Mooring Systems for Marine Energy Converters

John F. Flory, Tension Technology International, Morristown, NJ, USA, Flory@TensionTech.com

Stephen J. Banfield, Tension Technology International, Eastbourne, UK, Banfield@TensionTech.com

Dr. Isabel M.L. Ridge, TTI Testing, Wallingford, Oxfordshire, UK, Ridge@TensionTech.com

Ben Yeats, Tension Technology International, Inverness, UK, Yeats@TensionTech.com

Tom Mackay, Tension Technology International, Inverness, UK, Mackay@TensionTech.com

Dr. Pengzhu Wang, Bridon International, Doncaster, UK, wangp@Bridon.com

Tim Hunter, Bridon International, Doncaster, UK, huntert@Bridon.com

Prof. Lars Johanning, Uni. of Exeter, Exeter, UK, L.Johanning@Exeter.ac.uk

Manuel Herduin, Uni. of Western Australia, Crawley, Australia, manuel.herduin@research.uwa.edu.au

Peter Foxton, Vryhof Engineering Limited, Douglas, Isle of Man, UK, Peter. Foxton@Vryhof.com

Abstract

This paper discusses several new technologies for mooring floating marine energy converter (MEC) devices, such as wave energy generators, tidal current turbines and floating wind turbines.

The principal mooring component is a special nylon fiber rope which provides cyclic tension fatigue endurance much superior to that of conventional nylon ropes. The nylon fiber is treated with a new proprietary coating which has excellent wet yarn abrasion properties. The parallel-subrope type rope construction further reduces internal abrasion.

Extensive laboratory testing was carried out on this new nylon rope design. Cyclic tension fatigue tests were conducted at mean loads and load amplitudes typical of actual service conditions and at higher mean loads and amplitudes. These tests demonstrate that the special nylon rope has essentially the same, desirable stretch characteristics as conventional nylon rope and has much better endurance performance.

The mooring connection to the floating MEC device consists of a high-modulus fiber rope pendant which passes through a low-friction bell-mouth nylon fairlead on the MEC device. This eliminates the use of heavy, unreliable chain in this critical connection.

A unique bag anchor system would be used on sand, clay, rock and other sea beds in which conventional drag embedment anchors and driven piles are impractical. The bag anchor consists of a large abrasion resistant carcass with lifting straps and top closure. The bag is transported to site in a collapsed form and is filled with local sand or aggregate to provide ballast weight. Several or many such bags are enclosed within a fiber rope net for deployment and are grouped together for connection to the mooring line.

The paper will be of particular interest to designers of moorings for MEC systems in shallow water and severe wave environments. It will also be of interest for other mooring applications.

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Key Words – energy converter, wave energy, current energy, wind energy, buoy, mooring, anchor, rope, nylon, fairlead, test

INTRODUCTION

Marine energy converters (MEC) will generally be located in very demanding environments, often in shallow water depths and often on sand, clay, rocky or hard sea beds. The mooring systems for these MECs should keep the device on station in severe wave, current and wind conditions. They should also limit horizontal offset in order to accommodate power cables to the ocean floor. The mooring system footprint should be small to control installation costs and to reduce the area occupied by arrays of devices.

Conventional steel wire and chain mooring systems do not provide the necessary compliance (stretch) and reliability. A mooring component failure will necessitate high offshore repair costs or the need to take the device out of service.

With funding from the UK Carbon Trust and other agencies, Tension Technology International (TTI), Bridon International, Exeter University, Vryhof and other companies and institutions are developing and testing components for a MEC mooring system which provides the necessary strength, compliance and reliability.

MEC systems are typically moored in less than 100 m (300 ft) of water. The maximum peak to trough wave might be as high as 25 m (75 ft), with corresponding large wave-induced horizontal excursions. Thus in survival mode, the MEC mooring system might have to accommodate horizontal movements which are more than 25% of the water depth.

A schematic of a catenary anchor leg moored buoy is shown in Figure 1. Catenary mooring systems rely on the weight of chain to produce restoring forces. As the buoy is offset to the side by waves or other forces, the chain becomes taut and pulls up on the anchor. The mooring leg becomes stiff and cannot offset any further, resulting in very high tension.

A taut-leg fiber anchor leg moored buoy is also shown in Figure 1. This type of mooring is now used on many deepwater oil exploration and production platforms. In such applications, the fiber rope mooring legs typically extend down at about 45 degrees to anchors on the sea floor. As the buoy is offset, the mooring rope stretches, but it does not become as stiff as a fully offset catenary anchor chain.

The taut-leg fiber rope anchor leg mooring system now proposed for use on MECs is shown in Figure 2. A nylon rope mooring line is preferred because it has much more stretch than polyester rope. A high modulus fiber rope pendant is used to connect the mooring line to the buoy, eliminating the use of chain. The pendant passes through a low friction fairlead on the buoy. A bag anchor system would be used where conventional drag or pile anchors are not practical.

Nylon Mooring Rope

The principal mooring component is a special nylon fiber rope which provides the *compliance* (stretch) and cyclic tension fatigue performance necessary to moor MEC devices. The fatigue durability is much superior to that of conventional nylon ropes. The unit length cost of nylon is approximately half that of chain with the same break strength. In shallow water moorings, larger chain would normally be used to provide the necessary catenary mooring offset characteristics. Thus using nylon mooring lines can achieve substantial cost benefits.

Research in the 1980s showed that, when subjected to cyclic tension, wet conventional nylon ropes degrade rapidly due to internal abrasion.[1] [2] Special treatments to the nylon yarn were shown to greatly improve cyclic tension fatigue performance.[3] [4]

Because polyester ropes do not suffer from this internal abrasion problem, they are recommended for many mooring applications.[5] Research demonstrated that polyester mooring ropes have excellent durability when subjected to cyclic tension.[6] [7] [8]

Polyester ropes are now widely used for mooring oil exploration and production platforms in deep water.[9] One objective in this application is to minimize platform horizontal excursion in order to prevent overstressing the drill stem or production riser. Polyester rope taut leg mooring systems in water depths greater than 1,000 m (3,000 ft) can limit platform excursions to less than 2% of water depth.

MEC devices are typically moored in less than 100 m (300 ft) of water. Polyester ropes could be used in this application, but very long mooring legs would be needed to provide the necessary stretch. Shorter nylon ropes would provide the necessary stretch. But conventional nylon ropes would have very limited service life in this application. If nylon rope mooring legs could be used, it would save cost and reduce the footprint of the mooring arrangement.

Special Parallel Subrope Type Nylon Rope

Bridon has designed a special nylon rope which has much better endurance in tension cycling. Some test results for small rope specimens were discussed in a previous paper.[10] This paper provides additional test results and further information.[11]

Most conventional nylon mooring ropes are either double-braid or 8-strand construction. Figure 3 shows a double braid rope. It comprises a braided core surrounded by a braided cover. Internal abrasion takes place at the many cross-over points between the braided strands.

Figure 3 also shows the parallel-subrope type rope construction. It comprises many subropes which extend in parallel over the entire rope length and are covered by a braided jacket. The large polyester ropes used to moor deepwater platforms are of this construction. There is essentially no abrasion between the parallel subropes. These subropes are typically long-lay-length 3-strand construction which further reduces internal abrasion.

The nylon yarn used in this Bridon subrope is treated with a new proprietary coating which has excellent wet yarn abrasion properties. Figure 4 compares the wet yarn abrasion performance of this nylon yarn with that of another nylon yarn and with the Cordage Institute criteria for marine grade nylon yarn.[12]

In the yarn-on-yarn abrasion test, a yarn under tension is rubbed against itself until it fails.[13] The Cordage Institute minimum performance criteria for marine grade nylon yarn are shown on this graph as a dashed line.[14] Type 1, an earlier nylon yarn tested by Bridon for this application, performed better than most nylon yarns. The abrasion performance of the Type 3 yarn is more than ten times that of the Cordage Institute criteria. Bridon now uses the Type 3 nylon yarn in this new rope design.

Extensive laboratory testing has been carried out to demonstrate the endurance of this new nylon rope design. A first series of tests, reported in the previous paper, were conducted on a small 17 mm (0.7 inch) diameter subrope. That rope has an average wet new break load (NBL) of 68 kN (15.3 kip). It would be suitable for making parallel-subrope type mooring lines for small buoys.

This paper presents some of the results of a second series of tests conducted on a larger subrope, shown in Figure 5. The diameter of that subrope is 33 mm (1.3 inch) and the average wet NBL is 249 kN (60 kip). This large subrope would be used to make mooring lines for large renewable energy system moorings. Many such subropes would be arranged in parallel and covered by a braided jacket to make the mooring line.

The lay length to diameter ratio for both ropes was greater than 6:1. This is a longer lay length than that used in conventional 3-strand nylon ropes. The subrope can have such a long lay length because the assembled mooring rope is jacketed.

Figure 6 compares the broken-in stiffness (after 10 cycles) of this special nylon subrope with a comparable polyester subrope used in parallel strand ropes. At 50% of NBL, the strain in the polyester subrope is about 5% of its length, and the strain in the nylon subrope is about 13%. These strain values are similar to those for conventional polyester and nylon rope constructions.

Cyclic tension fatigue tests were conducted on both the small and large nylon subropes. Figure 7 is a cycles to failure (CTF) plot of the results of these tests. There is essentially no difference between the fatigue performance of the recently tested large subrope and that of the small subrope results reported in the previous paper. A dashed line shows the mean of these CTF data, determined by regression analysis.

The solid line is 2 standard deviations below the mean CTF line. It represents a suggested design CTF line, using the format employed in section 6.2 of API RP 2SK for fatigue resistance of mooring components.[15]

Figure 8 compares the cyclic load design line of this nylon subrope with those of other fiber and wire ropes and chain. It is similar to that of conventional polyester ropes. It is much better than that of conventional nylon rope constructions. It is also better than those of wire rope and chain in water.

For a typical renewable energy device mooring under consideration, the mean mooring load is 30% of NBL, and the cyclic load range is 6% NBL. A small subrope was cycled 10,000,000 times at this mean load and load range in a test which lasted thirteen months. After this cycling test, the rope's break strength was 94%of its original wet NBL.

A large subrope was cycled 20,000,000 cycles at that mean load and range. After this test, the rope's break strength was 108% of its wet NBL. It is not unusual for rope strength to increase during cycling. Examination of the rope interior after the break showed no apparent signs of abrasion wear.

Nylon Low-Friction Fairlead To Reduce Wear

A high-strength fiber rope pendant can be used as the connection to the MEC device instead of heavy, unreliable chain. The fiber rope pendant would pass through a low-friction nylon bell-mouth fairlead and a plastic lined hawse pipe. This work was funded by Innovate UK under the Marine Energy Supporting Array Technologies (MESAT) program.

The bell-mouthed fairlead is based on the nylon Panama fairlead developed by TTI and marketed by Nylacast. The material is Oilon grade nylon which has special lubricant to reduce friction and abrasion. That fairlead design is now used successfully on many gas carriers to reduce wear on synthetic fiber mooring lines.[16]

This bell-mouth fairlead is shown in Figure 9. The ratio of curvature of the bell-mouth to the rope diameter, D/d is 31:1. For testing, the fairlead was represented by a large Oilon grade nylon sheave having the same D/d ratio. It was repositioned before each series of tests to expose a new surface to the rope.

Tests were carried out on rope samples of three candidate materials for making the mooring pendants, Dyneema, Technora and Vectran.[17] The ropes were 32 mm (1.25 in.) diameter 12-strand braided fiber ropes manufactured by Bridon. The NBL of each of these ropes was about 83 tonnes. The rope and the fairlead represented the sizes of those which might be employed in field applications on WEC.

The portion of rope which passed through the fairlead was covered by a 4-layer protective sleeve designed to prevent the load bearing rope core from sliding within the rope cover. This sleeve also prevents heat generated by friction due to sliding over the fairlead from reaching the load bearing core.

The tests were conducted on a large cyclic bend and tension load test machine at TTI Testing in Wallingford, UK. This special test machine is shown in Figure 10. With this machine, one end of the test rope is cyclically raised and lowered to wrap around the fairlead while the entire rope is also cyclically tensioned to pull back and forth through the fairlead. Water was sprayed on the rope during testing.

In a first test series, all three candidate ropes were tension cycled 1419 times at a mean load of 40% of NBL and a load range of 20% NBL, while being cycled 473 times at angles up to 18 degrees. In these tests the protection sleeve showed no evidence of damage, and there was no measurable loss of nylon material on the fairlead. The Vectran and Dyneema rope samples did well in these initial tests.

A second test series was conducted on the Vectran rope and on both single and double Dyneema rope samples using a test matrix derived to represent 6 months of field service. This imposed over a million bend cycles and corresponding tension cycles. The mean bend angle throughout these tests was 12.5 degrees, with cyclic ranges of 6, 12 and 18 degrees. The mean load throughout most of the tests was 5% of MBL with load ranges up to 9% of MBL, but mean loads as high as 40% MBL with a load range of 20% were applied.

In these tests, the single Dyneema rope retained 64% of its new NBL. A second test was conducted with a doubled Dyneema rope to effectively double the strength and halve the rope stresses. In this test, the protection sleeve was placed by hand rather than braided by machine, and it was not firmly fixed in place. It slid along the rope and wore through, allowing the rope to rub directly on the nylon sheave. This caused the rope to heat up, weakening the HMPE fiber. As a result, that rope failed at 60% of its new NBL. This problem actually proved that the sleeve effectively serves as a thermal and abrasion resistant barrier to protect the rope.

After this test with the doubled rope, the internal fibers were in much better condition compared with the single rope. But bending and rubbing against the fairlead caused thermo-mechanical working of the fibers which altered the crystallinity of the HMPE material and caused the highly drawn molecular structure to revert towards its original undrawn state. The HMPE yarn lost strength as a result. This is a known characteristic with highly drawn rope making fibers and is especially a problem with highly drawn HMPE.

The 4-layer protective sleeve combined with the nylon liner performed well in protecting the pendant rope from external abrasion and frictional heating due to sliding over the fairlead.

These tests demonstrated that a special nylon bell-mouth fairlead in combination with a special 4-layer sleeve can successfully protect a synthetic fiber rope. A larger high modulus rope pendant with a properly applied protective sleeve would have performed much better. There was no significant damage to the nylon surface of the sheave which represented the bell-mouth fairlead.

The tests also identified the HMPE heat-induced strength loss problem and demonstrated a method of reducing and eliminating the problem.

Bag Anchors

A unique bag anchor system has been developed for use on sand, clay, rock, mud and other sea beds in which conventional drag embedment anchors and driven piles are impractical. It is a flexible bag filled with ballast appropriate for the specific site and application. The ballast is a heavy, pourable material, such as local sand or aggregate, or heavier “drilling” mud or scrap steel pellets.

The bag anchor functions as a conventional gravity type anchor. A group of anchor bags is enclosed within a fiber rope containment net and is joined to the mooring line by yokes, as shown in Figure 11.

Each cylindrical bag is about 2 m (6.6 ft) diameter and 2 m high. The bag consists of an abrasion resistant carcass with lifting straps and top closure. An inner impermeable liner might be used where the ballast poses an environmental concern. Lifting straps are sewn to the carcass.

The anchor bag is transported to the site in a collapsed form. The bag is filled with ballast weight on shore or offshore prior to deployment or it is filled after being placed on the seabed.

The bag anchor concept can be economical when compared with alternative gravity anchor systems. A bag anchor would cost about $250 per wet kip (1000 lb weight in water) using local aggregate and maybe cost less with denser material. Estimates show that cast reinforced concrete and scrap steel chain would each cost about $600 per wet kip and that fabricated steel gravity anchors would cost about $1000 per wet kip. The bag anchors could be delivered to the site empty, thus avoiding shipping costs incurred with the alternatives.

The bag anchor concept was originally conceived by TTI. It is being developed through a consortium with anchoring specialists at Vryhof Engineering, the University of Exeter and TenCate. The bag anchor development, along with the nylon rope development was funded by the UK Carbon Trust under the Carbon Trust Marine Energy Accelerator Grant and the Scottish Government Marine Renewables Commercilisation Fund.[18]

The investigation of feasible mooring systems began in 2008. The bag anchor design was developed in 2009. Small scale testing of bags, nets and deployment methods were carried out during 2010. A prototype bag anchor, using geotextile bags, was manufactured in 2011. Lifting trials were carried out on partially filled bags at the University of Exeter at Falmouth in 2012.

The empty bag anchors were then transported to the Isle of Man in 2013. An assembly of seven anchor bags was placed on the Douglas harbor floor at low tide, enclosed within a containment net, and filled with ballast. This arrangement is shown in Figure 12. After the assembly was submerged at high tide, a harbor tug pulled on it at an upward angle with the tugs full bollard pull capacity of 5 tonnes (11 kip). No displacement of the assembly was observed. This demonstrated a friction coefficient on the seafloor of at least 0.45, and it is probably substantially higher.[19]

A full-size bag anchor system was manufactured in 2015 for future deployment at a test site. Continuation of the test program is now awaiting further funding.

Conclusions

The nylon parallel subrope type rope design has been thoroughly tested to demonstrate its suitable for use on MEC moorings and other similar shallow water buoy and platform moorings. The nylon parallel subrope type rope has more stretch but less endurance than the similar polyester parallel subrope type rope. It has better endurance than chain and wire in water and much better endurance than conventional nylon rope constructions. When more stretch is needed than can be provided by polyester rope, the nylon parallel subrope design is a very good candidate for use in mooring systems.

The low friction nylon bell-mouth fairlead has been demonstrated to be suitable for use on buoys and platforms to protect fiber rope pendants. However, further development and testing of the high modulus fiber rope mooring pendant should be done. When fully developed, a fiber rope mooring pendant used with the low friction fairlead can replace heavy, failure-prone chain on buoys and platforms.

The bag anchor system has undergone limited testing. A prototype bag anchor system is ready for deployment but is awaiting funding. It can be used as a gravity anchor on rock, sand, clay and other sea beds on which drag anchors and piles are impractical. The bag anchor system can be more economical than other gravity anchor material alternatives.

Each of these new mooring system components can be used independently with other conventional components (e.g. nylon mooring line with drag embedment anchor). The high modulus fiber rope through low friction fairlead and the bag anchor system concepts require further development. The nylon parallel subrope type rope is ready for use on MEC device moorings and other suitable mooring applications.

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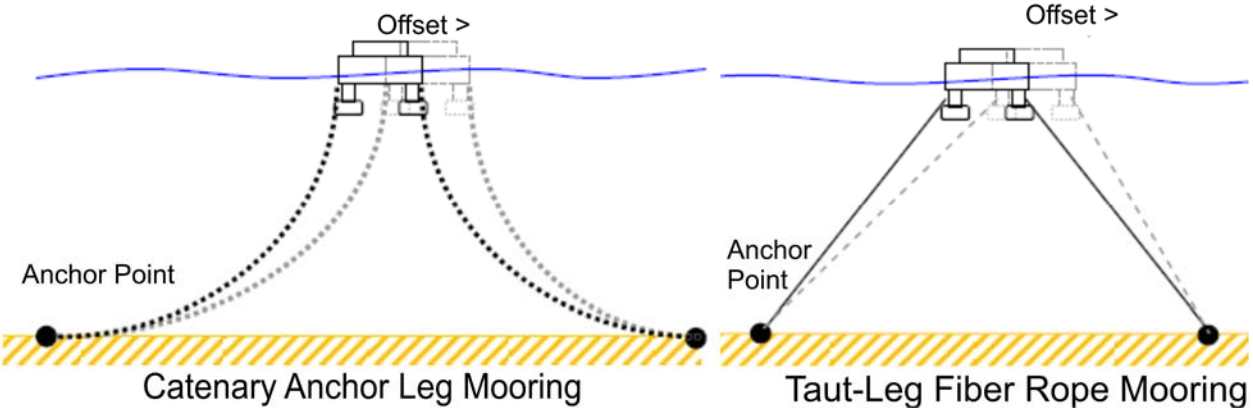

Figure 1 Catenary Anchor Leg and Taut-leg Fiber Rope Mooring Systems

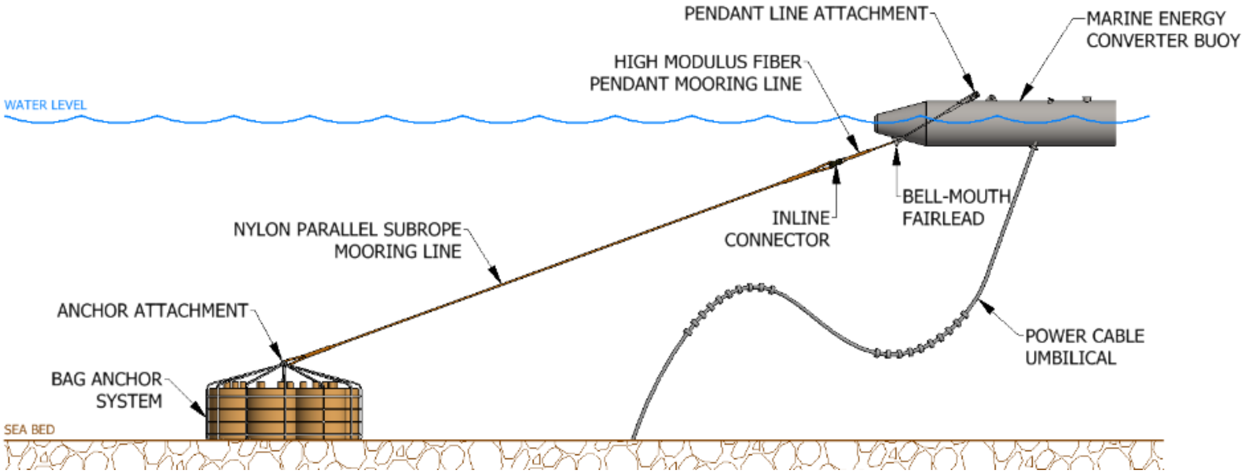

Figure 2 Marine Energy Converter Buoy Mooring System, with Bag Anchor System, Nylon Parallel Subrope Mooring Line and Bell-Mouth Fairlead

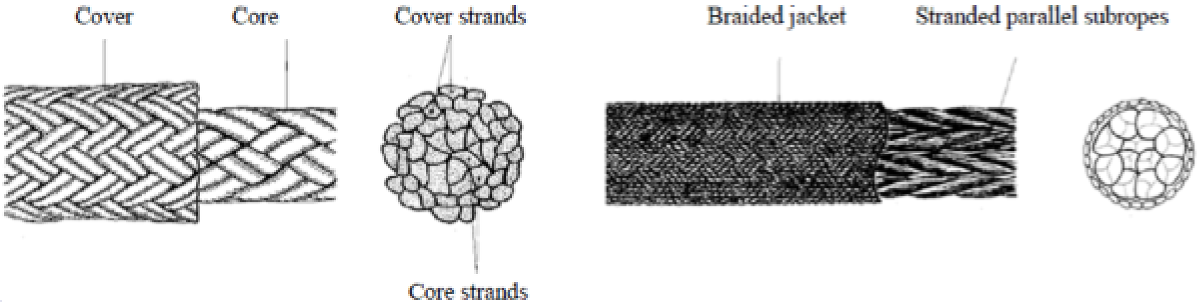

Figure 3 Double Braid and Parallel Subrope Constructions

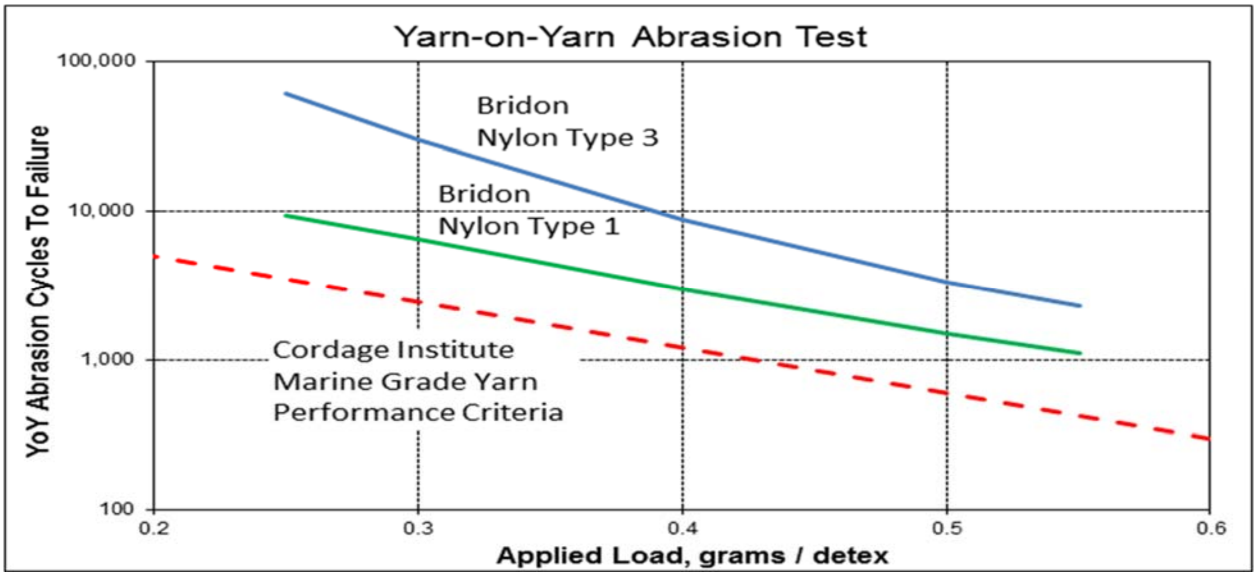

Figure 4 Bridon Subrope Nylon, Yarn-on-Yarn Abrasion Performance

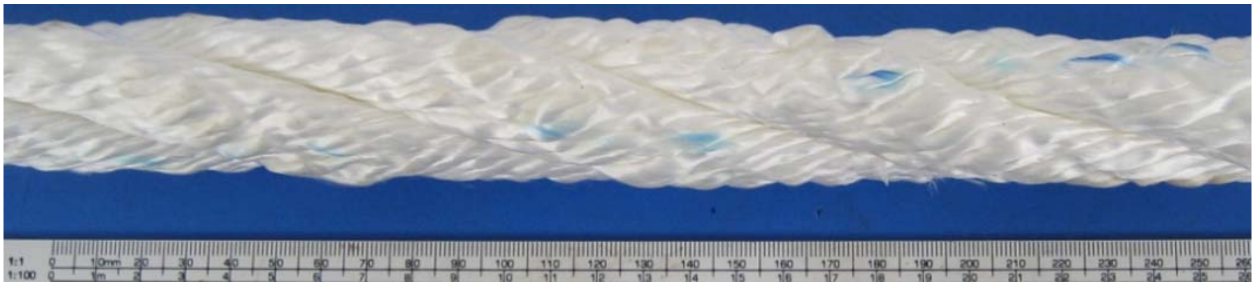

Figure 5 Bridon Nylon 3-Strand Subrope

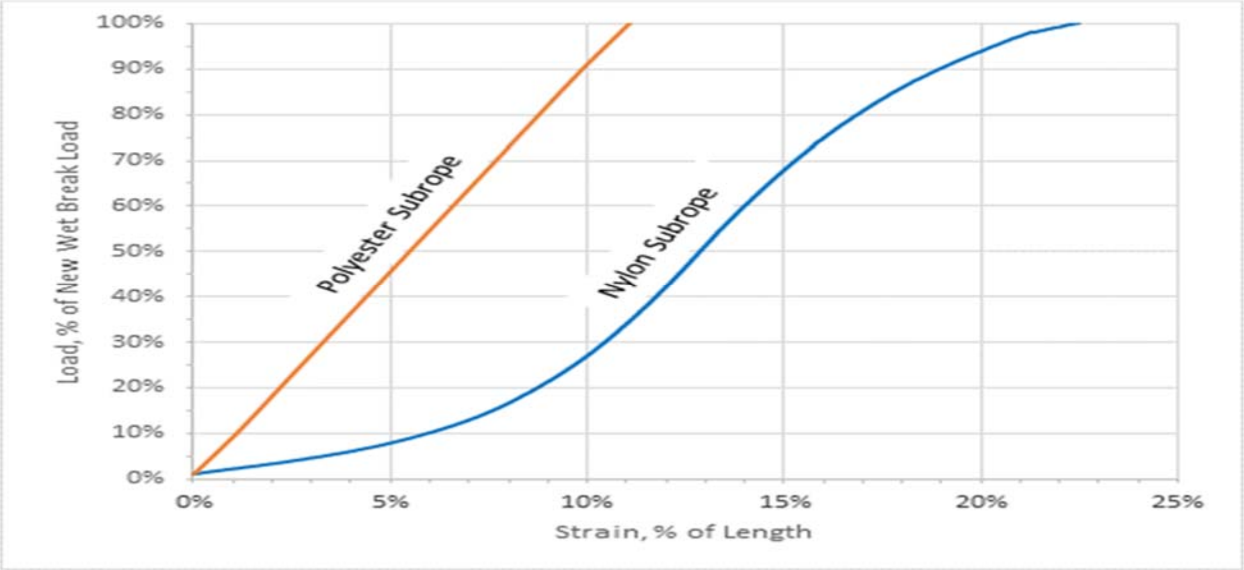

Figure 6 Nylon and Polyester Subrope Force vs. Strain Graphs

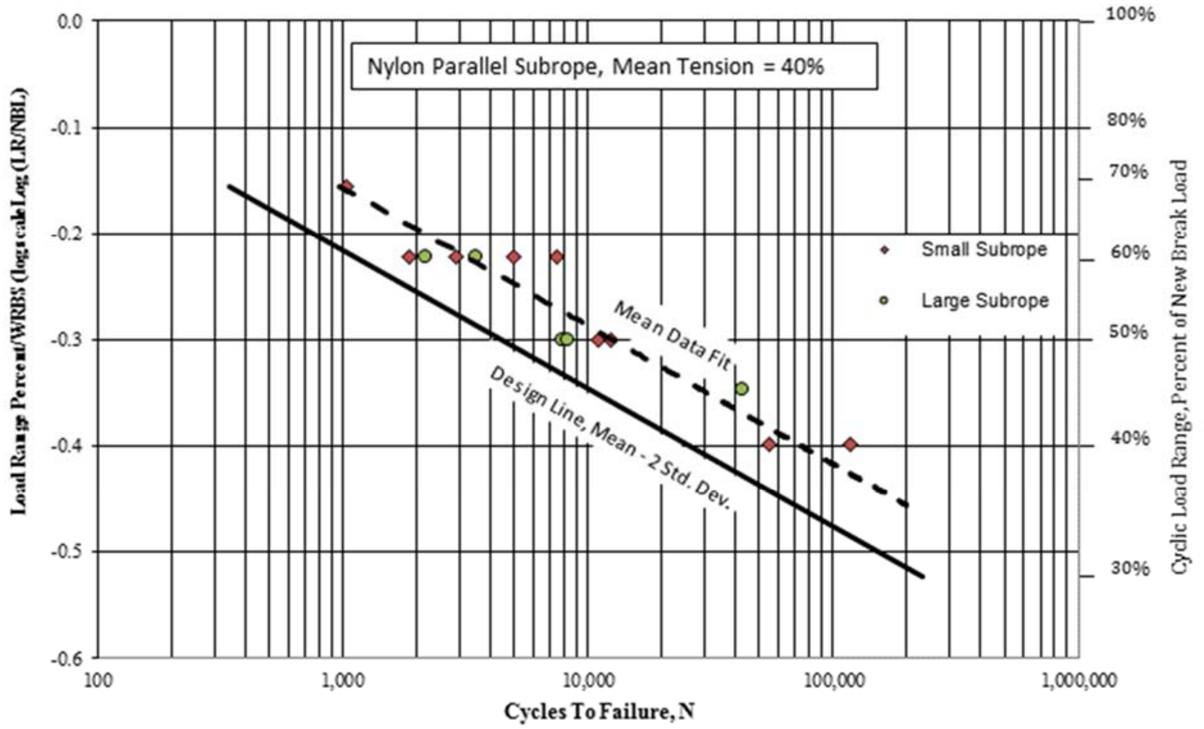

Figure 7 Nylon Subrope Cyclic Tension Fatigue Test Results

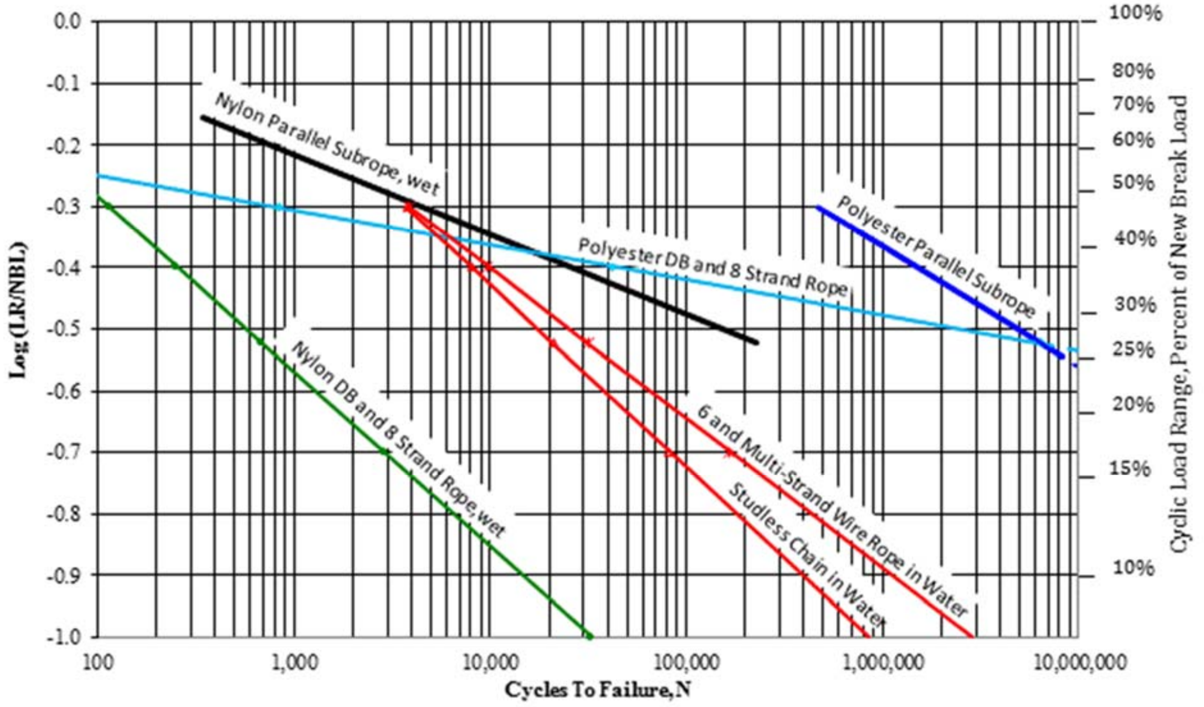

Figure 8 Comparison of Cyclic Tension Fatigue Performance

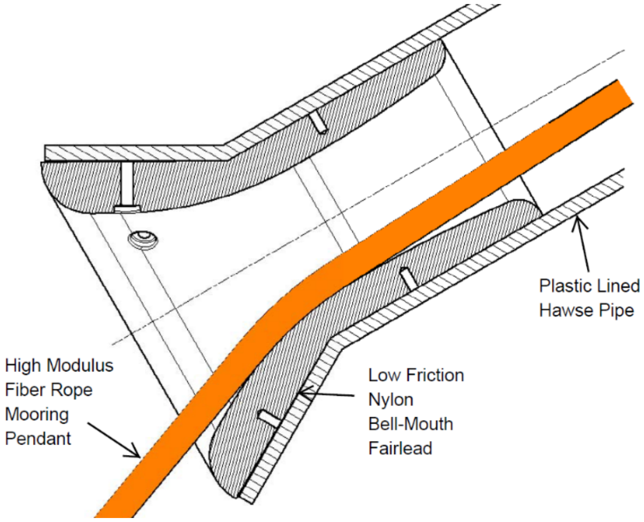

Figure 9 Nylon Bell-Mouth Fairlead Liner for High-Strength Fiber Rope Mooring Pendant

Figure 10 Cyclic Tension and Bend Test Machine, TTI Labs, Wallingford

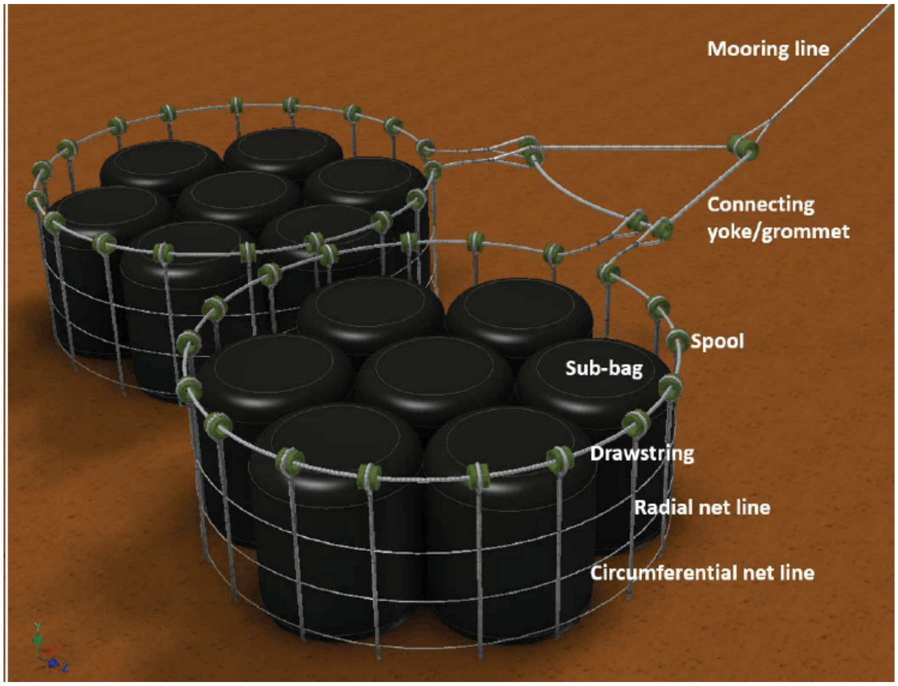

Figure 11 Tandem Anchor Bag System with Net and Connecting Yoke

Figure 12 Prototype Bag Anchor System on Harbor Seafloor, Isle of Man, for Pull Tests