European Journal of Mechanical Engineering Research, 12(2),30-52, 2025
Print ISSN: 2055-6551(Print)
Online ISSN: 2055-656X(Online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development-UK

Life Extension of Ageing FPSO and SPM Calm Buoy Mooring Chains Under Corrosion Effects - Part 2A

[1*]C. Ebunuoha **[1]E. G Saturday** **[2]C. E Ebieto**

1. Offshore Technology Institute, University of Port Harcourt, Rivers State, Nigeria.
2. Department of Mechanical Engineering, University of Port Harcourt, Rivers State, Nigeria.

*Corresponding author: chigozie_ebunuoha@uniport.edu.ng

doi: https://doi.org/10.37745/ejmer.2014/vol12n23052 Published October 12, 2025

Citation: Ebunuoha C., Saturday E.G., Ebieto C.E. (2025) Life Extension of Ageing FPSO and SPM Calm Buoy Mooring Chains Under Corrosion Effects - Part 2A, *European Journal of Mechanical Engineering Research*, 12(2),30-52

Abstract: *This study unveils the recent challenges that mooring chains used for station keeping of floating assets face while in operational marine environment. Considering the extremely harsh operating environment, the mooring chains on floating production, storage and offloading (FPSO) and single point mooring calm buoy (SPM) will definitely undergo degradation and deterioration over time. Although, general/uniform and pitting corrosion has been implicated as major cause of mooring chain degradation. Ageing and age related challenges such as pits, wear and corrosion wastages across the mooring chains intergrip, side and straight bars were key considerations for life extension evaluations since it weakens the strength of the chains. The biological phenomenon that causes pits on mooring chains were highlighted. Regrettably, the scarcity of real time corrosion wastage data has made researchers to adopt data from laboratory in corrosion coupon for the purpose of study. Although, laboratory data are usually under control, and hence researchers are looking for more realistic data from marine corrosion environment. It was observed that corrosion wastages are known to alter the geometry of mooring chains but not the chemical and mechanical properties. It was observed that real time corrosion wastage data from a floating asset in marine environment is key to drive life extension decision making. However, it was observed that there are still limited information as regards the type of data to measure, their collation, analysis and interpretations towards the ultimate goal of mooring chains mitigation strategy for longevity.*

Keywords: FPSO/SPM calm buoy, mooring chains, corrosion wastage, MIC, Re-evaluation, mitigation strategies, mooring longevity, life extension

INTRODUCTION

The FPSO and SPM calm buoy is an essential piece of equipment in the upstream oil and gas sector in the current competitive business climate with extremely low profit margins. Therefore, prolonging their operating life can yield substantial financial and ecological advantages. As a result, offshore engineers are regularly required to think creatively in order to design a framework, evaluate historical data gathered from floating assets, and make wise business decisions that minimise or completely eliminate the chance of incurring additional operating and capital expenditures, or OPEX and CAPEX. Many floating production installations, including as FPSOs, FSOs, and SPM calm buoy deployments, are either reaching or have gone beyond their initial designed operational life, according to recent surveys conducted worldwide [1], [2], [3]. Thus, life extension conversations have taken centre stage in the offshore Brazil and offshore West Africa markets. The mooring chains are an essential part of floating production installations, including FPSOs, FSOs, and SPM calm buoys used for station maintaining [4], [5], [6], [7]. The activities of sulphate-reducing bacteria, (SRBs), and acid producing bacteria, (APB) can cause pitting corrosion on mooring chains, making them susceptible to microbial induced corrosion, (MIC) [8]. Wear and uniform/general corrosion wastages are the others [9], [10]. A challenging issue is that within the water body where we have biofilm, a collection of bacteria, which accounts for both SRB and APB that causes major damage on mooring chains, in some cases shortens their original design life of 20 to 30 years. These bacteria are known to feed on debris and sediments in water. They usually find a conducive place between the mooring chain and marine growth fouling to live. Such places between the mooring chain and marine growth fouling usually have limited to zero oxygen [6]. Hence, these SRB and APB are grouped under anaerobic bacteria, which are bacteria that can survive without oxygen. But their wastes (metabolic by-products) contains H_2S, of which when deposited on the mooring chains causes pit on the chains in what is further called pitting corrosion. The water body is known to contain dissolved oxygen, the presence of the marine growth fouling on the mooring chains reduces or completely prevents oxygen penetrations and hence stops uniform or general corrosion on the chains and accessories. Frequent cleaning of the marine growth fouling using high pressure water jetting is usually not allowed by most operators because it exposes the chains to more devastating action of seawater. On the other hand, the marine growth fouling accounts for added mass on the mooring chains, there increasing the hydrodynamic loads on it. These added mass are the basis of coefficient of drag and inertia values selection when carrying out reverse engineering studies in mooring chains life extension. While research into the R7 mooring chain grade is still ongoing in an effort to increase quality and durability, advancements in mooring chain production for the offshore industry have developed throughout the following grades: ORQ, R3, R3S, R4, R4S, R5, and most recently, R6 [11], [12], [13]. Caternary anchor leg mooring, (CALM), usually come in different material composition for a particular mooring line depending on operator's mooring philosophy. Usually you can find all mooring chain material composition, chain - wire rope - chain material composition and lastly chain -polyester - chain material composition [13]. In some cases, by extending the length of the wire rope or polyester mooring engineers can cut down total costs of using chain material composition and at the same time reduce the weight of the system [12]. Notably, life extension initiatives for floating facilities offer greater financial benefits in terms of cost reductions because, from a business perspective, operators are constantly searching for methods to lower OPEX and remove CAPEX, but when it is not carried out completely in accordance with the classification society's regulations governing such floating assets and the satisfaction of the classification society surveyor present, it can also conceal hidden catastrophic accidents in the background. Major operators in the oil and gas industry are increasingly talking about extending the life of floating installations [14], [15], [16], [17], [18]. Therefore, compared to other floating facilities end of operational life management solutions, extending the design operational life of a mooring facility yields numerous cost savings benefits [19], [20]. The most difficult situation that FPSO and SPM calm buoy mooring chains encounter during their design service life is the problem of marine corrosion wastage [21], [22], [23]. The main component systems that are susceptible to corrosion wastage are the mooring chains of the FPSO and SPM calm buoy. However, as the FPSO and SPM calm buoy mooring chains age, the threat of corrosion wastage grows more serious and difficult. The most significant causes of age-related structural deterioration and deterioration of the FPSO and SPM calm buoy mooring chains are thought to be corrosion and corrosion-induced problems. From a safety perspective, corrosion can result in penetration and thickness reductions, which are harmful outcomes [24], [25], [26]. It is well recognised that the impacts of marine corrosion wastage might compromise the mooring chains' structural integrity and longevity. Some classification organisations, like ABS, advise reducing the thickness of moorings by around 35 percent due to strength considerations, as marine corrosion wastage limitation values trigger FPSO and SPM calm buoy mooring chains mitigations, such as repairs and replacements [26]. At this wastage percentage, the mooring chain must have experienced enough corrosion wastage and strength reductions to trigger retirement. The remaining thickness of a mooring chain is a direct measure of the remaining strength. Notably, when the mooring chain thickness reduction is as much as 15 percent for turret moored facilities, more care should be paid [27]. Segments like the upper chain, weight chain, mid-water chain, excursion limiter chain, and ground chain are typically included in an all-mooring chain materials composition. Typically, mooring chain connectors are used to join the chains. On steel, severe localised and uniform corrosions, like pitting corrosion, have been studied and documented on mooring components at several offshore locations worldwide [28], [29], [30], [31].

In recent years, this phenomenon has raised questions about whether the components can safely fulfil their design life [32]. In their research, [32] found that SRBs were causing significant pitting corrosion on a portion of mooring chain segment with shallow to deep trenching on the seabed. The mooring chains in the top 2 meters of silt on the seabed showed a significant localised corrosion attack with a pit depth of 3 to 4 mm and variable sizes from a few millimetres to larger areas. These pits were found to lower the safety fatigue strength factor and, unavoidably, the mooring chain's fatigue capacity. Furthermore, marine vegetation fouling attachments on mooring chains worsen the environment (wave and current) loads on the chains [33]. The SRBs are under the category of anaerobic bacteria, which are microorganisms that can grow, flourish, endure, and proliferate without oxygen. They typically reside between marine growth fouling and mooring chains. This indicates that they are covered in marine growth fouling and fastened to the mooring chains. The majority of previous studies on mooring chain corrosion wastages have relied on data collected in a controlled laboratory corrosion coupon. The mooring chain is intended to function in actual marine conditions, when corrosion wastages occurs naturally and uncontrollably. However, the scholarly literature that is now available frequently only discusses a few of the difficulties.

Although, the majority of classification societies merely gave the operators of FPSOs clumsy and cursory guideline notes as a framework for life extension. The current study offers a thorough technique for assessing the effects of corrosion wastage on the FPSO and SPM calm buoy mooring chains for a 15-year life extension. Notably, mooring chains are a crucial part of station maintaining in support of production and cargo unloading, and they work in concert with the life extension program for an FPSO and SPM calm buoy hull [31]. Operators are typically faced with making wise business decisions towards the end of an FPSO/SPM calm buoy's design life, such as whether to decommission, replace, divest, repurpose, or extend the life of the buoy. Decisions about life extension are influenced by important economic factors, including underestimated reserves, the discovery of new satellite wells or fields, improved production technologies, the cost of decommissioning or environmental remediation, and the cost of buying a new floater to replace an older FPSO/SPM calm buoy [32]. However, the facility's safety and structural soundness to sustain and endure the anticipated years of projected life extension are the technical factors taken into account. In order to determine the structural adequacy of the mooring chains for life extension, operators who have an idea of the volumes of reserves they have and the possibility of developing nearby/satellite fields in what is known as tie-back would typically consider the option of purchasing a new floater or performing reverse engineering on the existing FPSO/SPM calm buoy that has exceeded her design life. This is cost-effective and less expensive. As part of the implementation of a life extension program in accordance with class society regulations, the corrosion wastages and residual strength on the FPSO and SPM calm buoy's degraded and deteriorated upper mooring chains segment were examined [33].

The studless mooring chain links were exposed to microbial induced corrosion (MIC) due to the accelerated degradation and deterioration activities of marine growth organisms like sun corals, among other MIC contributors. The floating facilities are situated about 60 km within the Nigerian continental shelf in the Gulf of Guinea (GoG), operating in tropical waters that are characteristic of the region. The most difficult issue is the occurrence of pitting corrosion on different sections of the top chain links segment, which is a result of the threat posed by MIC operations. As a result, the top mooring chain segment's corrosion rate was marginally higher than the specified design requirement [33]. Use of mooring chains in temperate regions like the GoG, often known as offshore West Africa, have more rapid corrosion rate issues, GoG mooring chains operations were designed based on the North Sea corrosion rate criteria. Inspections were conducted using remotely operated vehicles (ROVs) and rope access technicians (RATs). Notably, underwater 3D photogrammetry and high pressure water jets for cleaning mooring chain links made it easier to record the surface geometry of the deteriorated mooring chains of the chosen and approved representative samples. In most cases, it is often recommended to have a representative sample links of 25 to carry out these examinations. This improved detailed primary data for subsequent mooring assessments and life extension decision making [33]. Measurements of the mooring chains' intergrip, side bar, and straight bar were among the information gathered to examine wear rate and overall corrosion wastage. The strength and remaining life of the mooring chains are shown by their remaining thickness. Class society typically sets a retirement criterion of 35 percent wastage for mooring chains used in spread moored FPSO [34]. However, at 15 percent corrosion wastage, FPSOs tied to turrets mooring arrangements/configurations needs more careful attention and observation. Although, the majority of writers support further case studies to promote knowledge exchange. The significance of the suggested methodology is justified by the fact that the data and research references that are now available in both the academic and industry domains do not provide a thorough assessment of that possibility. Guidelines for the management of the life extension process are proposed in this work. In order to help the decision-making process for mooring chain life extension and to make it easier to assess age-related difficulties, a framework comprising the primary evaluation steps has been strengthened. Extending the lifespan of ageing FPSO and SPM calm buoy mooring chains under the influence of corrosion is the goal of this project.

Mooring Chains Corrosion Wastage

According to [34], there have been multiple cases of premature mooring chain replacements during the last ten years as a result of unforeseen failures. The authors noted that the phenomenon of pitting corrosion had a substantial impact on the upper chain section, among other segments, upon retrieval of the mooring chains. A number of FPSO/SPM off the coast of West Africa have been severely impacted by this kind of corrosion, which is a process that happens in tropical waters and cooler regions. Also, [35] and [36] claim that the growing rate of pits can be many times faster than that of uniform or general corrosion. According to the authors, this concept is typically connected to an acidic atmosphere at the pit bottom. However, the pitting rate magnification in a coated surface has also been attributed to an area impact, such as a local coating failure [37], [38], [39], [40], [41], [42]. SRB has also occasionally been linked by researchers to pitting corrosion for mooring chains [35]. Concern over the threat, ramifications, and effects of corrosion wastage action on FPSO and SPM calm buoy mooring chains is growing worldwide. Mooring chains are typically prone to pitting and uniform/general corrosion. The threat of corrosion wastage often puts safety at risk, impedes the development of new technologies, and eventually results in missed production opportunities. The useful service life of floating facilities like FPSO and SPM calm buoy mooring chains is shortened by corrosion degradation.

One of the most prevalent types of corrosion that is frequently observed around any offshore structure that is experiencing corrosion wastage is general or uniform corrosion. General corrosion is the term used to describe the corrosion wastage that frequently forms uniformly on the metal surface [36], [43], [37]. Uniform corrosion is another term for general corrosion [38]. It typically results in consistent corrosion over the exposed mooring line and frequently leaves a scale on the surface. This happens as a result of oxidation and reduction reactions occurring at random throughout the whole surface. Sea water has a significant influence on the marine environment. The slow deterioration and destruction of metals in the maritime environment is referred to as marine corrosion. In order to avoid poor designs, subsequent structural failures or collapses, and high maintenance, repair, and renewable costs, offshore specialists and engineers are therefore expected to possess a thorough understanding of the basic principles of corrosion as well as the various strategies to mitigate or prevent corrosion effects [44]. The following activities may be connected to the beginning and development of marine corrosion with respect to mooring chains:

(a) Electrochemical actions.
(b) Microbial actions.

Another type of corrosion mechanism in the offshore environment is microbial activity. There is marine growth fouling in addition to the marine corrosive environment of seawater [36]. Plants and animals that live and thrive underwater or below sea level near offshore constructions or oil and gas production sites are considered marine growth [43]. In a process known as an anaerobic reaction, these plants and animals release metabolic by-products that are toxic to the steel surface of offshore structures, leading to corrosion [11], [26]. The term "anaerobic bacteria" describes a class of microorganisms that can live, flourish, and proliferate in oxygen-free settings. Fermentation is the term for anaerobic respiration in microorganisms [45].

MIC is the process by which a metal or material, like FPSO/SPM calm buoy mooring chains, gradually deteriorates due to the metabolic activity of microbes. The group known as sulphate reducing microorganisms or sulphate reducing prokaryotes is made up of sulphate reducing bacteria, SRB, and sulphate reducing archaea. Using sulphate as a terminal electron acceptor, these organisms may undergo anaerobic respiration, converting it to hydrogen sulphide [46]. According to [47], MIC is a multidisciplinary phenomenon that is mostly composed of microbiology and corrosion. The mechanisms underlying the MIC process have been the main focus of MIC studies in the literature; understanding, forecasting, and monitoring the MIC process all depend on an understanding of the processes [48].

MIC is generally linked to biofilm-containing regions [48]. According to [48], [46], and [47], a biofilm is a colony of various bacterial species that participates in activities that the individual microorganisms in that colony are unable to perform on their own. Therefore, a biofilm merely provides a home for microbes. Because the bacteria' synergistic connection enables them to metabolise, which in turn promotes corrosion, biofilm formation is a crucial phase in MIC [49]. When immobilised microbiological cells that can proliferate and thrive on a surface accumulate, biofilms are created [15]. It should be mentioned that biofouling is the term used to describe the growth of biofilm on a surface. The collected bacteria release extracellular polymers throughout the biofilm formation process [46]. Although it is a crucial finding when examining MIC, it is crucial to remember that the existence of a biofilm does not always indicate the presence of MIC [47]. A biofilm is the site of all bacterial activity that results in MIC [50], [26]. Numerous factors affect the production of biofilms; however, some important ones are as follows:

(a) Surface roughness/topography,

(b) Surface wettability, and
(c) The presence of nutrients.

However, the settling of microbiological cells depends on surface roughness. Cell adhesion to rough surfaces is generally higher. According to [45], rough surfaces typically offer increased surface area for the attachment of microbiological cells. When bacteria form biofilms on the surfaces of materials, this leads to corrosion. It's interesting to note that SRB can create hydrogen sulphide, which can damage metals, both in anaerobic and aerobic environments. As a result, the metal surface may be attacked by the metabolic wastage products of certain microbes. The very caustic biotic H_2S is produced by SRB metabolism. Carbon steel and biotic H_2S can react to form corrosion products [50]. On the other hand, aerobic bacteria refer to those group of microorganisms that requires oxygen to grow, thrive and multiply in an environment. Figure (1) shows pitting on mooring chains due to microbial induced corrosion.

Figure (1): Pitting on mooring chains due to microbial induced corrosion [35]

The following factors influences the rate of pitting corrosion on mooring chains: pitting potential, metallic composition, temperature, PH and concentration of aggregate ions. Different types of bacteria are involved in a MIC process. The common bacteria types include:

(a) Sulfate reducing bacteria/ Sulfate reducing prokaryotes
(b) Methanogens,
(c) Acid producing bacteria
(d) Iron oxidizing and reducing bacteria.

European Journal of Mechanical Engineering Research, 12(2),30-52, 2025
Print ISSN: 2055-6551(Print)
Online ISSN: 2055-656X(Online)
Website: https://www.eajournals.org/
Publication of the European Centre for Research Training and Development-UK

Each of these bacterial species contributes to MIC in a different way. All of them, though, are classified as Type I or Type II MIC. The following major categories apply to the processes of MIC:
(a) Concentration cells
(b) Microbiological processes generating corrosive by-products
(c) Bacteria working together in intricate biofilm consortia accelerate corrosion

One of the MIC's mechanisms is concentration cells. According to [48], anodic and cathodic zones can form on the surface of the FPSO/SPM calm buoy mooring chains/lines when a biofilm deposit forms on metal in an environment with a high dissolved oxygen concentration. Because of the difference in oxygen content throughout the biofilm, surfaces beneath a thick biofilm may be oxygen-deficient [46]. The mooring chain surface beneath the biofilm may have less oxygen than the nearby surface without a biofilm deposit due to the oxygen concentration gradient that is brought on by respiring aerobic microorganisms. A cathodic zone with a high oxygen content will form at the bare mooring chain surface near the pit beneath the biofilm if pitting has been started beneath the biofilm deposit [47]. But since oxygen can take up electrons, the anodic breakdown that creates pits beneath the biofilm will let electrons gather at the surfaces with high oxygen concentrations. As a type of MIC mechanism, microbial activity produces corrosive metabolites. Certain microorganisms' metabolic byproducts, including FPSO/SPM calm buoy mooring chains and lines, might target the metal surface. Biologic hydrogen sulphide, a highly caustic chemical, is produced by SRB metabolism.Biotic hydrogen sulphide can react with carbon steel to create corrosion products like mackinawite, an iron nickel sulphide mineral that is usually produced by SRB microorganisms and found in river sediment reducing environments [50]. The FPSO/SPM calm buoy mooring chain/lines surface may develop differential aeration cells as a result of these deposits, which can lead to additional corrosion.

One of the main mechanisms of MIC is the way that bacteria in intricate biofilm consortia work together to accelerate corrosion. The byproducts of one bacterium's metabolism may be necessary nutrients for the metabolism of another. Biodiversity depends on the bacteria in a biofilm working together [48]. When SRB's biotic hydrogen sulphide dissociates, H+ can be produced. Electrons from the metal surface then convert H+ to H2, which is a direct necessity for methanogens during metabolism. Electrons can be shuttled into the biofilm consortium by certain bacterial species having conductive structures, such as pilis or nanowires, and used by the bacteria within the biofilm [46]. By cultivating SRB in a system with only one electron donor and one carbon source (CO2), [51] proved the conductive nature of bacteria. The experiment's findings revealed "intimate SRB growth" and violent pitting on the metal surface. However, the offshore oil and gas sector agrees that there are far too many cases of early deterioration, damage, failure, repair, and replacement of mooring lines. Research and development pertaining to mooring integrity has expanded quickly worldwide in response to this circumstance. It is now challenging to monitor and document all of this activity.

Surveys and Data Gathering

Choosing which of the following parameters should be detected and evaluated is the fundamental decision in the evaluation of corrosion wastage: average remaining thickness, minimum thickness, maximum pit depth, or pit intensity (as a percentage of the plate surface). Although the tendency is currently towards a more quantitative definition of corrosion intensity (corrosion wastage), the average remaining thickness and maximum pit depth are still regarded as the fundamental parameters of corrosion in terms of repair requirements [43]. According to [35], the trend is currently towards a more quantitative definition of corrosion intensity (corrosion wastage rate), although the average remaining thickness and maximum pit depth are still regarded as the primary parameters of corrosion in terms of repair criteria. Regarding corrosion progression, wastage prediction, and corrosion rate over time, researchers do not appear to agree, according to [52]. Nonetheless, the researchers suggested that field data, not lab data, should serve as the foundation for a standard corrosion wastage model. Therefore, the data used and how these data are interpreted determine whether a corrosion wastage model is valid. Field data such as intergrip wear, side bar wastage, and straight bar wastage must be collected at various sites, averaged, and compared to the initial mooring chain thickness in order to conduct a thorough corrosion wastage study on mooring chains. A trend is then created to monitor further wastage. The list of newly constructed FPSO and SPM calm buoys in Nigeria is shown in Table (1). The technological drivers are mostly dictated by the data that is available for assessment and decision-making including

(a) Operators and class surveys technical assessments like fitness for service are based on the findings of surveys conducted either jointly or independently by the asset owner and the class society that covers such floaters. While the class society hires an impartial third party whose staff must have been approved by them to conduct such an inspection campaign, the floaters owner maintains an internal inspection team. Notably, the third party's findings-particularly with regard to mooring chain gauging are embraced by the class and have a significant influence on decisions on life extension. This is due to the fact that the class society will provide the certificate of life extension, which will attest to the facility's compliance and fulfilment of the minimal requirements for life extension. The class society is still in charge of issuing certificates of class and conducting renewal surveys every five years. When the class and extension certificates are shown, insurance firms use their professional judgement to insure the floater.
(b) Technical decisions are enforced using historical data from repairs and maintenance.
(c) Management of corrosion wastage and feasibility studies for upgrades, modifications, and repairs-these studies assist the owner/operator in making quick technical business choices.
(d) Corrosion protection system to assess the extent of repairs needed to support a life extension project on floaters, the ICCP, sacrificial anodes, painting, and coatings are often assessed.
(e) Mooring integrity, the crucial component is examined to determine whether it is suitable for its intended use or whether necessary repairs are suggested for close out.

Table (1): List of New Built FPSO/SPM calm buoy in Nigeria [53]

Operator/Owner	Facility Name	Water Depth (m)	Design Life	Year on Location	Expected End of Life
Esso	Usan FPSO/SPM calm buoy	850	20	2012	2032
Esso	Erha FPSO/SPM calm buoy	1200	20	2006	2026
Snepco	Bonga FPSO/SPM calm buoy	1000	20	2004	2024
Chevron	Agbami FPSO/SPM calm buoy	1450	20	2008	2028
TotalEnergies	Akpo FPSO/SPM calm buoy	1400	20	2009	2029
TotalEnergies	Egina FPSO/SPM calm buoy	1600	20	2018	2038

According to [54], floaters are placed in areas with a particular design life that is typically in line with the field life. Although there are floaters placed with design lives longer or less than 20 years, a typical design life is 20 years [55]. Remarkably, the majority of them are built to run continuously on-site without the need for dry docking [56]. The owner or operator of a floater may want it to stay in place and carry on with production operations as it nears the end of its design service life [57]. According to

[58], the owner or operator usually starts the life extension process with the local regulatory body or a classification society. To extend the life to the new working life decided upon by the owner or operator and the classification society, an assessment is conducted and the necessary steps are implemented [59]. This procedure involves re-evaluating the floaters' hull, mooring, and other components. Usually, both engineering and surveying are part in this re-evaluation. It's interesting to note that by measuring important dimensions, mooring components like chain and shackles may be assessed for residual strength rather simply [60]. Other methods include using historical data or component-specific finite element analysis, as well as visual inspection to assess the degree of corrosion or pitting [56].

Nevertheless, it is challenging to estimate the remaining fatigue life, and existing inspection techniques are unable to identify fracture start, growth, and propagation until the failure is imminent [59]. Current analysis techniques for estimating OPB fatigue provide a wide range of results because of the sensitivity of the analysis to very small changes in parameters [58], [61], [62], [63]. Access issues also make it difficult to survey links at the hawse pipe or fairlead [64]. Notably, the goal of a floater's different technical examinations is to conduct a thorough assessment and track the state of various components, including the hull, mooring, machinery, safety systems, and equipment, to ensure that it is suitable for its intended use. A certified surveyor from a registered classification association often undertakes it. Examples of survey types are:

(a) Initial survey
(b) Annual survey
(c) Periodic survey
(d) Intermediate survey
(e) Renewal survey
(f) Special purpose survey

Prior to the appropriate certificate being renewed, the renewal survey shall be conducted in accordance with the applicable maritime regulations [65]. With the intention of finishing by the fifth anniversary date, the floater renewal survey may be started at the fourth annual survey and may be advanced in the following year [66], [67]. Additionally, the completion of the renewal survey should not be attributed to the survey items from the fourth annual survey [68]. However, the renewal survey should include an examination of the structure, machinery, and equipment, along with tests if needed, to make sure that the requirements specific to the certificate are met, that they are in good condition, and that they are suitable for the service for which the floater is designed [58], [69]. However, verifying that all of the certificates, operation manuals, record books, and other documents included in the requirements pertinent to the specific certificate are on board the floater should also be part of the renewal survey [70]. Usually carried out every five years, it has the same scope as periodic surveys but results in the issuing of a class certificate of class. Another name for the special purpose survey is the supplementary survey. Usually, it is carried out following repairs. To address some specific difficulties or concerns, like repairs, maintenance, and structural adjustments, a thorough structural examination is conducted. The replacement or repair of a mooring line is an excellent illustration.

Mooring Life Extension

The general process for prolonging or extending an ageing floater's operational service life can be summed up as follows, according to [11]:

(a) A thorough examination of the existing state, engineering analysis, and baseline data.
(b) Examine and evaluate mooring systems as they are now being used.
(c) Identify areas that need to be repaired, modified, or subject to more thorough inspection and monitoring.
(d) Specify a way to modify the structure in areas that are prone to fatigue.

(e) Determine how long the mooring chains will last.
(f) Request clearance for a life extension from the classification society [11], [65].

In order to develop strategies that consider the current state of the mooring arrangements, the likelihood of damage, degradation, and deterioration of a mooring line, and the potential consequences, FPSO and SPM calm buoy owners/operators, along with their mooring and inspection engineers, can use a risk-based approach, which is made possible by the mooring line/chains and accessories integrity management process. Curiously, a risk-based approach acknowledges that more regular and targeted inspections are needed for mooring systems with higher hazards than for those with lower risks [71], [72]. The mooring risk category can be used to establish work scopes and inspection intervals when creating a survey strategy. Nonetheless, the scope of the survey should consider the most recent lessons discovered by all industry participants. Figure (2) shows the various aspects of mooring integrity management (MIM) leading to life extension. While figure (3) represents external turret mooring arrangement. The FPSO and SPM calm buoy mooring chains life extension strategies involves the following items:

(a) Regular chain inspections
(b) Mooring chain cleaning
(c) Mooring chain replacements
(d) Mooring chain load monitoring
(e) Material selection
(f) Maintenance planning
(g) Latest life extension technologies
(h) Fitness for service examination and evaluation

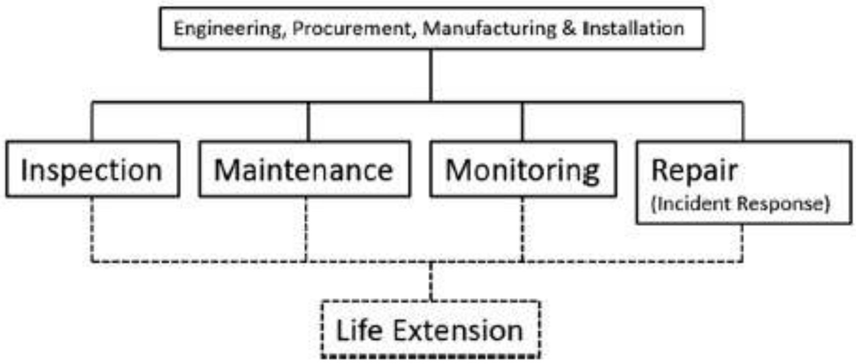

Figure (2): The various aspects of mooring integrity management leading to life extension [73]

Figure (3): External turret mooring arrangement [18]

1.4 Mooring Components Repairs and Replacement

On mooring chains, corrosion wastage leads to a decrease in thickness, geometric flaws, residual strength, load bearing capacity, fatigue strength factor of safety, and ultimately a crack. Chain cracks are nearly imperceptible to the unaided eye. A mooring chain's residual strength can be directly determined by its remaining thickness. A stud link chain's load regimes are depicted in Figure (7), along with failure zones, terminology, and high tensile stress locations surrounding the link. These days, operators typically set up their mooring chains in portions like the ground chains, weight chains, higher chains, mid-water chains, and excursion limiter chains. However, in addition to replacing mooring segments, thermally sprayed aluminium, TSA, and thermally sprayed carbide, TSC solutions are available to extend the usable lifespan of mooring chains. In certain instances, the pitting resulted in a 35 percent decrease in cross-sectional area [74]. Pattern recognition software was used to post-process the 3D photogrammetry results. For 25 links, corrosion was accurately traced across the whole link surface. According to the analysis's findings, the average corrosion rate of 0.4 mm/year provided in, for instance, API RP-2SK is substantially higher than the long-term corrosion rate for these links, which is roughly 1.5 mm/year of diameter loss for the pitted sections.

The typical surface water temperature at the floater location, according to the authors, is about 28°C, which is higher than the water temperatures used to create the mooring design codes. However, surface water temperatures in some West African offshore sites can reach 30.4°C. Since equivalent values for the pit depth were reported on mooring chain links from two different manufacturers, the current data demonstrated that the overall corrosion rate for diameter loss was independent of the steel qualities. This result aligns with studies published in the literature on corrosion science that demonstrate that in-situ corrosion rates are not significantly impacted by relatively minor changes in material properties. However, the authors of [34] noted that the proposal to update corrosion allowances as specified in applicable design codes for splash, mid-catenary, and touch-down zones is the most important recommendation from similar research conducted by seawater corrosion of steel wire rope and chain (SCORCH). However, subject matter experts have proposed using trademark chain coatings like thermally sprayed carbide (TSC) or aluminium (TSA) to increase wear resistance. Also, [74] state that in 2009, an operator used TSA on a floater in shallow water areas of West Africa as a way to limit the deteriorating impacts of MIC.

On the other hand, there is agreement within the offshore oil and gas industry that there are too many instances of premature mooring line degradation, deterioration, damage, failure, repair and replacement. In response to this situation, there has been rapid growth in mooring integrity related research and development across the globe. It has become difficult to keep track and record of all of this activity. The notable ones are the joint industry project, JIP tagged seawater corrosion of steel wire rope and chain, SCORCH among others. In various articles, the menace of marine corrosion wastage has always been implicated as the major cause of age related challenges on floating facilities. A combination of marine corrosion wastage and cyclic stress occurring simultaneously will result to corrosion induced fatigue and could lead to failure such as crack initiation when the limiting values are reached or exceeded. Cracks on mooring chains signals failure. Cracks on a chain is almost invisible to the naked eyes. Presently, there is no underwater technology that can spot in situ crack just like 3D photogrammetry can be used to capture pitting in situ.

The longevity of the mooring chain can be ensured by controlling the extensive attacks by MIC from the beginning through the use of appropriate protective coatings [43]. Applying epoxy or polyurethane coatings to the mooring chains is an excellent illustration [13]. Additionally, in certain offshore regions, particularly in West Africa, the application of TSA and TSC to mooring chains has resulted in a longer lifespan. Since 2001, mooring chains have employed the TSA, an aluminium-based coating, as a corrosion prevention strategy. However, it can be claimed that this coating has been field-tested in numerous mooring projects that have been in operation for more than 15 years. Additionally, evaluated were the coating's resistance to wear and its reaction to varying cathodic potential levels, both in controlled laboratory settings and in actual seawater situations. With a demonstrated endurance of over 25 years, the results demonstrated the advantages of applying TSA to offshore mooring chains by greatly increasing corrosion resistance. A thermally sprayed aluminium-coated mooring chain is depicted in Figure (4).

Figure (4): A Thermally sprayed aluminium coated mooring chains in operations [75]

TSA coatings have been used extensively to prevent corrosion in marine environments on steel components, including FPSO/SPM mooring chains [34], [76]. However, because aluminium has a low wear resistance, TSA has been found to sustain significant damage during transport operations to the necessary site for mooring chain replacements [77], which causes a rapid coating degradation and deterioration when fitted. Furthermore, in some applications, such mooring chains or lines, wear between mooring connections or links causes the aluminium to deteriorate quickly under operating conditions. To ensure the longevity of the coating, it is advised that enhancing the sprayed layer's wear resistance be a top priority. However, TSA coatings have been extensively utilised to preserve submerged parts, including FPSO/SPM calm buoy mooring chains, which have an effective 30-year service life in various exposure locations. In conclusion, the following advantages come from applying thermally sprayed aluminium for mooring chain coatings:

(a) It is less expensive;
(b) It is simpler to use.
(c) It offers unfathomable resistance to wear.
(d) It protects the mooring chains from seawater by providing a sacrificial coating.

However, a significant disadvantage to longevity may be aluminium's weak resistance to wear. According to [78], the idea behind thermal spraying is to melt coating material and then hit the molten particles into the substrate (layer) material's surface, where they will quickly solidify and form a coat. Because of this, the authors came to the conclusion that the bonding mechanism is mostly mechanical, with some metallurgical components. It's interesting to note that every TSA layer forms a lamellar structure by bonding to the one before it, but regrettably, inclusions, oxides, and pores do occasionally develop [79]. At least because of its neutral PH, aluminium is a metal that resists corrosion well [78]. According to the authors, aluminium's stability is due to a highly stable oxide that is present on its surface. Since TSA has been found to have a lifespan of more than 30 years with no service maintenance [77], [80], [81], [82], it is known as a lifetime coating system. The authors noted that when life cycle performance, life cycle cost, and the potential for employing lower corrosion allowances are taken into account, TSA coating is an appealing coating solution for splash zones.

This is because it offers superior corrosion protection qualities in a variety of settings and lengthens the mooring chains' lifespan, TSA-coated steel structures are extensively utilised in the industry, particularly in the mooring chains sector [11], [34]. According to reports by [78] and [83], blisters and coating failure may occur in specific situations due to insufficient sealing and an improper TSA thickness. The scientists also noted that if an organic coating is placed on top of the TSA coating, a quick deterioration of the coating has previously been found. A dual corrosion mechanism may arise in the event that the TSA's coating is damaged [78], [84]. It should be mentioned that the implementation of new TSA may be challenging because of restrictions on access to coating equipment and hot work restrictions offshore [85], [76]. Consequently, in relation to damage, a repair coating for TSA must be developed [86]. Similarly, [87] noted that the repair coating must be placed without removing the intact TSA and must offer corrosion protection without initiating the duplex corrosion mechanism [78].

However, the TSC was created to defend against wear and abrasion by applying hydrogen sulphide and wolfram carbide (tungsten carbide) to certain regions of the link. Interlink wear is decreased by this coating technique [75]. Typically, the coating has a thickness of 0.5 to 2 mm. Wear and corrosion cause significant surface degradation and deterioration for FPSO/SPM calm buoy mooring chains operating in tough environments in maritime and offshore locations. Because of their great hardness and chemical stability, TSC or carbide-based materials have been studied and shown to have a high resistance to deterioration under such circumstances [77], [85]. Utilising sophisticated thermal spray methods like plasma spraying, these carbides may be efficiently applied as coatings to the mooring chains [88], [84].

However, the performance of these coated mooring chains was found to be considerably impacted by the carbide composition, the type and proportion of binders, and the process parameters given in [83], [77]. In their research, [77] examined how the various carbide-based coatings performed and degraded in relation to the size of the carbide grains, the kind of metallic binders used, the parameters of the spray process, and the working environment [83]. The authors suggested post-processing carbide coatings, which they claim is also showing promise as a method to improve performance through coating structure modification and refinement. The aforementioned conversations demonstrated that TSC coatings have somewhat concealed the drawbacks of TSA coatings. TSC offers:

(a) Enhanced durability and

(b) Better resistance to wear.

(c) Better protection against corrosion;

(d) Greater durability; and

(e) Outstanding performance in application areas with heavy wear.

It is crucial to remember that there are two methods for preparing TSA coating: electric arc and flame spray. However, polymeric material-based coatings (PMBC) can be an appropriate solution for some mooring chains applications to improve corrosion and abrasion protection [75]. To enhance corrosion and abrasion resistance, PMBC, a coating based on polymeric materials, may be a suitable option for some mooring chain applications. However, a variety of corrosion and tribocorrosion tests were developed to demonstrate the advantages of this type of coating in both the actual marine environment on full-scale chain links and in laboratory testing using samples. Tribocorrosion, on the other hand, describes the combined effects of wear and corrosion on an engineered material's surface. It appears when a material experiences mechanical and chemical stresses. Among other things, the main reasons in the offshore and marine industries are abrasion, corrosion, and material characteristics. Among other things, the mitigation and preventative measures include material selection, design, surface treatments, and coatings. Although study is still in progress, PMBC shows promise for mooring chain lifespan as well. In certain documented instances, baby failure or damage resulted from improper handling or mistreatment of mooring lines during transit to the site and subsequent installation [83], [89], [9]. It has been claimed that the majority of mooring chains with customised coatings, such TSA and TSC, have sustained damage during handling during installation and transit. Also, [83] noted that customised mooring coatings are not cost-effective, which is understandable. Although manufacturers can paint or colour code the mooring chains to meet the specific needs of their clients, it has been demonstrated that painting or coating FPSO mooring chains does not significantly improve preservation or corrosion resistance, according to research published by [83].

Failures of mooring chains are typically caused by corrosion, wear and tear, installation, manufacturing flaws, mechanical issues, out-of-plane bending, and design. In contrast to offshore West Africa, which has recently been recognised as a temperate location with sea water surface temperatures reaching up to 30.4^{o}C in certain oilfields, the mooring chains deployed there were chosen based on the corrosion rates in the North Sea. Up to 28 ^{o}C was previously observed by certain researchers. The reasons for chain failure and preventive measures are shown in Figure (5). A stud link's load regimes and failure zones are depicted in Figure (6). A stud that is partially loose is seen in figure (7). Chain link wear and tear is depicted in figure (8). Although [90] states that the several factors impacting pitting corrosion include temperature, surface conditions, metallic composition, pitting potential, and environmental influences. The authors contended that environmental elements are the most important of these aspects. The authors came to the conclusion that among the environmental elements influencing pitting are the concentration of aggressive ions, PH, and inhibitors. However, alloys' propensity to pit is significantly influenced by their composition and microstructure [91]. In these situations, replacing the mooring chain pieces is typically the only practical solution [92], [93]. In most situations, it is economically challenging to justify the inclusion of particular pit-related corrosion margins during designs [36], [94], [95]. This is due to the fact that it is typically impossible to accurately forecast the likelihood of pitting and its density. Pitting corrosion is a poorly known process that is still being studied [43], [37], [95]. In some cases, the remaining strength of the corroded mooring chain ranges between 80 to 90 percent of the minimum breaking load value (MBL). Which mean that reduction in strength could be fall between 10 to 20 percent of the MBL. An operator's strategy to maintain its inspection, maintenance and repairs (IMR) plan is key for mooring longevity. IMR programs helps to identify imminent mooring issues prior to failure.

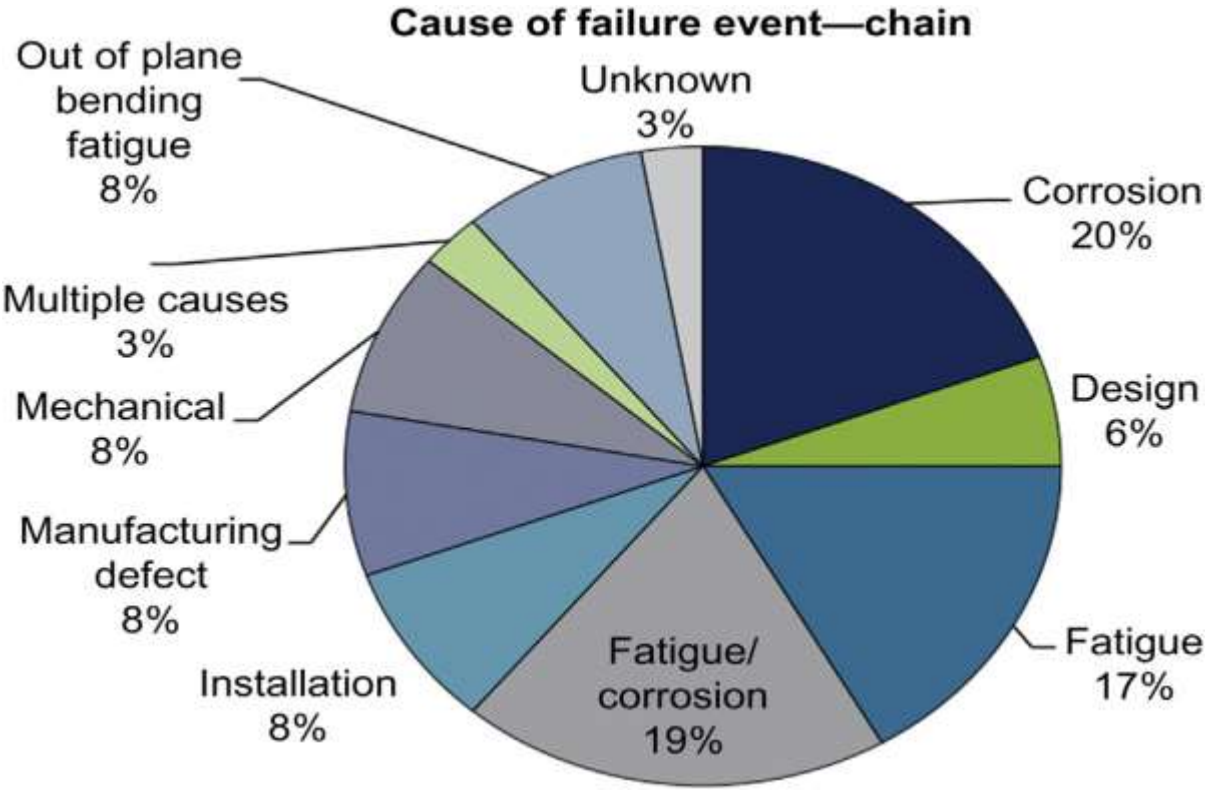

Figure (5): Causes of failure and pre-emptive events for chain **[96]**

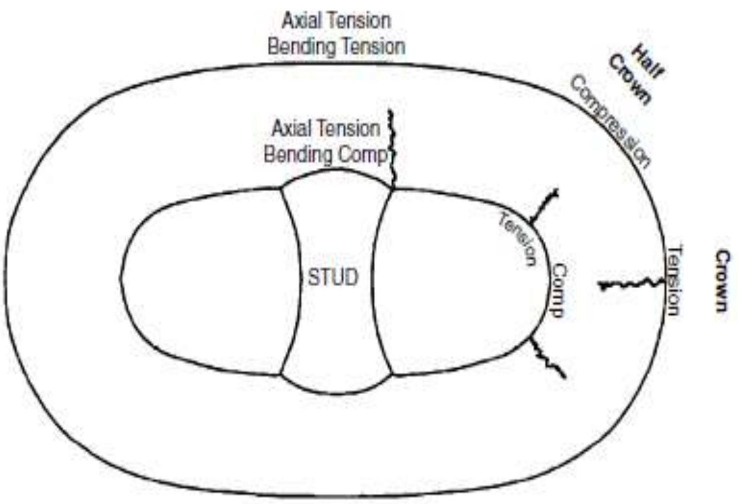

Figure (6): load regimes for a stud link showing failure regions [49]

Figure (7): Partially loosed stud [56]

Plate (8): Wear and tear on chain link [91]

CONCLUSION

Over time, the FPSO and SPM calm buoy mooring chains degrade. There are serious safety concerns as a result of this structural deterioration, which may also require expensive repairs. One important type of age-related deterioration that compromises the integrity and safety of FPSO and SPM calm buoy mooring chains is marine corrosion wastage. Due to lost production opportunities during mooring chain repairs or replacements and high levels of intrinsic linked direct and indirect expenses, severe corrosion wastage can result in significant downtime costs. In order to identify corrosion wastage and determine the remaining thickness of chain links and other structural parts before replacement is necessary, FPSOs and SPM calm buoy mooring chains are surveyed on a regular basis. In order to identify limiting values of corrosion and replace or repair damaged links, it is advised that close-up surveys, such as thickness gauging surveys, be carried out on a regular basis. The longevity of mooring chains and, eventually, life extension benefit from some ideas, such as the application of customised coating solutions on mooring chains like TSA, TSC, and most recently, PMBC. Instead of using the generic North Sea corrosion rate data found in the existing code, it is advised that mooring designs use corrosion rate data particular to offshore regions. Utilising regional data lowers the overall expenses of extending the life of mooring chain configurations and helps to guarantee mooring lifetime in operations.

REFERENCES

[1] Boutrot, J., Giorgiutti, Y., Rezende, F., & Barras, S., (2017). Reliable and Accurate Determination of Life Extension for Offshore Units. Bureau Veritas Asset Integrity Services. *OTC-27547-MS, Houston, Texas, USA*, 1–4 May 2017. Pp. 5-7.

[2] Fontaine, E., Orsero, P., Ledoux, A., Nerzic, R., Prevosto, M., & Quiniou, V. (2013). Reliability Analysis and Response Based Design of a Moored FPSO in West Africa. *Structural Safety*, 41. Pp. 82-96.

[3] Fontaine, E., Kilner, A., Carra, C., Washington, D., Ma, K.T., Phadke, A., Laskowski, D., & Kusinski, G. (2014a). Industry Survey of Past Mooring Failures, Pre-emptive Replacements and Reported Degradations for Mooring Systems of Floating Production Units. *OTC 25273, OTC Conference. May 2014.* Pp. 1-9.

[4] Ma, K.T., Price, R., Villanueva,D., Monti, P., & Tan, K. (2014). Life Extension of Mooring System for Benchamas Explorer FSO. *Proceedings of the 19th SNAME Offshore Symposium, Society of Naval Architects and Marine Engineers, Houston, TX, February 2014.*Pp. 1-7.

[5] Allan, S., De Gier T., & Hall, A. (2013). Mooring System Life Extension Using Subsea Inspection Technologies, Welaptega Marine Ltd. *Offshore Technology Conference, OTC* 2013, Houston Texas, USA. OTC 2013-24184. 6-9 May 2013. Pp. 1-9.

[6] Wang, M. & D'Souza, R. (2004). Mooring Chain Corrosion Design Considerations for an FPSO in Tropical Water. *Paper No. 04-0046, Proc. OMAE-FPSO 2004, OMAE Specialty Symposium on FPSO Integrity, Houston, TX, 2004*. P.8.

[7] Ma, K.T., Orisamolu, I. R., & Bea, R. G. (1999). Optimal Strategies for Inspections of Ships for Fatigue and Corrosion Damage. *Ship Structure Committee, SSC-407, Washington, DC*, 1999. Pp. 1-8.

[8] Brown, M., (2013). Ten Years' Experience of North Sea FPSO Moorings Repair, Renewal and Life Extension Work. *SPE 166602*. Pp. 1-6.

[9] Brown, M., Hall, T., Marr, D., English, M., & Snell, R. (2005). Floating Produciton Mooring Integrity JIP – Key Findings", Proc. Offshore Technology Conference, OTC 17499, 2005.

[10] Sharp, J.V., Stacey, A. & Birkenshaw, M. (2001). Life Cycle Integrity of North Sea Installations. *Proceedings of 11th ISOPE Conference, Stavanger*. Pp. 1-10.

[11] Ma, K. T., Luo, Y., Kwan, T. & Wu, Y. (2019). *Mooring System Engineering for Offshore Structures*. Gulf Professional Publishing, Cambridge, MA.Pp. 1-200

[12] Ma, K.T., Garrity, R., Longridge, K., Shu, H., Yao, A., & Kwan, K. (2017). Improving Reliability of MODU Mooring Systems Through Better Design Standards and Practices. *OTC 2017-27697, OTC Conference, May 2017*. Pp. 1-6.

[13] Ma, K.T., Celikkol-Aydin, S., Gaylarde, C. & Makama, K. (2016a). Field Studies of Microbiologically Influenced Corrosion of Mooring Chains. *Offshore Technology Conference, OTC2016-27142-MS*. Pp. 1-9.

[14] Liu,Y., Wang, H., Luo, Y., Zhu, W., Shen, H., Tao, X., & Shao, Y. (2019). Evaluation and Life Extension of Mooring Systems. *Proceedings of the 29th International Ocean and Polar Engineering Conference, Honolulu, Hawaii, USA, June 16-21, 2019*. Pp. 1211-1215.

[15] Ersdal, G., Sharp, J.V. & Stacey, A. (2019). *Ageing and Life Extension of Offshore Structures: The Challenges of Managing Structural Integrity.* 1st Edition, John Wiley and Sons Publishers, United Kingdom. Pp. 1-190.

[16] Shafiee, M., Animah, I. & Simms, N. (2016). Development of a Techno-Economic Framework for Life Extension Decision Making of Safety Critical Installations. *Journal of Loss Prevention in the Process Industries*, 44. Pp. 299–310.

[17] Ma, K.T. & Laskowski, D. (2014). Integrity Management of Mooring Against Corrosion. *DeepStar Phase XII Proposal, CTR 12402*. P.4

[18] Maslin, E. (2013). Mooring Line Failures Attract Industry Attention. *OE Digital, 01 July 2013.* P.1.

[19] Animah, I., & Shafiee, M., (2017). Condition Assessment, Remaining Useful Life Prediction and Life Extension Decision Making for Offshore Oil and Gas Assets, School of Energy, Cranfield

University, College Road, Bedfordshire MK43 0AL, United Kingdom, *Journal of Loss Prevention in the Process Industries* (2017), doi: 10.1016/j.jlp.2017.04.030. Pp. 1-10.
[20] Animah, I., Shafiee, M., Simms, N. & Considine, M. (2016). Techno-Economic Feasibility Assessment of Life Extension Decision for Safety Critical Assets. *Proceedings of 26th European Safety and Reliability Conference* (*ESREL*), Glasgow, UK. Pp. 1-12.
[21] Arredondo, A., Altuzarra, J., Mena, A., & Fernández, J., (2018). Stress Intensity Factors in Fitness-for-Service Assessment of Cracks in Mooring Chains. *In Pro. AMSE 37thIntl Conf. Ocean, Offshore and Arctic Engineering,* OMAE 2018-77496, June 17-22, Madrid, Spain. Pp. 1-9.
[22] Wintle, J. (2010a). The Management of Ageing Assets, *Presentation given at TWI Technology Awareness Day, TWI, Cambridge, UK (14 October 2010).* P.5.
[23] Wintle, J. (2010b). Management of Ageing and Life Extension Issues. *TWI Power Point presentation at HSE KP4 Launch, 28 July 2010*. Pp. 1 -20.
[24] Solland, G., Gudfinnur S., & Anupam, G., (2011). Life Extension and Assessment of Existing Offshore Structures. *SPE 142858*. Pp. 5 – 6.
[25] Sharp, J.V., Wintle, J.B., Johnston, C., & Stacey, A. (2011). Industry Practices for the Management of Ageing Assets Relevant to Offshore Installations. Paper no. *OMAE2011–49264.* Pp. 1-6.
[26] Stacey, A., Birkinshaw, M. & Sharp, J.V. (2008). Life extension issues for ageing offshore installations. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE),* June 15–20, Estoril, Portugal, Pp. 199–215.
[27] Si, X.S., Wang, W., Hu, C.H. & Zhou, D.H. (2011). Remaining Useful Life Estimation - A Review on the Statistical Data Driven Approaches. *European Journal of Operational Research, 213(1).* Pp.1–14.
[28] Fontaine, E. (2013). A Stochastic Model for the Design of Mooring System Against Squall Events. *Proc. 23rd ISOPE Conf.* Pp. 1-10.
[29] Fontaine, E., R. Armstrong, A. Potts, R. E. Melchers, C. R. Chapman & M. François (2009). Semi-Empirical Modelling for Seawater Corrosion of Wire Rope. *Proc. 19th ISOPE Conf*. Pp. 1-9.
[30] Serratella, C, & Spong, R. (2005). Understanding Through Experience-Key Findings from the FPSO Structural Performance Joint Industry Project. *Offshore Technology Conference*, Houston, TX, 2-5 May 2005. Pp. 1-8.
[31] Sharp, J.V., Stacey, A. & Birkenshaw, M. (2002). Reassessment Issues in Life Cycle Structural Integrity Management of Fixed Steel Structures. *Proceedings of 21st OMAE Conference, Oslo, Mattoc, Paper No. 28610*. Pp. 1-8.
[32] Gabrielson, O., Liengen, T. & Molid S. (2018). Microbiologically Influenced Corrosion on Seabed Chain in the North Sea. *Proceedings of OMAE2018, Paper OMAE2018-77460, Madrid, Spain.*Pp. 1-9.
[33] Rosen, J., Farrow, G., Potts, A., Galtry, C., Swedosh, W., Washington, D., & Tovar, A. (2015). Chain FEARS JIP: Finite Element Analysis of Residual Strength of Degraded Chains, *Proc. Offshore Technology Conference, OTC2015-26264, May 2015*. Pp. 1-9.
[34] Ibekwe, A., Sorensen, K., Fernandez, J., Arredondo, A., & Mena, A. (2018). Remnant Life Assessment of Bonga FPSO and SPM Mooring Chains. Shell Nigeria Exploration and Production Company, Lagos, Nigeria. *Proceedings of the OMAE 2018, ASME 37th International Conference on Ocean, Offshore and Artic Engineering, June 17-18, Madrid, Spain. OMAE 2018 – 77941*. Pp. 1-12
[35] Melchers, R. E. (2003). Modelling of Marine Immersion Corrosion for Mild and Low Alloy Steels: Part 1. Phenomenological model. *Corrosion*, 59(4). Pp. 319–334.
[36] Paik, J.K. (2022). *Ship-Shaped Offshore Installations- Design, Construction, Operations, Health Care and Decommissioning*. 2nd Edition, Cambridge University Press, United Kingdom. Pp 1-547.
[37] Wang, H., Zhang, Q., Liu, Y., & Mao, J., (2019a). Liuhua 11-1 FPSO and FPS Mooring System Life Extension Evaluation and Challenging Issues. CNOOC China Ltd. *OTC2019-29338-MS, Houston, Texas, USA, 6 – 9 May 2019*. Pp. 1-5.

[38] Wang, S., Zhang, X., Kwan, T. & Ma, K.T. (2019b). Assessing Fatigue Life of Corroded Mooring Chains Through Advanced Analysis. *Proc. Offshore Technology Conference, OTC2019-29449, May 2019*. Pp. 1-9.
[39] Rosen, J., Potts, A., Fontaine, E., Ma, K.T. & Chaplin, R. (2014a). SCORCH JIP-Feedback from Field Recovered Wire Ropes. Proc. *Offshore Technology Conference, OTC2014-25282, May 2014*. Pp. 1-9.
[40] Rosen, J., Potts, A., Fontaine, E.,Ma, K.T., Chaplin, R., & Storesund, W. (2014b). SCORCH JIP—Feedback from Field Recovered Mooring Wire Ropes. *OTC2014-25282, OTC Conference, May 2014*. Pp. 1-9.
[41] Rosen et al., (2014c). Mic and Pitting Corrosion On Field Recovered Mooring Chain Links. AMOG Consulting. Pp. 1-9.
[42] Rossi, R; Del Vecchio, C; & Goncalves, R (2010). Moorings with Polyester Ropes in Petrobras: Experience and the Evolution of Life Cycle Management. *OTC2010-20845, Offshore Technology Conference, May 2010*. Pp. 1-8.
[43] Paik, J.K. & Thayamballi, A.K. (2007). *Ship-Shaped Offshore Installations- Design, Building and Operations*. 1st Edition, Cambridge University Press, United Kingdom. Pp 1-536.
[44] John, W. & Sharp, J.V. (2008). *Requirements for Life Extension of Ageing Offshore Production Installations*. Petroleum Safety Authority, Norway. Pp. 1-46.
[45] Korber, D., Choi, A., Wolfaardt, G., Ingham, S., & Caldwell, D., (1997). Substratum topography influences susceptibility of Salmonella enteritidis biofilms to trisodium phosphate. *Appl. Environ. Microbiol. 63*. Pp. 3352-3358.
[46] Liengen, T, Féron, D, Basséguy R., Birrien, V., & Beech, I. (2014). *Understanding Biocorrosion: Fundamentals and Applications*. Woodhead Publishing Cambridge. (EFC 66). Pp. 50-55.
[47] Revie, R.W. (2008). *Corrosion, and Corrosion Control: An Introduction to Corrosion Science and Engineering*. John Wiley and Sons. Pp. 2-8.
[48] Xu, D., Li, Y. & Gu, T. (2016). Mechanistic Modelling of Biocorrosion Caused by Biofilms of Sulfate Reducing Bacteria and Acid Producing Bacteria. *Bioelectrochemistry. 110 (2016)*. Pp. 52-58
[49] Sharp, J.V. & Ersdal, G. (2021). *Underwater Inspection and Repairs for Offshore Structures*. 1st Edition, John Wiley and Sons Publishers, United Kingdom. Pp. 1-348.
[50] Venzlaff, H, Enning, D, Srinivasan, J, Mayrhofer, K. J.J., Hassel, A.W., Widdel, F. & Stratmann, M. (2013). Accelerated Cathodic Reaction in Microbial Corrosion of Iron due to Direct Electron Uptake by Sulfate-Reducing Bacteria. *Corrosion Science 66*. Pp. 88–96.
[51] Enning, D., Venzlaff, H., Garrelfs,J., Dinh, H.T., Meyer, V., Mayrhofer,K., Hassel, A.W., Stratmann, M. & Widdel, F. (2012). Marine Sulfate-Reducing Bacteria Cause Serious Corrosion of Iron Under Electroconductive Biogenic Mineral Crust. *Environ. Microbiol. 14 (2012)* Pp.1772-1787.
[52] Pham, H.H. & Vu, D.C. (2019). Re-Evaluation of Mooring System Durability for Renewal and Reuse of Floating Offshore Structures. *Proceedings of the 10th International Conference on Asian and Pacific Coasts, Hanoi, Vietnam, September 25-28, 2019*. Pp. 1-2.
[53] Boggs, D., Barton, C., Albaugh, E. K. & Davis, D. (2021). 2021 Worldwide Survey of Floating Production, Storage and Offloading (FPSO) Units'. *Offshore Magazine / Endeavor Business Media*, Houston, TX, July/August. Pp. 5-8.
[54] Witt, D., Ma, K.T., Lee, T., Gaylarde, C., Celikkol, S., & Makama, Z. (2016). Field Studies of Microbiologically Influenced Corrosion of Mooring Chains. *OTC 27142. OTC Conference, May 2016.* Pp. 1-5.
[55] O'Driscoll, M., Yan, H., Ma, K.T & Stemmler, P. (2016). Replacement of Corroded Mooring Chain on an FPSO. *Ship Production Committee, SNAME Maritime Convention, 2016.* Pp. 1-6.

[56] Brown, M., Comley, A., Eriksen, M., Williams, I., Smedley, P. & Bhattacharjee, S. (2010). Phase 2 Mooring Integrity JIP – Summary of Findings, Proc. Offshore Technology Conference, OTC 20613, 2010.

[57] Fontaine, E., Rosen, J., Potts, A., Ma, K.T., & Melchers, R. (2014b). SCORCH JIP-Feedback on MIC and Pitting Corrosion from Field Recovered Mooring Chain Links. Offshore Technology Conference, OTC 2014-25234, May 2014. Pp. 1-9.

[58] Gordon, R.B., Brown, M.G., & Allen, E.M. (2014). Mooring Integrity Management: A State-of-the-Art Review, DNV GL. Offshore Technology Conference, OTC 25134, Houston, Texas, USA, 5–8 May 2014. DOI: 10.4043/25134-MS. Pp. 1-9

[59] Ma, K.T., Duggal, A., Smedley,P., Hostis, D.L., & Shu, H. (2013). A Historical Review on Integrity Issues of Permanent Mooring Systems. *OTC2013-24025, OTC Conference, May 2013*. Pp. 1-9.

[60] Brown, M. (2005). FPS Mooring Integrity JIP, *Noble Denton, A4163, Rev. 1,* Dec. 21, 2005. Pp. 2-3.

[61] Ridge, I.M.L., Smedley P. & Hobbs, R.E. (2011). Effects of Twist on Chain Strength and Fatigue Performance: Small Scale Test Results. *Proceedings of 30th OMAE Conference, OMAE2011-49206*. Pp. 1-8.

[62] Rampi, L. & Vargas, P. (2006). Fatigue Testing of Out-of-Plane Bending Mechanism of Chain Links, *OMAE2006-92488*. Pp. 1-8.

[63] Ridge, I. M. L., Hobbs, R.E. & Fernandez, J. (2006). Predicting the Torsional Response of Large Mooring Chains. *OTC2006-17789*. Pp. 1-8.

[64] Ma, K.T (2010). Splash Zone Corrosion Assessment on Mooring Chains in West Africa. *Presentation at SCORCH JIP Meeting, FPSO Forum, Aberdeen, 15 October, 2010*. Pp. 1-14.

[65] ABS (2021). *Guidance Notes on Life Extension Methodology for Floating Production Installations*. Pp. 1-51. American Bureau of Shipping, July, 2021. Pp. 1-20.

[66] ABS (2018a). *Rules for Building and Classing Floating Production Installations*. American Bureau of Shipping, July, 2018. Pp. 1-12.

[67] Cutts, S. (2005). Offshore Safety Division Response to Concerns About Installation Integrity on UKCS. *SPE Paper 96318 Presented at Offshore Europe, Aberdeen, 2005*. Pp. 1-5.

[68] BV (2015). *Rule Note NR 493 DT R03 E: Classification of Mooring Systems for Permanent and Mobile Offshore Units*, 2015. Pp. 1-6.

[69] Zuccarelli, F., Diamantidis, D., Righetti, G. & Valente, E. (1991). Lifetime Extension of Existing Offshore Structures. *Proceedings of 1st ISOPE Conference, Edinburgh*. Pp. 43-48.

[70] IMO (2006). *Guidelines for Performance Standard for Protective Coating MSC.215(82) Resolution*, International Maritime Organization. Pp. 1-7.

[71] ABS (2018b). *Guidance Notes on Cathodic Protection of Offshore Structures.* American Bureau of Shipping, New York, US. July, 2018. Pp. 5-15.

[72] Gordon, R.B. (2015). Considerations for Mooring Life Extension, DNV GL, Proceedings of the 20th Offshore Symposium, February 2015, Houston, Texas, Society of Naval Architects and Marine Engineers. Pp. 1 – 8

[73] ABS (2015). *Guidance Notes on Life Extension Methodology for Floating Production Installations*. American Bureau of Shipping, July 2015. Pp. 1-14.

[74] Fontaine, E., Potts, A., Melchers, R., Arredondo, A., & Ma, K.T. (2012a). Investigation of Severe Corrosion of Mooring Chain in West African Waters. *22nd International Offshore and Polar Engineering Conference*. Pp. 389 – 394.

[75] Vicinay (2013). *Vicinay Research, Development and Engineering Services*. Parque Empresarial, Plaza Ibaiondo 1, 48940 Leioa, Bizkaia. P. 1.

[76] López-Ortegaa, A., Aranab, J.L., Rodríguezc, E., & Bayóna, R. (2018). Corrosion, Wear and Tribocorrosion Performance of a Thermally Sprayed Aluminium Coating Modified by Plasma Electrolytic Oxidation Technique for Offshore Submerged Components Protection. Department of Metallurgical and Materials Engineering, University of the Basque Country, Spain. *Elsevier Journal of Corrosion Science. Corrosion Science 143 (2018).* Pp. 258–280.
[77] Govande, A.R., Chandak, A., Sunil, B.R & Dumpala, R. (2022). Carbide-Based Thermal Spray Coatings: A Review on Performance Characteristics and Post-Treatment. Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India. *International Journal of Refractory Metals and Hard Materials 103 (2022) 105772*. Pp. 1-10.
[78] Kahar, S., Singh, A., Dabhekar, S., Vala, U., Navadiya, B., & Patoliya, K. (2020). Thermally Sprayed Aluminium Coatings: A Review. Department of Metallurgical and Materials Engineering, Faculty of Technology and Engineering, The M.S University of Baroda, Vadodara. *International Journal for Research in Applied Science and Engineering Technology (IJRASET), 8 (6).* www.ijraset.com Pp. 1-9.
[79] Syrek-Gerstenkorun, B., Paul, S., & Davenport, A.J. (2020). Sacrificial Thermally Sprayed Aluminium Coatings for Marine Environments: A Review, Coating 10(3). P. 267.
[80] Ce, N & Paul, S., (2016). Thermally Sprayed Aluminium Coatings for the Protection of Subsea Risers and Pipelines Carrying Hot Fluids. *Coatings, 6(4).* P. 58
[81] Heath, G.R., Heimgartner, P., Irons, G., Miller, R.D., & Gustafsson, S. (1997). An Assessment of Thermal Spray Coating Technologies for High Temperature Corrosion Protection. *Materials Science Forum.* Pp. 809 – 816.
[82] Herman, H., & Sampath, S. (1996). Thermally Sprayed Coatings, Metallurgical and Ceramic Protective Coatings. Pp. 261 – 289.
[83] Yaghin, A.L. (2016). Long-Term Wear of Model Offshore Mooring Chains Under Simulated Working Conditions. *A Thesis Submitted in Fulfilment of the Requirements for The Degree of Doctor of Philosophy, School of Engineering, The University of Newcastle Australia.* Pp. 1-3.
[84] Usmani, S., Sampath, S., Houck, D.L. & Lee, D. (1997). Effect of Carbide Grain Size on the Sliding and Abrasive Wear Behaviour of Thermally Sprayed WC-Co Coatings. *Tribol. Trans. 40 (1997).* Pp. 470–478.
[85] Liao, H., Normand, B., & Coddet, C. (2000). Influence of Coating Microstructure on the Abrasive Wear Resistance of WC/co Cermet Coatings. *Surf. Coat. Technol. 124 (2000).* Pp. 235–242.
[86] Silva, F.S., Bedoya, J., Dosta, S., Cinca, N., Cano, I.G., Guilemany, J.M & Benedetti, A.V (2017). Corrosion Characteristics of Cold Gas Spray Coatings of Reinforced Aluminium Deposited onto Carbon Steel. *Corros. Sci. 114 (2017).* Pp. 57–71, https://doi. org/10.1016/j.corsci.2016.10.019.
[87] Momber, A.W. & Marquardt, T. (2018). Protective Coatings for Offshore Wind Energy Devices: A Review. *J. Coat. Technol. Res. 15 (2018)*. Pp.13–40. https://doi.org/10. 1007/s11998-017-9979-5.
[88] Herath, A. (2019). The Influence of Nitrate on the Short Term Corrosion of Steel Catalysed by Marine Microorganisms. *A dissertation Submitted to the Graduate Faculty In Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy, University of Oklahoma Graduate School, Norman, Oklahoma.* Pp. 1-5.
[89] Minnebo, J., Aalberts, P., & Duggal, A. (2014). Mooring System Monitoring Using DGPS. *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2014-24401, San Francisco, CA, 2014*. Pp. 1-8.
[90] Birades, M. & Verney, L. (2018). Fatigue Analysis, Lifetime Extension and Inspection Plans. *Proceedings of the 3rd Offshore Reliabilty Conference (OSRC2016),* Stavanger, Norway (14–16 September 2016). Trondheim, Norway: Norges teknisk-naturvitenskapelige universitet, Institutt for marin teknikk (IMT). Pp. 3-9.

[91] HSE (2017). *RR 1090 Mooring Integrity for Floating Offshore Installations Joint Industry Project. Phase 2: Summary*. Health and Safety Executive (HSE), London. Pp. 1-6.

[92] Bhattacharjee, S., Angevine, D., Majhi, S. & Smith, D. (2015). Permanent Mooring Reliability and Mooring Risk Management Plan (MRMP): A Practical Strategy to Manage Operational Risk, *Offshore Technology Conference, OTC-25841-MS, 2015*. Pp. 1-9.

[93] Bhattacharjee, S., Majhi, S., Smith, D. & Garvity, R. (2014). Serpentina FPSO Mooring Integrity Issues and System Replacement: Unique Fast Track Approach. *Offshore Technology Conference, OTC -25449-MS*. Pp. 2-8.

[94] Ersdal, G. (2014). *Ageing and life extension of structures*. Compendium at the University of Stavanger. Pp. 1-50.

[95] Ho, K.H. & Roy,S.K. (1994). Corrosion of Steel in Tropical Sea Water. *Brit. Corros. J. 29 (3), 1994*. Pp. 233-236.

[96] Fontaine, E., Potts, A., Ma, K-T., Arredondo, A., & Melchers, R. E., (2012b). Scorch JIP: Examination and Testing of Severely-Corroded Chains from West Africa. OTC-23012-MS, *Offshore Technology Conference*, April 30 -May3, Houston, Texas. Pp. 1-9.

[97] Ma, K.T., O'Driscoll, M., Stemmler, P., & Yan, H., (2016). Replacement of Corroded Mooring Chain on an FPSO. Chevron Energy Technology Company. *SNAME-SMC-2016-045. Paper presented at the SNAME Maritime Convention, Bellevue, Washington, USA, November 2016*. Pp. 1-9.

LIST OF ABBREVIATIONS/SYMBOL

ABS - American Bureau of Shipping
APB - Acid Producing Bacteria
BV – Bureau Veritas
CALM - Catenary Anchor Leg Mooring
CAPEX – Capital Expenditure
C-MIC - chemical MIC
FPSO - Floating Production, Storage and Offloading
FSO - Floating Storage and Offloading
GoG - Gulf of Guinea
ICCP – Impressed Current Cathodic Protection
IMO – International Maritime Organisation
IMR - Inspection Maintenance and Repair
JIP - Joint industry project
MBL - Maximum Breaking Load
MIC - Microbial Induced Corrosion
MIM - Mooring integrity management
M-MIC – Metabolite MIC
OPB = Out of Plane Bending
OPEX – Operating Expenditure
ORQ - Offshore Rig Quality Mooring Chain
PMBC – Polymetric Material - Based Coating
ROV - Remotely Operated Vehicle
SCORCH - Seawater Corrosion of Steel Wire Rope and Chain
SPM - Single Point Mooring
SRB - Sulfate Reducing Bacteria
TSA - Thermally Sprayed Aluminium
TSC - Thermally Sprayed Aluminium