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Enabling Ultra-Deepwater Mooring with Aramid Fiber Rope Technology

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Abstract

New high-strength synthetic ropes constructed of para-bonded aromatic polyamide (aramid) fiber are being developed for ultra-deepwater mooring applications. This paper highlights new laboratory tensile/fatigue testing of rope assembly, computer modeling analysis of mooring performance under operating conditions, and the potential economic impact.

As the industry moves into ultra-deep water, traditional steel wire rope and chain moorings are being gradually displaced by polyester ropes. These synthetic ropes have been used in water depths between 3,000 feet and 8,000 feet. Questions arise, however, about whether polyester mooring ropes provide enough stiffness to maintain acceptable platform offsets in increasingly deeper water in all cases. Aramid fiber ropes are inherently stiffer and stronger than polyester ropes and therefore offer new solutions for ultra-deepwater mooring, as well as for other applications where production platform offsets may be critical.

Advanced technologies are being developed to optimize aramid fiber performance and rope design configurations. New laboratory tensile and fatigue data are presented to demonstrate aramid fiber rope properties, performance capabilities, and minimum tension settings meeting API RP 2SM guidelines. Mooring analysis comparing the performance of an aramid mooring system with that of a polyester mooring system under simulated hurricane and loop current conditions shows significant reductions in platform offsets are achieved with the aramid system without compromising safety.

This paper describes a new technology for ultra-deepwater mooring. The new approach offers the opportunity to design mooring systems for deeper water without modifying certain platform components and systems by incorporating stiffer, high-strength aramid fibers in the platform mooring system. Potential benefits include achieving optimal offsets for production risers in ultra-deep water, easier handling and installation due to smaller rope size, and greater flexibility in mooring system design. Economic analyses are presented to illustrate the advantages of the new technology as well as the financial impact.

Introduction

Industrial and commercial grades of aramid fiber have been used successfully for more than 25 years in numerous marine rope and cable applications, because of their unique combination of physical characteristics and performance capabilities. The linear molecular structure of aramid fiber yields a strength-to-weight ratio more than five times that of steel wire in air and more than 20 times steel wire in water. Aramid fiber is corrosion-resistant, nonconductive, and exhibits low elongation properties—or stiffness--in response to high loads, variations of mean load and rapid cyclic loading. Aramid fiber also performs well in arctic or elevated temperatures and is highly resistant to tension-tension fatigue.

Because of its high specific strength, aramid fiber has been recognized for more than 20 years as an option for mooring mobile offshore drilling units and production platforms in deepwater (Koralek, et. al., 1987). All-chain catenary mooring systems begin to approach the limits of their capabilities when operating water depths reach about 1,500 feet; combination chain-wire rope mooring systems are useful to water depths of about 3,000 feet. Beyond those depths, the sheer weight of either mooring option begins to develop the same fundamental performance problems: excessive catenary sag and poor station-keeping. High-performance mooring ropes made from high-strength, lightweight aramid fiber exhibit Minimum Breaking Strengths (MBS) comparable to chain and wire rope, so lengths of aramid rope can be substituted for sections of cable or wire rope in a catenary or taut-leg mooring system to improve station-keeping performance when a lighter mooring system is specified.

The reliability of aramid rope in deepwater mooring applications came into question in 1983 when four mooring ropes on the derrick ship Ocean Builder I failed—reportedly at 20% of MBS--during first tensioning in preparation for installation of the Lena guyed tower in 1,045 feet of water in the Gulf of Mexico. All four failed lines had been pre-set four to six weeks prior to the arrival of the derrick ship, deployed between an anchor on the seafloor and a buoy at the surface. Results of an extensive study, conducted to identify the causes of the premature failures and to identify potential solutions, were reported in a paper presented at the Offshore Technology Conference (Riewald, 1986). Factors contributing to the failures included rope damage and bending fatigue in an instance in which one rope was too long for the water depth. In addition, a previously unknown strength-degradation mechanism was identified that had been activated by the response of the aramid ropes to environmental loading under low tension from wind, waves, and currents.

Riewald and others reported in a separate technical paper about the Ocean Builder I mooring system failure that torque generated under low tension in the buoyed aramid ropes induced rotation, causing shear and compressive strains and fiber kinking. Damaged fibers subsequently suffered torsional (shear) and compressive fatigue due to prolonged exposure of the lightly constrained aramid ropes to the constant loading of the open-ocean environment, resulting in loss of 40% to 50% of rope strength (Riewald, et. al., 1986). The authors opined that compression fatigue likely would not have occurred in the aramid ropes if the mooring system had been connected to the derrick ship immediately upon deployment. Based upon laboratory testing, the authors determined the survivability of aramid rope in deepwater mooring applications could be improved significantly with the following measures:

- Use rope-construction designs that are either torque-free or generate low torque.
- Increase compliance or the extent of fiber freedom of movement by introducing additional levels of twist in the rope-construction process.
- Keep all elements of the rope under tension at all times to prevent excitation of compressive forces or development of bending hinge points.
- Provide cushioning and compliance in the rope jacket design to avoid constraining fiber or strand movement during rotation or bending.

Koralek and others, in the 1987 OTC technical paper cited above, reported the results of a five-month-long field test in the Gulf of Mexico of a 1,000-foot length of 4-inch aramid rope, inserted into the chain and wire rope mooring system of the Zapata Lexington drill ship. Based upon previous work documenting the strength loss in aramid rope caused by the low-tension compression fatigue mechanism, it was necessary to design the aramid rope to be torsionally compatible with the wire rope to which it was to be coupled. Post-deployment testing conducted four months after recovery of the aramid rope found retained strength was 93% of original strength. This led the authors to conclude that aramid fiber ropes are a technically viable option for mooring floating drilling and production facilities in deep water.

Ultra-Deepwater Mooring Systems

Despite research that identified the compression-fatigue mechanism excited by cyclic loading under low tension that caused strength loss in aramid rope—as well as solutions for preventing it—aramid ropes have been used only sparingly in mooring applications since the 1980s. As offshore producers pushed exploration and development into even deeper water during the 1990s, polyester ropes emerged as the leading method of minimizing the weight of taut-leg mooring systems while retaining acceptable station-keeping performance. Pioneering applications by Petrobras, in particular, increased the precision of designing polyester mooring systems for deep water (Del Vecchio, 1996, Costa, et. al., 2001).

When BP Exploration and Production and partners in March 2004 installed a taut-leg polyester mooring system in more than 4,400 feet of water on the truss spar for Mad Dog field, on Green Canyon Block 782 in the Gulf of Mexico, it marked the first deployment of a permanent polyester mooring system on a floating production system (FPS) outside of Brazil’s Campos Basin (Petruska, et. al., 2004). Early design studies indicated a polyester mooring system could reduce vertical hull loads by 3 million to 4 million lbs; offsets of the Mad Dog spar were limited to 5.5% of water depth for the intact case and 6.25% in damaged case. The polyester rope in the final mooring design was 10.6 inches in diameter and had a calculated minimum break load (MBL) of 3,778 kips, the largest ever for a polyester rope at that time.

Then in April 2004, the former Kerr-McGee Oil & Gas Company installed a cell spar equipped with a six-leg taut polyester mooring system in 5,300 feet of water at Red Hawk field, on Garden Banks Block 877 (Lamey, et. al., 2005). Platform offset is an important driver for design of risers supported by an FPS. For this project, the mooring requirements dictated by riser design necessitated the use of a stiffer polyester fiber. The ropes were about 9 inches in diameter and have a rated breaking strength of 2,750 kips. Detail of the design, analysis, and testing of the mooring rope were summarized in the literature (Haslum, et. al., 2005).

The successful deployment of polyester mooring systems at Mad Dog and Red Hawk demonstrated the utility of polyester ropes in deep water mooring. However, with numerous discoveries of large reserves in water depths approaching 10,000 feet, questions have arisen about whether polyester ropes can be used at extreme depths. Will the absolute platform offset be too high for conventional riser systems? Furthermore, the size and weight of large polyester rope for ultra-deepwater mooring applications has implications for the required capabilities of handling equipment and installation procedures. A study of synthetic rope fibers for mooring systems showed that a 2,000 kips MBL polyester rope would have a diameter about 7.9 inches, while the diameter of an aramid rope with the same MBL would be about 5 inches, very close to the diameter of a 2,000 kips MBL wire rope (Davies, et. al., 2002). A polyester mooring line would require two to three times the storage capacity needed for an equivalent aramid rope; a reduction of weight also would be achieved with the aramid fiber rope, which to some extent would mitigate its higher cost.

To explore the potential of aramid fiber ropes for ultra-deep water applications, the authors initiated a project to conduct mooring system analysis comparing aramid fiber rope versus polyester fiber rope. In addition, small aramid ropes were assembled and tested for tensile and compression fatigue performance. The results are summarized in the following sections.

New Aramid Fiber Mooring Rope Development

In the 1990s, several joint industry projects (JIPs) were conducted to further develop technical data and fundamental understanding of aramid fiber rope in deepwater mooring applications. In 1993, Aker Omega led a JIP to study tensile and cyclic fatigue properties of 1,000 kips break strength aramid ropes (Aker Omega, 1993). Three ropes were tested to have average tensile break strength of 994 kips, indicating the rope and splice design were adequate for strength requirements. For cost reasons, fatigue tests were conducted at loads higher than those which might be experienced in service. Eleven (11) ropes in total were tested for cyclic fatigue performance under four load cycles: 2%-60%, 2%-52%, 10%-60%, and 10%-52% of new rope breaking strength. The results showed that the cycles-to-failure (CTF) is a strong function of the trough load and the load range. Ropes cycled between 2% and 60% of breaking strength failed after 4,650 cycles (average of 3), while ropes cycled between 10% and 52% load had an average number of CTF of 25,200 (Aker Omega, 1993). Although the ropes never went into compression, visual inspection indicated that some yarns in the ropes did go into localized compression, which caused rope failure. It's important to note that, although no tests were conducted at lower loads, the authors stated that ropes cycled at lower loads are not expected to fail due to axial compression fatigue.

In the “Fibre Tethers 2000” JIP conducted in the early 1990s, various high performance fibers, including aramid fibers, were studied for mooring applications (Nobel Denton Europe/NEL, 1995). Fibers were tested for tensile strength, creep, buckling, abrasion, and frictional properties while 10,000-lb and 240,000-lb break strength ropes were tested for static strength and fatigue properties. The results are too rich and complicated to be summarized here. On the cyclic fatigue property of aramid fiber, the CTF was found to be affected by the load range and the trough load. At a trough load of about 10%, an aramid fiber rope of 240,000-lb break strength sustained 1,000,000 cycles of tensile fatigue, cycled between 10%-30% nominal strength. The study showed that there was no evidence of kink banding in the rope and the residual strength was 90% in the central bundle and 84% in the outside bundle of the rope (Nobel Denton Europe/NEL, 1995). The authors also suggested that some of the axial compression fatigue problems can be minimized by careful rope and termination design.

Flory studied rope axial compression fatigue phenomena in great detail and proposed a model to explain the occurrence of axial compression fatigue in a synthetic rope under low tension-tension cycles (Flory, 1996). His model suggests that small variation in length of elements of rope during assembly is the key contributor to this phenomenon. As the rope undergoes tensile fatigue cycles, the longest elements can go into compression and may eventually fail. The remaining elements then experience higher tensions than before, which causes lower total cycles to failure. The author also suggested various rope design principles to mitigate the axial compression fatigue issue.

As a result of some these studies, provisional guideline was given in the API RP 2SM (2001) and the ABS Guidance Notes (1999) to set the minimum tension in service at 10% MBS for higher modulus ropes (including aramid fiber rope). The provisional guideline figure for the number of allowable cycles below the minimum tension level is set at 2,000 cycles for aramid fiber rope. These guiding documents state that if these criteria are overly restrictive, the specific rope design can be tested for residual strength after specific numbers of cycles to a specific minimum tension. The API RP 2SM sets the test procedure to be 10,000 cycles at 1%-25% of MBS.

A minimum tension requirement of 10% MBS is very restrictive for mooring designers. It necessitates the use of higher pre-tension in the rope, which in turn reduces the tension load range available for the design to be within the safety factor requirements. The current study provides new test data on aramid fiber rope which suggests a minimum tension requirement of 5% MBS can be achieved with proper fiber selection and rope construction.

In our continuing effort to develop new systems for mooring applications, one of the authors discovered that fiber finish can significantly affect the compressive fatigue performance of aramid fiber rope, especially the minimum tension level to initiate compressive failure (Huntley, 2006). The aramid fiber used in this study was the commercial-grade Kevlar® 29 fiber made by DuPont. Three types of finish were included in the initial scouting study. Finish 1 was a commercially available cordage finish, while Finish 2 and Finish 3 were test finishes. The ropes were designed to have a rated breaking strength (RBS) of 70,000 lbs and they were tested to have an average breaking strength (ABS) of 77,000 lbs. All of the rope samples were made by Whitehill Manufacturing, using the same construction. The ropes were tested under three test conditions:

Test 1: API RP 2SM Axial Compression Performance Test – 10,000 cycles, 1%-25% RBS, test residual strength
Test 2: Cycle 1%-50% ABS until failure
Test 3: ISO 18692:2007 Appendix B.5 Test - Cycle 5%-55% ABS until failure (5,500 cycles to pass test)

The results are shown in Table 1:

- In Test 1, ropes were cycled at 1%-25% RBS for 10,000 cycles. The results showed samples with any of the three finishes performed well and retained at least 93% of RBS.
- In Test 2, the load cycle was 1%-50% ABS and the average cycle to failure was 1,165 cycles for Finish 1, 2,141 cycles for Finish 2, and 2,225 cycles for Finish 3. This test condition seems to be so harsh that all of the samples failed due to compression.
- In Test 3, the load cycle was 5%-55% ABS. With a 4% increase of the trough load versus Test 2, the cycles to failure increased significantly. For samples with Finish 1, the CTF increased from 1,165 to 4,281 cycles (3.7 times). More importantly, the CTF for samples with Finishes 2 and 3 increased by about one order of magnitude in Test 3 versus Test 2. Post-test visual inspection showed that there was a shift in the failure mechanism, as no evidence of compressive failure was observed in the Test 3, Finish 3 rope.

Table 1: Effect of Fiber Finish on Compression Fatigue Performance

	Test 1 (API RP 2SM, Appendix D)	Test 2	Test 3 (ISO 18692, Appendix B.5)
Trough Load	1% RBS	1% ABS	5% ABS
Peak Load	25% RBS	50% ABS	55% ABS
No. of Cycles	10,000 cycles, then test for residual breaking strength	Cycle to failure (CTF)	Cycle to failure (CTF)
Finish 1 (control)	65,300 lbs. (93% RBS)	1093, 1237 (avg.=1165)	4281
Finish 2	68,200 lbs. (97% RBS)	2141	21714, 18458 (avg.=20086)
Finish 3	75,000 lbs. (107% RBS)	2479, 1970 (avg.=2225)	72068

From this data set, it is apparent that fiber finish can significantly affect rope compression fatigue performance. The new test finishes appear to give significantly better performance than Finish 1 (the cordage finish). Ropes made of aramid fiber with Finish 1 had been used in most of the previous studies (Koralek, et. al., 1987, Aker Omega, 1993). Due to differences in rope construction and test conditions, a direct comparison between this study and previous studies can not be made. However, all data appear to suggest that ropes made of aramid fiber with Finish 1 exhibit lower resistance to axial compression fatigue failure. The results also show that significant improvement can be made with the new test finishes so that a minimum tension of 5% ABS becomes possible. Further work is underway to conduct additional tests between 1% and 5% trough load to determine the critical minimum tension threshold.

To better understand the compressive fatigue properties of aramid fiber rope, it may be useful to examine the axial compressive fatigue behavior of aramid fiber at the yarn or filament level. A typical aramid fiber axial compressive stress-strain curve is shown in Figure 1 (DuPont, 1991). As shown in the figure, when aramid fiber is compressed axially, it behaves elastically (linear portion) until it reaches the elastic limit strain (ELS), which is approximately 0.6% in this case. Further compression will result in plastic deformation and kink band formation. Once kink bands are formed, the fiber will maintain strength for some number of cycles and eventually will start to lose strength under repeated compressive cycles. This is supported by experimental filament compressive fatigue data shown in Figure 2 (DuPont, 1991). When aramid filament is cyclic-fatigued between zero and 0.5% of compressive strain (which is below the ELS), it retains 100% strength for up to 1 million cycles. When the filament is compressed between zero and 0.8% strain (which is above the ELS), it retains strength for approximately 20,000 cycles before gradually losing strength. At 1.0% compressive strain, the no-damage threshold becomes 1,000 cycles. As summarized in Table 2, the onset of compressive fatigue damage is strongly affected by the maximum compressive strain and load range in testing. When the fiber is compressed beyond the ELS, an increase of compressive strain from 0.8% to 1.0% can decrease the CTF by 20 times. On the other hand, if the fiber is compressed below the ELS, it will retain strength for many cycles.

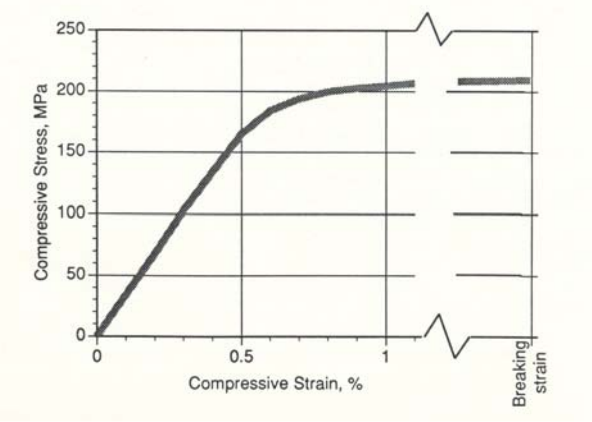

Figure 1. Axial Compressive Stress-Strain Curve

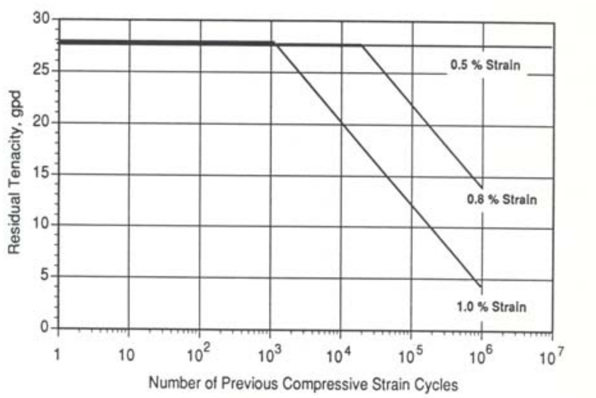

Figure 2. Aramid Filament Compression Fatigue Data

Table 2: Summary of Aramid Filament Compression Fatigue Data

	Test A	Test B	Test C
Maximum compressive strain	1.0% strain	0.8% strain	0.5% strain
Minimum compressive strain	0% strain	0% strain	0% strain
No-damage threshold	1,000 cycles	20,000 cycles	1,000,000 cycles

This basic knowledge of fiber behavior can be used to help explain the rope performance data. In the rope testing described earlier, the trough load was increase from 1% ABS in Test 2 to 5% ABS in Test 3. If 100% ABS of the rope corresponds to a breaking strain of 3.3%, then this change of 4% ABS would correspond to a change of 0.13% in strain. For ropes made of fiber with Finish 1, this increase of the trough load was not sufficient to move all fibers out of the localized compression fatigue conditions. It did increase the CTF from 1,165 to 4,281 (3.7 times). In the case of Finish 3, the same increase in trough load apparently moved the fiber out of kink-band forming conditions which resulted in excellent improvement in compression fatigue performance.

The fact that aramid fiber exhibits such a sharp threshold for onset of compressive fatigue behavior offers engineers and scientists both challenges and opportunities in using aramid fiber for mooring line applications. The key challenge is to design, construct, and install the ropes according to some of the guiding principles described in the literature to eliminate axial compression concerns. A relatively small change such as the fiber finish can greatly improve the compressive fatigue performance, bringing it into a performance range suitable for commercial deployment.

Aramid Mooring System Performance Analysis

A mooring system analysis was conducted by InterMoor to investigate the performance of aramid rope in deepwater and ultra-deepwater mooring applications. The objectives of the study were:

- Quantify the impact of aramid fiber rope on platform offset reduction and determine the maximum mooring line tension (and therefore safety factor) in ultra-deepwater mooring.
- Study the effects of blending segments of aramid and polyester rope as well as effect of line pre-tension on mooring performance.
- Estimate and compare the relative total installed cost of various solutions versus polyester systems.
- Investigate the potential benefits of reducing platform offsets for ultra-deepwater riser systems.

InterMoor used a frequency domain analysis software to perform the mooring analyses. In the analytical methodology, mooring line configurations were modeled to accurately simulate each mooring component's dynamic characteristics, including length, diameter and stiffness. The mooring system layout was modeled to simulate seafloor bathymetry and slope, such that the water depths at the rig's location and at each anchor were modeled accurately. Quasi-static and dynamic analyses were performed by imposing collinear environments on the rig and its moorings omni-directionally from headings encompassing the full 360° in 5° increments. Intact and damaged (i.e., one (1) line broken and modeled as missing) conditions were analyzed for each heading. During the analysis for damaged conditions, all twelve (12) of the lines were broken sequentially for each environmental heading, but at no time were two (2) lines broken simultaneously. Wind, waves, and current were modeled as recommended in the API RP 2SK Appendix K and API 2INT-MET using 100-year hurricane and 100-year loop-current metocean data for the Gulf of Mexico.

A deep draft hull form with about 120 million lbs displacement was selected for the modeling analysis. In each of the mooring systems studied, a 500-foot, 5-inch anchor chain was connected to the synthetic rope, followed by a 500-foot, 5-inch fairlead chain. The minimum breaking strength for the synthetic rope was 3,500 kips and the rope property data were calculated and provided by Whitehill. The diameter of the aramid fiber rope was 7.5 inches versus 9.75 inches for the polyester fiber rope. More importantly, the stiffness (or modulus of elasticity) of aramid fiber rope was three times that of the polyester fiber rope.

In order to fully explore potential uses of aramid fiber rope in mooring, modeling of three scenarios of mooring systems were carried out:

- Scenario 1 – Compare 12-leg all-aramid, all-polyester, and blended systems in 10,000 ft water
- Scenario 2 – Compare 12-leg blended systems to 15-leg all-polyester rope in 10,000 ft water
- Scenario 3 – Relocation of existing platform from 4,000 ft to 7,000 ft water

Several hundred modeling runs were conducted and more data were generated than will be discussed in this paper. The following summarizes some of the most significant results.

Scenario 1

In Scenario 1, the cell spar was anchored in 10,000 feet of water by a 12-leg mooring system, in which each line contained 14,000 feet of synthetic rope with an MBL of 1,750 tons. The amount of aramid fiber in the mooring rope was varied from zero to 100% in six (6) incremental steps. Mooring pre-tension was varied from 300 tons to 400 tons to determine the optimal tension for balancing offsets, safety factors, and minimum tension. Based on the initial results, a pre-tension of 400 tons was used for most of later analysis. It was noted that, in general, loop current environmental conditions controlled offsets, while hurricane environmental conditions controlled the safety factors. Consequently, only the most critical results will be discussed below.

At 10,000 ft water depth and under 100 year loop current conditions, the all-aramid fiber rope can achieve a maximum platform offset of 1.4% vs. 3.9% for the all-polyester system in the intact case. The offset becomes 2.2% (aramid) vs. 6.1% (polyester) in the damaged case. This is illustrated in Figure 3, which also shows the results for the blended systems of aramid and polyester fiber rope. In general, the rule of mixing applies, which makes it convenient for the mooring system designers.

In terms of safety factors, API RP 2SK requires offshore mooring systems to maintain minimum dynamic safety factors while in service. The safety factor requirements are 1.67 in the intact case and 1.25 in the damaged case. Under 100 year hurricane conditions, the minimum dynamic safety factor for the all-aramid fiber rope in Scenario 1 analysis was 1.96 versus 2.15 for the all-polyester system in the intact case. The safety factor became 1.55 for all-aramid fiber rope and 1.66 for all-polyester fiber rope in the damaged case. Although the safety factors for the aramid fiber rope were slightly lower than those of the polyester system, they remained well above levels required by API RP 2SK in both intact and damaged conditions. The results are shown in Figure 4, which also includes data for the blended systems.

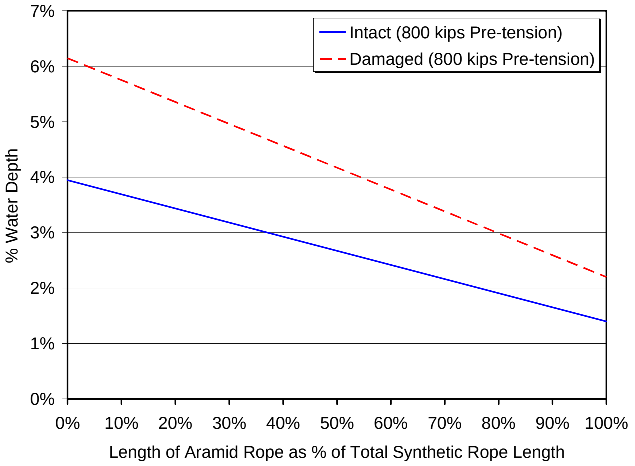

Figure 3. Scenario 1 Loop Current Offset Comparison

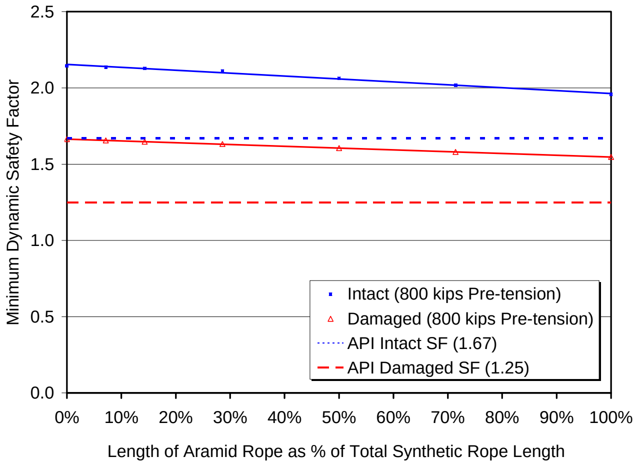

Figure 4. Scenario 1 Hurricane Safety Factor

From this analysis, one can conclude that the use of aramid fiber rope in ultra-deepwater mooring can significantly reduce platform offset without sacrificing the safety factors. A blended system approach could provide mooring system designers a useful tool to gain additional offset margin on borderline systems.

Discussions were held with riser design specialists to understand potential benefits of reducing platform offsets for riser design and cost. It was concluded that the reduction of platform offset would not necessarily be beneficial for all types of riser systems. For example, offsets do not usually control the design of steel catenary risers (SCRs), so the smaller offsets achieved with aramid mooring ropes probably would have little effect on SCR design. However, offset is a significant contributor to riser stroke, which usually controls the design of top-tension risers (TTRs). Therefore, aramid mooring ropes might well have some impact on decisions affecting TTRs.

Designers speculated that reduced offsets could decrease air can size or length or the required tensioner stroke. A shorter stroke or smaller tensioning components could free up FPS payload and deck space for other uses. Reduced offsets might allow TTRs to become viable mooring system options for semi-submersible shaped hull forms, which they currently are not. Reduced offsets also could reduce required jumper lengths for freestanding risers and could therefore lead to cost savings. These questions need to be addressed in detail by future research.

Scenario 2

In Scenario 2, comparisons were made between the 12-leg blended systems as analyzed in Scenario 1 and a 15-leg all-polyester system in 10,000 ft water. The 15-leg polyester fiber rope was slightly smaller than in Scenario 1, having a diameter of 8.5 inches and MBL of 3,150 kips. The length of mooring rope is still 14,000 ft. Of particular interest in this analysis is the amount of aramid fiber rope needed in the 12-leg system in order to achieve the same offset as the 15-leg all-polyester system. The modeling results showed that approximately 4,600 ft of aramid fiber rope would accomplish this goal (see Figure 5). This amounts to about 33% of the total length.

A high-level cost estimate was made to compare the total installed cost for these two mooring systems, based on the following assumptions:

- Component cost for items other than polyester and aramid rope were adjusted based on ratios of MBL
- Installation costs for polyester and aramid rope were the same for a given MBL
- No step change in installation spread between 3,150 kips MBL system and 3,500 kips MBL system
- Installation performed by large construction vessel/derrick barge with support barge
- Additional mooring legs did not require additional trips from the beach
- Installation performed in 3 phases: anchor installation, mooring installation, and mooring hook-up

The result of the cost estimate is shown in Figure 6. The component cost for the 15-leg all-polyester system is slightly lower than the 12-leg blended aramid-polyester system. However, the 15-leg system requires additional mooring equipment such as winching equipment and fairleads as well as additional installation cost. As a result, the 12-leg blended aramid-polyester system will have a lower total installed cost than the 15-leg all-polyester system.

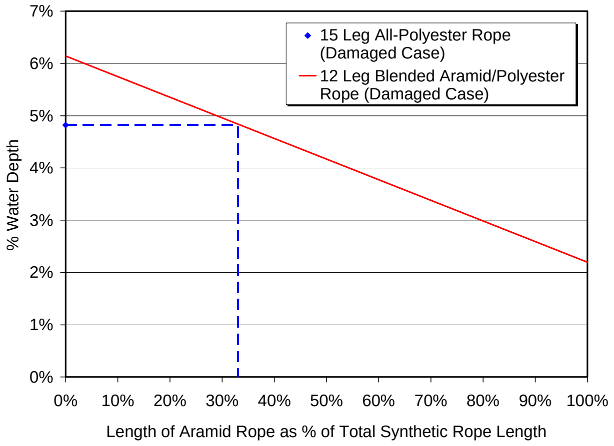

Figure 5. Scenario 2 Loop Current Offset Comparison (Damaged Case)

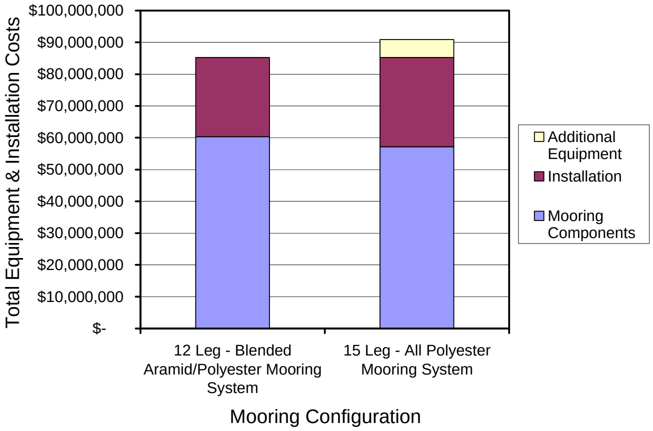

Figure 6. Scenario 2 Total Installed Cost Comparison

Scenario 3

The purpose of Scenario 3 was to simulate a situation in which a platform was relocated from 4,000 feet water depth to a deeper water site of 7,000 feet. In order to maintain the same absolute platform offset, a stiffer mooring rope would be required for the deeper water site. For this analysis, a base case was created in which a deep draft hull form was anchored in 4,000 feet of water by a 12-leg mooring system, in which each line contained 6,500 feet of polyester rope. The test cases were created in which the hull was anchored in 7,000 feet of water, in which each mooring line contained 10,000 feet of rope with varying amount of aramid and polyester segments. Because of the relatively shallower water depths in this scenario, mooring pre-tension of 300 tons was deemed acceptable and was used in most analysis.

The result of the loop current offset analysis is shown in Figure 7. In 4,000 feet of water, the maximum platform offset was 181 feet (i.e. 4.5%) in the intact case for the all-polyester rope. In 7,000 feet of water, the absolute offset became 326 feet in the intact case for the all-polyester rope. By interpolation from the figure, a blended system with about 70% aramid component will be sufficient to keep the absolute offset below 181 feet in 7,000 feet of water. Figure 8 shows the maximum offset comparison in the damaged case, which leads to similar conclusions.

The potential cost-benefit achieved by using a blended aramid-polyester mooring system to anchor an FPS in ultra-deep water would be derived from re-using the existing on deck riser equipment and certain other equipment from the shallow-water location.

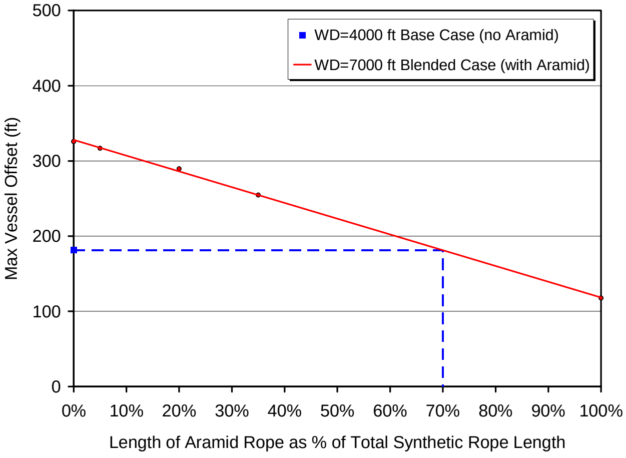

Figure 7. Scenario 3 Loop Current Offset Comparison (Intact Case)

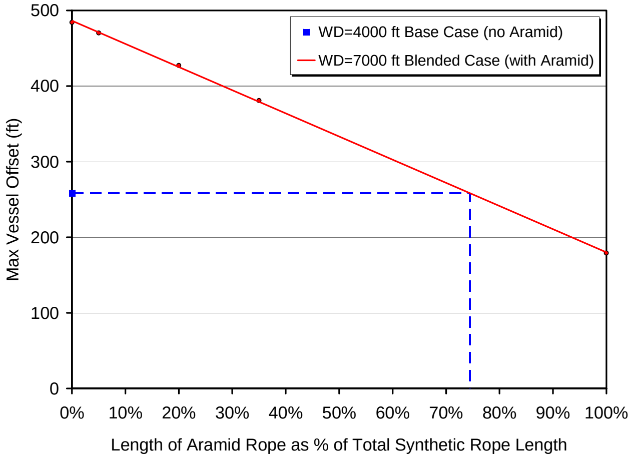

Figure 8. Scenario 3 Loop Current Offset Comparison (Damaged Case)

Conclusions

As the offshore oil and gas industry moves into ultra-deep water, traditional steel wire rope and chain mooring system gradually are being displaced by polyester ropes. Questions arise, however, about whether polyester mooring ropes provide enough stiffness to maintain acceptable platform offsets at extreme water depths. Aramid fiber ropes are inherently stiffer and stronger than polyester ropes and therefore offer new solutions for ultra-deepwater mooring.

Several joint industry projects were conducted in the 1990s to develop technical data and fundamental understanding of aramid fiber rope in deepwater mooring applications. As a result of these studies, provisional guidelines have been given in the API RP 2SM and the ABS Guidance Notes to set the minimum tension in service at 10% MBS for higher modulus ropes (including aramid fiber rope) to avoid axial compression fatigue failure.

This study demonstrates that it is possible to reduce these minimum tension requirements to 5% MBS for properly designed and manufactured aramid fiber ropes. The new compression fatigue data shows that:

- Fiber finish can significantly affect aramid fiber rope compression fatigue performance
- When tested at 5%-55% ABS load range, the cycle-to-failure of aramid fiber rope improved from 4,300 cycles for the standard finish to 20,000 – 70,000 cycles for the new test finishes
- When tested at 1%-25% RBS load range, the aramid fiber ropes retained at least 93% RBS after 10,000 cycles

The fact that aramid fiber exhibits a sharp threshold for onset of compressive fatigue behavior offers engineers and scientists both challenges and opportunities in using aramid fiber for mooring line applications. The key challenge is to design, construct, and install aramid ropes according to the guiding principles described in the literature to eliminate axial compression concerns. A relatively small change such as the fiber finish can greatly improve the compressive fatigue performance, bringing it into a performance range suitable for commercial deployment.

A mooring system analysis was conducted to compare the behavior of aramid and polyester ropes in 100-year hurricane and loop current conditions. It was concluded that:

- The platform offset was reduced significantly as the content of the mooring rope was changed gradually from all-polyester to all-aramid fiber. This offset reduction could be beneficial in enabling preferred riser configurations or reducing overall system cost.
- A 12-leg blended aramid-polyester mooring system can achieve the same offsets in 10,000 feet of water as a 15-leg, all-polyester mooring system when the mooring line of the blended system contained about 4,200 feet of aramid rope, or 30%. A high-level cost analysis indicates that the total installed cost of a 12-leg, blended aramid-polyester rope mooring system at an ultra-deepwater location could be less than a 15-leg polyester mooring system.
- A 12-leg blended synthetic mooring system containing about 70% aramid rope can achieve the same absolute offset in 7,000 feet of water that a 12-leg all-polyester synthetic mooring system can achieve in 4,000 feet of water, potentially enabling a platform to be relocated to deeper water without replacement of topside hardware.

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Notes:

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