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

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Abstract: *Mooring chains replacement and life extension campaigns is trending in offshore West Africa and the rest of the world is not left out. Mooring chains being a critical component of floating production, storage and offloading (FPSO) and single point mooring (SPM) calm buoy for the purpose of station keeping. However, considering the extremely harsh environmental conditions the mooring chain is subjected to, the mooring chains will definitely undergo corrosion wastages over time. Although, general/uniform and pitting corrosion has been implicated by several researchers as major cause of mooring chain degradation and deterioration among other new discoveries. For example, the activities of microbial organisms referred to as microbial induced corrosion (MIC) has been identified and implicated in most cases as the key cause of pitting corrosion on mooring chains and its mechanism is highlighted on this paper together with other mooring chains challenges and mitigation strategies which are beneficial to mooring and marine engineers. Ageing and age related challenges such as wear and corrosion wastages across the mooring chains intergrip, side and straight bars were key considerations for life extension evaluations. It was remarked that marine corrosion wastage on mooring chains do not alter their chemical and mechanical properties but only changes their geometry. Thus, the remaining thickness is a measure of the remaining strength. It was observed that most design codes for mooring chains in temperate or tropical regions like Gulf of Guinea (GoG) are based on the code for North Sea. It was also noticed that temperature, dissolved nitrogen, and current velocity effects mooring chains corrosion wastage. Thus, the higher the temperature especially in GoG the higher the rate of corrosion wastage in the splash zone. Thus, usually higher than the immersed zones. It was also observed that the scarcity of real marine environment data made most researchers to adopt data from corrosion coupon in laboratory for the purpose of studies. However, there are still limited information as regards the type of data to measure, their collation, analysis and interpretations. While class society guidance notes appeared large to manage, this paper presents in a nutshell the relevant information that will serve as a guide to mooring, marine and subsea engineers involved in asset integrity management of FPSO and SPM calm buoy mooring chains/lines to have a first-hand knowledge of the data required for mooring performance evaluation and ultimately mooring chains life extension studies. The paper also, presents some new generations issues and mitigation strategy towards mooring chains longevity*.

Keywords: FPSO/SPM calm buoy, mooring chains, Pitting corrosion, MIC, Mitigation strategies, Life extension

INTRODUCTION

In today's competitive business environment with extremely low profit margins, the FPSO and SPM calm buoy represents a critical infrastructure in the upstream oil and gas industry. Thus, extending their operational life can have significant economic and environmental benefits. Therefore, offshore engineers are frequently challenged to think out of the box to engineer a frame work, analyze historic data obtained from floating assets and make intelligent business decisions that reduces to minimum or eliminates the possibility of incurring additional operating and capital expenditures, OPEX and CAPEX. Marine economics and finance is known to play pivotal role in planning and scheduling surveys, maintenance, repairs, replacement and life extension. Recent surveys showed that many floating production installations like FPSOs, FSOs SPM calm buoy installations around the globe are either reaching or have exceeded their original designed operational life. Hence, life extension discussions have dominated the offshore Brazil and offshore West Africa markets (Arredondo et al., 2018; Allan et al., 2013). A key component of floating production installations such as FPSOs, FSOs and SPM calm buoy used for station keeping is the mooring chains. Mooring chains are vulnerable to microbial induced corrosion (MIC) resulting from the activities of sulphate reducing bacteria (SRBs) causing pitting corrosion on the chains. Others are wear, uniform/general corrosion wastages. The advances in mooring chains production for the offshore industry progressed across the following grades of ORQ, R3, R3S, R4, R4S, R5 and most recently R6 while studies for R7 mooring chain grade is still ongoing in an attempt to improve quality and durability. Notably, floating facilities life extension programs proffers more economic advantages in terms of cost savings since from business point of view, operators are always looking for opportunities to reduce OPEX and eliminate CAPEX, but also shadow hidden catastrophic accidents in the background when it is not done thoroughly according to the rules of the classification society covering such floating assets and satisfaction of the classification society surveyor in attendance. Floating facilities life extension discussions is growing among major operators across the oil and gas world (Animah et al., 2018; Animah et al., 2016). Thus, by extending the design operational life of a mooring facilities, a wide range of benefits is obtained in terms of cost saving, when compared with other floating facilities end of operational life management strategies. Surveys are required to examine the potential for life extension. Although, permanent mooring arrangements are selected using a wear and corrosion allowance. Thus, the whole essence of a survey program campaign is to establish that the wear and corrosion status are within the design limits. The most vulnerable points considered during surveys are the splash zone/turret interface, connectors and wire rope interfaces with other components, and touchdown zone from touchdown point.

The phenomenon of marine corrosion wastage is the most challenging condition experienced by FPSO and SPM calm buoy mooring chains during their design service life (ABS, 2018b; ABS, 2018a; ABS, 2015). The mooring chains of the FPSO and SPM calm buoy are the major component systems vulnerable to corrosion wastages and their failure directly impacts loading and offloading decisions. Although, the menace of corrosion wastage becomes more significant and challenging over time as the FPSO and SPM calm buoy mooring chains ages. Corrosion and corrosion-induced issues are considered to be the most important factors leading to age-related structural degradation and deterioration of the FPSO and SPM calm buoy mooring chains. Corrosion has a dangerous consequence from the stand point of safety and can lead to thickness reductions and penetration. Marine corrosion wastage effects are known to cause structural integrity issues on the mooring chains (Sharp and Ersdal, 2021; Solland et al., 2011). As marine corrosion wastage limiting values triggering FPSO and SPM calm buoy mooring chains mitigations such as repairs, replacements, some classification societies such as ABS recommend mooring chains thickness reductions of about 35 percent from considerations of strength. Notably, for turret moored facilities, it is recommended to pay closer attention when the mooring chain thickness reduction is up to 15 percent. Usually an all mooring chain materials composition contains segments such as the upper chain, weight chain, mid-water chain, excursion limiter chain and ground chain. Usually, the chains are linked by mooring chain connector. Severe uniform and localized corrosions such as pitting corrosion has been investigated and reported on steel mooring components at several offshore locations worldwide. This occurrence has generated concerns in recent years as to whether the components can safely meet their design life (Ma et al., 2016; Sharp et al., 2011; Sharp et al., 2002; Sharp et al., 2001). Gabrielson et al., (2018) in their investigations reported a severe pitting corrosion on a section of mooring chain segment with shallow to deep trenching on the seabed due to SRBs. The severe localized corrosion attack of 3 to 4mm pit depth of varying size from a few millimetres to larger areas was observed on the mooring chains in the top 2m of sediment on the seabed (Si et al., 2011; Serratella and Spong, 2005; Ma et al., 1999). The occurrence of these pits was observed to reduce the fatigue strength factor of safety and inevitable the fatigue capacity of the mooring chain. Additionally, the attachments of marine growth fouling on mooring chains increases environmental (wave and current) loads on the chains (Ma et al., 2017; Ma et al., 2016; Shafiee et al., 2016; Ma et al., 2014). The SRBs are grouped under anaerobic bacteria, which are bacteria which grow, thrive, survive and multiply in the absence of oxygen. They usually live between the mooring chains and marine growth fouling. This means that they are attached to the mooring chains and covered by marine growth fouling. In the past most research works on mooring chains corrosion wastages rely on data obtained from the laboratory in a corrosion coupon which is under control. In a real seawater condition which the mooring chain is designed to operate, corrosion wastages occur naturally and is uncontrolled. Although, the available academic literature often addresses singly only specific aspects of the challenges. On the other hand, most classification societies only provided cumbersome and superficial guidance notes as life extension frame work to the FPSOs operators. This present research proposes a comprehensive methodology for evaluating the FPSO and SPM calm buoy mooring chains for life extension of 15 years under the effects of corrosion wastages. Notably, the life extension program for an FPSO and SPM calm buoy hull also go in tandem with the mooring chains as a major key component for station keeping in support of production and cargo offloading. Towards the end of design life of FPSO/SPM calm buoy, operators are usually challenged with intelligent business decisions as whether to: decommission, replacement, divestment, repurpose its use, or life extension of such FPSO/SPM calm buoy. Key economic factors such as under estimated reserves, discovery of new satellite wells/fields, enhanced production technologies, cost of decommissioning/environmental remediation and cost of purchase and replacement of an older FPSO/SPM calm buoy with a new floater drives life extension decision making. On the other hand, the technical factors considered are the structural integrity and safety of the facility to support and withstand the intended years of planned life extension. Usually for operators having an idea of the volumes of reserves they have and the possibility of developing nearby/satellite fields in what is called tie-back would consider the option of going for a new floater or do a reverse engineering on the existing FPSO/SPM calm buoy that has exceeded her design life, to ascertain the structural adequacy of the mooring chains for life extension, which is cheaper and cost effective. The corrosion wastages and remaining strength on the degraded and deteriorated upper mooring chains segment of the FPSO and SPM calm buoy were studied as part of a life extension program execution in line with class society rules. The floating facilities are located approximately 60 km within the Nigerian continental shelf in the Gulf of Guinea, GoG thus operating in tropical waters which the region is known for, where the studless mooring chain links were subjected to the actions of microbial induced corrosion, MIC by the accelerated degradation and deteriorations activities of marine growth organism such as sun corals among other MIC contributors (Liu et al., 2019; Pham and Vu, 2019). The menace of MIC activities has resulted to increased corrosion rate and most challenging is the occurrence of pitting corrosion on various segments of the upper chain links segment. Thus, raised corrosion rate of the upper mooring chains segment slightly above the tabulated design requirement (Ibekwe et al., 2018; Boutrot et al., 2007). Mooring chains used GoG mooring operations were selected based on the North Sea corrosion requirements, whereas temperate regions like the GoG otherwise known as offshore West Africa has greater corrosion rate challenges. Rope access technicians, RAT; remotely operated vehicle, ROV were used during inspections. Notably, mooring chain links cleaning with high pressure water jets and underwater 3D photogrammetry facilitated the capturing of the degraded mooring chains surface geometry of the selected and agreed representative samples to enhance detailed primary data for further mooring evaluations and life extension decision making. Mooring chains intergrip, side bar and straight bar measurements were among the data obtained to analyze wear rate and general corrosion wastage. The remaining thickness of the mooring chains is a measure of the remaining strength and remaining life. Usually, class society place 35 percent wastage as retirement criteria for mooring chains employed in spread moored FPSO. While 15 percent corrosion wastages on turret moored FPSOs requires more close attention and monitoring (Ma and Laskowki, 2014). While most authors advocates for more case studies to increase knowledge sharing. The available data and research references across the industry and academic spheres does not present a comprehensive evaluation of that possibility, which justify the importance the methodology proposed. This paper proposes a guidance for the life extension process management. Thus, strengthening a framework containing the main evaluation stages, aiming to facilitate the evaluation of challenges related to ageing and to support the mooring chain life extension decision-making process. The aim of this work is to carry out life extension of ageing FPSO and SPM calm buoy mooring chains under corrosion effects.

Mooring Chains Degradation and Deterioration

As stated in Ibekwe et al., (2018) over the past decade there have been several instances of premature mooring chain replacements due to unexpected failures. The authors observed that on retrieval of the mooring chains, it has been found that the upper chain segment among other segments have been significantly affected by the phenomena of pitting corrosion. This phenomenon occurs in tropical waters/colder climates, and several FPSO/SPM off the coast of West Africa have been particularly badly affected by this type of corrosion. According to Melcher (2003) and Paik (2022), the rate of pits growth can be many times that for a uniform or general corrosion. The authors explained that this idea is usually thought to be associated with an acidic environment at the pit bottom. However, in a coated surface, an area effect such as a local coating breakdown, has also been cited as a reason for the pitting rate magnification (Wang et al., 2019a). Researchers have also implicated SRB in pitting corrosion in some cases for mooring chains (Melchers, 2003). The menace, implications and consequence of corrosion wastage action on mooring chains of FPSO and SPM calm buoy is gaining global concern. Usually mooring chains are susceptible to uniform/general and pitting corrosion. The menace of corrosion wastages tends to jeopardize safety, retard technological advancement and ultimately lead to loss of production opportunities. Corrosion degradation reduces the useful service life of floating facilities such as FPSO and SPM calm buoy mooring chains. General or uniform corrosion is one of the dominating type of corrosion often found around any offshore structure undergoing corrosion wastage (Birades and Verney, 2018). The corrosion wastage which is formed often uniformly on the surface of metal is referred to as general corrosion (Paik, 2022; Paik and Thayamballi, 2007; Wang et al., 2019b). Another name for general corrosion is uniform corrosion (Wang et al., 2019b). Usually, it causes corrosion of uniform intensity over the entire exposed mooring line and often deposits a scale on the surface (Bhattacharjee et al., 2015; Bhattacharjee et al.,2014). Thus, this occurs due to random occurrence of oxidation and reduction reactions over the entire surface. As stated in Ibekwe et al., (2018) over the past decade there have been several instances of premature mooring chain replacements due to unexpected failures. The authors observed that on retrieval of the mooring chains, it has been found that the upper chain segment among other segments have been significantly affected by the phenomena of pitting corrosion (Rosen et al., 2015; Rosen et al., 2014a; Rosen ett al., 2014b; Rosen et al., 2014c; Rossi et al., 2010). This phenomenon occurs in tropical waters/colder climates, and several FPSO/SPM off the coast of West Africa have been particularly badly affected by this type of corrosion.

Marine environment is profoundly dominated by sea water (Melchers, 2003). Marine corrosion refers to the gradual deterioration and degradation of metals in the marine environment. Therefore, offshore specialists and engineers is expected to have an excellent knowledge and understanding of the fundamental principles of corrosion and the various methods to mitigate or prevent corrosion effects such that inadequate designs and subsequent structural failures or collapse and high maintenance, repairs and renewable costs can be avoided (Ersdal, 2014; John and Sharp, 2008). The process of initiation and progression of marine corrosion as regards to mooring chains may be related to the following actions:

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

Microbial action is another form of corrosion mechanism in the offshore environment. Apart from the seawater marine corrosive environment, there exist marine growth fouling (Paik, 2022). Marine growth are plants and animal origins that live and survive under water/below sea level within the proximity of offshore structures or oil and gas production installations (Paik and Thayamballi, 2007). These plants and animal secretes metabolic by products toxic in nature on the steel surface of offshore structures, thus causing corrosion to occur, in a process called anaerobic reaction (Ma et al., 2019; Stacey et al., 2008). Anaerobic bacteria refer to those group of microorganisms that grow, thrive and multiply in environments without oxygen. Anaerobic respiration in microorganisms is called fermentation (Korber et al., 1997). MIC is the process whereby the metabolic activities of microorganisms results to gradual degradation or deterioration of a metal or a material such as FPSO/SPM calm buoy mooring chains. Sulfate reducing microorganisms or sulfate reducing prokaryotes are group composed of sulfate reducing bacteria, SRB and sulfate reducing archaea, both of which can perform anaerobic respiration utilizing sulfate as terminal electron acceptor, reducing it to hydrogen sulphide (Liengen et al., 2014). MIC is an interdisciplinary phenomenon broadly made of corrosion and microbiology (Revie, 2008). MIC studies in literature have been focused on the mechanisms involved in its process, studying the mechanisms is required to understand, predict, and track the MIC process (Xu et al., 2016).

MIC is typically associated with areas where biofilms are present (Xu et al., 2016). A biofilm is a colony which consists of different bacteria types that engage in processes that the individual microorganisms in that colony cannot independently engage in (Xu et al., 2016; Liengen, 2014; Revie, 2008). Thus, a biofilm simply serves as a habitat for microorganisms. Biofilm formation is an important step in MIC because the synergistic relationship between the microorganisms allow them to metabolize, which in turn influences corrosion (Sharp and Ersdal, 2021). Biofilms are formed due to the accumulation of immobilized microbiological cells that can grow and reproduce on a surface (Ersdal et al., 2019). It should be noted that the process of biofilm growth on a surface is called biofouling. During biofilm formation, extracellular polymers are secreted by the accumulated microorganisms (Liengen et al., 2014). It is important to note that the presence of a biofilm does not necessarily mean that MIC is present; however, it is a key observation when investigating MIC (Revie, 2008). All bacteria activities that causes MIC takes place within a biofilm (Venzlaff et al., 2013; Stacey et al., 2008). Biofilm formation is influenced by so many conditions, and some key ones include;

(a) Surface roughness/topography,
(b) Surface wettability, and
(c) The presence of nutrients.

Although, surface roughness is critical to the settlement of microbiological cells. In general, there is higher cell adhesion to rough surfaces. Korber et al., (1997) proposed that rough surfaces tend to provide more surface area for microbiological cell adhesion. This results to corrosion when microbes are present in biofilms on the surfaces of materials. Interestingly, SRB functions under both anaerobic and aerobic conditions to produce hydrogen sulphide, which can corrode metals. Thus, the metabolic by-products from some microorganisms can attack the metal surface. SRB metabolism produces biotic H_2S, which is a highly corrosive substance. Biotic H_2S can react with carbon steel to produce corrosion products (Venzlaff et al., 2013). 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
(Source: Melchers, 2003)

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.

All these bacteria types have a unique way of contributing to MIC. However, they all fall under either Type I or Type II MIC. The mechanisms of MIC can be broadly categorized as;

(a) Concentration cells
(b) Microbial activities producing corrosive metabolites
(c) The synergy of bacteria in complex biofilm consortia accelerating corrosion

Concentration Cells is one of the mechanisms of MIC. As stated in Xu et al., (2016) a biofilm deposit on metal in an environment where dissolved oxygen concentration is high can induce anodic and cathodic zones on the FPSO/SPM calm buoy mooring chains/lines surface. Surfaces underneath a thick biofilm may lack oxygen because of the oxygen concentration gradient across the biofilm (Liengen et al., 2014). The oxygen concentration gradient can be caused by respiring aerobic bacteria, thereby leaving the mooring chain surface underneath the biofilm with less oxygen compared to the adjacent surface with no biofilm deposit. If pitting has been initiated under the biofilm deposit, this will create a cathodic zone at the bare mooring chain surface with high oxygen concentration close to the pit underneath the biofilm (Revie, 2008). However, because oxygen can accept electrons, the anodic dissolution causing pit formation under the biofilm will allow electrons to accumulate at the surfaces where oxygen concentration is high.

Microbial activities producing corrosive metabolites as a form of MIC mechanism. Metabolic by-products from some microorganisms can attack the metal surface such as FPSO/SPM calm buoy mooring chains/lines. SRB metabolism produces biotic hydrogen sulphide, which is a highly corrosive substance. Biotic hydrogen sulphide can react with carbon steel to produce corrosion products such as mackinawite which is an iron nickel sulphide mineral, which is typically found in river sediment reducing environments and it is usually generated by the action of SRB microorganisms (Venzlaff et al., (2013). These deposits formed can contribute to the formation of differential aeration cells on the FPSO/SPM calm buoy mooring chain/lines surface, which induces further corrosion.

The synergy of bacteria in complex biofilm consortia accelerating corrosion is a key mechanism of MIC**.** A bacteria’s metabolic by-products can be a nutrient requirement for another bacteria’s metabolism. The synergy between bacteria in a biofilm is important for biodiversity (Xu et al., 2016). Biotic hydrogen sulphide from SRB can produce H+ when it dissociates. H+ is subsequently reduced by electrons from the metal surface to form H2, which is a direct requirement for methanogens during metabolism. Some bacteria types with conductive structures like nanowires or pilis can shuttle electrons into the biofilm consortium which can then be utilized by bacteria inside the biofilm (Liengen et al., 2014). This conductive property of bacteria is demonstrated by Enning et al., (2012), whose experiment cultured SRB within a system where the only one electron donor was present and with CO2 as the only carbon source. The result of the experiment showed aggressive pitting and “intimate SRB growth” on the metal surface. On the other hand, there is agreement within the offshore oil & 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.

1.2 Mooring Chains Inspections, Data Gathering and Storage

In the evaluation of corrosion wastage, a primary decision arises as to which parameter must be detected and measured: average remaining thickness, minimum thickness, maximum pit depth or pit intensity. In current practices, average remaining thickness and maximum pit depth are considered to be primary parameters of corrosion in terms of repair criteria, but the trend is now toward a more quantitative definition of corrosion intensity (corrosion wastage) (Paik and Thayamballi, 2007). It was established that in current practises, the average remaining thickness and maximum pit depth are considered to be primary parameters of corrosion in terms of repair criteria, but the trend is now toward a more quantitative definition of corrosion intensity (corrosion wastage rate). According to Witt et al., (2016) there does not seem to be a consensus among researchers with respect to the progress of corrosion, prediction of wastage and corrosion rate over time. However, the researchers advised that a common corrosion wastage model should be based on field data rather than laboratory data. Thus, the validity of a corrosion wastage model is dependent on the data used and proper interpretation of these data. A comprehensive corrosion wastage studies on mooring chains requires field data such as wear on the intergrip, wastages on the side bar and straight bars take at multiple points and their average computed and compare to the original mooring chain thickness. Thereafter, a trend is developed to track future wastages. Table (1) presents the list of new built FPSO and SPM calm buoy in Nigeria, the technical drivers are mainly determined by the availability of data for evaluation and decision making such: Operators and class surveys-The results of surveys either jointly or separately carried out by the asset owner and the class society covering such floater is used to make technical evaluations such as fitness for service. The floaters owner has an internal inspection teams while the class society engages an independent third party whose personnel must have been certified by them to carry out such inspection campaign. Notably, the finding of the third party especially on mooring chain gauging is adopted by class and it has overriding effects in life extension decision makings. This is because the certificate of life extension will be issued by the class society stating that the facility is in compliance and has met the minimum requirement for life extension. The subsequent five years' renewal surveys and issue of certificate of class is still the responsibility of the class society. Insurance companies rely on their expert judgement to insure the floater upon the presentation of class certificate and extension certificate. Historic data from maintenance and repairs are used to enforce technical decisions. Corrosion wastage management, feasibility studies on repairs, upgrade and modification-These studies help the owner/operator to make fast technical business decisions. Corrosion protection system-The ICCP, sacrificial anodes, painting and coatings are usually inspected to determine the level of repairs required to drive a life extension project on floaters. Mooring integrity- The critical element is surveyed to ascertain that it is fit for purpose or relevant repairs are recommended for close out. It is important to point out that some levels of delays such as the availability of diving vessels, attending class surveyors, original equipment manufacturer (OEM) representative/engineers as the case might be could result to not carrying out some surveys. Data loss could result from an improper storage, management and frequent change of personnel. Thus, this emphasises the importance to retain asset integrity personnel on long term basis and have a centralized data storage system for continuity.

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

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

(Source: Boggs et al., 2021)

Floaters are installed at locations with a specific design life, which usually aligned with the field life (Witt et al., 2016). A typical design life is usually 20 years, although there are floaters installed with design life greater or less than 20 years (O'Driscoll et al., 2016). Interestingly, most of them are designed for uninterrupted operation onsite without any dry docking (Brown et al., 2010). When a floater approaches the end of its design service life, the owner or operator may desire to have it remain on its location and continue with production operation (Fontaine et al., 2014b). Consequently, the owner or operator typically initiates a life extension process with a classification society or the local regulatory agency (Gordon et al., 2014). An evaluation is carried out and appropriate actions taken to extend the life up to the new operating life agreed by the classification society and owner or operator (Ma et al., 2013). This process includes a reassessment of the floaters system such as hull, mooring and other. This reassessment normally includes both engineering and survey activities. Interestingly, mooring elements such as chain and shackles can be evaluated for remaining strength relatively easily by taking measurements of key dimensions (Brown, 2005). Others are visual inspection to determine level of corrosion or pitting, and using historical data or component specific finite element analysis (Brown et al., 2010). However, the estimation of remaining fatigue life is difficult and current inspection methods cannot detect crack initiation, growth and propagation until it is close to failure (Ma et al., 2013). Links at the hawse pipe or fairlead are also difficult to survey due to access difficulties (Ma, 2010), and current analysis techniques for estimation of out of plane bending (OPB) fatigue provide a wide range of results due to the sensitivity of the analysis to very small changes in parameters (Gordon et al., 2014; Ridge et al., 2011; Rampi and Vargas, 2006; Ridge et al., 2006). Interestingly, OPB refers to mooring chain bending which is perpendicular to the mooring chain natural plane, thus creating a 3 dimensional twisting/torsion. It is usually caused by floaters horizontal motion (sway and yaw) and soil – mooring chain interaction on seabed. Hence, the mooring chains links undergo twisting relative to one another, thereby going out of the 2 dimensional plane. OPB is also called unintended 3 dimensional mooring chain links twisting, resulting to mooring chain kinking which primarily occurs when currents changes. Regrettably, it causes multi-axial combined stresses such as tension, bending and torsion on mooring chain links, thereby developing some sought of significant localized stress hotspots around the inter bars (side bars/straight bars) and mooring chain crown areas. It ultimately lowers the fatigue life of mooring chains when compared to out of plane bending (IPB). On the other hand, IPB is generated in the vertical plane of the mooring chain presumed natural catenary curve. IPB of mooring chain links is also described as the expected 2 dimensional vertical plane bending of mooring chains links. It is primarily caused by floaters heave and pitch motions, some wave motions generated perpendicular to the seabed. Thus, created bending and axial tension on the mooring chain links. However, its less severe than OPB because it is associated with more uniform stress distribution on the mooring chain links. Although, in practise, IPB and OPB can be mitigated by using a more outward projected hawse pipe/fairlead to guide the chains to chain stopper. Some mooring designers prefers to use studlink mooring chains as part of top chain from the chain stopper region within the chain support assembly. Mooring chain tightness and slack management can also go a long way to reduce the chances of IPB and OPB occurrences. Similarly, the optimization/selection of a suitable hawse pipe/fairlead departure angle for mooring chains could also reduce the possibilities of IPB and OPB occurrences.

Notably, the various technical examination of a floater is aimed at carrying out detailed evaluation and monitor the conditions of several elements such as hull, mooring, machinery, safety systems and equipment to ascertain that it is fit for purpose. It is usually undertaken by a certified surveyor from a recognised classification society. Examples of survey types are:

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

The renewal survey, as required by the relevant maritime regulations should be held before the appropriate certificate is renewed (ABS, 2021). Although, the floater renewal survey may be commenced at the fourth annual survey and may be progressed during the succeeding year with a view to completion by the fifth anniversary date (ABS, 2018a; Cutts, 2005). Furthermore, the survey items of the fourth annual survey should not be credited to the completion of the renewal survey (BV, 2015). However, the renewal survey should consist of an inspection, with tests when necessary, of the structure, machinery and equipment to ensure that the requirements relevant to the particular certificate are complied with and that they are in a satisfactory condition and are fit for the service for which the floater is intended (Gordon, 2015; Gordon et al., 2014; Zuccarelli et al., 1991). Nevertheless, the renewal survey should also consist of a check that all the certificates, record books, operating manuals and other instructions and documentation specified in the requirements relevant to the particular certificate are on board the floater (IMO, 2006). It is usually conducted every five years and is the same survey scope with periodic survey, however, it leads to the issuance of a class certificate of class. The special purpose survey is also called additional survey. It is usually conducted after repairs. It is an in-depth structural assessment to address some specific issues of concerns such as repairs, maintenance and structural modifications. A good example is the repair or replacement of a mooring line.

Mooring Life Extension

According to Ma et al., (2019) the general procedure for continuing or extending the operational service life of an ageing floater can be summarized as follows:

(a) Detailed review of baseline information, engineering analysis and current condition.
(b) Survey and reassess mooring systems under as is conducted.
(c) Determine areas requiring repairs, modification, enhanced inspection and monitoring.
(d) Define solution for structural modification to fatigue – prone locations.
(e) Establish the remaining/remnant life of the mooring chains.
(f) Apply to classification society for life extension approval (Ma et al., 2019; ABS 2021).

The mooring line/chains and accessories integrity management process provides the opportunity for FPSO and SPM calm buoy owners/ operators and their mooring and inspection engineers to adopt risk-based approach for developing strategies that take into account the current condition of the mooring arrangements, the likelihood of damage, degradation and deterioration of a mooring line, and the potential consequences. Interestingly, a risk-based approach recognizes that moorings systems with higher risks requires more frequent and more focused surveys than moorings with lower risks. During the development of a survey strategy, the mooring risk category can be used for setting inspection intervals and work scopes. However, the surveys scope of work should take into account the latest lessons learned from all operators in the industry. Figure (2) shows the various aspects of mooring integrity management 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

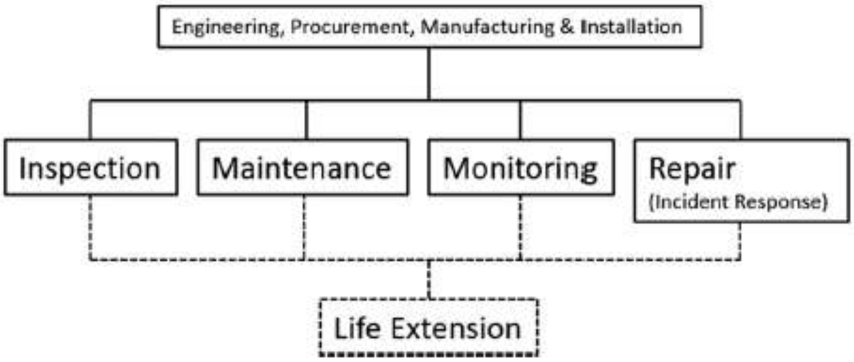

Figure (2): The various aspects of mooring integrity management leading to life extension (Source: Ma et al., 2019)

Figure (3): External turret mooring arrangement
(Source: Maslin., 2013)

1.4 Mooring Components Repairs, Retire and Replacement

Corrosion wastages on mooring chains results to thickness reduction, geometric defects, reduction in remaining strength, reduction in load bearing capacity, fatigue strength factor of safety is reduced and eventually a crack. Cracks on a chain is almost invisible to the naked eyes. The remaining thickness of a mooring chain is a direct measure of the remaining strength. Figure (7) shows load regimes for a stud link chain showing failure regions, terminology and areas of high tensile stress around the link. Usually, operators now configure their mooring chains in segments such as upper chain, weight chain, mid water chain, excursion limiter chain and ground chains. On the other hand, apart from mooring segments replacements, there is thermally sprayed aluminium, TSA and thermally sprayed carbide, TSC solutions to prolong the useful lives of mooring chains. According to Fontaine et al., (2012a), in some cases, the pitting caused a reduction in cross-sectional area of 35 percent. Results of the 3D photogrammetry were post-processed using pattern recognition software. Corrosion was mapped with high accuracy all over the surface of the link for 25 links. The results from this analysis can be interpreted as showing that the long-term corrosion rate for these links is approximately 1.5 mm/year of diameter reduction for the pitted areas, which significantly differs from the average corrosion rate of 0.4 mm/year given in, for example, API RP-2SK. The authors reported that the averaged surface water temperature at the floater location is around 28°C, which is warmer than the water temperatures on which the mooring design codes were based. Although, in some offshore locations in West Africa, surface water temperature is up to 30.4°C. The present data showed that the overall corrosion rate for diameter loss was independent of the steel properties as similar values for the pit depth were reported on mooring chain links from two different manufacturers. This observation is consistent with research publications in the corrosion science literature that proof that relatively small variations in material properties have little practical effect on in-situ corrosion rates. However, the authors in Ibekwe et al., (2018), pointed out that the foremost among the recommendations from similar research performed by joint industry projects include the proposal to update corrosion allowances as stipulated in applicable design codes for splash, mid-catenary, and touch-down zones. On the other hand, there has been suggestions by subject matter experts to improve wear resistance by the application of trade mark chain coatings such as thermally sprayed aluminium, TSA or thermally sprayed carbide, TSC. According to Fontaine et al., (2012b) as part of measure to control the deterioration effects of MIC an operator applied TSA to a floater in shallow water regions of West Africa in 2009. By the use of adequate mooring chains protective coatings, the extensive attacks by MIC can be controlled from onset and thus ensures the longevity of mooring chain (Paik and Thayamballi, 2007). A good example is the application of epoxy or polyurethane coatings to the mooring chains (Ma et al., 2016). Additionally, the use of TSA and TSC on mooring chains, has yielded an extended longevity of mooring chains in some offshore locations especially in West Africa.

The TSA, which is aluminium-based coating, has been used as corrosion protection measure in mooring chains since 2001. Although, it can be said that this coating is field-proven in many mooring projects with more than 15 years in service. The capability of the coating to resist wear and its response under different cathodic potential levels were assessed as well, both in the laboratory, under controlled conditions, and in the sea water real environments. Results showed that the benefits of applying TSA to offshore mooring chains by significantly enhancing corrosion resistance with a proven durability of more than 25 years. Figure (4) shows a thermally sprayed aluminium coated mooring chains.

Figure (4): A Thermally sprayed aluminium coated mooring chains in operations
(Source: Ma et al., 2019)

TSA coatings have been widely employed to protect steel components such as FPSO/SPM mooring chains from corrosion in marine environment (Ibekwe, et al., 2018; López-Ortegaa et al., 2018). However, TSA has been reported to be highly damaged during transport operations to the required site for mooring chains replacements, due to the low wear resistance of aluminium (Govande et al., (2022), leading to a rapid coating degradation and deterioration when installed. Additionally, in certain applications such as mooring chains/lines, wear between mooring connectors or links also leads to fast degradation or deterioration of the aluminium in working conditions. Therefore, it is recommended that the improvement of the wear resistance of the sprayed layer is a major concern to assure the durability of the coating. Nevertheless, TSA coatings have been widely used for the protection of submerged components such as FPSO/SPM calm buoy mooring chains providing effective service life for 30 years in different exposure sites. In summary, using thermally sprayed aluminium for mooring chains coatings provides the following benefits:

(a) It is cheap
(b) It is easier to apply
(c) It provides unimaginable wear resistance
(d) It provides sacrificial coating, thus protecting the mooring chains from sea water.

However, the poor wear resistance of the aluminium can be a major drawback to longevity.
As evident in Kahar et al., (2020) the principle of thermal spraying is to melt coating material and molten particles are impacted on the surface of substrate (layer) material which will solidify rapidly and built a coat. This made the authors agreed that the bonding mechanism is primarily mechanical and in some cases metallurgical. Interestingly, each layer of TSA bonds to the previous, making a lamellar structure, but unfortunately with some occurrence of

inclusions, oxides and pores (Syrek - Gerstenkorun et al., 2020). Aluminum is quite corrosion resistance metal, at least with a neutral PH (Kahar et al., 2020). The authors attribute the stable nature of aluminum to the presence of a very stable oxide on the surface. TSA is called a lifetime coating system since it has been identified with a life in excess of 30 years with zero service maintenance (Govande et al., 2022; Herath, 2019; Ce and Paul, 2016; Heath, et al., 1997; Herman and Sampath, 1996). The contributors pointed out that TSA coating is an attractive coating system for splash zone when life cycle performance, life cycle cost and the possibility of using reduced corrosion allowances are considered. TSA coated steel structures is widely used in the industry, especially mooring chains industry because it provides excellent corrosion prevention properties in various environments and increases lifespan of the mooring chains (Ma et al., 2019; Ibekwe et al., 2018; Fontaine, 2013; Fontaine et al., 2009). It was reported in Kahar et al., (2020) and Yaghin (2016) that the inadequate sealing and inappropriate TSA thickness can result in blisters and failure of the coating under certain circumstances. The authors also reported that a rapid degradation of the TSA coating has earlier been discovered, if organic coating is applied on top of the TSA coating. In case of coating damages on the TSA, a duplex corrosion mechanism may occur (Kahar et al., 2020; Usmani et al., 1997). It should be noted that due to access limitations with coating equipment and hot work limitations offshore, the application of new TSA may be difficult. (Lopez-Ortegaa et al., 2018; Liao et al., 2000). Therefore, it is necessary to develop a repair coating for TSA in connection with damage (Silva et al., 2017). Momber and Marquardt (2018) pointed out that the repair coating must provide corrosion protection without triggering the duplex corrosion mechanism and shall be applied without removing the intact TSA (Kahar et al., 2020.

On the other hand, for protection against abrasion and wear, the TSC was developed, which applies wolfram carbide (tungsten carbide) with hydrogen sulphide protection to certain areas of the link. This coating method reduces interlink wear (Vicinay, 2013). The coating is usually 0.5 to 2mm thick. FPSO/SPM calm buoy mooring chains working under harsh environments in marine and offshore sites are subjected to severe surface degradation and deterioration because of wear and corrosion. TSC or carbide-based materials have been investigated and proven to exhibit high resistance to degradation under such conditions because of their high hardness and chemical stability (Govande et al., 2022; Liao et al., 2000). These carbides can be effectively deposited as coatings on the mooring chains using advanced thermal spray techniques such as plasma spraying (Usmani et al., 1997). Although, the composition of the carbides, the type and percentage of binders, and process parameters reported in Yaghin (2016) and Govande et al., (2022) was found to significantly affect the performance of these coated mooring chains. Govande et al., (2022) in his investigations reviewed the degradation and deterioration behaviour and performance of the different carbide-based coatings as a function of carbide grain size and type of metallic binders, spray process parameters, and working conditions (Yaghin, 2016). The authors recommended the post-processing of carbide coatings, which according to them is also emerging as a promising strategy to enhance the performance by modifying and refining the structure of coatings. The above discussions revealed that TSC coatings to an extent have covered up the shortcomings of TSA coatings. TSC provides:

(a) Improved wear resistance
(b) Increased durability
(c) Enhanced corrosion protection
(d) Increased durability
(e) Excellent performance in high-wear zones of application.

It is important to note that TSA coating can be prepared by either electric arc technique or flame spray technique. However, polymeric material-based coatings (PMBC) can be an appropriate solution for some mooring chains applications to improve corrosion and abrasion protection (Vicinay, 2013). Although, different corrosion and tribocorrosion tests were made to prove the benefits of this kind of coating not only in laboratory testing with samples, but in the real marine environment on full-scale chain links as well. Although, tribocorrosion refers to the combined effects of corrosion and wear on the surface of an engineering material. It manifests when a material is subjected to both chemical and mechanical stressors. Abrasion, corrosion and material properties are the major causes in marine and offshore industries among others. Material selection, design, surface treatments and coatings are the mitigation and prevention strategies among others. PMBC is also promising in terms of longevity of mooring chains, however research works is still ongoing. There have been some reported cases where mistreatment or poor handling of mooring lines during transportation to site and subsequent installation led to infant failure or damage (Yaghin, 2016; Minebo et al., 2014; Brown et al., 2005). Most customized coating on mooring chains such as TSA and TSC has been reported to have damaged during transportation and installation handling. No wonder Yaghin (2016) reported that customized mooring coatings is not economical. According to the investigations reported by Yaghin (2016) for FPSO mooring chains, it has been proven that painting or coating offers no notable benefit in terms of preservation or corrosion resistance on mooring chains, although manufacturers can paint or colour code the mooring chains to clients' specific requirements.

Most of the events that triggers mooring chains failures are: corrosion, fatigue, installation, manufacturing defects, mechanical, IPB, OPB and design. For instance, the mooring chains installed in offshore West Africa were selected based on the corrosion rates in North Sea, whereas the offshore West Africa has recently been identified as a temperate region with sea water surface temperature rising up to 30.4^{o}C in some oilfields. Some researchers reported up to 28 ^{o}C in the past, while in some locations you have 26.9 ^{o}C. Figure (5) presents the causes of failure and pre-emptive events for chain. Figure (6) shows load regimes for a stud link showing failure regions. Figure (7) represents a partially loosed stud. Figure (8) represents wear and tear on chain link.

According to ISSC (2009), environmental factors, pitting potential, metallic composition, temperature, surface conditions and among others are the diverse parameters influencing pitting corrosion. The authors argued that among these factors, environmental parameters are the most critical factors. The authors concluded that the concentration of aggressive ion, PH and inhibitor concentration are some of the environmental factors that affect pitting. While composition and microstructure greatly influence pitting tendency of alloys. Mooring chains segments replacements are usually the only viable options in such cases (Wang and D'Souza, 2004). The addition of specific pit related corrosion margins during designs is economically difficult to justify in most cases (Paik, 2022; Ersdal, 2014; Wintle, 2010a; Wintle, 2010b). This is because the possibility of the occurrence of pitting and its likely density, usually cannot be well predicted (Brown, 2013; Melchers, 2003). The phenomenon involved in pitting corrosion is still being researched because it's not well understood (Paik and Thayamballi, 2007; Wang et al., 2019a; Melchers, 2003; Ho and Roy, 1994).

In the past decades, mooring failures had always been attributed to wear, abrasion, corrosion, damage, flawed material, excessive tension and fatigue damage. However, several incidents were reported as a surprise to industry subject matter experts (Mao, 2014). One particularly surprising finding was the novel nature of the failure mechanisms of some incidents, such as OPB, IPB, chain hockling/twisting, flawed flash welds, low metal toughness, pitting corrosion, etc (Ma et al., 2017). Unknown or new failure mechanisms are troubling because, since they are unanticipated, they cannot be easily detected and prevented with existing integrity practices (Maslin, 2013). Following a small scale tests carried out, it has been indicated that, mooring twist may not have a remarkable effect on either ultimate or fatigue strength of chain links even at very high degrees of twist such as 24 degrees per link (Ridge et al., 2011). Although, on Dalia FPSO, twists in the pigtail chains running from the buried pile pad eye to a connector on the seabed led to two failures (Ma et al., 2013). The reports from this incident shows that a hockle (knob) is believed to have formed in the mooring chain which ordinarily would simply pull out (Ma et al., 2019). However, being within the seabed there was sufficient soil resistance due to soil- mooring structure interaction to prevent this, thus tension loading was thereby taken across a link rather than the normal end-to-end (Ma et al., 2017; Ma et al., 2013). This led to early fatigue failure in a very difficult location to repair (Witt et al., 2016). The authors suggested that improved installation practice would have probably prevented this failure. Duggal and Fontenot (2010) reported that wear between links can also be an issue when the relative motions between links exceed 0.5 degrees, although this depends on tension level or when the chain is in dynamic contact with a hard surface either at the fairlead or the seabed.

However, it was found that most of the failures were not due to excessive tension from heavy weather, but were caused by many other failure mechanisms (Ma et al., 2013; Brown et al., 2010). These failure mechanisms included OPB fatigue, pitting corrosion, flawed flash welds, unauthorized chain repair, chain hockling (knotting) due to twist, low fracture toughness, and many others (Ma et al., 2019; Ma et al., 2016). Based on the 21 number of mooring incidents data made available between 2001 to 2011. A number of mooring lines failed due to chain manufacturing deficiencies that were introduced to the surface of chain when improper weld-repairs were done by the manufacturer to patch manufacturing defects. Some notable manufacturing defects are: dimensional defects, welding defects, material defects, heat treatment defects, assembly defects, surface defects, testing and inspection defects, certification and documentation defects. However, the consequences of these defects are: the likelihood of failure is high, reduction in strength and longevity, premature or infant corrosion and degradation and ultimately a costly mooring repair or replacement. Although, to reduce the risk of manufacturing defects, mooring engineers are advised to: select outstanding mooring chains manufacturers, request and witness in-depth factory examination, testing, certification and documentation.

However, mooring chain with manufacturing defects should not be scrapped and not be repaired (Ma et al., 2013; Ma et al., 1999). Notably, the other areas with a history of defects are the flash butt weld and loose studs on stud link mooring chain. Brown et al., (2010) reported that as mooring chain size and grade increases, it becomes increasingly difficult for the vendor to produce or inspect flash butt welds, and any submerged defects or lack of fusion can lead to premature fracture or fatigue failure (Gordon et al., 2014). Although, vendors are asked to produce larger components and use higher grade steels, which sometimes compromise the ability to maintain good quality. Nevertheless, a higher degree of quality assurance, control, testing and certification is required and needs to be agreed between the manufacturer, class surveyor and the purchaser prior to the start of manufacturing (Smedley, 2009; Melis et al., 2005). According to Mao (2014) studs in stud link chain is known to have a historical issue around fixity and fusion (loose studs). However, where stud link chain is used for long term moorings, corrosion can also lead to loose studs (Sharp and Ersdal, 2021), and the fatigue life of stud link chain becomes shortened (Sharp et al., 2011). Mooring chains slack and tight management also known as tensioning and alignment helps to solve other new mooring chains issues such as OPB (Ma et al., 2013). In such cases, it is recommended that mooring lines should be periodically adjusted so that the same links are not under bending load and wear for a prolonged duration

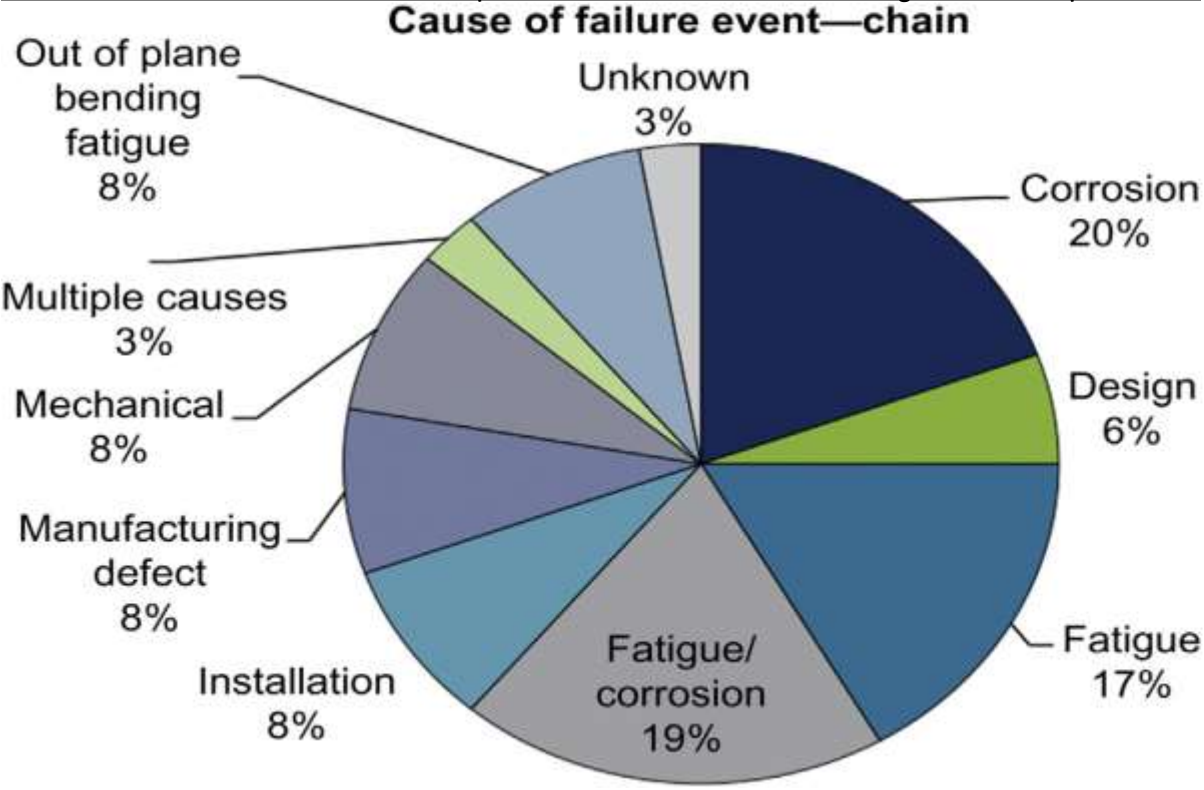

Figure (5): Causes of failure and pre-emptive events for chain
(Source: Fontaine et al., 2012a)

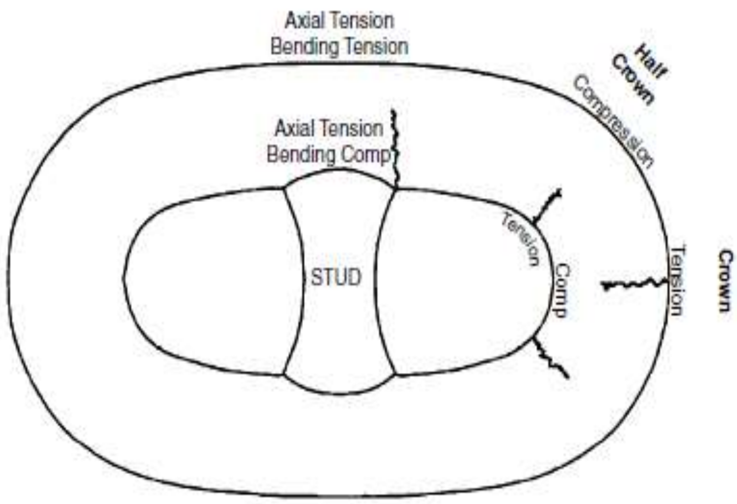

Figure (6): load regimes for a stud link showing failure regions
(Source: Sharp and Ersdal, 2021; HSE, 2017)

Figure (7): Partially loosed stud
(Sharp and Ersdal, 2021)

Figure (8): Wear and tear on chain link
(Source: Birades and Verney, 2018; HSE, 2017)

CONCLUSION

FPSO and SPM calm buoy mooring chains deteriorate overtime. This structural degradation and deterioration leads to significant issues in terms of safety and may demand significant financial expenditure to fix. Marine corrosion wastage is a key form of age-related degradation and deterioration that affects the safety and integrity of FPSO and SPM calm buoy mooring chains. Severe corrosion wastage may lead to substantial downtime costs owing to loss of production and offloading opportunities during mooring chains repairs/replacements and high levels of inherent related direct and indirect costs. Therefore, FPSOs and SPM calm buoy mooring chains are subjected to periodic surveys to detect corrosion wastage and estimate the remaining thickness of chain links and other structural members before replacement is required. It is therefore recommended that close-up surveys such as intermittent surveys and thickness gauging surveys must be performed regularly to detect limiting values of corrosion, such that affected plates can be repaired or replaced. Some concepts like the use of TSA, TSC and recently PMBC are handy for the longevity of mooring chains and ultimately in life extension. It is recommended to adopt offshore region specific corrosion rate data in mooring designs rather than the generic North Sea corrosion rate data contained in the current code. Using regional data will help to ensure mooring longevity in operations and reduces the overall costs of life extension of mooring chains arrangements.

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