Anchor Leg System Integrity – From Design through Service Life

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This paper focuses on the authors' experience with the long-term performance of anchor leg components for floating production facilities. The paper shows that good long-term performance starts with design and is also influenced by the installation of the system, and in-service monitoring and maintenance programs. The paper also presents data on chain corrosion from anchor leg systems collected over the past twenty years. Guidelines based on the authors' experience for design, installation, and monitoring and maintenance are also provided.

INTRODUCTION

Anchor leg components are not like fine wine; they do not improve with age! Thus, it is important to recognize that anchor leg components degrade with use and exposure to the environment, and that this should be considered in the design, installation, inspection, and maintenance of the system.

The long-term, in-service performance of mooring system components is becoming increasingly important with the exponential increase in the number and complexity of floating production facilities worldwide. The trend of floating production systems being developed in deeper waters and harsher environments, coupled with longer service life requirements, make incorporating the knowledge and understanding of long-term anchor leg component performance in the design and maintenance of future systems even more important. This paper provides some insight into the design and specification of anchor leg components from the fairlead to the anchor based on the authors' experience with the long-term performance of these systems.

The industry has a lot of experience with the long-term performance of mooring systems due to the use of these components for permanent mooring systems for over 30 years. However, until recently, data on anchor leg component performance has not been readily available to the industry as a whole. The Mooring Integrity Joint Industry Project (JIP) has allowed the collection of data from various sources to be presented in the public domain (Brown et al., 2005, HSE Report 444, 2006). The data collected demonstrates the degradation of anchor leg components over time and provides insight into where improved design methodology and details can improve the long-term performance. The data also shows that anchor leg failures tend to occur in regions of highly dynamic behavior, (i.e., at or near the fairlead, at the interfaces with other components [mooring support buoys, subsea connectors], and the touchdown area). The data also shows that connector design, especially devices to prevent rotation or disassembly, is not robust enough in many cases to provide the desired long-term performance. It is important to note that the majority of permanent mooring systems have performed well and have good long-term performance of the anchor leg components beyond expected wear and corrosion. This paper's intent is to learn from the existing systems and provide some guidance on improving long-term performance of future permanent mooring systems.

The paper focuses on permanent mooring systems which typically have a service life from about 10 years to over 30. For permanent mooring systems, the anchor leg systems are designed by code to ensure sufficient ultimate strength, fatigue life, and corrosion and wear allowance for the service life. However, the paper shows that other factors in engineering design, system dynamics, installation, and maintenance also play a role in the integrity of the system over time.

Given that the mooring system is underwater, it does not lend itself to monitoring and maintenance like other offshore equipment. The system is very dynamic and instrumenting the system for the long term has its share of challenges. The industry and class requirements for monitoring and inspection of mooring systems has not been very specific and in many cases not much is done until there is evidence of an actual failure. With the increasing database on permanent moorings, and as operators begin to gain long-term experience; we have seen changes in mooring system monitoring and maintenance requirements. Past guidelines for anchor leg components were based on inspection criteria for MODUs that was not directly applicable to permanent mooring systems as the guidance assumed that components would be retrieved for inspection. In the latest edition of the API RP 2I (2008) there is a section dedicated to permanent mooring system inspection that provides good information that can be used to develop an inspection and maintenance program. In general, inspection programs focus on both overall anchor leg performance (anchor leg configuration, load sharing between members in a group, etc.) and detailed inspection of connectors and components to monitor their current condition.

Anchor leg monitoring systems have been used in the past and are still specified, but have a history of poor reliability over the long term. Most monitoring systems measure anchor leg tension by instrumenting a component in the load path, while others monitor fairlead angle using inclinometers. Tension measurements are used routinely in MODUs; however, these systems use the tension measurements to make adjustments to the anchor leg system depending on offset requirements or storm conditions. A permanent mooring system in most cases is designed to not require any adjustments for storms and thus is not always supported by winches. Monitoring systems can also be used to provide line break detection. The problem with the low reliability is that one could expect a large number of false alarms that then cause the system to be ignored. However, based on the specific mooring system characteristics for a floater, one could incorporate a means of monitoring the system that is more robust than direct tension measurement. It is important to recognize that monitoring is just one means of detecting changes in the anchor leg system, and it does not replace good engineering design, inspection programs, or recommended maintenance.

GENERAL COMMENTS ON PERMANENT MOORING SYSTEMS

Permanent mooring systems for Floating Production Systems have been in service since the early 1980s in shallow water. By the mid-1990s, systems were being installed in water depths of around 1,000 meters. Currently we are seeing systems being installed in 2,500+ meter water depths. The focus on mooring integrity and maintenance is primarily due to the criticality of mooring system reliability to continued production on the floating production system. Past experience has shown that anchor leg damage or failure has led to long periods of downtime and lost production that have been very expensive for the operators.

Most of the anchor leg component performance data collected to date is based on shallow and intermediate depth mooring systems that have been in operation for a long duration, with some data from some of the earlier deepwater systems. The characteristics of a shallow water mooring system are very different from a deepwater system and it is important to recognize the general differences between the two.

Shallow water systems use very heavy components that may have a minimum break strength (MBS) well above the required minimum factor of safety, as weight is used to provide the desired stationkeeping performance (based on geometric stiffness). This is especially true for the early mooring systems that were all chain of one nominal size. A large portion of the anchor leg lies on the seabed and is activated as the vessel offset increases. It is also common to include a long length of ground wire on the seabed in conjunction with heavy chain through the touchdown region, as wire provides much more axial elasticity than chain. These systems have a low pretension compared to the MBS and in general their performance has been quite good (aside from corrosion of the chain and wear at regions of high dynamic loading [fairlead and touchdown point]). As shallow water systems moved into regions of harsher environment or shallower water, the anchor leg systems were optimized to include heavy weighted sections at the touchdown point, most commonly using clump weights or draped chains connected by shackles. Experience has shown that these systems, though having a lower initial cost, have had issues with reliability due to failure of the clump weight/weight chain connectors, resulting in loss of stationkeeping performance (addressed in a later section of this paper). A shallow water mooring system can require tight installation tolerances; however, the actual installation of the mooring system may involve low-specification vessels and the installation engineering may not be rigorous, so an accurate as-built mooring system inspection is very important to ensure that the mooring system was installed as designed. Inspection is easier to perform and has been performed subsea with divers and/or ROVs.

Shallow water floating systems are complex to analyze, the low-frequency dynamics can be very large, and mean wave and current forces can be much larger than in deep water due to the influence of the seabed, low system damping, etc. (Duggal et al, 2004). Small variations in input conditions and dynamic response can lead to large changes in anchor leg loads. As we continue to optimize anchor leg systems based on multiple dynamic analyses and cost (minimum factor of safety), we run the risk of having a less reliable anchor leg system than what was designed more conservatively in the past. This opens up the controversial debate on whether the same factors of safety should be used for a harsh environment dynamic system compared to a mild environment system with relatively small dynamic response.

Deep and ultra-deep water mooring systems tend to be designed as taut-leg or semi taut-leg systems and the offset is maintained by both the axial and geometric stiffness. The anchor legs are also optimized to provide this restoring force for minimal weight. Steel wire or polyester rope comprises most of the suspended portion of the anchor leg. Chain is commonly used as the interface between the floater and the rope and also at the seabed. It is also becoming increasingly common to include a subsea connector in the lower chain portion to allow ease of installation and possible future replacement. Based on the floater and riser system, the stationkeeping requirement for the mooring system may be quite tight, resulting in anchor legs with high pretension as a percentage of MBS. This high pretension has been shown to cause additional bending and torsional stresses in the chain links at the fairlead (Jean, P. et al., 2005).

Deep and ultra-deep water mooring leg installation typically requires higher-specification vessels and detailed engineering to ensure that the anchor legs are properly installed. Position tolerances can be higher due to the water depth and the deep water can also result in additional twist being introduced into the anchor leg system. Monitoring of the installation is also more difficult and there is an increased risk of damage to mooring components during simultaneous or future operations (e.g. riser pull-in) due to the large water column and the difficulty in monitoring the pull-in system lines and the anchor legs. There have been several instances in the industry where sheathed spiral strand and polyester rope has been damaged while retrieving installation equipment or pulling in risers. Inspection of the anchor leg system is commonly performed by ROV. In general, deepwater anchor leg systems can be simpler in their design, though the number of connections may vary due to installation limitations.

The low-frequency response of most deepwater systems is much less “dynamic” than shallow water systems due to the large amount of damping from the mooring lines and risers and the much lower natural period. Dynamic variations about the mean are typically less than that for shallow water systems and estimated variations are less. However, current industry experience has highlighted differences in anchor leg component performance with a few fatigue related failures in the past 10 years, focused at the fixed terminations of the anchor leg at the fairlead and the anchor. Figure 1 provides a comparison between shallow and deepwater mooring systems for an FPSO system.

In the end we recommend the mooring designer to use good engineering judgment in selecting the components for an anchor leg system, keeping in mind the variations in response and loading from their analysis rather than solely relying on simplistic design criteria provided by most industry guidelines. The discussion in the following sections provides some guidelines that help in making these judgments.

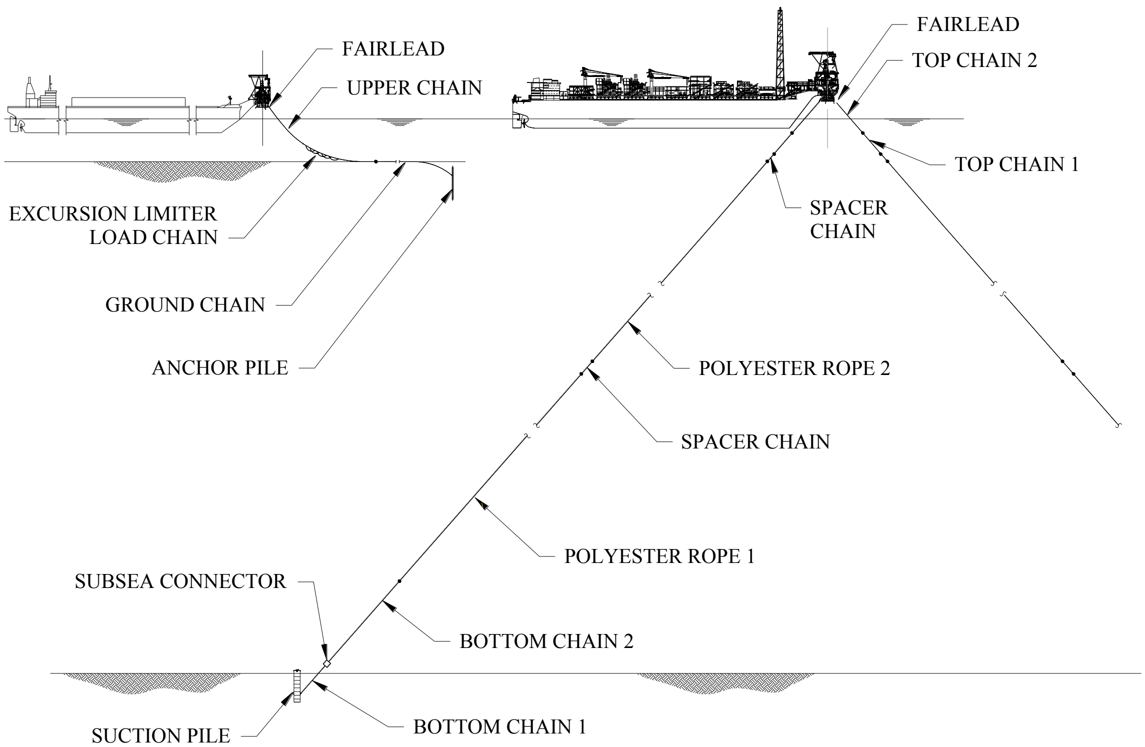

Fig. 1: Typical shallow (left) and deep water (right) mooring systems

CORROSION AND DEGRADATION OF ANCHOR LEG COMPONENTS

Chain

Chain corrosion is inevitable, given the nature of the material and the harsh environment in which it is deployed. Since chain is typically not coated or protected, it is subject to general corrosion as would be expected for any bare steel structure. This lack of protection is typically accounted for in design by imposing a wear and corrosion allowance on the chain with some variation of the allowance depending on the design code and the location of the chain with respect to the water surface and the seabed. In addition to corrosion, wear between links can also be an issue when the relative motions between links exceed 0.5 degrees (depending on tension level) or when the chain is in dynamic contact with a hard surface either at the fairlead or the seabed.

Typical requirements for wear and corrosion vary between industry guidelines and design codes and can range from 0.2 mm/year to 0.8 mm/year depending on whether the chain is in an almost static position on the seabed versus in the active splash zone area. This corrosion and wear allowance is generally applied to the new chain component size and assumes a uniform reduction in bar diameter and thus minimum break strength. While this may approximate the break strength of the corroded chain, the impact on fatigue life is typically not addressed other than the impact of scaling of fatigue loads with corroded break strength; i.e. the stress concentration factors are unchanged.

Depending on the type of corrosion, e.g., pitting corrosion versus general corrosion and the location of the corrosion on a link, one could expect the stress concentration factors to be different from those derived from a pure tensile loading and the corrosion could possibly initiate cracks that would accelerate fatigue at that location. The authors are unaware of any test data on the fatigue life of corroded chain to see if the typically adopted methodology provides a robust estimate of fatigue life.

Fig. 2 is a photograph of the top portion of an anchor leg on an external turret mooring system that has been in service for 15 years. The figure illustrates the type of corrosion one could expect with a higher level of corrosion near the splashzone.

Figures 3 to 5 present chain diameter measurements for three FPSO mooring systems (5, 8, and 15 years in service) that have either an external turret mooring or a spread mooring system with deck-based fairleads in tropical and sub-tropical waters. For all of the measurements, the links were cleaned of all corroded material and chain diameter measurements were made at three general locations: (a) near the chain stopper (i.e, fairlead), (b) midway to the water line, and (c) just above the water line (splash zone). Figures 3 and 4 give the average chain diameter (Grade ORQ+20%) calculated from measurements made on the chain body (two perpendicular axes were measured) and can be considered an estimate of corrosion only. Fig. 5 gives average grip section chain diameter measurements (Grade 3) calculated by dividing the two diameter grip measurement by two to provide the average diameter. This estimate can be considered to include both corrosion and wear. For all cases no as-built chain dimensions were available and thus the horizontal lines representing corrosion rate is based on the nominal chain diameter.

Typically, chain is manufactured from bar stock that is greater than the nominal chain diameter (by a few millimeters depending on chain size) and after bending and proof loading, the bar at the grips is ovalized with a diameter that could be as much as 4mm less than the nominal chain diameter (for d > 122mm) so long as the cross sectional area does not have a negative tolerance. Thus the variations in as-built link geometry can result in errors in predicting corrosion rates. Comparing field measurements with the nominal chain diameter can possibly result in underpredicting the corrosion of the chain body while overestimating the corrosion of the grip section. Thus it is important to make baseline measurements of the as-built chain and use the same procedure to measure the chain diameter during every inspection.

The data in Figures 3 through 5 shows that the corrosion rate of chain in the splash zone can be close to 1 mm/year (more in line with the ISO 19901-7 (2005) guideline of 0.8mm/year) which is much greater than the 0.4 mm/year recommended in the API RP 2SK (2005). For systems with submerged fairleads (and chain terminations), corrosion is observed to be less, and although the number of observations and measurements are limited, a corrosion allowance of 0.4mm/year seems appropriate.

Fig. 2: Variation in corrosion damage from the splash zone to the in-air zone after 15 years in a tropical environment

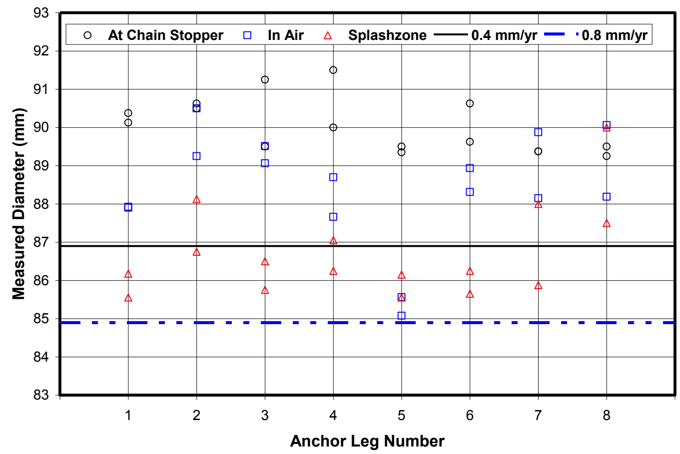

Fig. 3: Average chain diameter measurements after 5 years of service (FPSO 1, tropical)

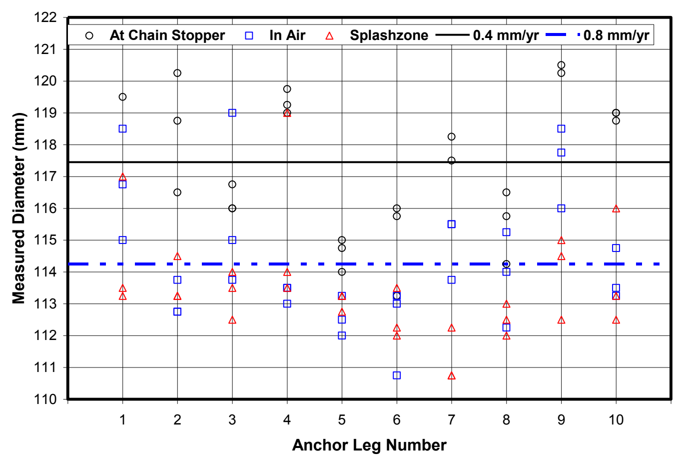

Fig. 4: Average chain diameter measurements after 8 years of service (FPSO 2, sub-tropical)

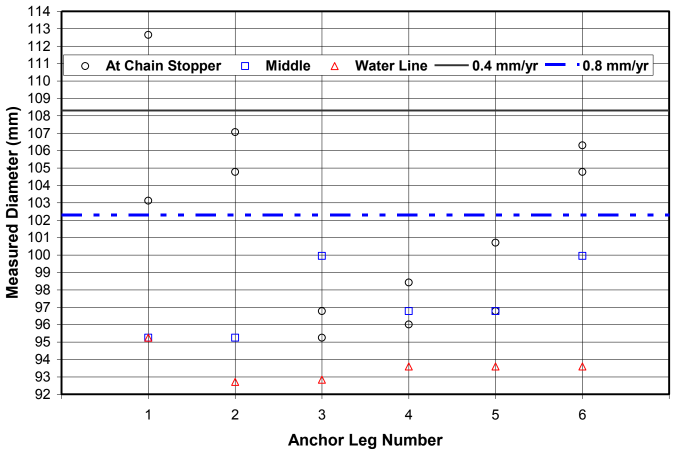

Fig. 5: Average grip section chain diameter measurements after 15 years of service (FPSO 3, tropical)

Fig. **6** shows chain and wire rope recovered from an installation that had been in service for 10 years where the measured corrosion rate on the chain was less than 0.4 mm/year.

Fig. 6: Chain submerged for 10 years in a sub-tropical environment

Note that recently, coatings have been applied to chain segments with some success – a ceramic coating like Ceramkote that is used in other offshore applications and a thermal sprayed aluminum coating. The coatings need to be applied manually and they are expensive (order of magnitude of bare chain cost depending on size). In addition they can be damaged during handling or installation. This approach may provide value where coating the chain in the splash zone or in the air may provide additional protection from corrosion and provide longer service life, but there is not sufficient field data to demonstrate this at this time. An alternative to designing the chain elements to last the entire service life is to engineer the ability to change out segments of top chain as a maintenance operation when the level of corrosion exceeds a pre-determined level. Top chain change-out is typically considered once the chains reach a level of corrosion like the chain shown in Fig. 2.

Connectors

In terms of connectors (shackles, H-links, triplates, etc.), the corrosion performance is similar to that of chain, unless the connector is coated and provided with cathodic protection (most commonly used on triplates). A higher corrosion rate is possible if the connector is made of a number of dissimilar components or from a very different material compared to the chain. One major issue is that there is no specific industry guideline that addresses all aspects of connector design – there is now a strong focus on material and mechanical properties specified in chain manufacturing specifications, but design principles for the various components are not properly captured. There is a long history of performance, especially in MODUs, of standard components, e.g. shackles, used in "standard" applications (ISO 1704, 1991) performing as designed. However, when used in permanent mooring applications, these standard components may not be used in a typical way and thus may not perform as expected. One important design feature that does not get the attention it deserves is the mechanical devices used to maintain the pin in position (anti-rotation and pin retaining hardware). Typical designs use a nut on the pin that is retained with a cotter pin. Cotter pins can be either mild steel (as used in temporary applications) or stainless steel as currently specified in many long-term applications, but the design and implementation of these devices is not rigorous and many inspections have shown that in some cases the cotter pins have corroded or failed. Additional details on improved connector design and consequences of failure are addressed in a later section.

Fig. 7 is a photograph of a triplate with spelter socket on one end and a shackle on the other that was recovered from a mooring system (same as Fig. **6**) deployed for 10 years. The photograph shows that the condition of all connecting components is excellent and that the anode on the triplate is not completely consumed. This mooring system had a 10 year design life. All retaining equipment on the connectors is in good condition.

Fig. 7: Triplate with connectors after 10 years in service.

Wire Rope

Two constructions of wire rope are used for permanent mooring – six strand and spiral strand constructions. Six-strand construction is typically used in applications with short design lives (less than 8 or 10 years) while spiral strand construction is designed to be used in applications from 10 to 30 years (depending on the level of corrosion protection).

Six strand wire is traditionally used due to its low elastic stiffness, cost, and ease of handling. The disadvantages are low service life (the individual wires are galvanized, providing corrosion protection for about 8 years) and due to its construction it rotates under load. This construction-induced rotation can induce permanent twist into the anchor leg system, and changes in tension can induce cycles of rotation, resulting in torsional loading of the chain that could result in undesired stresses and a reduction of the estimated fatigue life.

Spiral strand wire is supplied either unsheathed or sheathed with a service life ranging from 10 to 30 years, respectively. Tests of unsheathed wire rope in laboratory conditions shows that the combination of blocking compounds and galvanized or Galfan coated wires provide the stated design life, but experience has also shown that in actual applications wire ropes may degrade faster than expected, especially in tropical waters. This is true for the wire rope segment that is suspended in the water column. Our experience with wire rope used as a ground wire on the seabed, from the few wire ropes we have retrieved, is that corrosion is minimal.

Unsheathed spiral strand wire requires care during installation; re-spooling the wire rope from a shipping reel onto an installation reel, deploying it over a stern roller, or using grippers to support the wire during deployment can cause “gaps” in the construction that can in extreme cases result in “loose” wires at the socket. In addition, careful handling of the socket during installation is important and imparting twist in the wire can result in the construction “opening up” or birdcaging. Though this in itself may not be a concern, as the wires can be coaxed back into position, this highlights a possible issue if the termination is subject to bending or torsion due to twist imparted in the anchor leg during installation, or motions of the terminations at mooring support buoys or fairleads. We have seen cases in the field where wires near the socket continue to break and are corroded almost to the center of the wire rope. However, 20 meters away from the socket the condition of the rope can be like new. Note that this experience was for unsheathed wire with no bend stiffener at the socket, and thus any bending at the socket resulted in localized bending at the wire-socket interface, accelerating the damage in the area. Currently, most wire rope suppliers provide a bend stiffener with defined characteristics and the opportunity exists to specify a particular bend stiffener, similar to that for a riser or umbilical. The spelter socket was connected to a submerged mooring support buoy that may have caused both torsion and bending at the termination.

Typically, wire rope segments are electrically isolated from the connecting components using Orkot or equivalent bushings and washers. The spelter sockets are coated and the wire terminations are made such that there is electrical isolation between the wires and the socket. Thus the anode provided with the socket is designed primarily to provide protection for the socket. It is our experience from surveys and from recovered wire rope that these anodes are depleted much faster than expected, even if the socket coatings are in good condition. In a recovered mooring the connecting triplate, which was electrically isolated, still had anodes with more than 75% of the design life remaining, so this may imply that the socket anodes were being consumed through the wires. This again indicates accelerated corrosion of the wire but the cause is not well understood. The concern from a mooring integrity perspective is that inspection of the wire’s condition at the socket or in the bend stiffener is very difficult and possibly cannot be determined. Fig. 8 presents a figure of a spiral strand rope and socket recovered after 10 years of service. Note the opening of the outer strands and the corrosion on the lower layer. The anodes in the spelters were completely consumed.

Fig. 8: Wire rope and socket recovered after 10 years of service.

Sheathed spiral strand wire has a polyurethane sheathing typically ranging from 9mm to 12mm thick, which is vacuum extruded onto the wire rope. This results in a wire rope construction that can be designed for a life of up to 30 years. The sheathing at the socket has a watertight seal. Individual wires are galvanized so corrosion protection of a damaged rope is still available until the damage can be repaired or the wire rope replaced. A major advantage that we see with sheathed spiral strand rope is that the sheathing maintains the rope construction, and the manufacturer’s limits for tension and bending during installation favors the sheathed spiral strand rope over unsheathed. However, handling of sheathed wire rope is important and the use of wire grippers to install it in deep water can cause the sheathing to slip on the wire rope, impacting the integrity of the system. The sheathing can also be provided with both a line over the length of the rope for twist monitoring, and also markings of wire rope length, both of which are useful for installation purposes.

Polyester Rope

Polyester rope has been used for deepwater mooring systems for about 15 years. The long-term performance of polyester rope has been excellent as long as the rope was not damaged during installation or during its service life. Experience has shown that polyester rope is easily damaged during installation and it is common to always include a spare polyester rope segment while the system is being installed to ensure that the installation can go on while rope damage is being evaluated.

Polyester rope retrieved from service has not shown significant degradation of strength or any form of "corrosion." Concerns with polyester rope deployment have always been associated with exposure to sunlight, marine growth and soil particle ingress that could cause abrasion between fibers. Polyester rope is used in the suspended section of the anchor leg due to its low weight and high elasticity and it is typically placed below the hard marine growth zone (70 to 100 meters) and above the sea floor to ensure minimal touchdown on the seabed. Polyester rope is commonly provided with a soil barrier (5 micron filter cloth) between the jacket and the core that has proven to be very effective, as demonstrated in rope recovered after Hurricane Rita in the Gulf of Mexico where the rope was dragged several miles through the soil and as demonstrated by actual laboratory tests with soil and rope segments. This has allowed the pre-installation of polyester rope on the seabed for permanent mooring systems (DeAndrade and Duggal, 2010). In addition, properly qualified rope splices have not shown any degradation over time, and the overall fatigue life is very high, resulting in excellent long-term performance as an anchor leg component.

DESIGN ASPECTS

This section of the paper focuses on design aspects for an anchor leg system based on the experience of the authors and the permanent mooring industry. The discussion focuses on some lessons learned from existing systems and possible improvements to current industry standards. This discussion is by no means comprehensive but does try to capture some key design issues that can impact the mooring system integrity.

The paper indicates that there are two main drivers for anchor leg integrity – (a) general component degradation due to wear and corrosion and (b) improper or poor design and installation of the entire anchor leg system. To improve anchor leg system integrity we need to properly account for the general degradation and to improve the design and installation of these systems based on these findings.

Since an anchor leg system is composed of several different components, it is important that the complete assembly is designed to perform as required. Therefore all interfaces between components, locations of connections, and material characteristics must be considered, from a global design perspective:

- Ensure a robust design by considering all input data including metocean, floater characteristics, etc. When developing environmental load cases consider the quality of the metocean data set and adjust conservatism based on that. For example, there have been many instances of metocean data sets developed for fixed jacket structures being supplied for the design of floating systems where joint distribution information on wind, wave, and current intensity and direction is not provided, which can be important for FPSO systems. Consider the variations in extreme responses when determining factors of safety based on the most probable response as discussed earlier.
- Consider a two-leg damaged case in addition to the traditional 1-leg damaged case in the mooring design. This will result in a more robust mooring system in the intact condition. This approach is being taken by some operators for floaters with long design lives.
- Keep the anchor leg assembly simple, i.e., minimize the number of components and connections.
- Keep connectors out of the active dynamic zone as much as possible. When connectors have to be used, ensure that the mechanical assembly is robust enough to withstand constant motion and impact for the service life.
- Review design of existing systems with similar anchor leg systems and utilize lessons learned.

In addition to the above, some additional design guidance for the various components is presented below:

Fairleads

Anchor legs are terminated at the floater using some type of fairlead. Fairlead type varies from single axis chain supports to multi-axis chain stopper fairleads depending on requirements, preference, application, and ease of handling and installation using floater-based installation equipment. The fairlead should allow for easy adjustment and support the chain using a self-ratcheting stopper. In some cases wire or chain segments are directly connected to the fairlead, which does not allow for easy adjustment.

The fairlead is an extremely important interface on the anchor leg system as it is one of the regions of high dynamic activity of the anchor leg and the behavior of the fairlead can have a large impact on the top end of the anchor leg. Traditionally, these two systems were designed and specified independently and the same assumptions on behavior may not have been considered at the interface. This has lead to issues with wear, corrosion, and fatigue of the top end of the anchor leg. Listed below are some aspects of the design of a fairlead that can allow for improvement of the overall reliability.

- Design of the fairlead impacts the long-term wear and fatigue performance of the chain at the fairlead. Traditional anchor leg fatigue analysis is based on tension-tension fatigue testing and although it is applicable to the majority of the anchor leg, it may not accurately represent the actual loading at the links that are supported at the fairlead. Depending on how the chain is supported at the fairlead, the SCF along the chain link can be very different than that assumed in the commonly used tension-tension fatigue curves. For example, when designing a mooring system where the chain passes over a chain wheel under load, an additional SCF of the chain on the chain wheel must be included in the chain tension-tension fatigue analysis (Vargas, et al. 2004). It is very important for the mooring designer to have knowledge of the type of fairlead being specified so the appropriate SCF can be included when performing the fatigue analysis to confirm the size of the top chain. It is important to include in the fairlead specification a requirement for the fairlead manufacturer to calculate or confirm this additional chain SCF to account for the chain being tensioned over the chain wheel in addition to break-out torque characteristics as a function of load, etc.

- ***Out of Plane Bending:*** Rotating chain fairleads have a breakout torque based on the friction at the bushing and the length of the lever arm. This break-out torque is applied as a bending moment in the chain links at the fairlead. All angle variations between the mooring leg and the fairlead introduce bending moments (and bending stresses) into the chain links up to the moment required to overcome the fairlead breakout torque. The bending stress induced into the chain link is a function of the mooring leg pretension and the angle variation, so the higher the pretension, the higher the bending moment. This is especially true for deepwater mooring systems with tight offset requirements; the pretension in these anchor legs is high (as a percentage of MBS) compared to shallow water systems where most of the past experience on fairlead performance is based.
- Fairlead design to minimize breakout torque is especially important in environments where the average wave environment is large compared to the design survival environment, such as in West Africa. This is typically accomplished by increasing the lever arm (or hawse pipe) between bushings and the chain reaction point.
- Consider using a larger top chain size than the minimum required to ensure additional margin in the top chain and to ensure some margin to account for differences between the assumed and actual performance of the fairlead (SCF and break-out torque).
- Protect the chain from wear by making surfaces contacting the chain softer than the chain. 75 BHN softer than the chain is usually preferred. Also, position the chain at the exits of hawse pipes such that it does not rub against the hawse pipe to trumpet weld.
- Submerged fairleads must be electrically connected with the vessel and emerged fairleads should be electrically isolated from the vessel. Electrically isolating submerged fairleads will result in excessive corrosion of the fairlead as the fairlead will serve as the anode for the chain. Experience has shown that the DNV recommendation to include 30 meters of chain per mooring leg in the cathodic protection system design is valid when the chain is electrically connected to the vessel.

Chain

The previous sections have provided some background on the long-term performance of chain in a permanent mooring system. Chain has the lowest fatigue resistance of all standard permanent mooring components and thus anything that impacts the fatigue resistance of the chain is important. Thus, designers must properly consider all sources of fatigue loading on the chain to ensure long-term performance.

- As discussed above, it is important to consider the influence of the fairlead on the stresses at the links near the interface. This is also true for all regions of the chain that are not in "pure" tension and either come in contact with hard surfaces or impact solid bodies. Perform finite element analysis using proof-loaded "as-built" chain link geometry (rather than theoretical dimensions) to determine SCFs whenever mooring components are not in pure tension. This is also true for chain supported on bending shoes or other structures.
- Use ISO 19901-7 (2005) guidelines for sizing chain for corrosion and wear, as experience indicates that the API RP 2SK (2005) requirements do not adequately address chain corrosion in the splashzone.
- Utilize a larger top chain size than the minimum required for design loads (or along the rest of the anchor leg). This is sometimes specified in Functional Specifications (typically 15%) and the authors believe it provides an additional level of conservatism in the design, as differences between the fairlead and chain behavior assumed in design and practice can be very different and the consequences can be very high. This also provides additional allowance for corrosion and wear in the upper chain area in general.
- An advantage of an easily adjustable chain stopper is that the design could incorporate a procedure for making small adjustments to the anchor leg over time to ensure that the links at the fairlead interface are shifted every few years, ensuring that damage is not concentrated on one or two critical links. This is easier to implement in deepwater given the length of the catenary and is almost "built-in" for systems with polyester rope segments as the change in length due to creep and construction elongation typically requires top chain adjustment over time.
- The use of coatings like Ceramkote or Thermal Sprayed Aluminum may provide additional corrosion protection to the chain and connectors in the regions of high corrosion. This approach has been utilized on a few systems but the long-term performance of these coatings is not known for this application.
- Consider designing the anchor leg system where a section of the top chain is replaced once corrosion/wear reaches a predetermined level. This may provide the desired reliability/performance for long service life (over 15 years). As discussed in the corrosion section, corrosion allowance

provides for reduced MBS but may not properly account for the impact of corrosion on fatigue, especially when considering the impact of localized or pitting corrosion.

- In shallow water systems that require heavy sections of chain at the touch down location, the use of draped chain connected with shackles, or clump weights on a main chain, is prone to failure or disassembly due to the dynamic loading. Clump weights can also place high stresses into the links supporting the clump weight and produce large relative motions between the links supporting the clump weight and the neighboring links, resulting in wear. If a heavy section of chain is required, use the largest chain size available or consider parallel chains connected to triplates with shackles located out of the touchdown zone. Fig. 9 is a photograph of an anchor leg with draped chain where the round pin shackle provided with anti-rotation and pin retaining mechanisms disassembled after 5 years in service.

Fig. 9: Disassembled shackle from draped chain in touchdown zone.

Connectors

No unique industry or class society specification has been developed for the manufacture and design of connectors for permanent mooring systems. They currently focus on material properties and manufacturing processes but do not provide clear guidance on the design of retention hardware, etc. In principle, a mooring designer wants a connector that behaves like a welded chain link but is easily assembled and disassembled, and in many cases the design is almost the same for lifting applications as for permanent moorings. This can be fine for applications where the connector is always in tension, does not impact other objects and has very little relative motion with adjacent components. However, when used in a dynamic region with large motions, the easy to assemble connector can disassemble over its service life. Field experience shows this is one of the major causes of anchor leg failure.

- Connectors should be manufactured from the same material as the chain to prevent the connector from becoming an anode for the chain. A connector made from a material that is anodic to the mooring chain will quickly corrode away due to the large difference in area between the connector and the chain. Anodes can be used to cathodically protect connectors that are electrically isolated from the rest of the mooring leg but the anodes will be quickly consumed if the connector is not isolated.
- Connectors should preferably be located outside of regions of high relative motions; for example, the touchdown location. Large relative motions can cause rotation of round pins and can also damage the pin-retaining devices, which can cause the nut to back-off and the anti-rotation device to disengage. Oval or wedge shaped pins should definitely be used in this application to prevent pin rotation.
- Shackle and H-link pins should preferably be wedge shaped pins. Wedge shaped pins prevent rotation of pin in the body. All round pin shackles must have very robust anti-rotation and pin retaining devices.
- Care should be taken to ensure a robust pin retaining system. Typical shackle and H-link pins are retained using a nut and a cotter pin. For round pins, the combination of the anti-rotation device design and the pin-retaining device need to be integrated. The cotter pin must be located very close to the nut to ensure that if nut / pin gets loose, the round pin cannot shift such that anti-rotation device is not engaged. If this is the case, large motions can result in the nut being forced against the cotter pin, which may fail if it is not adequately designed. For long-term mooring, stainless steel cotter pins are preferred, but they can crack when bent more than once, so a full set of spare cotter pins is necessary if you are shipping the connectors with the cotter pins installed. Mild steel cotter pins are commonly used for lifting shackles but they do not last long (due to corrosion) and can fail if the nut backs off, so they should not be used for permanent moorings (but are commonly supplied). Cotter pins can be misplaced during shipping and installers may use other components such as mild steel pins, welding rods, etc. An alternative to the cotter pin design is to use a large stainless steel bolt with a Nyloc nut (to prevent it backing off) through a hole drilled through the nut and pin as shown in Fig. 10.
- H-links can be preferred over shackles, especially when connecting common links (when a large amount of chain adjustment is necessary) or components with very different pin size requirements. There is some debate in the industry on whether H-links are a superior connector to shackles, but the authors believe that with proper design and manufacturing control, shackles can be designed to be fit for purpose, and they have a long history of acceptable performance in permanent moorings when used correctly. An H-link consists of two pins and associated retaining devices, so one could argue that they are inherently less reliable as they require two connections for every one with a shackle. However, again if properly designed and used, they perform well.
- Tensile and impact testing should be performed on shackles and other mooring accessories in every zone that is processed differently. For example, a cast component would only need to be tested in one location whereas a shackle formed from bar stock may need to be tested in three locations: Straight Section (original rolled bar diameter),

Crown (bent bar) and Palms (upset forged), as each section is produced by a different forming process.

- Shackle manufacturers should perform mechanical and toughness tests of the break load test samples and compare the results to the proof load tested links to develop a database of the effect of the break testing load on the mechanical properties, so eventually the number of sacrificial shackles is reduced.

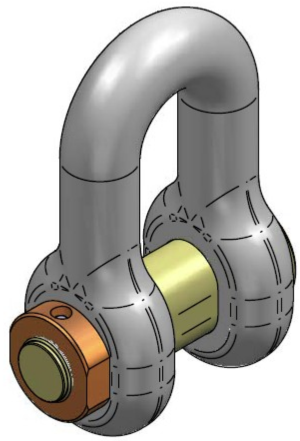

Fig. 10: Illustration of oval pin shackle with drilled nut for Nyloc bolt.

Wire Rope

Wire rope is commonly used in intermediate and deep water systems in the suspended catenary of the anchor leg and as a ground wire in shallow water systems. As discussed earlier, six-strand and unsheathed spiral strand ropes are susceptible to corrosion in the water column and should not be used beyond their recommended service life, e.g., as part of a life extension. Inspection of unsheathed wire rope is difficult, especially in the termination area, as it is not possible to determine the condition of the rope under the outer layer. Unsheathed wire on the seabed seems to be less susceptible to corrosion based on the authors' experience with after-recovery inspections of existing anchor leg systems.

- Six-strand wire rope has good handling characteristics but as it rotates under load it can induce twist into the anchor leg system both during installation (e.g., during drag anchor installation) and while in service. This can result in twist in the anchor chain that, depending on the application and the loading, can affect the design life of the chain. When properly installed it is very effective as a ground wire for shallow water systems.
- Unsheathed spiral strand wire can be easily damaged during handling and installation, as discussed in an earlier section, and can birdcage if twisted. Sheathed spiral strand rope can be easier to handle and install as long as the necessary precautions are taken to protect the sheathing. The markings on the rope are useful installation and survey tools to monitor twist. One recommendation is to consider sheathed spiral strand rope over unsheathed, especially if the field life is close to the service life of the unsheathed rope to allow for possible life extension.
- Care should be taken in designing the connection and rotation interfaces between spiral strand rope and mooring support buoys, as the buoys can introduce dynamic motions (bending and twisting) that could affect the integrity of the wire rope.
- The bend stiffener characteristics should be evaluated based on the tension and bending at the interface both during service and installation.

Polyester Rope

Polyester rope has now been used in permanent mooring systems for over 15 years and has been an enabling technology for extending mooring design to ultra-deepwater. Polyester, as a material and mooring component, has been studied extensively by the industry and all major class societies. Industry groups like API have issued various design guidelines and detailed manufacturing and testing procedures to ensure suitability for offshore mooring (API RP 2SM, 2001; ISO 18692, 2007). These guidelines are currently in the process of being updated with new information and refined design and installation guidance. This paper will not attempt to capture all these details.

As mentioned in the previous section, polyester has developed an excellent track record for long-term performance, other than for its susceptibility to damage by contact with sharp or abrasive objects. This requires well-defined installation equipment and procedures, and awareness of the polyester mooring catenaries in the water column once the system is operating through its design life to ensure no interference during rig moves, pull-in of additional risers, dropped objects, etc.

From a mooring design perspective there are major differences when it comes to representing polyester mooring ropes in analysis software compared to chain and wire mooring components. Polyester rope has a non-linear axial stiffness that can be represented as a function of the mean load, load amplitude, and frequency of loading (Del Vecchio, 1992). In addition, polyester fiber exhibits creep, and once a new rope is worked, the subropes and fibers "bed-in", resulting in a change of rope length as a function of load. This increase in length from a new rope to a fully worked rope can be as much as 4 to 5%, which can be significant when polyester ropes are used in deepwater moorings. This behavior needs to be well understood since it plays a major role in the overall performance of the mooring system.

Due to the dependence of the rope length and stiffness on the load history and the specific dynamic loading on the system, it is important that the designer understand the overall response of the floater system being analyzed before selecting the appropriate stiffness and length values for the polyester rope modeling. This implies that both the floater and the design environmental criteria can have an influence on the actual design "stiffness" of the rope.

Installation Aspects

The installation of the mooring system can have an impact on the long-term performance of the mooring system – especially ensuring that the mooring is installed in a manner that is consistent with its design basis. This is a two-edged sword, as the mooring system must also be designed to ensure it can be efficiently installed and that appropriate installation tolerances are considered.

- Accurate measurement of anchor leg component lengths, weights and stiffnesses (as-built) are very useful for installation purposes and the final adjustment of the anchor leg system. In addition, actual measurement of chain diameters and grip dimensions can provide a baseline for chain corrosion measurements. In shallow water moorings, fairlead angle measurements can be used to ensure proper pre-tension and load sharing, but in deepwater moorings, fairlead angles are less sensitive and tension measurement may not be accurate (due to friction in the load path, low end of the measurement range of the load cell, etc.). In deep water moorings, monitoring vessel position and a well defined point in the catenary (say the shackle between top chain and wire) can result in more accurate feedback on anchor leg configuration and load sharing between legs.
- The impact of installation on spiral strand wire rope construction is lower for sheathed wire (other than damage to the sheathing, which can be avoided with proper equipment and procedures), than for unsheathed spiral strand wire rope. The allowable tension/bend radius ratio is actually more forgiving for sheathed rope and the vacuum extruded sheathing maintains the rope construction even if the rope twists. This should allow for a more robust mooring system once installed.
- Like polyester, sheathed spiral strand rope is subject to damage due to dropped objects and riser pull-in/payout procedures. The sheathing is prone to damage, but wire rope is less susceptible to total failure than is polyester rope, if damaged. Ensure that all future operations once the anchor legs are installed are always aware of the catenaries of the polyester or wire rope segments to ensure that proper precautions are taken to ensure no contact. There have been several instances of anchor leg damage occurring during riser pull-in.
- Haul in twist-sensitive mooring legs using low-rotation wire or synthetic rope to reduce the number of turns induced into the mooring leg during haul-in. This is important for laying and pulling-in anchor legs in deep water as anchor leg components like chain and spiral strand wire are quite sensitive to twist in the anchor leg at high loads. Note that studless chain develops high stresses when the interlink twist exceeds approximately 0.5 degrees/link.
- For systems with subsea connectors, it is important to ensure that the section of ground chain connected to the pile is properly stored (draped) with the pile to ensure that once the connection is made the chain can be pulled away from the pile without twisting or hockling, as the twist may exist in the inverse catenary and not be visible.
- Installation (pull-in) wire ropes with streamlined closed spelter sockets can be hauled across fixed turning shoes during mooring leg installation. However, the wire rope's outer strands need to be regular lay to reduce cutting into the surface. Hardness is also important. Some multi-strand low-rotation wire ropes have Lang's lay outer strands, which have the individual wires in each strand oriented at an angle to the axis of the rope, whereas in regular lay ropes the individual wires in each strand lie parallel to the axis of the rope.
- Once the anchor leg system is installed and accepted in its as-installed configuration, a good as-built survey with quantitative measurements of floater position and specific locations of shackles or other connectors for each anchor leg can provide a good set of baseline measurements for the future monitoring and inspection of the system. In addition, good video of all connectors and terminations provide a good reference for future inspections.

Monitoring and Maintenance

It is becoming increasingly common for operators to want to supplement ROV and/or diver inspection of the entire anchor leg system with a direct means of determining the integrity of the anchor leg system and its stationkeeping performance. Typically the requirement is for measuring anchor leg tension and vessel position with a means of providing alarms in case of exceedence of pre-determined bounds. However, the majority of permanent mooring systems for floating production facilities are designed to operate for all design operating and survival conditions passively, i.e., no adjustment to the anchor leg system is required to maintain position or minimize anchor leg tensions, unlike for many MODUs. From this perspective, most permanent mooring systems have anchor legs terminated in chain stoppers rather than winches that monitor tension, like on MODUs.

From an engineering perspective, direct tension measurement of each anchor leg tension is the "best" solution to theoretically monitor a mooring system, as it can be used for simple functions like line break detection and anchor leg configuration in calm water to detailed time histories of loads and responses. Obviously a good dataset of system responses could provide a means for a database to validate design calculations in extreme storm conditions or provide feedback if the platform is abandoned during a storm. Unfortunately the track record for the long-term reliability of direct tension measurement equipment is not so stellar and can lead to a number of false alarms that can result in the system being ignored. In the end the operator has to develop a mooring system integrity plan that utilizes both inspection of the anchor leg system at pre-determined intervals supplemented by monitoring parameters that can provide feedback on the stationkeeping performance which is a major driver. The API RP 2I (2008) provides good information on performing detailed inspection plans for anchor leg integrity, so this section provides a few key points that may supplement the information there.

- Systems like external turret systems or spread moored systems with deck mounted fairleads can be effectively monitored by visual observations and angle measurements. Angle measurements are accurate for shallow water, less so for deep water. Monitoring angles can also provide feedback if there is a sudden change in anchor leg configuration due to lost weight or anchor drag etc. An eyeball ROV, either deployed from the floating facility or a supply vessel, could be used to monitor anchor legs at the fairleads. This inspection would be similar to a visual check for anchor leg configuration.
- Accurate monitoring of facility position is one of the most robust and effective monitoring systems and provides immediate feedback on stationkeeping performance. This is also standard equipment in many floating systems and in deep water can provide input for line break detection due to a large offset change in calm water.
- Understanding the characteristics of the particular anchor leg system can help determine which parameters of the catenary to monitor – fairlead angle, depth at a defined location, etc. This may allow the use of more robust field proven equipment to measure parameters of interest that can be used to obtain feedback on anchor leg integrity. For example, in deep water, measuring the depth of an interface in the anchor leg can provide good information on anchor leg performance including load sharing, line break detection, etc., and it can be done using acoustic transducers and transponders that are readily available and inexpensive. Use of acoustics to transmit data is more robust than cables over a long period of time, but a balance between monitoring frequency and battery replacement must be developed.
- As discussed above, polyester ropes are subject to constructional elongation and creep as the rope is loaded and worked, and this change in length can affect the stationkeeping performance of the mooring system. This effect can be considered in the design to a point but it should be anticipated that most permanent polyester rope systems will need to be re-tensioned over their lives. This would require tension, angle, or depth information at a defined point on the catenary to estimate the amount of adjustment. In our experience, for very deepwater systems, measuring the depth (accurately) at a shackle (say at the top chain/polyester interface) can provide accurate feedback on the anchor leg configuration and thus the pretension if the vessel position is also known.
- Avoid load monitoring devices in the mooring line load path that cannot be easily replaced, as the track record of direct tension measuring systems is not very good over the long term.
- If load cells are used, size them so they accurately measure the loads you are interested in measuring, such as the installation pretensions, because choosing a load cell with a rated load equal to the breaking strength of the mooring leg will result in a load cell too large to measure the loads you are interested in measuring. Consider choosing a load cell with a zero drift load (i.e., proof load) equal to the maximum expected load and accept the possibility that an overload will result in the load cell's zero being shifted.
- In most cases, monitoring of anchor legs using instruments provides feedback once a catastrophic failure has occurred – inspections can provide input on accelerated degradation compared to the design assumptions that may allow rectification before failure.
- Underwater inspection should still play a big role in monitoring anchor leg systems – baseline measurements are important to serve as a benchmark. Quantitative measurements should be taken consistently – there are too many qualitative ROV inspections performed at a great cost with limited useful data from a monitoring perspective. See API RP-2I for a list of recommended baseline measurements and manufacturing records that should be recorded and retained for reference during future inspections.
- Chain should be baselined by identifying, marking, and measuring representative chain links in the different corrosion and wear zones for reference during future inspections. It is especially important to record these measurements for the chain links in the fairlead and in the splash zone.
- Monitoring anodes in spelter sockets etc. provide important feedback on corrosion and can provide an early warning if depleted prematurely.

CONCLUSIONS

The offshore industry has a long and successful history of providing permanent mooring systems for floating facilities. This history stretches over 30 years for a variety of floating systems, locations, water depths, and environmental conditions. Most anchor leg components in use today have been used repeatedly in the past 30 years, with the exception of synthetic rope, of which polyester has a history of 15 years. Thus there is much data and information that can be obtained from the field on the performance of anchor leg system components in general, and mooring system integrity in particular.

A major premise of this paper is that past experience, good design, properly installed components, and good inspection and maintenance programs all play a role in improving the integrity of anchor leg systems. As discussed in the paper, most anchor leg components degrade with exposure to the environment and so the design of permanent mooring systems must take this into account. In addition to this degradation, a review of the few anchor leg failures in the industry has shown that they occurred by not accounting for loading in the components that they were subjected to, e.g., out of plane bending fatigue of chain at fairleads, and the disassembly of connectors (for which there is no specific industry design guideline) at the seabed due to repeated impact with the seabed or chain components. With the information available in the industry and a greater appreciation of the dynamic loading in the offshore environment, issues like these are more easily identified and rectified at the design phase. Installation plays an important role in ensuring the anchor leg system is installed as designed, proper installation equipment and procedures ensure that anchor leg components are not damaged during installation, and inspection, monitoring, and maintenance programs provide the operators with feedback on the system performance and integrity.

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