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Life Extension of Ageing FPSO and SPM Calm Buoy Hulls and Deck Plates Under Corrosion Effects - Part 1B

[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

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Abstract: *Corrosion wastages occurs in the form of pitting corrosion or uniform/general corrosion. However, it was observed that previous academic studies relied on data obtained from shuttle tankers and imposed such to FPSO for the purpose of studies. While other scholars took data obtained from laboratory in corrosion coupon for the purpose of research. The state-of-the art is the use of data obtained from FPSO and SPM calm buoy in real marine environment operational location. It was revealed that most of the offshore structural design codes for floating assets in tropical waters or temperate region were still based on the codes for North Sea installations, even when both were known to have obvious different environmental conditions. These data are a true representation of the state of marine corrosion wastages associated with the floating assets. The data obtained from laboratory is usually simulated and controlled while that of marine environment occurs naturally. It was also observed that the validity of data suitable for life extension studies is placed at 18 months by some class societies, while some oil majors allows data obtained within 60 months and provided that such data will be scrutinized by relevant subject matter expert. Usually a minimum of five points thickness gauging and maximum of eight-point thickness measurements where there is marginal wastage is required per strake of a square metre. It was also observed that the collection, collation, analysis and interpretation of these data drives the technical aspect of the intelligent business decision aimed at making life extension repairs decisions of FPSO and SPM calm buoy. Although, it was remarked that corrosion wastages do not alter the chemical and mechanical properties of steel but only changes their geometry. Thus, the remaining thickness is a representation of the remaining strength of the steel plate. It was also remarked that these repairs are done according to class society requirements and supervisions from material selection, verifications and repairs. Steel plate grade, heat number, attending surveyors work order number, mill test certificate and reports signed at steel yard during manufacturing testing by the surveyor are some of the requirements. Others are the steel plates welding processes, sighting of procured steel plates and welders' certificates at repair sites. Thus, steel plates repairs on classed vessels must be done with classed steel plates of the same grade and thickness to the badly corroded one being renewed. Although, in the absence of the same thickness, a higher thickness can be used but must be approved by the class society covering such asset. Regrettably, steel plates of different grades mean that they have constituents' elements percentage composition and hence microstructure which can pose a threat of galvanic corrosion if applied in such marine environment.*

Keywords: classed vessels, end of design life, corrosion wastages, mitigation strategies, classed steel plates, crop and renew, life extension, certificate of class.

INTRODUCTION

Recently, the number of new build floating production, storage and offloading (FPSO) and single point mooring (SPM) calm buoy/refurbished SPM calm buoy and converted tanker FPSO in order by various oil companies will continue to increase while the existing ones is near the end or have exceeded the end of their original design service life. Life extension discussions is gradually dominating the oil and gas sphere. However, to get the project studies going, historic data play tremendous roles in making key technical decisions for repairs. The menace of corrosion wastage is one of the ageing issues faced by FPSO and SPM calm buoys hulls and deck plates. The FPSO represents a new technology with a promising future for the upstream oil and gas exploration and exploitation players. The available data across the globe especially in Gulf of Guinea (GoG) shows that the demands for FPSOs (new build or converted tanker) has increased and the forecasts for productive oilfields have grown. The result of these developments is the need to extend the service life of existing FPSOs (John and Sharp, 2008; Machado and Chand, 2013; Halsne et al., 2020; Moura, 2022). Although, approximately 45 percent of all FPSOs have hulls that are more than 30 years of age. FPSOs represent a viable option for life extension whether at the same oilfield location or relocation to a new oilfield at the end of its original designed service life. However, most FPSOs have been in operational duty for an extended life, whereas others are being converted from existing shuttle or trading tankers. It is important to note that a reliable procedure for the assessment of FPSO structures with designated scantling to validate structural integrity after FPSO life extension and relocation is called for, considering the expectations of safety, structural integrity and economic concerns (Wang et al., 2003c; ISSC, 2009; Wang and Sun, 2014; Patil and MacDonald, 2015; Paik, 2020). One of the main concerns with FPSO integrity management is the availability and accessibility periods for various tanks inspections during their operations and maintenance as required by both in-house operator integrity program and class society integrity surveillance programs. Therefore, operators and indeed researchers involved in life extension studies should focus on a detailed methodology for corrosion wastages and rates to achieve scope of inspection definition and allow for more precise mitigation actions to be put into action to reduce or prevent an increase in future surveys (Machado et al., 2015; Piscopo and Scamardella, 2021). As FPSOs near the end of their design life, operators are often faced with the requirements of making a firm business decision aimed at extending the operational life of the FPSO. This firm intelligent business decision has the economic and technical aspects of it. Either to continue production from an existing/productive oilfield or to harness/explore new satellite oilfields opportunities with potentials for tie-back to the existing host FPSO. The technical aspect is aimed at deferring new CAPEX in purchase of new floater as is often the case with leased FPSOs (Shama et al., 2002; Boutrot et al., 2017; Liu et al., 2018; Liu et al., 2020). In today's competitive business environment with low profit margin, FPSO owners/operators prefers the execution of life extension program on ageing FPSO rather than building a new one once the existing FPSO has been confirmed structurally adequate for the intended years of life extension. The technical aspect of life extension presents a unique reverse engineering challenges and opportunities from the perspective of costs and risk management. Thus, requiring a complete structural re-assessment of an existing FPSO from its current, as-in condition in other to determine its suitability in terms of safety and integrity for the intended period of life extension, with any mitigation/repairs done to achieve the ultimate goal of defined additional life of extension. According to Ugbelase et al., (2024) the Bonga FPSO was installed in 2004 to serve a design life of 20 years. Recently, the Bonga main life extension project achieved the life extension of the FPSO for additional 15 years to produce the tail volumes of hydrocarbon from the field in addition to infill volumes from satellite developments including the Bonga North tie-back project. The authors concluded that an insitu (on site) life extension rather than dry docking was adopted.

The devastating menace of marine corrosion wastage is the most challenging issues experienced by FPSO during their design service life. The hull and deck plates of the FPSO are the major components vulnerable to corrosion wastages. The phenomenon of corrosion wastage becomes more significant and challenging over time as the FPSO 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 hull and deck plates. Corrosion has a dangerous consequence from the stand point of safety, integrity and can lead to thickness reductions and penetration. Marine corrosion wastage effects are known to cause structural integrity problems on the hull and deck plates. As marine corrosion wastage threshold values triggering FPSO hull and deck plates strakes mitigations such as protective coating replacement, plate repairs, plate replacements, some classification societies such as ABS recommend local plate thickness reductions of about 20 - 25 percent from considerations of strength. Plates are rated in terms of original thickness and ultimate tensile strength, the reduction in plate thickness results to a reduction in strength, this means that the remaining thickness of a plate is a measure of the remaining strength. The layout of FPSO deck plates strakes is done in such a way that were higher deck loading is expected will have a thicker plate strake. Most research on this area were done with data obtained from trading tankers which is imposed on FPSO for the purpose of studies and knowledge sharing. Others were done with data obtained from laboratory in corrosion coupon under a controlled condition. Paik and Thayambali (2007) and Paik (2022) advocated for more corrosion wastage case studies and recommended that future research should consider to take monitored data in real marine corrosion environment which is uncontrolled from a floater in operations, rather than data from a trading tankers or in laboratory from corrosion coupon. This is because data from real corrosion environment is more realistic in corrosion wastage studies. This present work applied historic data taken from an FPSO in Gulf of Guinea to ascertain its structural adequacy for intended life extension of 15 years. The historic data were collected, collated and analyzed to make life extension decisions. Firstly, to determine the suitability of the FPSO hull remaining thickness to serve for additional 15 years in life extension. Secondly, to determine the condition of the deck plates and make repairs, renewal and replacement recommendations. Although, a survey report carried out on the hull and deck plates prior to this analysis showed that there were neither crack nor dent but the hull and deck plates in various strakes only sustained certain degrees of general/pitting corrosion wastage. Class society rule based equations were applied for the evaluation of the FPSO hull suitability for intended years of extension, while mitigation measures were applied to the deck plates strakes/zones that were either badly corroded or pitted base on class society rule equations. Interestingly, the available academic publications mainly address singly only specific aspects of the challenges. On the other hand, most classification societies only provided clumsy and trivial guidance notes as life extension frame work to the FPSOs owners. This present work proposes a comprehensive methodology of as-gauged scantling method normally preferred by FPSO owners and operators for evaluating the FPSO hull for suitability of 15 years' life extension under the effects of corrosion wastages. Interestingly, Collins et al., (2015) advised that in other for the upgraded and refurbished floating facilities to be more economical and profitable in the long term, the expected life extension should be greater than 16 years. Notably, asset economics and econometrics plays pivotal role during inspections, maintenance, repairs and life extension planning. Similarly, the projected costs for the life extension of the Bonga FPSO and SPM calm buoy was USD 2 billion while the cost of purchase of a new build FPSO and SPM calm buoy was placed at USD 12 billion. The costs differences justify the reasons why operators prefer floating facilities life extension. According to Ugbelase et al., (2024) the Bonga FPSO was installed in 2004 following a design life of 20 years. The authors revealed that the Bonga main life extension project achieved the life extension of the FPSO for additional 15 years to produce the tail volumes of hydrocarbon from the field in addition to infill volumes from further

developments including the Bonga North tie-back project. The authors concluded that an insitu (on site) life extension rather than dry docking was adopted. While class society rule based equations are applied to analyse corrosion wastage data on the main deck plates to ascertain the level of plates strakes repairs, renewal and replacements required. Some of the repairs strategies are protective paint coating, additive patch, crop and weld, weld infill and sandwich plate system. Notably, most academic publications recommended that future works on FPSO should consider more case studies on corrosion wastages to increase knowledge sharing. The available data and research publications across the industry and academic spheres does not present a comprehensive evaluation of that possibility, which justify the importance of the methodology proposed. This paper proposes a guidance for the life extension process management for FPSO hull and deck plates with the aid of a computer program. Thus, strengthening a framework containing the main evaluation stages, aiming to facilitate the assessment of problems related to ageing and to support the hull and deck plates life extension decision-making process. Structural damage has been implicated in several reports to be a major contributing factor to marine incidents, while ageing has been observed to be a significant influence in hull damages.
Thus, the aim of this research paper is to address issues on life extension of ageing FPSO and SPM calm buoy hulls and deck plates under corrosion effects.

Ageing and Age-Related Structural Degradation and Deterioration
Ageing of FPSO and SPM calm buoy hull may be defined as the progressive degradation and deterioration of hull structures due to normal operational use and environmental factors. However, the various patterns of their structural degradation and deterioration comes in the following forms:

(a) Protective coating damage
(b) Corrosion wastages
(c) Cracking
(d) Deformations (dents), and
(e) Changes in material properties.

Protective coating damage
Protective coating degradation and deterioration can take the pattern of through-film breakdown, delamination, cracking, too-thin coating, edge breakdown, blistering, weld corrosion, rust, calcareous deposits induced coating failure, reverse impact damage, stress related coating failure and flaking (Satoshi et al., 2005; Hörnlund et al., 2011; Shafiee et al., 2016). However, protective coating cracking occurs when structural deformation surpasses the lengthening of the paint film. On the other hand, blisters occur where the grip of the protective paint coating is locally lost. Notably, blisters are known to contain liquid, although there is no corrosion under the blister. Also, flaking refers to the lifting of paint coating from the underlying surface. The loss of protective coating paint bonding is the consequences of poor surface preparation, incompatibility with under-layer and contamination between layers (Paik and Melchers, 2008; Bodule et al., 2014). Surface preparations for protective paint coating applications is best at (SA 2.5 or SA 3.0). That is thorough blast cleaning and very thorough blast cleaning.

Similarly, the factors affecting protective paint coating performance are grouped into:

(a) Environmental factors
(b) Operational factors
(c) Coating related factors
(d) Design and fabrication factors
(e) Maintenance and inspection factors.

The elements of the environmental factors are high humidity, high salt concentration, weathering, temperature and ultra violet radiation. On the other hand, coating related factors are paint thickness and uniformity, drying and curing, method of paint application, surface preparation, paint type and quality. Similarly, the operational factors are cleaning and maintenance, mechanical stress, chemical exposure, foot traffic and maintenance. The laydown/landing base areas on main deck of FPSOs usually have high foot traffic. More so, the design and fabrication factors are usually deck design and layout, material selection, fabrication and welding. Lastly, the maintenance and inspection factors looks into regular surveys, maintenance scheduling, protective paint coating repairs and touch up purpose (Animah et al., 2016; Animah and Shafiee, 2017). Many factors contribute to the degradation and deterioration of coatings and corrosion. These contributing factors are: type of cargoes/acidity of the cargo, frequency of ballasting, frequency and method of tank cleaning, trapped water or oil, oxygen concentration, sulphur concentration, salinity of ballast water, temperature, humidity, pollution, trade route, structural flexibility, corrosion protection effectiveness, marine fouling, corrosion films, speed of flow, stray-current, cargo residues and mechanical abrasion, maintenance and repair, material of construction, microbial attack, sludge/scale accumulation, etc. (Woinin, 2001; Gardiner et al., 2003, Hu et al., 2004, Panayotova et al., 2004a; Panayotova et al., 2004b; Panayotova et al., 2007; RINA 2004). These factors act individually or in combination, and their influences are difficult to quantify. As a result, corrosion wastage of structural members is dependent on the location of the member (IACS, 2005; Wang et al., 2003a; Wang et al., 2003b, Yamamoto, 2005; Paik and Melchers 2008).

Corrosion wastage

Corrosion is the gradual degradation and deterioration of a metal due to its chemical or electrochemical reaction with the environment such as seawater. The general patterns of corrosion are uniform or general corrosion, pitting corrosion, stress corrosion cracking, corrosion induced fatigue, microbiological induced corrosion etc. (Boon et al., 1997; Cox, 2004; Ok and Pu, 2005; Paik et al., 2006; Duo, 2006). General or uniform corrosion is the most common form of corrosion wastage form; its effects of degradation and deteriorations spreads uniformly over the surface of the hull and deck plate.

Pitting corrosion

Pitting corrosion, is a localized corrosion pattern, is often seen on the bottom of ballast tanks and some areas on main deck plates. The shape of the pits depends on the surrounding environment (Yamamoto 2008a). Akpanyung and Loto (2019) in their investigations reported that pit with open (uncovered) or covered mouth can be formed by pitting corrosion via semipermeable membrane products. Although, pits may also appear as cup-shaped or hemispherical shape as in Paik (2022), sometimes flat-walled, showing metallic crystal structure while some may be totally irregular in shape (Paik and Thayamballi, 2007). However, pit shapes are commonly grouped into trough pits (upper) and sideway pits (lower), Chernov (1990) reported that the cavities of pitting may be filled with corroded products forming caps over it and at times forming nodules or tubercles. In the present reliability assessment, it is assumed that the most heavily pitted cross section of any structural member extends over the plate breadth (Tamburri et al., 2003; Devanny, 2006; Wintle, 2010a; Wintle, 2010b). This may provide a somewhat pessimistic evaluation of residual strength but is convenient for the reliability assessment (Vaidya and Rausaud, 2011; Solland et al., 2011; Paik, 2022). The author stated that in reality, pits will be repaired once they reach certain depths and extents, regardless of the related strength criteria, although this is not accounted for in the present illustrative calculations. Pitting is a dangerous localized corrosion and not easily detected due to its microscopic nature. Although at the surface of a deck plate, pit may be small, but however may appear bigger beneath the undercut surface, thus are covered with film or rust deposit. Although by through perforation, deck plates fail by the menace of pitting corrosion with very little effect of weight loss. The measurement of pit is challenging because its depth and spreads varies greatly under similar conditions. Interestingly, the incubation period of pits may run into months or years. The

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pits incubation period refers to the total time required for a deck plate strake or zone to go through crack nucleation to the point and time the crack progresses to a critical intensity, which could eventually lead to strake or zone failure. Induced corrosion pits are points of stress concentration where cracks could initiate, grow and propagate. However, the determinants of pitting intensity or the rate of pit growth once it initiate are mainly the type of material, the state of the stress and lastly, the local solution conditions (Paik et al., (2003a; Paik et al., 2003b; Paik et al., 2003c; Paik et al., 2003d). The application of inorganic-based inhibitors enhances the mitigation of deck plates pitting corrosion wastages in aggressive medium such as seawater. Figure (1) represents the various pitting profiles. While figure (2) represents Presumed progress of corrosion diminution for selected members in the object FPSO structure. The factors affecting pitting corrosion are: environmental factors such as PH, inhibitor concentration, concentration of aggressive ion, surface condition, temperature, pitting potential and metallic composition. The notable impacts of corrosion wastages on deck plates strakes are: thickness reduction, reduction in loading bearing capacity, reduction in fatigue strength factor of safety, reduction in remaining strength, geometric defects and cracks. However, thickness reductions beyond a threshold value could lead to crack if immediate repair actions are not taken. On the other hand, the factors that influence deck plates thickness are: material selection, loading conditions, floater size, shape and operating conditions. Others are design and regulatory requirements which are bent on corrosion protection, structural integrity and class society rules.

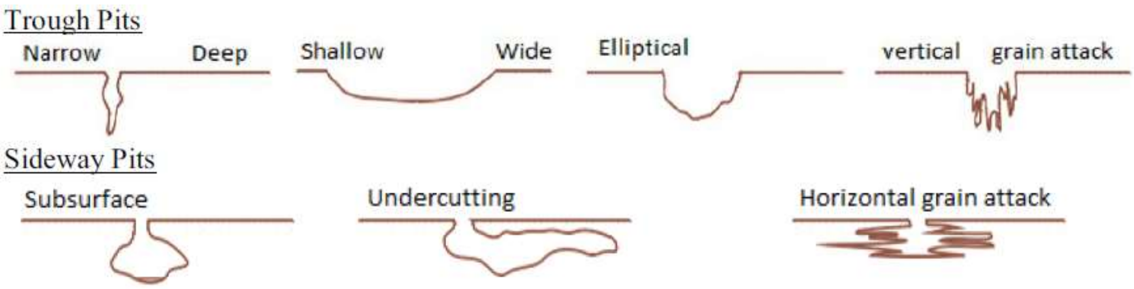

Figure (1): Various pitting profiles
(Source: Akpanyung and Loto, 2019)

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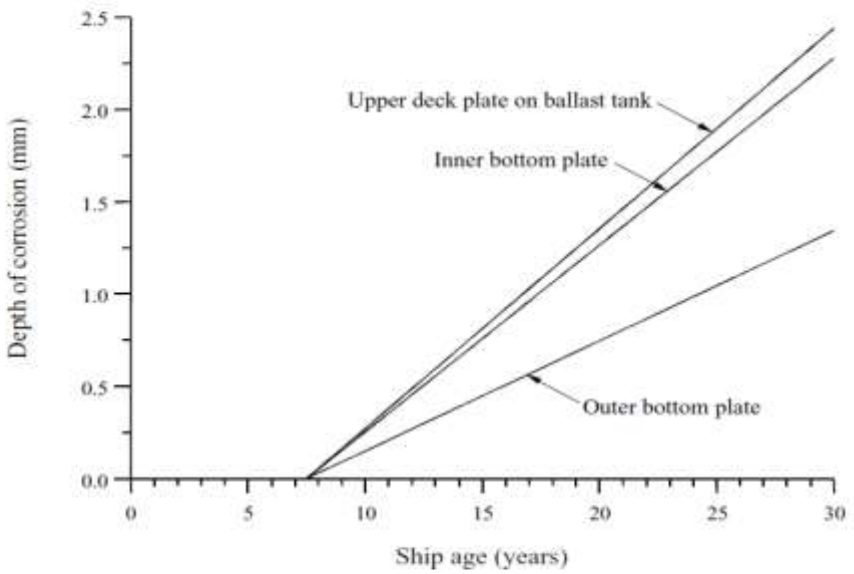

Figure (2): Presumed progress of corrosion diminution for selected members in the object FPSO structure.
(Source: Paik, 2022)

Microbial induced corrosion and cracks

Microbial induced corrosion is also a form of localized corrosion caused by the activities of microbes, even on strakes of ballast tanks plates, due to their corrosive waste products. The most common bacteria are sulphate-reducing bacteria, SRB and acid producing bacteria, APB. SRB cause corrosion under anaerobic conditions. The SRB enters the ballast tanks through ballasting operations, alongside sediments and debris which they feed on. These metal eating bacteria as they are fondly called, live, grow, thrive and multiply in the absence of little to zero oxygen, hence are called anaerobic bacteria. Specific combinations of alloy and environment can lead to stress corrosion cracking when the metal is mechanically stressed while being exposed to the corrosive environment (Porter, 1992; Pedera, 2013). Rust is a corrosion product of an oxide and hydroxide generated to the surface of metal. Since the initial rust is porous and hygroscopic, the range of rusting expands and the paint film is destroyed. Rust is generated from the part where an adhesion of paint film is insufficient and a paint film is broken. Cracks often originate from defect of welds. Impact from a dropped object or accidental overload may also potentially lead to initiation of cracks. If such initial cracking is left undetected, not repaired immediately, it can grow into a crack that continues to propagate under repeated loads, hence enter the aging regime. However, corrosion precedes cracks in what is called corrosion induced cracks.

Life Extension Procedures and Process

Essentially, in this research, the big question must be whether to continue using the floaters in life extension or to decommission it. The engineering solution depends on whether a combination of structural upgrades/modifications and mitigating actions will be sufficient to demonstrate compliance with national and international safety requirements such as that of a classification society covering such assets and whether a business economic case can be made for oil and gas reserves in the oilfield and consequently for the FPSO/SPM calm buoy life extension. Table (1): Oil reserves in deep offshore Nigeria by oil majors. Table (2): List of new built FPSO in Nigeria. To actualize these items, the balance between revenue and cost with time, indicating timescale associated with economic end of life is presented in figure (3).

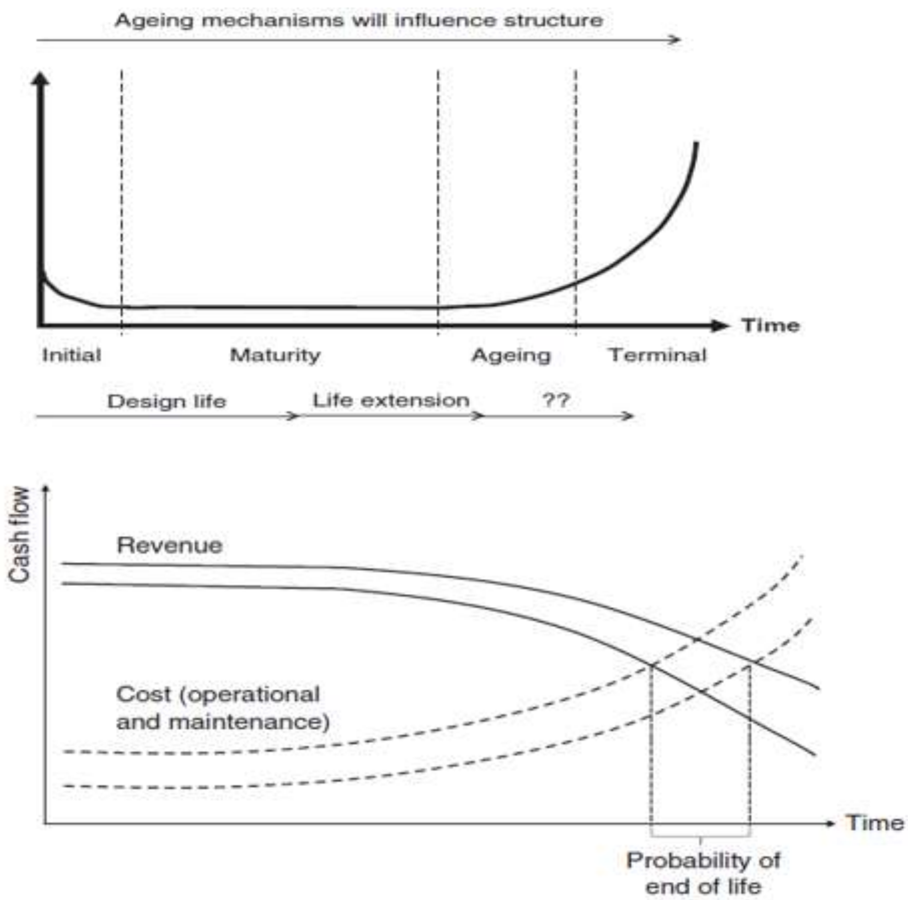

Figure (3): Balance between revenue and cost with time, indicating timescale associated with economic end of life

The technical drivers are mainly determined by the availability of data for evaluation and decision making such:

(a) Operators and class surveys-The results of surveys either jointly or separately carried 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 hull and deck plates gauging is adopted by class and it has overriding effects in life extension. 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.
(b) Historic data from maintenance and repairs -Are used to enforce technical decisions.
(c) Corrosion wastage management, feasibility studies on repairs, upgrade and modification -These studies help the operator to make fast technical business decisions.
(d) 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.

(e) Hull integrity-The critical element is surveyed to ascertain that it is fit for purpose or relevant repairs are recommended for close out.

Table (1): Oil reserves in deep offshore Nigeria by oil majors

Oil Field	Water Depth (m)	Operator	Reserve
Usan	850	Esso	Recoverable reserve: 68 x 10^6 tons.
Erha	1200	Esso	Recoverable reserve: 68 x 10^6 tons.
Bonga	1000	Snepco	Recoverable reserve: 82 x 10^6 tons.
Agbami	1463	Chevron	Estimated total reserves: 136 x 10^6 tons.
Akpo	1400	TotalEnergies	Proven and potential reserve: 85 x 10^6 tons. of condensate oil and 28.3 x 10^9 m^3 natural gas
Egina	1600	TotalEnergies	Probable reserve: 75 x 10^6 tons.

(Source: Ophori et al., 2020)

Table (2): List of new built FPSO in Nigeria

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

(Source: Boggs et al., 2021)

Floaters are installed at locations with a specific design life 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 and deck plates. This reassessment normally includes both engineering and survey activities. The FPSO and SPM hulls and deck plates life extension strategies involves the following items: For hull deck plates, we have:

(a) Cathodic protection
(b) Painting and Coating
(c) Frequent plate thickness measurements or gauging (UTM)
(d) Fitness for service examination and evaluation
(e) Repairs and replacements

Inspections/Surveys and Data Gathering Methodologies

However, ultrasonic thickness measurement (UTM) in floating structures is primarily used for thickness measurements and is particularly used for monitoring corrosion on components (Paik and Thayamballi, 2007). Thus, in this mode the focus is on measuring the time required to receive a signal reflected from the back wall (Paik, 2022). Usually for deck plates, 5 gauging points per strake of 1 square meter is recommended, unless where there is evidence of substantial corrosion wastage that 8 points gauging is done followed by close and general visual inspections, and the attention of the class surveyor in attendance drawn to it alongside operator marine program owner and such strakes or zones is therefore marked for close monitoring in subsequent surveys. Figure (4) shows UTM set up.

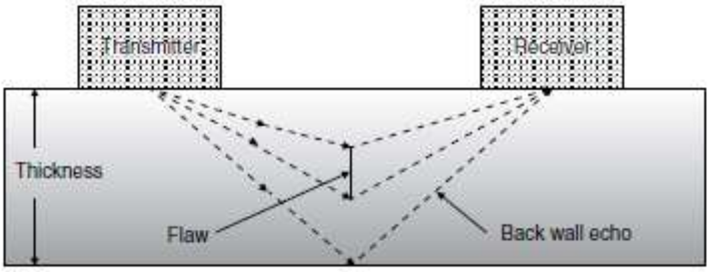

Figure (4): UTM set up
(Source: Ersdal et al., 2019)

The critical components of a floating production installations are the machinery, station keeping and hull girders such as main deck plate, ballast tanks, transverse and longitudinal girders, vertical and horizontal girders, frames, stiffeners, web frames, stringers etc. Ditchburn et al., (1996) and Demsetz et al., (1996) reported that in the evaluation of FPSO/SPM calm buoy hull deck plates corrosion wastage, a primary decision arises as to which parameter must be detected and measured:

(a) Average remaining thickness,
(b) Minimum thickness, and
(c) Maximum pit depth or pit intensity (as a percentage of the plate surface).

However, Paik (2022) concluded that in current corrosion wastage monitoring practices;

(a) Average remaining thickness and
(b) Maximum pit depth; are considered to be primary parameters of corrosion in terms of repair criteria (Conachey and Montgomery, 2003), but the trend is now towards a more quantitative definition of:
(c) corrosion intensity.

Interestingly, 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. For SPM calm buoy, the OEM defines a survey and maintenance plan and the asset operator follows such plan through implementation. However, if the SPM calm buoy is classed vessel, the class society rule will also take its course and the asset is occasionally surveyed by the attending classification society surveyor. The operator in most cases carry out weekly, monthly, quarterly and annual OEM surveys alongside the class society survey program for the SPM calm buoy and both programs runs concurrently.

Inspection/surveys planning philosophy

The development of planning philosophies for inspection of structural condition is shown in figure (5). A good inspection campaign is dependent on time, cost and technology involved.

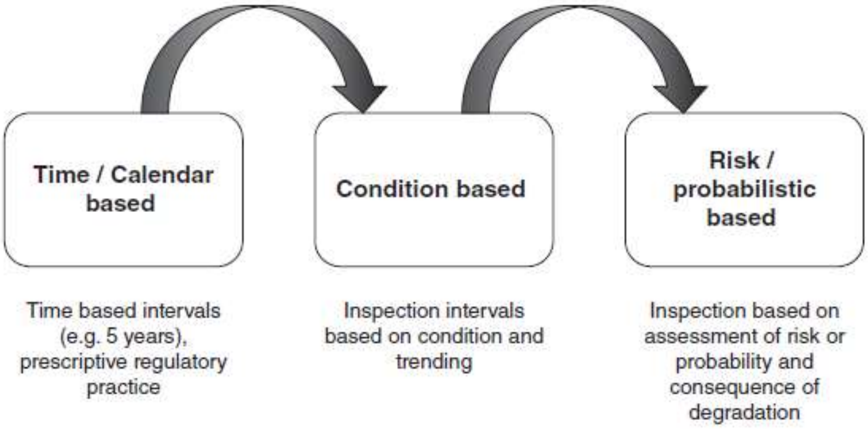

Plate (5): Development of planning philosophies for inspection of structural condition
(Source: Ersdal, 2014)

Although floating facilities do not possess the same level of inherent redundancy as fixed installations, they are more easily surveyed (Ersdal, 2014). Whether by dry-docking or de-ballasting, some underwater surveys can be done in the dry dock (Ersdal et al., 2019). This requires that the floating facility must be taken out of service for this purpose (Sharp and Ersdal, 2021). Paik and Thayamballi (2007) pointed out that **c**urrently, many operators of floating facilities prioritise their surveys towards the components which, from structural analyses or historical data, are most likely to show premature degradation, deterioration, damage or failure. Floating facilities are constructed with engineering materials manufactured in different factories. Interestingly, the greatest among all engineering materials in terms of applications is steel. Notably, engineering materials change from the day they are fabricated and subsequently installed (Paik, 2022), these changes have to be managed in order to ensure that the fixed and floating facilities remain sufficiently safe (Ersdal et al., 2019). Some of these changes influence the floating facilities and its safety directly (Ersdal, 2014). Examples of this may be fatigue, corrosion, material degradation, changes in loads and weight on the facilities and how the facilities are used (Paik and Thayamballi, 2007). Although, engineering practise involves design, fabrication and installation of floating structures for safe operation during their design life (Sharp and Ersdal, 2021). However, the nature of operational environment, cyclic loading and accidental occurrences will cause anomalies, which if not detected, managed and repaired have the potential to cause failure of the affected component of the floating facilities (Ersdal, 2005). Nevertheless, ageing increases the probability of such anomalies occurring (Stacey, 2010). Non-destructive testing, NDT techniques have revolutionized the detection and prevention of material failures across various industries most especially the offshore industries (Sharp et al., 2011). Generally, defects occur during construction and operations (Paik, 2022). Metal can exhibit different types of fracture depending on the material, the temperature, state of stress and rate (frequency) of loading (Paik and Thayamballi, 2007). Interestingly, the failure of engineering materials causes loss of life, economic loses and interference with the availability of products and services (Ersdal, 2019). The failure of engineering structure is attributed to improper material selection, improper processing, and inadequate design of the component or its misuse (Ersdal and Selnes, 2010). Failure is known to occur in three stages of crack initiation, growth and propagation. 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

According to ABS (2018a) the initial survey, as required by the relevant maritime regulations, should be carried out before a floater is put in service, or when a new instrument applies to an existing floater, and the appropriate certificate is issued for the first time (LR, 2003). However, IACS (2005) and ISSC (2009) pointed out that the initial survey should include a complete 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 the structure, machinery and equipment are fit for the service for which the floater is intended (ABS, 2021; Paik and Thayamballi, 2007). However, at the end of the initial survey, a certificate of class will be issued for the first time along other certificates and it usually last for a period of five years. The certificate of class attests that the floater was designed and constructed in accordance with the classification society rules and regulations. Although, during the five years, the classification society will still be attending the floater for periodic surveys and annual surveys to maintain class. It is important to note that certificate of class is different from other certificates such as: safety construction certificate, safety equipment certificate, load line certificate and international oil pollution prevention certificate. A key item is that the certificate of class is pivotal in the sense that it is being demanded and presented to the insurer of the floater (insurance company). Nevertheless, the initial survey should consist of the following:

(a) A review of the plans, diagrams, specifications, calculations and other technical documentation to verify that the structure, machinery and equipment comply with the requirements relevant to the particular certificate (IACS, 2005).
(b) An inspection of the structural integrity, machinery and equipment to ensure that the materials, scantlings, construction and arrangements, as appropriate (LR, 2003), are in accordance with the approved plans, diagrams, specifications, calculations and other technical documentation and that the workmanship and installation are in all respects satisfactory (IMO, 2000).
(c) A check that all the certificates, record books, operating manuals and other instructions and documentation specified in the requirements relevant to the particular certificate have been placed on board the floater and readily available for sighting (IMO, 2006).

As evident in ABS (2021) The annual survey, as required by the relevant regulations should be held within three months before or after each anniversary date of the certificate (BV, 2015). According to ISSC (2009) an annual survey should enable the classification society to verify that the condition of the floater, its machinery and equipment is being maintained in accordance with the relevant requirements (IMO, 2006). However, the scope of the annual survey should be as follows:

(a) It should consist of a certificate examination, a visual examination of a sufficient extent of the floater and its equipment, and certain tests to confirm that their condition is being properly maintained (BV, 2015).
(b) It should also include a visual examination to confirm that no unapproved modifications have been made to the floater and its equipment (IMO, 2000).

Notably, the periodical survey of a floater, as required by the relevant maritime regulations should be held within three months before or after the second anniversary date (HSE, 2006; IMO, 2006).

Interestingly, the periodical survey should consist of an inspection, with tests when necessary, of the equipment to ensure that 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 ship is intended (ABS, 2021; Gordon, 2015). However, the periodic 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 (ABS, 2018a). Gordon et al., (2014) reiterated that the intermediate survey, as required by the relevant maritime regulations should be held within three months before or after the second anniversary date or within three months before or after the third anniversary date of the appropriate certificate and should take the place of one of the annual surveys (Gordon, 2015). Although, the intermediate survey should be an inspection of items relevant to the particular certificate to ensure that they are in a satisfactory condition and are fit for the service for which the floater is intended (DNV, 2015). The aim is to ensure that the floater remains in compliance with all applicable rules and regulations and is safe to remain in operations. It is usually schedule every 2.5 years and aimed at verifying critical floater components.

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 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 society 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 deck plate strake or zone. According to ABS (2021) 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 hull structure.
(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 hull deck plates.
(f) Apply to classification society for life extension approval (ABS 2021).

Hull Data Measurements, Management and Interpretations

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 (as a percentage of the plate surface). 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). As a base line condition, in a life extension project for FPSO and SPM calm buoy, class society rule requires that if ultrasonic thickness measurement gauged data was collected within the previous 5 years, then it can be used for hull and deck plates strakes or zones assessment. Notably, before using data that is older than 5 years, concurrence should be obtained from a subject matter expert. Paik and Melchers (2008) 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 ISSC (2009) 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. Recently, a lot of marine corrosion wastage data due to ageing related issues has become available in many corrosion publications (ISSC, 2009; Seo et al., 2007). Although, the hull deck plates thickness measurement data is useful in identifying the trends in corrosion degradation and deterioration. However, they were extensively used in developing analytical models for predicting corrosion wastage and time-variant reliability analysis (Paik and Kim, 2012; Paik and Melchers, 2008; IACS, 2006). Nevertheless, the interpretation of the trends revealed in various database remains, however, limited (Park et al., 2020; ISO, 2016; Osawa et al., 2007; Guedes Soares and Garbatov, 1996). However, Sakashita et al., (2007) revealed that the continuous collection and updating of these databases is also necessary for industry and research works such as life extension case studies for floating assets like FPSO/SPM calm buoy hulls and deck plates. Interestingly, most of the available data is about uniform or general corrosion (Melchers, 2002; Gardner and Melchers, 1999; Gardner and Melchers, 1998). Nevertheless, data of other types of localised corrosions such as pitting and grooving still remain scarce (Melchers, 2005; Melchers and Jeffrey, 2004; Melchers, 1997). This has made it difficult for floating facilities designers to design against localised corrosion such as pitting corrosion.

Interestingly, data management for corrosion wastage and coating degradation is key in managing life extension campaigns. Operators of floating ship shaped floating facilities used in oil and gas production operations such as FPSO/SPM calm buoy are required to store class and statutory documents and reports onboard (ISSC, 2009; IMO, 2004). Most of these documents or reports which are frequently updated to reflect the latest survey findings and the floating facilities class status. This report is often referred to as class status reports and it details all the defects found during surveys and their repairs recommendations. The idea of keeping documents onboard is traditional shipping practise. According to IACS (2005) FPSO are also required to keep documents onboard, although the difference between ship and FPSO is that verifying documents are kept offshore for FPSO. Thus, an onshore support team is set up to keep updates of documents (ISSC, 2009). This can best be achieved by using data management tools (ISSC, 2009). This ensures uniformity in documents and procedures stored on-board are the same with documents available to onshore support teams (IMO, 2006). The authors explained that this task can be addressed by the use of an efficient centralized document management system (IACS, 2006).

According to ISSC (2009) such a system allows fast and easy access to relevant documents onboard. It also provides a central system for sharing these documents with onshore base teams (Seki et al., 2007). The use of satellite communication systems allows internet access from almost any part of the globe. The authors explained that the use of this system is effective for offshore production operations. Recently, major classifications societies now provide services on data management and structural integrity using web interfaces (Lanquetin et al 2007a, 2007b) for inspection, maintenance and repair for hull. The authors pointed out that the use of such techniques allows sharing of documents by various people. Nevertheless, it also helps operational teams to keep access to and track design and maintenance documents. According to Paik and Thayamballi (2007) it was reported that excessive corrosion wastage may result to fracture, buckling or yield failure (Paik, 2022). Corrosion wastage results to thickness reduction in hull deck plates. The degradation and deterioration of FPSO/SPM calm buoy hull structures reduces the remaining strength, local and global strength and can finally lead to disastrous casualties in extreme conditions.

The technical implications and economic cost of pitting corrosion

The implications and consequence of corrosion action is a global concern. 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. The corrosion cost incurred from manufacturers of plates also passes cost onto the operators of floating facilities when the right corrosion margin is not kept to. The menace of corrosion is experienced by the FPSO and SPM calm buoy hulls and deck plates. The SPM calm buoy is built in compartments for the seawater ballast tanks such that each compartment is made up of top plate, mid upper plate, mid lower plate, bottom plate and floor plate. The FPSO ballast tanks is also compartmentalised. Notably, by class society standards, pitting depth up to 15 percent plate thickness is recommended for epoxy coating repairs to stop pit growth. For scattered pitting depth up to 33 percent plate with small diameter with low pit density less than 20 percent area is recommended for belzona epoxy paint putty and coat. On the other hand, deep pits greater than 33 percent thickness, that is smaller diameter pits less than 300mm is recommended for repair by weld infill and coating. Also, for average remaining thickness for pitted area greater than 50 percent as-built plate thickness, composite cold work repairs or crop and renew is recommended. Similarly, for remaining thickness less than or greater than 33 percent of as-built, such as large diameter pits or high pit density, crop and renew mitigation strategy is recommended. Finally, for insufficient remaining plate thickness less than 6 mm, crop and renew mitigation is recommended. Figure (6) represents a turret type SPM calm buoy view.

Figure (6): A turret type SPM calm buoy.

(Source: Ma et al., 2019)

6. Maintenance, Repairs and Mitigation Strategies

All of these mitigations strategies are also handy solutions in extending the life of the floaters when properly done to the satisfaction of the classification society covering such floater. Most floating production installations worldwide is nearing or have exceeded the end of their design life. In recent times, to keep up the floating facilities safety and reliability at a certain degree or higher, requires that a proper, cost-effective scheme for maintenance must be set up. In this regard, some considerations for repair strategies of structural members assumed to be heavily damaged by corrosion and fatigue cracking are now explained (Paik, 2022). The IMO (2006) requires that one should keep the longitudinal strength of an aging ship and indeed ship shaped floating facilities at the level of at least 90 percent of the initial state (Paik and Thayamballi, 2007; IMO, 2000). According to the authors, although the IMO requirement is in fact based on the floaters section modulus (IMO, 2006), the present illustrative examples are extended as a device to establish a more sophisticated maintenance scheme based on hull girder ultimate strength (Paik and Thayamballi, 2007). The investigations of Paik et al., (2004) shows that the aim of the illustrated strategy is that the ultimate hull girder strength of an aging floater must always be at least 90 percent of the initial, as-built floater value (Paik et al., 2006). According to the illustrators, the renewal criterion for any damaged member is based on the member's ultimate strength rather than member thickness as traditionally done (Paik et al., 2006). The authors pointed out that this concept is advantageous because member thickness-based renewal criteria cannot disclose the effects of pitting corrosion, fatigue cracking, or local dent damage adequately even though it may handle the thickness reduction effects of general corrosion reasonably well (Park et al., 2020).

Although Paik and Kim (2012) explained that, structural member's such as deck plate ultimate strength-based renewal criteria are acceptable and better equipped to handle all types of structural damage (Paik and Melchers, 2008). The illustrations conveyed the idea that, the more heavily damaged members need to be renewed or repaired to their as-built state, immediately before the ultimate longitudinal strength of an aging floater reduces to a value less than 90 percent of the original floater (Park et al., 2020). The structural safety and reliability of aging vessels can, of course, be controlled by proper maintenance strategies (Paik and Thayamballi, 2007). The authors reported that the repair criterion based on member ultimate strength can provide a potential improvement to better control the age-dependent degradation of a floater longitudinal strength (Paik et al., 2004). ISO (2016) and Paik (2022) explained that the illustrations demonstrate that the percentage reduction in critical ultimate strength of structural members such as plates that need to be repaired is not constant as might be expected and is in the range of 2-7 percent of the as-built state (Belzona, 2020; ABS, 2018a).

The hull main deck plates of an FPSO and SPM calm buoy floaters are exposed to severe environmental conditions, which can cause corrosion degradation and deterioration of the steel structure. According to MOG (2023) in order to maintain the integrity of the floater, the corroded main deck plating will have to be renewed when the thickness is below the limiting values of the classification society covering such floater (Paillusseau et al., 2019). Interestingly, the main deck of a floater is the zone where the topside process modules are positioned (MOG, 2023; SPS, 2005). However, these modules are used to handle, treat and process the oil and gas produced from the subsea wells to the desired quality (Talei-Faz et al., 2004). Nevertheless, the process handling and treatment equipment usually undergo ageing due to corrosion, fatigue and presents the risk for volatile flammables gas leakage or spill from the process equipment, piping, valves, or storage tanks (Tiku and Pussegoda, 2003; Carvallo et al., 2015). During life extension structural inspections, evaluations and recommendations for repairs and replacements, two methods are usually compared towards final decision. They are:

(a) On-site (In-situ)

(b) Dry Docks

The in-situ or on-site repairs allow for continuous production operations, eliminates or reduces the possibilities of loss of production opportunities. The on-site method is becoming attractive because it minimizes or is associated with little down time costs. However, the dry docking method creates room for more intensive repairs. However, dry docking attracts huge cost, but it usually results to long-term cost savings by reducing the need for frequent future repairs. This is because dry docking allows unrestricted access to every zones of the FPSO such as the hazardous zones, cargo tanks and cofferdam making repairs more comprehensive and convenient. Nevertheless, dry docking allows for more exact and thorough repairs, thereby minimizing the probability of such technical challenges occurring any time soon. In the absence of dry docking FPSOs, operators and owners plan and schedule turnaround maintenance, TAM every four years to fall in line with the year preceding certificate of class renewal survey. The TAM window is usually associated with planned shutdown and loss of production opportunities for an agreed period of time. During this period, the cargo tanks are opened and inspected by various vendors, suppliers and classification society using a third party inspection contractor licenced and accredited by the classification society covering such floater. For the SPM calm buoy, during this TAM period, it can be disconnected and towed to ship yard for repairs and refurbishments and towed back to field for reconnection. There the following points favours dry docking method:

(a) Reduced cost
(b) Enhanced quality
(c) Better accessibility

According to Ersdal et al., (2008) and Paillusseau et al., (2019) an increasing number of FPSO/SPM calm buoy units are currently entering the end of their design life thus, inducing numerous asset integrity challenges (McGeorge et al., 2009). As corrosion wastages damages FPSO/SPM calm buoy hull structures such as deck plates (Baker et al., 2004), costly structural repairs operations in extreme marine conditions are sometimes necessary (Frost, 2005). Usually, crop and renew techniques are very labour-intensive operations and usually require dry docking (Marsh, 2006). The nature of production operation practically requires that an FPSO stays offshore in location, which raises several operational, safety and financial concerns (Ersdal, 2014). Although, the storage of volatile and flammable liquids onboard means that the use of conventional hot works techniques, such as welding or grinding induces some level of threat to operational safety of lives and asset and ultimately loss of production opportunity depending of the area where such hot work will be done (Weitzenbock and McGeorge, 2004). Usually, FPSO are arranged in zones, thus having the harzadous and non harzadous zones. Thus, the threat would be to carry out these repairs offshore while guaranteeing high safety standards and avoiding loss of production opportunity (McGeorge et al., 2009). FPSO owners and operators prefers the cold work in-situ solutions that guarantee safe and economical hull plates repair (Marsh, 2006; Hokstad et al., 2010; Paillusseau et al., 2019).

Paillusseau et al., (2019) states that if repair work of the hull of an FPSO becomes necessary, economic considerations demands that, if at all possible time, repair be carried out with the FPSO remaining on location, thus minimizing any loss of production opportunities (Weitzenbock and McGeorge, 2004). Thus, any repairs of defects in the hull bottom of an FPSO must therefore be carried out underwater (Baker et al., 2004). The preferred technique is to attach an enclosed dam to the underside of the floater, pump out the water and then complete the repair from the inside (Paillusseau et al., 2019). Although, where the risk of fire or explosion or ballast considerations require, it may be necessary to complete the welded repair from inside the vessel by wet underwater welding (Echtermeyer et al., 2005). The results of surveys are used to plan remedial actions such as maintenance, repair or steel renewal (DNV, 2006; DNV, 2005; BS, 2005). To minimise financial expenditure, a systematic plan is established to maintain the safety and integrity of structural components and hull girders to the required levels (Paik and Thayamballi, 2007). Classification societies provide useful plans for the maintenance and repair of FPSO/SPM calm buoys (Ersdal, 2014). For a successful maintenance and repair of FPSO/SPM calm buoy, the following must be delivered to the set standard:

(a) Carry out in situ repair without departing the field or dry-docking.
(b) Carry out repair that affects only the target area without functional stoppage or interruption to the production storage areas and offloading in other areas.
(c) Carry out repair without hot work, such as cutting or welding.
(d) Strategic and cost-effective repair.
(e) Carry out repair using easy-to-apply and readily/locally available technologies and personnel and.
(f) Carry out reliable repair methods backed up by a large amount of experience.

The following are the existing repair and replacement methods available for hull deck plates:

(a) Protective paint coating method
(b) Weld infill method
(c) Crop and weld or hot work method
(d) Adhesive patches method
(e) Sandwich plate system method

According to Paik and Thayamballi, (2007) if extensive areas of a floater require repair by welding, the floater must cease production, transit to a repair yard, undergo dry-docking for repair, transit back to the field and be recommissioned (Paik, 2022). Depending on the scope of work, availability of materials and resource persons, this might take several months. Although, the on-site welding repairs on small areas of a floater is usually achieved by waiting for calm weather condition and involves limited production shutdown, repair and then production restart (Andersen and and Echtermeyer, 2006). However, even small repairs may take several weeks due to uncertainties in planning. A group of researchers agreed that the best way to minimise the need for expensive on-site repairs is by building in additional structural design safety margins at the outset of construction (Paik, 2022; Andresen, 2005; Hart-Smith, 1995). The authors explained that these margins must be as large as possible and much larger than those of shuttle tanker, given their five-yearly dry docking period (Park et al., 2020). It is usually adopted for deck plates repairs in non-hazardous areas like water ballast tanks. It was reported in Paillusseau et al., (2019) that an alternative to welding-based repair methods is to use adhesive patches (McGeorge et al., 2009). Notably, these are applied without hot work and thus present no fire hazard (Paillusseau et al., 2019). For example, composite fibre–reinforced plastic patches may be bonded (Paik, 2022) or laminated over structures to bridge and reinforce corroded or cracked areas (McGeorge et al., 2009). However, such adhesive patching may not restore the lost strength (McGeorge et al., 2009; Paik and Thayamballi, 2007), and imperfectly bonded parts may accumulate cargo and gas as the case might be. Interestingly, adhesive patches may prevent corrosion-associated leakage (Andresen, 2005). According to McGeorge et al., (2009) composite patch-based repair methods have been successfully applied to service naval ships, bridges and some infrastructures, and thus such methods should be considered for remediating damage on FPSO (Paik, 2022). Appendix AD shows the repair of the corroded deck plate of the FSO Abu Cluster. (Inset shows the deck plate before repair).

Another novelty repair technology is the sandwich plate system (SPS), which consists of two metal plates bonded to a compact elastomer core (SPS, 2005). The elastomer provides continuous support to the plates, stops local plate buckling and eliminates the need for stiffeners (Paik, 2022). Notably, the

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SPS can be used to replace conventional stiffened steel plates in naval, offshore, mechanical and civil engineering structures (McGeorge et al., 2009). The SPS is also used for repair and modification (SPS, 2005), wherein the SPS overlay bonds a new top plate to an existing structure in a relatively rapid and economical process (Marsh, 2006). Paillusseau et al., (2019) proved that SPS technology is certified by several classification societies and is becoming more widely used in the new construction of barges and the repair of parallel mid-body-damaged hull parts, although the required levels of shear strength and fatigue performance remain to be achieved in routine practice (DNV, 2005). SPS was developed by SPS technology, the world's leading supplier of structural composite solutions to the offshore and maritime industries (MOG, 2023). SPS was first patented in 1996 and is a mature proven cold repair technology solution in the maritime and offshore industry market. Therefore, SPS has been in the market for about 25 years. The first accomplished project involving SPS was carried out on the P&O pride of cherbourg, a Lloyd's register classed vessel in 1999. The first cold work application was carried out in 2003 for conoco phillips FPSO Independences while on site.

The renewal of floaters steel plating normally requires hot work, such as cropping and welding (Sumpter and Kent, 2004). This can result to fire or explosion hazards, most especially if there are leaking flammable liquids or gases in close proximity (Vanlanduit et al., 2003). Although, hot work on FPSO main deck can require extensive planning and preparation, installation, and survey period (Frost, 2005). Nevertheless, depending on locations of corroded deck plates, hot work can also interfere with the normal production operation of the FPSO, which can affect its daily production capacity and revenue generation over time. However, the considerations of doing hot work on FPSO main deck can also demand additional manpower and material. A possible classification society recommended alternative is to apply cold repair methods, such as sandwich plate system (SPS), which will eliminate the need for hot work and offer several benefits over conventional techniques MOG, 2023). SPS composite repair technology for FPSO is promising, developing and gaining wide acceptance in the offshore and maritime industry (MOG, 2023; SPS, 2005). Although, the cold repair technology is constantly improving to meet the issues and demands of the maritime and offshore industry (Marsh, 2006). However, new products are being developed to enhance the performance, durability, and reliability of composite repair solutions (MOG, 2023). Figure (7) shows repair of the corroded deck plate of the FSO Abu cluster, while figure (8) represents a composite repair on FPSO main deck plate. SPS is usually adopted for deck plate repairs in hazardous areas like cargo tanks.

Figure (7): Repair of the corroded deck plate of the FSO Abu Cluster
(Source: McGeorge et al., 2009)

Figure (8): Composite repairs on FPSO main deck plate
(Source: MOG, 2023)

SPS techniques provides several advantages over traditional hot work methods for FPSO main deck repairs. Some of these advantages are:

(a) Safety - SPS repair methods eliminate the need for hot work in hazardous areas, such as those involving volatile flammable cargo, materials, liquids or gases. Thus, it reduces the risk of fire, explosion, or injury to personnel and the environment. Confine space entry requirements are minimized or completely eliminated with SPS cold work solutions as all cold repair works are carried out on the main deck without any entries into the tank.

(b) Time - SPS repairs techniques require less planning, preparation, installation, and survey time than conventional techniques. SPS can be installed while other activities are ongoing and most especially without disrupting the normal production operation of the FPSO. SPS methods also eliminates the need for tank cleaning, which can be costly and time-consuming. Interestingly, all SPS face plates and perimeter bar are all fabricated in the workshop on shore. Thus, it has reduced the schedule of the process on board.

(c) Cost - SPS repairs techniques require less labour and material than conventional methods. SPS can save up to 90 percent of labour and 56 percent of steel compared to crop and renew methods. Therefore, SPS repairs method can also reduce the maintenance and operational costs of the FPSO by extending its service life and enhancing its performance. Nevertheless, the requirement of persons on board during SPS repairs work is greatly reduced as the majority of the fabrication works are done on shore.

(d) Quality - SPS repairs techniques provide a permanent, durable, and class-approved repair that restores or improves the structural integrity and longevity of the FPSO. Although, SPS can also provide superior protection against corrosion, fatigue, impact, and blast. Therefore, SPS can provide a safe, fast, cost-effective, and high-quality alternative for FPSO main deck repairs. Interestingly, SPS is approved by all major classification societies and has been applied in over 500 projects across maritime and offshore oil and gas industries.

Most FPSO/SPM calm buoy in operations experience some level of corrosion, even when protective systems are in place (Sharp and Ersdal, 2021). Some cases investigated are due to damaged protective coatings or inadequate control of the cathodic protection voltage (Ersdal, 2014; Ersdal, 2005). Although, a thorough assessment of degree of corrosion prior to the implementation of mitigating measures is important (Si et al., 2011). Nevertheless, one possible outcome from the corrosion degree examination may be that the corroded component or area still has sufficient strength for all relevant limit states (Stacey et al., 2008). However, in the event of such cases, it will be sufficient to prevent further corrosion by cleaning, sandblasting and re-applying a protective coating (Ersdal and Selnes, 2010). Interestingly, if the corrosion degradation and deterioration is found to be more severe after survey, then a remedial measure are required. It should be noted that Bahadori (2014) reported that the offshore industry practises for corrosion breakdown, failure, degradation, deterioration and corrosion protection systems damage mitigation includes:

(a) Repair of damaged coatings
(b) Replacement of material and
(c) Repair or replacement of the corrosion protection system.

Protective coatings are used for corrosion control on floating assets such as FPSO/SPM calm buoy as they act as primary barriers that isolate the floaters hulls from the corrosive marine environment. Marine protective coatings can be applied in the ship yard, dock yard, construction yard or offshore. Nevertheless, offshore coating works is more expensive, time consuming but often less effective. Although, the typical coatings used offshore include coal tar epoxy, epoxy resins and passive fire protection (Matsuda et al., 1999). Coatings on FPSO/SPM calm buoy are mainly applied on the external hull structures. Coatings are examined as part of a surveys programme and may require repair or replacement depending on the degree of degradation and deterioration, breakdown or damage. As stated in ISO (2016) several scales exist for measuring the level of damage such as blistering, rusting, flaking or cracking which may occur with protective coatings. Ersdal (2005) published that pin point rusting or spot rusting has been implicated as one of the most common types of coating breakdown or failure, mainly due to ageing. Assessing the level of damage to a coating layer during surveys can be tough without removing the coating, which can be expensive and will require substantial remedial work (Sharp and Ersdal, 2021; ISO, 2016; Perera, 1995). According to Martins et al., (1996) coating repairs plans need to include proper cleaning of the FPSO/SPM calm buoy hulls surface for marine growth removal by using brushes or water jet. Additionally, the sandblasting of the surface is required to remove the damaged, degraded or deteriorated protective coatings and to ensure good adhesion before re-applying some protective coatings (Johnson, 1999; Lambourne and Strivens, 1999; Rolli, 1995). However, Melchers and Jiang (2006) pointed out that some protective coatings exist that can be applied manually underwater with efficient adhesion, although a good environment is required to perform the protective coating repair more effectively. Interestingly, ROV can operate and do repair works underwater but are primarily used for pipeline repairs (Sharp and Ersdal, 2021). The replacement of coatings in the splash zone of floating offshore structures has access difficulties and requires a coating to be applied to a wet surface (Craig and Anderson, 1995; Scully and Hensley, 1994). In order to obtain good quality adhesion in the splash zones, special coatings are required (Belzona 2020; ABS, 2018a). As highlighted in TSCF (1992) and TSCF (1995) coatings and anodes are also important techniques of corrosion protection for ballast tanks in floating installations life FPSO/SPM calm buoy. The degradation, deterioration, breakdown, damage or failure of these protective coatings can lead to localised corrosion and eventually loss of watertight integrity on FPSO/SPM calm buoy tanks compartments on extreme cases. Periodic and continuous surveys, followed by good planning and proper re-instalment of protective coatings in such delicate zones is an important corrosion mitigating measure.

A more comprehensive measure to corrosion degradation and deterioration is replacement of material, which may be strakes of deck plates for FPSO/SPM calm buoy when field application and usage limiting values are exceeded. This means that hull deck plate zones or strakes need to be partly or completely replaced with exact grade of new material or alternatives such as sandwich plate system (epoxy) for deck plates. According to Sharp and Ersdal (2021) the following techniques are commonly used in steel plate replacement:

(a) Insert plates
(b) Buttering and

(c) Doubler plates.

These techniques are used when zones or strakes is so severely corroded beyond the limiting minimum thickness that it is considered that complete zone or strake replacement is the most appropriate solution.

(a) Notably, insert plates for FPSO/SPM calm buoy repairs are primarily used to return the strake(s) or zone(s) to its original state. However, thicker insert plates than the original can be used to increase the plate thickness thereby obtaining a larger corrosion allowance for further operation (Sharp and Ersdal, 2021; Ersdal, 2005).
(b) Weld beads can be added to replace lost FPSO/SPM calm buoy hull deck plates material and is called buttering (Ersdal, 2014). It is considered a good option in cases where the plate strakes of reduced thickness are limited such as pitting corrosion and where corrosion is limited to zones adjacent to welds (Ersdal and Selnes, 2010).
(c) Doubler plates can be welded to a plate or member to increase thickness (Stacey et al., 2008). The introduction and consequent application of doubler plates in FPSO/SPM calm buoy hull deck plates repairs is primarily considered as a temporary measure but can occasionally be applied as permanent strengthening (Sharp and Ersdal, 2021; Belzona, 2020).

Corrosion protection systems are applicable to FPSO/SPM calm buoy by means of sacrificial anodes or ICCP systems. Sacrificial anodes are selected with an expected life proportionate with the FPSO/SPM calm buoy design life, typically 20 to 30 years. Sacrificial anodes are selected to provide the expected current demand of the system over the expected service life. As part of the survey program, the anode condition and the cathodic potential are examined. However, depending on the remaining anode material, replacement may be recommended. At extreme stage, such as the severely pitted example above, the loss of sacrificial anode material results in a less negative protection potential and therefore less efficient cathodic protection (Sharp and Ersdal, 2021). Thus at this stage, anode replacement is recommended to maintain efficient protection (Ersdal, 2014). Although, individual anodes can be replaced, but this may require considerable hours of underwater working time, usually requiring divers or ROV. The selection of a corrosion protection systems for floating facilities is carried out in such a manner that the designed life is commensurate to the offshore installation design service or operational life. Life extension processes require a thorough survey of these systems and consideration of any required mitigation or remedial works to meet the extended life. Figure (10) represents the required mechanical properties of steels grades for marine plates renewal applications.

Grade	Elastic modulus, E (GPa)	Yield stress, σ_Y (MPa)	Ultimate tensile stress, σ_T (MPa)	Fracture (failure) strain, ε_f
A B D E	≥ 200	≥ 235	400–520	≥ 0.22
AH32 DH32 EH32 FH32	≥ 200	≥ 315	440–570	≥ 0.22
AH36 DH36 EH36 FH36	≥ 200	≥ 355	490–630	≥ 0.21
AH40 DH40 EH40 FH40	≥ 200	≥ 390	510–660	≥ 0.20

Figure (10) Mechanical properties of steels grades for marine plates renewal applications.
(Source: IACS, 2017)

CONCLUSION

Every floating facility such FPSO and SPM calm buoy during transition periods from design life to end of service life undergo the initial, maturity, ageing, and terminal stages. Although, various inspections, repairs and maintenance philosophies have been put in place to help the FPSO and SPM calm buoy to serve their design life. Interestingly, the influencing of operations in marine/offshore environment will definitely make a floater to age. However, it should be noted that ageing may set in earlier if the floater is not managed and maintained correctly. For reasons of OPEX and CAPEX operators prefers extending the life of FPSO and SPM calm buoy rather than purchasing a new one. Life extension refers to using the floating facility beyond this originally defined operational design life. In a life extension feasibility studies/assessment process, the tail end comes with an operators' firm decision on further/future use is pertinent, by making a business case. The technical aspect of this decision must address questions such as if the facility is fit for. Very often, when it comes to whether to continue using a floating facility in life extension or decommission it, the answer depends on whether a combination of mitigating actions and structural refurbishment, modifications/upgrades will be sufficient to demonstrate regulatory compliance with national safety and classification society requirements/satisfaction and whether an economic case can be made for life extension.

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LIST OF ABBREVIATIONS/SYMBOL

ABS - American Bureau of Shipping
APB - Acid Producing Bacteria
BV – Bureau Veritas
CAPEX – Capital Expenditure
DNV - Det Norsk Veritas
FPSO - Floating Production, Storage and Offloading
FSO - Floating Storage and Offloading
GoG - Gulf of Guinea
HSE – Health Safety and Environment
IACS – International Association of Classification Societies
ICCP – Impressed Current Cathodic Protection
IMO – International Maritime Organisation
ISO - International Standard Organization
ISSC - International Ship and Offshore Structures Congress
MOG – MOG Technologies
NDE – Non Destructive Examination
NDT – Non Destructive Testing
OPEX – Operating Expenditure
ROV - Remotely Operated Vehicle
SPM - Single Point Mooring
SPS – Sandwich Plate System
SRB - Sulfate Reducing Bacteria
TAM – Turnaround Maintenance
TSCF – Tanker Structures Cooperative Forum
UTM – Ultrasonic Thickness Measurement