are integral parts of larger systems and are connected to pipelines and other equipment through a network of valves, fittings, and piping. Failures in these ancillary components, such as leaks due to wear and tear, improper installation, corrosion, or seal degradation, can have direct and indirect impacts on the tank's integrity. A direct failure might involve the loss of stored product, while an indirect failure could lead to pressure imbalances within the tank or create hazardous conditions in the surrounding area [10].

Liner Failure: Some storage tanks, particularly those designed for specialized applications like high-pressure gas storage or the containment of highly corrosive substances, incorporate internal liners made from materials such as polymers or composite materials. These liners provide an additional barrier between the stored substance and the primary structural material of the tank. Degradation or failure of these liners, which can occur due to factors like chemical attack, mechanical damage, or fatigue under cyclic loading, can compromise the tank's ability to effectively contain the stored substance, potentially leading to leakage or structural issues in the primary containment vessel [46].

Thermal Stress: Temperature gradients that develop within a storage tank, either due to differences in the temperature of the stored substance versus the external environment or due to localized heating or cooling, can induce thermal stresses in the tank material. Similarly, rapid changes in temperature can cause differential expansion and contraction of the tank components, also leading to thermal stresses. If these thermally induced stresses are sufficiently high, they can contribute to failure mechanisms such as cracking, particularly in areas with pre-existing defects or stress concentrations, or to overall deformation of the tank structure [54].

2.3. Impact of Reduced Wall Thickness (Due to Corrosion or Erosion)

Among the tank failure mechanisms, the most encountered is reduced thinning, primarily due to corrosion (Table 2). Erosion is rarely involved; the most common site is at the tank inlet areas, near the mixers, basically where the product enters or leaves the tank, or near any moving parts (like impellers). Being static equipment, the tank erosion can most of the time be absent. On the other hand, corrosion is commonly an issue. The most affected areas are the following:

Table 2. Corrosion and erosion on tank elements.

Tank Component	Corrosion Factors	Mitigation
Bottom upper side	The tank bottom is one of the areas most susceptible to corrosion due to the fact that water accumulates due to the higher density and corrodes, especially the HAZ of the welds	Cathodic protection, internal lining, and higher corrosion allowance
Bottom lower side	The lower side of the bottom is susceptible to aggressive corrosion depending on the foundation solution (elastic bed, concrete slab, etc.). When elastic beds without insulation is used there is a high risk of galvanic corrosion, which cannot be controlled. This could lead to bottom leaks.	Bitumen sand elastic bed provision or active cathodic protection

Table 2. *Cont.*

Tank Component	Corrosion Factors	Mitigation
Lower Shell	The same as the bottom; the lower inner side of the tank shell is susceptible to corrosion due to water accumulation. The bottom-to-shell weld and especially its HAZ is a critical area to be considered from a corrosion protection point of view	Cathodic protection; internal lining
Upper shell	The upper courses of the shell, especially the last one, is the most susceptible to corrosion due to water vapor condensation on the inner side of the upper shell and, sometimes, depending on the stored product, vapors, combined with water, can conduct to chemical corrosion.	Internal lining; increased corrosion allowance
Roof	The same as the upper shell; the inner side of the roof elements are subjected to corrosion, and special attention needs to be given to the areas that can accumulate condensate (horizontal surfaces with no drain holes, areas where plates are overlapping steel structure beams, etc.). The roof-to-shell joint is a critical area from corrosion point of view because a minimum allowable section is considered during calculation and this needs to be available until the end of the equipment lifetime.	Internal lining, corrosion allowance, and natural drain means considered during the design stage
Outer tank surfaces	Corrosion of the outer tank surfaces is dependent on the environment where the tank is located. Usually, aggressive corrosion occurs on the tanks located ashore; hence, proper paint systems should be considered. Here, besides corrosion, erosion can also be considered in desert areas, where sandstorms can blast the tank's outer surfaces and affect the coating and even the metal.	Proper corrosive protection classes to be considered according to standards (i.e., ISO 9223 [59]) along with a proper coating system.

The first impact of corrosion and/or erosion is a thinned element that leads to a weak area that leads directly to higher stress and, sometimes, depending on the element geometry, to a stress concentrator. This is, most of the time, a point of failure. These scenarios have to be anticipated during the design phase, and, most importantly, should be highlighted during the inspection and condition assessment and subjected to revamp activities.

2.4. Studies on Local Stresses and Their Propagation

According to the design standards, for common storage tanks (except when higher temperatures or more stringent conditions are imposed), there are no mandatory stress analysis requirements. The standards calculation methods are conservative enough, but, in special cases, where they should be identified through the design engineer's experience, stress analysis is required.

Because the tanks are basically thin-walled elements, but, at the same time, have beam structure components (roof steel structure) and nozzles (susceptible to loads from piping), special considerations need to be given to the stress analysis. The main challenge is not to model the tank elements but to merge different elements with different design rules and different load combinations in the same analysis. Also, the areas where different elements are joined together are critical (i.e., steel beams that are welded on the tank upper shell corner ring). These aspects, together with the differences in calculation and analysis within the design standards that have been highlighted in [2], make it very difficult to consider even a well-prepared 3D model the digital twin of the equipment.

On the other hand, since there is no rule prohibiting it, a digital twin can be considered for further in-depth analysis, but only after the mandatory inspection applicable standards (like API 653 [5]), calculation, and evaluation requirements have been met. The stress analysis of a digital twin prepared by a very experienced engineer should not only confirm

the findings of the standard evaluation but, furthermore, highlight elements that are susceptible to failure.

2.5. Gaps in Current Research

As mentioned before, tanks are basically standardized equipment, and are rarely designed with consideration to special conditions, like high temperature variations, or complex machinery installed, etc. This is why design and inspection standards have been developed conservatively enough for all common types. The challenge comes when tanks need to be designed to meet special needs, with one of the most common examples being the double shell tank, which is used when there are area restrictions (i.e., in refineries) and there is no space for a dike large enough to contain 110% of the tank contents as per BAT/NFPA/API/EEMUA and local regulations requirements. There is no standard to regulate double-shell/double-bottom tank design and inspection. The common practice is to treat and calculate both inner and outer tanks separately, but it is known that this is not 100% accurate. There are two separate thin bodies, acting in slightly different ways in different conditions (i.e., operation: one filled with liquid and one empty, or earthquake: different behavior), not to mention their combinations. One of the most critical components is the interstitial piping connecting both shells' nozzles.

Also, one of the other subjects that are not extensively treated is the condition assessment of tanks using combined methods, such as modern inspection (using 3D scan, drones, digital twin) combined with classic tensometry. One of the main reasons is that the tanks, which are generally common equipment that rarely have special service requirements, require advanced inspection techniques that involve special equipment and highly experienced personnel, which finally result in high costs that, most of the time, clients are reluctant to accept, unless there is a mandatory requirement.

However, customized AI-powered software solutions still need to be developed to automate the process and reduce costs. As for the tank inspections themselves, they remain necessary, with limited opportunities for cost reduction on that front.

At the end, it is both the engineer's and the owner's decision to choose the best design/inspection/technical assessment techniques in order for the equipment to meet the higher standards of operational safety.

3. Methodology of Tank Evaluation

3.1. Description of Tank Geometry and Importance of Each Component

ASTs are thin-walled cylindrical vertical equipment, the main components of which are the bottom, the shell, the roof, the nozzles, and, finally, steel access structures. Each main component has some specific roles in the tank stability and safe operation as in (Table 3):

Table 3. Importance of tank components.

Tank Component	Importance of Tank Stability and Tank Safe Operation
Bottom	The tank bottom is one of the components that assures the product containment. Even if less design calculation consideration is given for its design, being supported by the foundation, special attention should be paid to its welds (especially the bottom-to-shell one), and corrosion protection. Bottom containment failure can lead to product spillage, with environmental, cost, and social impact. It should also be noted that bottom leaks are the most difficult leaks to identify.
Shell	The tank shell is the most critical part of the tank; it is a thin wall that is treated with membrane design theories. The tank shell not only contains the whole hydrostatic liquid column and internal vapor pressure, but also the loads of the roof, snow and other equipment, and access steelwork. Shell failure can lead to catastrophic tank rupture and entire product content spillage.

Table 3. *Cont.*

Tank Component	Importance of Tank Stability and Tank Safe Operation
Roof supporting steel structure	The roof steel structure is also of critical importance, since it supports not only the entire roof cover plates, nozzles, equipment, and access steelwork, but also the snow that may accumulate.
Roof plates	The roof plates seal the tank top, preventing any product vapors from escaping into the atmosphere, or any lightning from causing an explosion, and rain and other elements from coming in contact with the stored product.
Nozzles	The nozzles are the objects that make the connection between the tank containment and the piping, and their proper dimensioning is of the highest importance.
Access steelwork	The steelwork is important for tank access, especially on the roof for manual product level measuring and inspection/maintenance. The access steelwork, as with the tank structure, is of the highest importance for the personnel safety.
Corrosion protection	The corrosion protection, both external and internal, is the barrier that protects the metallic components from the corrosive action of the product and environment.

3.2. Evaluation of Each Possible Degradation Mechanism and Its Grade of Importance in Tank Stability

Each degradation mechanism, as they are presented in Section 2, can have a grade of importance in the tank stability. This grade can be measured from different perspectives, but of most importance is the possibility of tank failure (Table 4).

Table 4. Degradation mechanisms and their grade of importance in tank stability.

Degradation Mechanism	Consequences	Grade of Importance
Corrosion	Local thinning of the tank components can lead to loss of containment and product loss, and even tank catastrophic collapse.	Very high
Erosion	It is less encountered, even if it can have the same consequence of corrosion, due to the fact that the tank configuration can only have local, limited effects.	Medium
Fatigue	Fatigue can lead to local material property alterations and can finally result in containment loss and even tank catastrophic collapse.	High
Buckling	Buckling is widely encountered when tanks are not properly designed and can lead to loss of containment and product loss, and even tank catastrophic collapse.	Very high
Fracturing	Fractures are most commonly generated by either weld defects or plates/profiles flaws and can lead to loss of containment and product loss and even tank catastrophic collapse.	Very high
Overloading	This is classified also as a human error and can put the tank through loads that it was not designed for and can finally lead to loss of containment and product loss, and even tank catastrophic collapse.	Very high

3.3. Tank Non-Destructive Examination and Defects Identification

Main types of defects considered (plates and elements thinning due to corrosion, deformations, and their effect).

As a case study, the same AST M6 was considered, which was previously addressed in [2]. In order to analyze the tank technical conditions, some NDT activities were performed. Besides the welds testing, which has a direct consequence of repair works in case of defect, other NDTs were performed, as follows:

Wall thickness measurements of plates (according to API 653 [5]), structurals and nozzles are the main tank components. The method used was ultrasonic, using dedicated equipment. The output was a series of tables containing at least five measurements for each shell plate.

A shell and bottom deformation study was made using the LIDAR technology and special FARO equipment.

The deformation investigation report was based on a 3D Laser Scanning survey of the tank, and it refers to significant findings in accordance with API 653 [5] requirements. The factors included roundness (API 653 [5], cap. 10.5.3 Table 10-2 Radii Tolerances), Plumbness (API 653 [5] cap. 10.5.2-1/100 of tank height with a max. of 127 mm), and Shell settlement API 653 [5] Appendix B.2 (B2.2.2 Rigid body tilt and B2.2.3 Out-of-plane settlement).

The tank deviations were investigated for plumpness by twenty stations around the shell and for circularity by horizontal cross sections at an equidistance of twenty centimeters. The origin of all representation is the center of the manhole and the minimum level of the bottom–shell welding.

The following maximum deviations are found at verticality survey locations (Stations 1÷20), with one exceeding API 653 requirements. The maximum inward deviation was found at Station No. 20 at an elevation of 12.6 m, inward by −0.159 m. The maximum outward deviation was found at Station No. 11 at an elevation of 2.6 m, outward by 0.101 m.

The measurements were made with the measuring stations (represented as green dots) and disposed according to the sketch in (Figure 1) below:

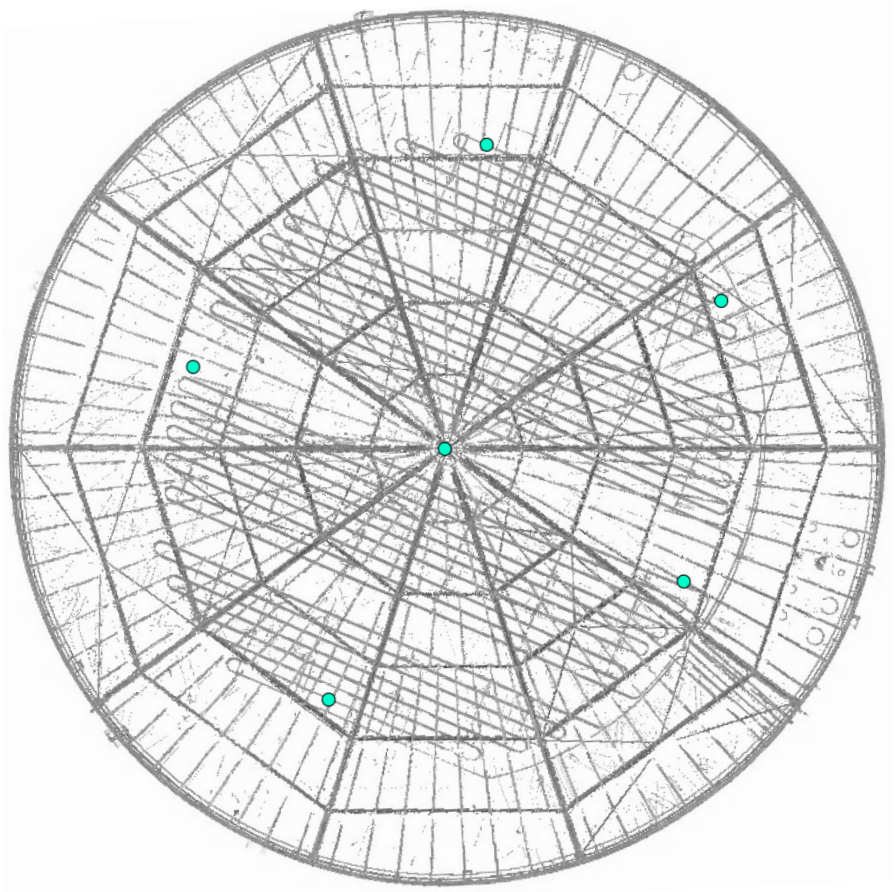

Figure 1. 3D scanning stations positioning within the tank interior.

The measurements made using the FARO LIDAR scanner (Lake Mary, FL, USA) were processed by the measurement contractor, and the output was the 3D Measurements report that highlighted the areas that exceeded the allowable deformation limits, and also a model

having multiple visualization options, along with accurate measurement possibilities, as seen in the image below, as a capture of the visualization software (Figure 2). In the right corner of (Figure 2) is a map representing the scanner positions, as red dots and the red cone is the view range.

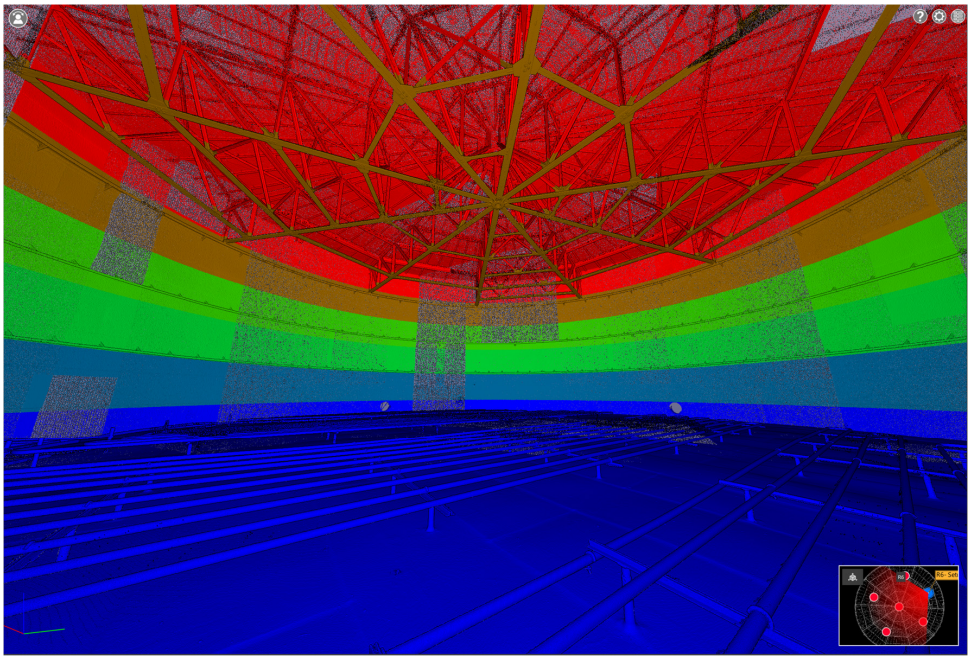

Figure 2. 3D visualization software of Tank M6.

3.4. Tank Condition Assessment by Digital Twin and FEA

Processing of the Input Data to Create a Tank Digital Twin

As mentioned before, the most susceptible to failure due to the hydrostatic, snow, wind, seismic, and combined loads are the tank roof structure and shell. The roof structurals were analyzed in [2] using the FEA method according to EUROCODE [60]. Also, the shell was analyzed by numerical methods according to various standards as API 653 [5], API 650 [4], and EUROCODE [60]. Now, using the 3D scan and the deformation map along with the wall thickness measurements, a partial digital twin of the shell can be produced. The digital twin will have three main input data sources:

- Shape, which can be produced by either cloud point data or a 3D deformation map.
- Minimum wall thickness is measured separately by operators for each circular section.
- Material, which is known to be S235 (corresponding to the old Romanian OL37).

Now, the 3D scanner output is a point cloud that contains a huge amount of data, which can be very difficult to process by the usual office computers. Just to have a term of comparison, the study below was performed on a laptop having an i9-10885H Intel processor, 32 GB DDR5 RAM, and a 4 GB Nvidia Quadro P620 graphics card, and took around 36 h to be performed in Autodesk Inventor 2026 and around 2 h in Autodesk Fusion 2026, but using cloud-based processing. This study is meant to be performed by engineers using common computers, not industrial workstations that are difficult and costly to access. Instead, there is another possibility to model the shape of the shell to a reasonable accuracy that can be used for an FEA study. To be clear, this study is meant on one side to confirm the result that was obtained by the analytical method [2] and on the other side to identify an approximate relation of the contribution of the deformed shape to the results obtained on the undeformed ideal cylindrical shell.

The deformed shape of the shell can be obtained in a 3D model using parametric modeling in a piece of dedicated software (like Autodesk Inventor or Fusion) and having as input a thoroughly prepared table that combines the local deformation of the shell (for 200 mm by 200 mm areas highlighted by the deflection value from the ideal cylindric shape of the shell) and the same local shell thickness, separately and added. This table will generate a set of data readable by the modeling software that will eventually create a working 3D model of the tank shell.

The 3D deformations report is usually presented in the form of a table containing the deviations from the ideal circular shape, in meters, that is positive for the outer deformations and negative for the inner ones. The table is in Cartesian coordinates: height on the column and unfolded length on the horizontal (Figure 3).

H/circumf	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2
12.7	-0.109	-0.110	-0.110	-0.109	-0.107	-0.109	-0.110	-0.104	-0.103	-0.107	-0.106	-0.105	-0.107	-0.109	-0.115	-0.115	-0.119
12.6	-0.108	-0.114	-0.115	-0.121	-0.126	-0.129	-0.126	-0.120	-0.116	-0.108	-0.114	-0.113	-0.115	-0.119	-0.116	-0.112	-0.123
12.4	-0.092	-0.096	-0.099	-0.113	-0.130	-0.133	-0.132	-0.123	-0.116	-0.108	-0.111	-0.105	-0.103	-0.103	-0.103	-0.101	-0.109
12.2	-0.082	-0.085	-0.094	-0.102	-0.116	-0.130	-0.128	-0.126	-0.114	-0.105	-0.101	-0.099	-0.098	-0.098	-0.097	-0.097	-0.100
12.0	-0.075	-0.082	-0.087	-0.095	-0.108	-0.120	-0.129	-0.123	-0.113	-0.104	-0.098	-0.095	-0.095	-0.097	-0.098	-0.101	-0.102
11.8	-0.072	-0.082	-0.088	-0.093	-0.105	-0.119	-0.125	-0.120	-0.113	-0.106	-0.104	-0.101	-0.100	-0.102	-0.103	-0.102	-0.104
11.6	-0.070	-0.082	-0.090	-0.093	-0.103	-0.115	-0.115	-0.115	-0.107	-0.108	-0.105	-0.105	-0.107	-0.111	-0.107	-0.106	-0.107
11.4	-0.063	-0.074	-0.083	-0.090	-0.097	-0.102	-0.103	-0.106	-0.098	-0.102	-0.104	-0.105	-0.108	-0.108	-0.110	-0.109	-0.110
11.2	-0.051	-0.061	-0.070	-0.073	-0.078	-0.083	-0.084	-0.085	-0.079	-0.082	-0.085	-0.086	-0.089	-0.091	-0.091	-0.092	-0.094
11.0	-0.054	-0.062	-0.067	-0.069	-0.072	-0.075	-0.080	-0.075	-0.072	-0.074	-0.077	-0.077	-0.077	-0.080	-0.083	-0.084	-0.089
10.8	-0.056	-0.060	-0.063	-0.068	-0.068	-0.071	-0.073	-0.070	-0.070	-0.072	-0.075	-0.076	-0.075	-0.078	-0.081	-0.085	-0.089
10.6	-0.066	-0.068	-0.069	-0.072	-0.073	-0.074	-0.073	-0.072	-0.072	-0.075	-0.078	-0.086	-0.080	-0.084	-0.085	-0.087	-0.090
10.4	-0.087	-0.086	-0.089	-0.091	-0.088	-0.086	-0.086	-0.085	-0.090	-0.088	-0.089	-0.100	-0.093	-0.094	-0.095	-0.098	-0.100
10.2	-0.111	-0.108	-0.109	-0.114	-0.109	-0.110	-0.109	-0.108	-0.112	-0.115	-0.105	-0.109	-0.113	-0.111	-0.115	-0.118	-0.117
10.0	-0.128	-0.128	-0.130	-0.134	-0.133	-0.127	-0.134	-0.127	-0.133	-0.129	-0.129	-0.134	-0.125	-0.137	-0.138	-0.142	-0.138
9.8	-0.092	-0.094	-0.096	-0.099	-0.099	-0.104	-0.104	-0.108	-0.115	-0.106	-0.099	-0.100	-0.101	-0.102	-0.106	-0.106	-0.106
9.6	-0.077	-0.079	-0.083	-0.085	-0.089	-0.090	-0.091	-0.098	-0.106	-0.098	-0.088	-0.088	-0.087	-0.090	-0.092	-0.096	-0.094
9.4	-0.073	-0.073	-0.079	-0.080	-0.083	-0.084	-0.085	-0.090	-0.096	-0.089	-0.084	-0.083	-0.083	-0.085	-0.086	-0.088	-0.089
9.2	-0.067	-0.071	-0.074	-0.077	-0.078	-0.080	-0.081	-0.084	-0.088	-0.085	-0.080	-0.081	-0.083	-0.084	-0.086	-0.089	-0.087
9.0	-0.068	-0.070	-0.075	-0.077	-0.078	-0.079	-0.079	-0.082	-0.084	-0.081	-0.080	-0.082	-0.087	-0.088	-0.090	-0.089	-0.089
8.8	-0.067	-0.072	-0.077	-0.079	-0.079	-0.079	-0.078	-0.077	-0.078	-0.079	-0.082	-0.087	-0.089	-0.094	-0.096	-0.094	-0.094
8.6	-0.069	-0.074	-0.075	-0.079	-0.077	-0.076	-0.075	-0.075	-0.075	-0.078	-0.082	-0.086	-0.092	-0.098	-0.100	-0.099	-0.099
8.4	-0.051	-0.052	-0.056	-0.055	-0.054	-0.052	-0.050	-0.054	-0.057	-0.059	-0.058	-0.068	-0.077	-0.084	-0.087	-0.089	-0.089
8.2	-0.045	-0.045	-0.042	-0.041	-0.041	-0.039	-0.038	-0.042	-0.050	-0.046	-0.045	-0.052	-0.062	-0.071	-0.074	-0.077	-0.077
8.0	-0.044	-0.041	-0.041	-0.037	-0.035	-0.033	-0.032	-0.035	-0.038	-0.037	-0.037	-0.043	-0.050	-0.058	-0.063	-0.067	-0.069
7.8	-0.047	-0.043	-0.040	-0.037	-0.035	-0.030	-0.030	-0.032	-0.032	-0.032	-0.033	-0.039	-0.045	-0.053	-0.059	-0.065	-0.068
7.6	-0.055	-0.049	-0.043	-0.038	-0.034	-0.031	-0.028	-0.028	-0.030	-0.028	-0.032	-0.036	-0.043	-0.052	-0.058	-0.064	-0.069
7.4	-0.062	-0.056	-0.050	-0.043	-0.039	-0.035	-0.029	-0.029	-0.030	-0.027	-0.031	-0.036	-0.042	-0.052	-0.060	-0.066	-0.070

Figure 3. Section of the tank deformation 3D measurements report.

To begin the modeling, it all started from the assumption of a perfect cylinder with a diameter of Ø32.217 m and a height of 12.7 m, respectively. Based on the 3D measurements and the deformations report provided (Figure 3), the tank shell was afterwards split into 507 × 65 cells that are approximately 200 × 200 mm areas. Those area cells were assigned an average deviation calculated for that 200 × 200 area. By using trigonometry formulae, a set of points was created.

By dividing 360 degrees by 507 slices, each cell represented an angle of 0.710059°.

$$\text{Angle} = \frac{360^\circ}{507} = 0.710059^\circ$$

$$Cell\ angle = Previous\ cell\ angle + Angle$$

$$Cell\ angle = Corresponding\ cell[1, \ldots, 507] + Angle$$

For the starting cell, the angle is also 0°. As such, this enables us to find the angle, in polar coordinates, of each cell. Using this information, each point of each cell in polar coordinates (represented as dots in Figure 4) for the three dimensions was calculated as follows:

$$Point(x, y, z)\begin{cases} x = \left[\frac{Tank\ diameter}{2} + (cell\ deviation)\right] \times cos\ (Cell\ Angle) \\ y = \left[\frac{Tank\ diameter}{2} + (cell\ deviation)\right] \times sin\ (Cell\ Angle) \\ z = Coresponding\ cell[1, \ldots, 65] \times 200 \end{cases}$$

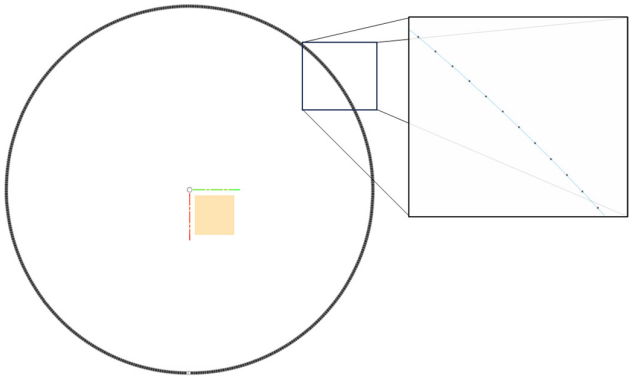

Figure 4. The points that generated the deformed shape.

As such, each segment generically considered as a ring was saved as a .csv file, to be imported into CAD software (in this case Autodesk Inventor 2026) (Figure 5)). Rings were preferred as they require less human input and create a more rounded shape as opposed to creating an edge using the same idea and then connecting them.

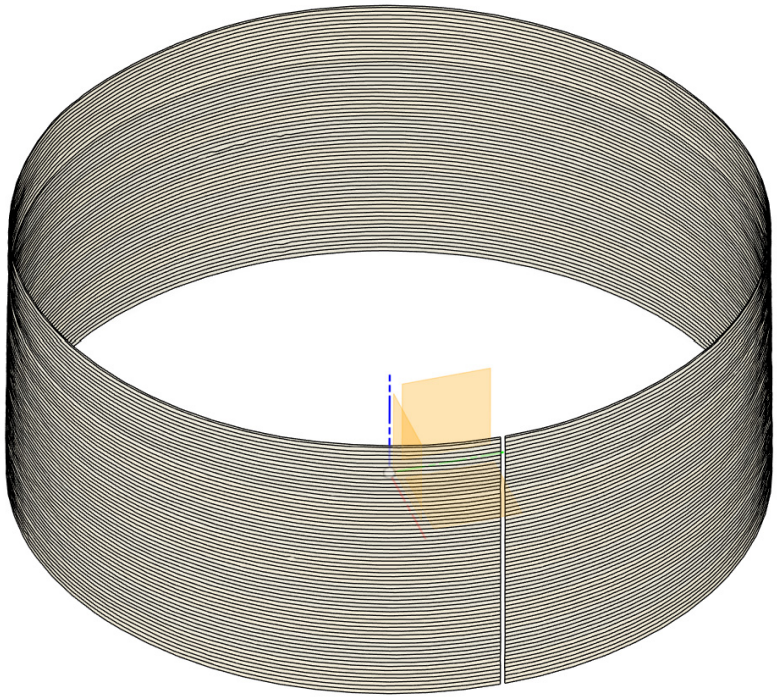

Figure 5. The primary generated shell model, including a gap.

Creating a loft between each defined "ring", using the surface command, generated a 3D model of the data. However, due to limitations in both hardware and software, a gap can be formed. This can be mitigated by just uniting the ends together using a loft between the two edges.

Moreover, the loft may not include all profiles, in which case the loft can be generated in batches, connecting each ring to its immediate ring over, and then combining all rings into one (Figure 6).

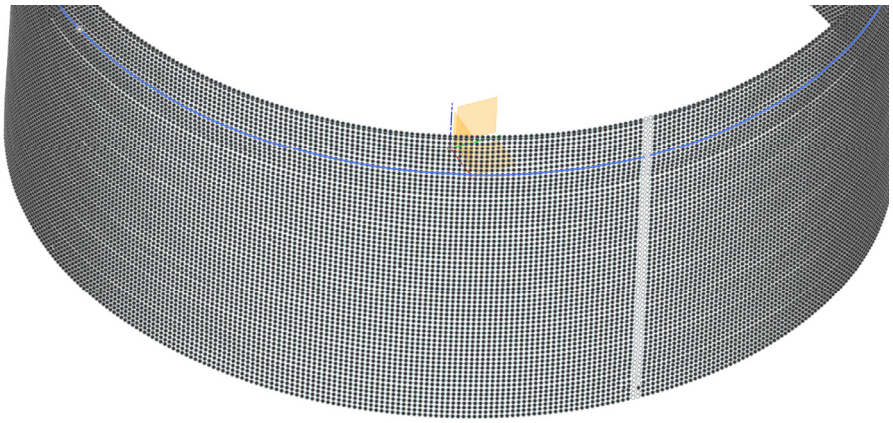

Figure 6. The loft generated to close the shell section and to eliminate the gap.

With the final shape, the thickness was added for each course in accordance with the measured values minus the considered corrosion allowance to finally create a body that would later receive an attribute with the proper material. In this way, a final model was generated for the analysis to be performed on (Figure 7).

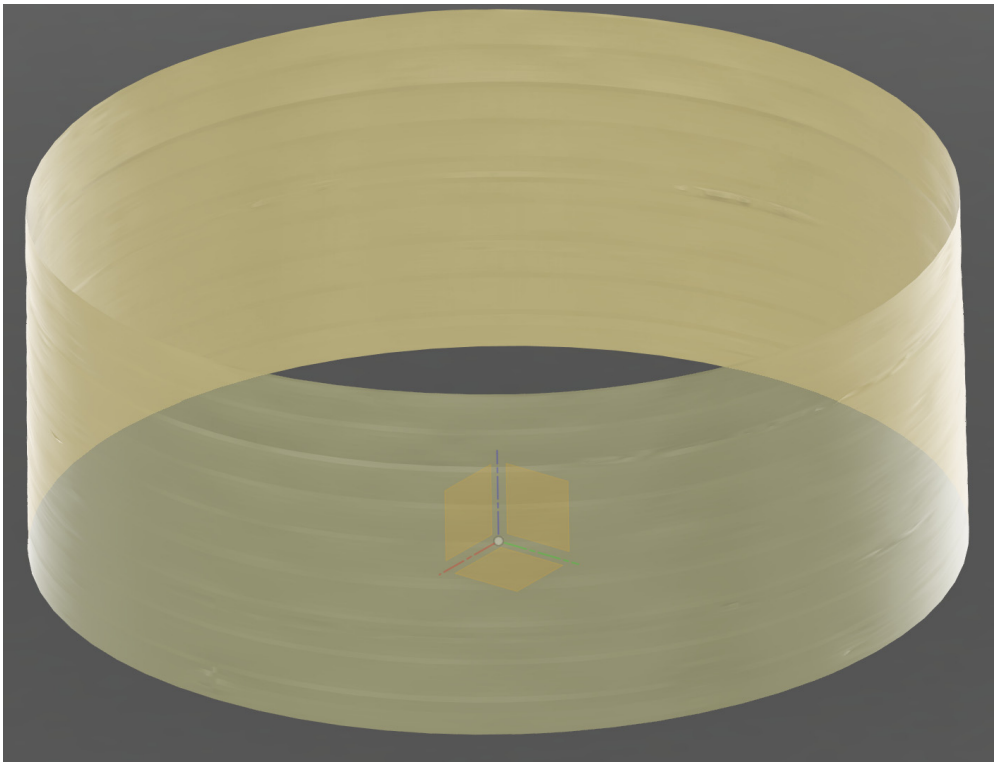

Figure 7. The final tank shell surface generated after the gaps have been eliminated.

We combined the generated rings into groups, forming the actual shell tank courses (represented in alternate blue and white colors), in accordance with the equipment inspected on site (Figure 8).

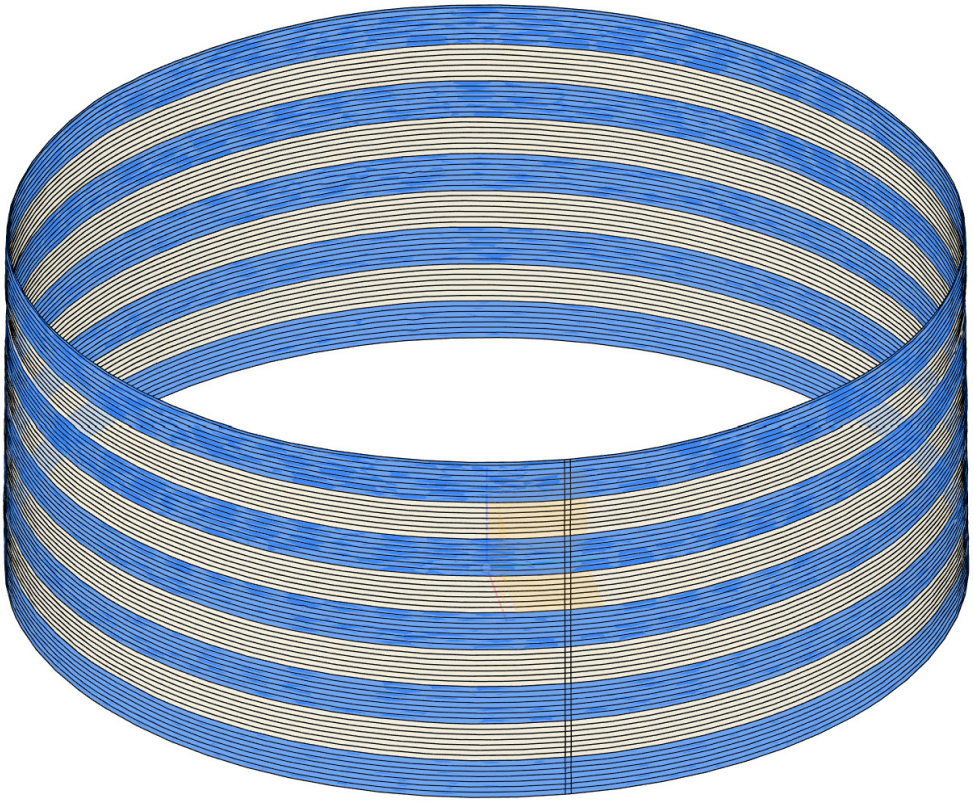

Figure 8. The tank shell model having the generated rings grouped in courses according to the tank design.

The accuracy loss, considering the overall dimensions of the tank, is negligible, since the whole deformed shell surface was defined by 200 mm × 200 mm sections followed by a smoothing of the connections between them in order not to create stress concentrators.

The corrosion rate was defined based on the experience in the local refinery with the same type of product stored in tanks made of the same material, along with the literature guidelines: 0.1 mm/year.

The resulting full deformed shell shape (Figure 9) generated using the method described matches the unfolded deformed shell presented in Figure 3 of [2].

The red and green colored areas represented in (Figure 9) are the ones with the largest deviation from the perfect cylinder, which is considered to be the ideal shape of the shell and for which the analytic calculations described in the design and repair standards can be safely performed.

For the simulation, the hydrostatic load together with the dead load, including the roof, was considered, as follows:

Roof dead load: Uniform distributed force on the top course: 420 kN that represented the roof steel structure, the roof cover plates, and nozzle weights applied as an even distributed force on the top shell circumference.

Hydrostatic load, as uniform pressure on each course, is as in (Table 5):

Since the analytical model considered the hydrostatic load at the bottom of each shell course, the same approach was made here, with the hydrostatic pressure being calculated using the classical formula $Ph = \rho \times g \times h$, where ρ is the hydrotest water density, in kg/m^3, g being the gravitational acceleration in m/s^2, and h being the height of the liquid column corresponding to each course base, in m.

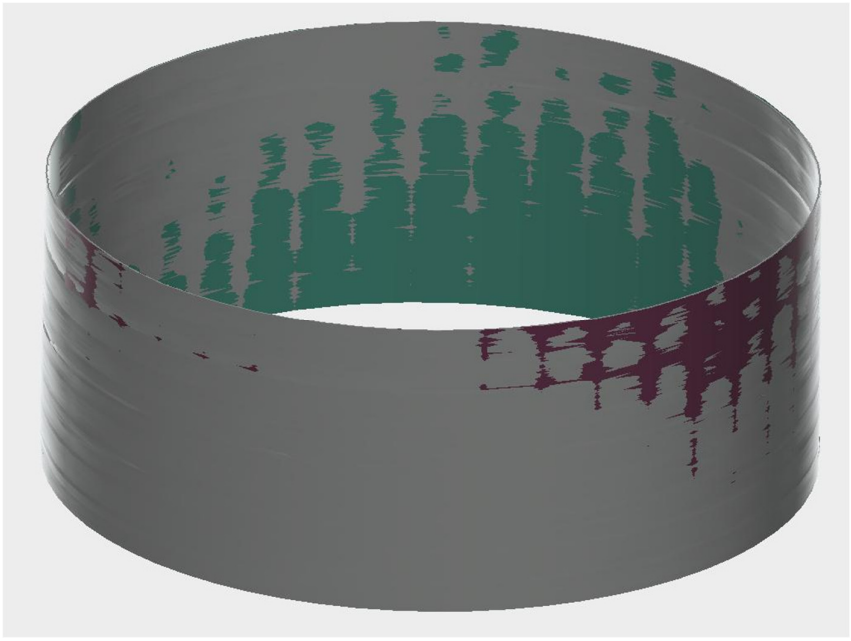

Figure 9. Deformed shape of the shell generated using the 3D measurements.

Table 5. Hydrostatic pressure considered for the shell.

Course Number	Course Height (m)	Hydrostatic Pressure (MPa)
1	1.5	1.055
2	1.4	0.0928
3	1.4	0.0800
4	1.42	0.0673
5	1.43	0.0545
6	1.43	0.0417
7	1.45	0.0289
8	1.45	0.0162
9	1.49	0.0034

The existing tank material was found to be S235JR (equivalent to ASTM A36). This investigation was made using two methods, the first one being the PMI, where the chemical composition matched the percentages of S235JR, and the second being the mechanical destructive tests on a test sample taken from one section of the bottom. These tests were performed by an authorized company.

The mechanical properties of S235JR were considered as follows:

Density: 7850 kg/mm^3;

Young's Modulus: 210,000.00 MPa;

Yield Strength: 235.00 MPa;

Tensile Strength: 360.00 MPa.

No thermal stress was considered, as the tank operates at ambient temperature, without any heating system.

In regard to the model boundaries, the tank shell was considered fixed on its lower edge by a fixed constraint that was applied to the model. This fixed constraint can be considered because the tank anchorage forces the lower tank shell course to be kept on the ground.

The model mesh finite element type chosen for this analysis was "shell", characterized by a mid-surface and a thickness. The mid surface was actually the one parametrically generated during modelling, refined by a local smoothing at the joint of two adjacent sections (the 200 × 200 mm ones). The shell elements were also divided into smaller finite elements, with local discretization especially where the adjacent sections had slightly different deformations. Since the shell has irregular thickness and deformations, the element sizes were automatically adjusted by the Fusion meshing engine.

After the stress analysis, the maximum value obtained was found on the most deformed area of the tank, in the upper region, which is also combined with shell thinning due to corrosion (Figures 10 and 11).

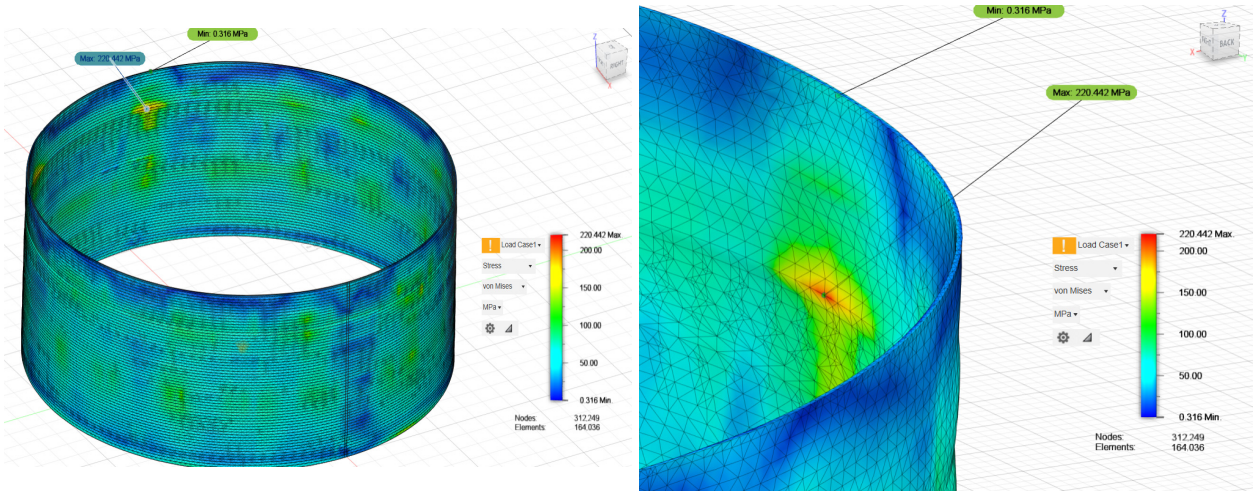

Figure 10. Maximum value obtained from the stress analysis result.

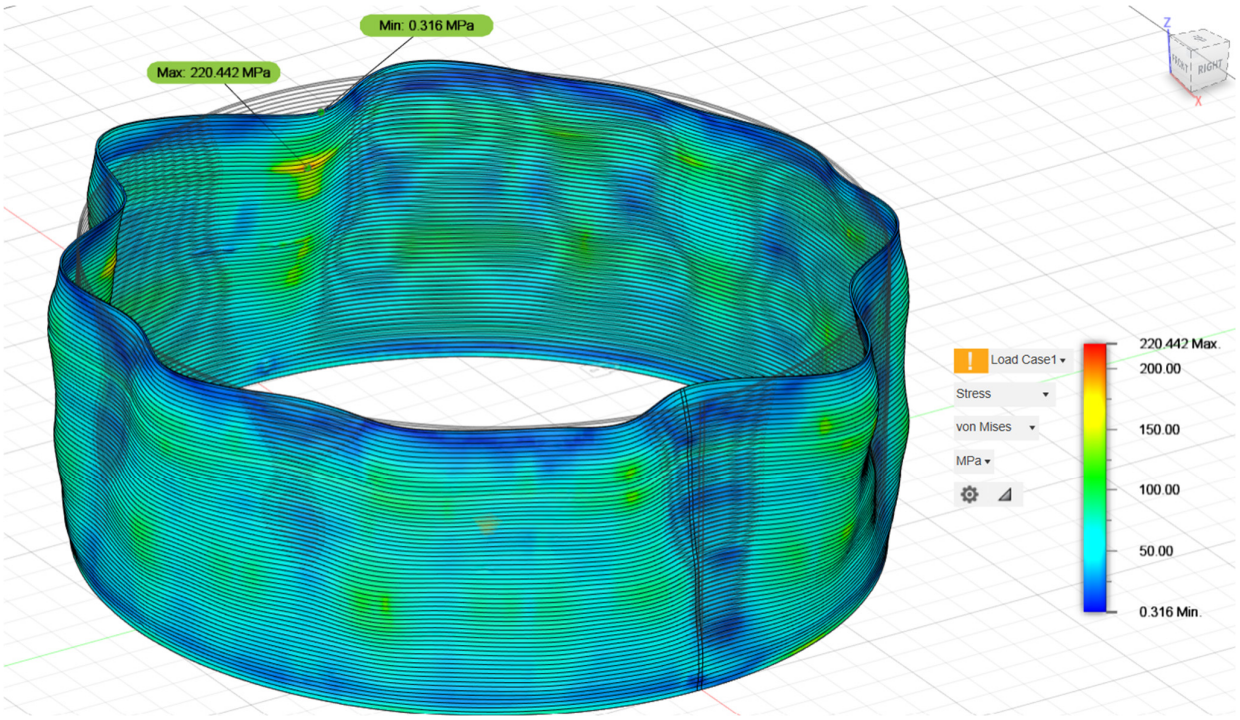

Figure 11. Deformed shape of the tank, exaggerated to highlight the higher stress in the local already deformed area.

To have a term of comparison, local probes were used to inspect the values in the most stressed areas of the tank (Figure 12). These values were compared with the values obtained from checking against EUROCODE in Table 3 of [2].

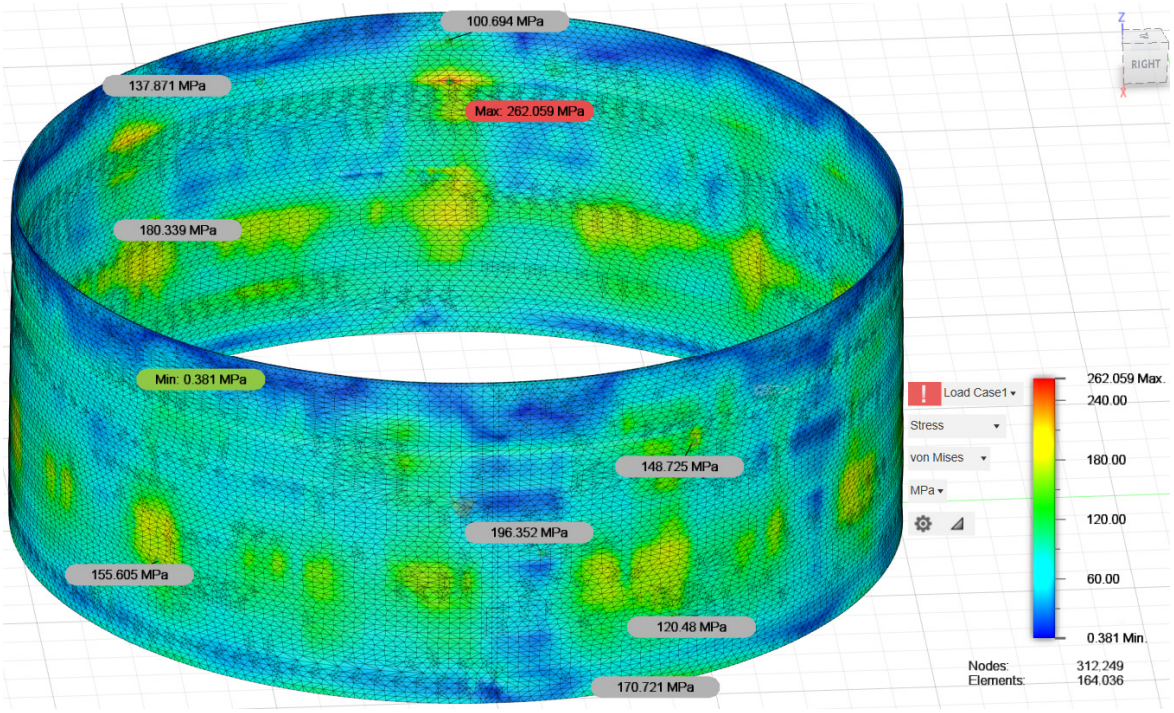

Figure 12. Tank stress values for each course.

As can be observed in Table 6, the actual stress resulting from the FEA simulation is significantly higher than the one obtained by the numerical model, which is calculated for the ideal cylindrical shape, so it can be concluded that the EUROCODE calculation can be used, but for shells that have deformations within the allowable API 653 limits.

Table 6. Hydrostatic operation case, stress values comparison, EUROCODE versus FEA.

Course Number	EUROCODE Stress Value (MPa)	FEA Stress Value (MPa)
1	119.508	170.721
2	148.361	120.480
3	151.625	155.605
4	212.771	180.339
5	162.660	196.352
6	189.295	148.725
7	111.700	262.059
8	108.178	137.871
9	58.568	100.694

For reference, the percentage of each shell course that is deformed beyond the allowable limits has been computed as per Table 7. The maximum allowable deformation limit, depending on tank size, is 57 mm.

Table 7. Shell course percentage that exceeds the maximum allowable deformation limit according to API 653.

Course Number	% of the Shell Deformed Beyond Allowable Limit
1	17.3
2	16.88
3	13.35
4	14.65
5	18.82
6	32.82
7	45.59
8	58.46
9	60.45

The higher stresses converged in the most deformed areas mainly for two reasons, one being the overstress of the deformed areas and the other due to the smoothing process between the sections considered for the parametric modelling.

It is to be considered that, in the most deformed areas, the local deformations exceeded by three times the maximum allowable by the standard.

It can be considered from this case study that a very high deformation can cause a local higher stress, but, for example, if a plate section is slightly deformed beyond the standard maximum tolerance, it can be accepted if a thorough local stress assessment is performed. This is worth doing if the area that needs to be replaced implies revamp difficulties, for example, if it is located behind a stiffening ring, or near an access platform, or similar situations. These situations can only be evaluated and treated by an experienced engineer.

4. Results and Discussion

4.1. Wall Thickness Reduction

Wall thickness reduction has the highest impact on tank stability because local thinning of the material directly results in a higher stress in the area, which makes it more susceptible to failure.

Since corrosion is not usually uniform, localized thinning, most of the time caused by pitting, results in stress concentrators that, eventually, if not eliminated by repairs and/or reinforcing, will lead to material failure in that exact area. This is highlighted in Figure 10, where a local thinning, together with excessive deformations, leads to a stress value that is significantly higher than the adjacent areas.

It is of the highest importance that all the shell plates have the measured thicknesses higher than the minimum allowable by the standards, excluding, of course, the corrosion allowance that is a fixed value established from the beginning.

4.2. Deformations and Geometric Imperfections

The local shell deformations, as highlighted by the case study considered, have a significant impact on the shell stress, especially since they exceed the maximum allowable by the standard.

One of the highest deformations is 149 mm in the outer direction (Figure 13), exceeding by almost three times the allowable value is localized on the eighth shell course, exactly in the same area where the calculated plate stress is the highest. In the table produced by the scanners, darker colors indicate greater deformation. The value is highlighted below in an extract from the measuring report:

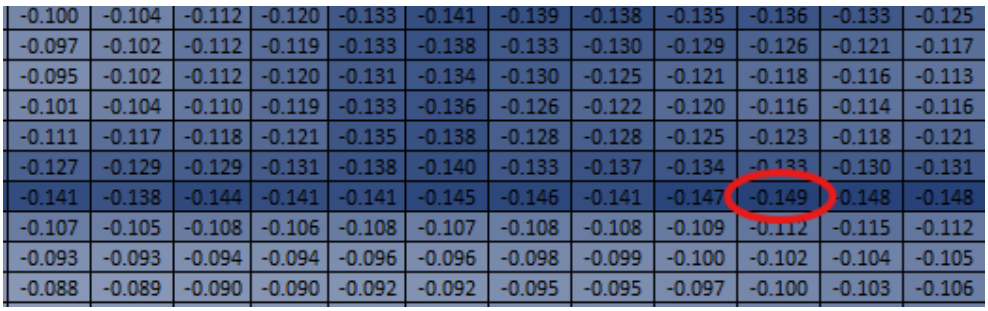

Figure 13. Tank eighth shell course area with a higher deformation value.

4.3. Local Stress Concentrations

The most difficult aspect in a tank integrity evaluation is the combined effects of local thinning, local deformations, local loads, and especially their combinations, all acting on the thin membrane that is the tank shell. Basically, this is why standards were adopted, taking into consideration allowable limits that are conservative enough to assure that, if there are no significant defects to be taken into consideration separately, the assessment will assure a safe level of accuracy.

On the other hand, if the engineer who performs the assessment considers it necessary and has available all the required data (3D deformation scans, precise wall thickness measurements) and tools (dedicated FEA capable software and a huge computer processing power), a comprehensive local analysis can be performed to assess a tank component.

4.4. Equipment, Personnel Requirements, and Cost–Benefit Analysis

This section addresses some aspects that are not technical, and hence are sometimes overseen by engineers, but that can have a significant impact on the methods used for a tank inspection or, in some cases, can even lead to some radical decisions, like to postpone inspection/revamp works or replace equipment that can be repaired with minimum cost due to the fact that the inspection and condition assessment methods selected were too expensive. As an example, a 50.000 m^3 tank that has exceeded its life time but is in good shape is worth allocating resources to in order to perform a thorough analysis, with complete 3D deformations, SLOFEC wall thickness scans, and full FEA analysis, while, for a 1000 m^3 tank that is already in bad technical shape, a smaller budget for measurements and an analytical calculation according to a standard is enough to decide that it needs full replacement. As a note, Non-Destructive Testing of the welds shall, nonetheless, be performed.

The equipment used for the measurements and scans is very expensive, the personnel operating them are highly skilled, and the post-processing work also uses high-performance computer stations and skilled engineers, so the end cost for these services is very high.

Another approach that can bring benefit to the client is the succession of the inspections, which allows for evaluating the equipment's technical condition after each stage. The first inspection shall be the visual one, which brings the most important information about the tank's overall state. Then, the wall thickness measurements, five points for each plate according to API653, followed by a calculation to see if the structural integrity of the equipment is maintained. If a high percentage of the tank shell/bottom/roof fails the minimum structural strength requirements and needs replacement, then it is obvious that there is no longer a need for 3D deformation scans or FEA analysis, and that budget transforms to a cost saving.

5. Conclusions

The method proposed in the case study was considered to be accessible to engineers skilled in parametric modelling and FEM, but without the need to use high computational resources to perform an analysis of a tank shell. The results have proven that the most deformed areas have the highest stress values and confirm, to some extent, the analytical calculation.

The downside of this method is that a statistical validation is very difficult to perform, as there are significant differences in the existing storage tanks' technical state in terms of materials, wall thicknesses, deformation patterns, etc. This method of analysis highly depends on the engineer's skills to refine and smooth the model in order to obtain a satisfactory level of accuracy.

On the other side, there is the possibility to perform a complete scan of a tank, using combined methods, like 3D LIDAR for deformations and roof structure, and SLOFEC for wall thickness and wall thickness measurements for the roof structure through an extensive post-processing to obtain the true digital twin. However, from experience, all these activities can only be performed by dedicated companies and cost a great amount of money that some clients are simply not willing to pay, especially for smaller tanks. This case study was based on these situations encountered in practice.

The usage of AI can significantly add value to the process, but it also takes a lot of resources to teach the AI to perform such complex tasks and successfully implement it in these calculations and methodologies that represent a niche that may be too small for someone to be willing to put such effort into. The inspection and condition assessment activities still rely on the skill and experience of the engineer.

6. Recommendations and Suggestions for Future Work

For a tank evaluation to be at a sufficient level of accuracy to assure that the result will reflect the actual situation of the equipment, the most important thing is the input data, which include the actual measurements and inspection activities:

- Visual inspection to be performed by an experienced engineer;
- Wall thickness measurements, preferably performed by a SLOFEC scanner;
- Shell 3D scan to investigate the local deformations;
- Welds NDT Testing;
- Material identification (PMI).

All of these, together with the process data provided by the tank owner, represent the base for the tank assessment that needs to be performed according to the applicable standards.

For a more comprehensive analysis, it is important to consider together the minimum, the local wall thickness, the tank deformed geometry, and, if any, nozzles or local appurtenances that are welded on or are part of the tank shell. All these need to be modeled based on a cloud point model exported by the 3D deformations and wall thickness scans. This means that either the equipment used for these measurements is of the same type or can export similar data to be automatically merged, or this is performed by post-processing, which usually requires a great amount of computing power, which is usually not available through common computers. After the model is complete, the loads/loads combinations are applied, the material mechanical properties are defined, the local constraints are set, and, after the post processing, the FEA results can be interpreted.

The easiest way to speed up the process of preparing the model, which can take a lot of time, is to find a way to automate the data acquisition from the scanner's output and prepare a parametric model. This is very complex and time-consuming, especially because each scanner operates differently, but a common data type might be identified that the

parametric design software is able to use. In this process, AI can contribute through its adaptive learning capacity to process data.

Another matter that can be improved is the corrosion prediction. There are dedicated inspection systems (usually automated drones) that scan the internal surface of the tank plates at different wavelengths, and the successive scans performed during scheduled inspections could be used to predict the future affected area and probable failures through a self-learning algorithm within an AI system. Being a very complex task, this could be developed by a software company, together with experienced corrosion engineers.

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Abbreviations

The following abbreviations are used in this manuscript:

NDT	Non-Destructive Testing
FEA	Finite Element Analysis
AST	Above-ground Storage Tank
API	American Petroleum Institute
EEMUA	Engineering Equipment and Materials Users Association
LIDAR	Light Detection and Ranging
SLOFEC	Saturated Low-Frequency Eddy Current
UT	Ultrasonic Testing
MPT	Magnetic Particle Testing
AE	Acoustic Emission (testing)
RT	Radiographic Testing
PT	Dye Penetrant Test
LCO	Light Cycle Oil
IFR	Internal Floating Roof
SHM	Structural Health Monitoring
DT	Digital Twin
SLS	Service Limit State
PMI	Positive Material Identification
AI	Artificial Intelligence
IoT	Internet of Things
HAZ	Heat Affected Zone
EU	European Union
CA	Corrosion Allowance
MDMT	Minimum Design Metal Temperature
VCE	Vapor Cloud Explosion

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