

OTC 20844-PP

Fiber Rope Tether Manufacturing - Current Best Practice and a Vision of the Future

David S. Rowley, Offspring International Ltd
Sergio Leite, Lankhorst Ropes S.A.

Copyright 2010, Offshore Technology Conference

This paper was prepared for presentation at the 2010 Offshore Technology Conference held in Houston, Texas, USA, 3–6 May 2010.

This paper was selected for presentation by an OTC program committee following review of information contained in an abstract submitted by the author(s). Contents of the paper have not been reviewed by the Offshore Technology Conference and are subject to correction by the author(s). The material does not necessarily reflect any position of the Offshore Technology Conference, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper without the written consent of the Offshore Technology Conference is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 300 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgment of OTC copyright.

Abstract

Polyester Mooring Tethers are gaining wide acceptance in the Gulf of Mexico, Brazil and other areas of deepwater mooring operations. This paper looks at current rope manufacturing, developments in splicing technology, length accuracy measurements systems, rope manufacturing length and breaking strength limitations, and developments in synthetic polymer raw materials.

Current areas of deepwater rope research and development include improvements in jacket cut resistance, improved termination designs between rope and rope or rope and chain or wire, higher integrity sand barriers and stiffer materials for next generation mooring lines at ultra-deepwater depths. These developments are necessary to allow the deployment of fiber rope moorings in harsh environments such as the Arctic, into ultra-deepwaters and conversely into shallower water applications, and to embrace alternative deepwater installation techniques, such as pre-lay on the sea bed.

In recognition of the need to give naval architects and installation contractors' more options and ideas to develop alternative, cheaper and quicker methods of installing mooring systems, the future for Fiber Rope Tethers is reviewed. Of particular importance is the need for longer, stronger, lighter and more robust Fiber Rope tethers, composite rust free lightweight connectors to complement the rope's characteristics, installation using low cost anchor handling vessels and rental deployment systems, pre-laid moorings deployed on the seabed months before hook-up, and better ways of bedding in creep and use of lower pre-tensioning loads in mooring ropes.

Introduction

Polyester rope mooring tethers are gaining wider acceptance in deepwater mooring operations. The benefits of polyester rope moorings are compelling: lighter, easier to handle and with excellent mechanical properties to withstand the loads and elasticity demands of deepwater mooring.

As mooring lines move to greater water depths, and further offshore, however, the engineering integrity of the mooring rope and its splice are critical to effective station-keeping. With improvements in anchoring systems design and chain quality, the focus is now on the mooring rope, and its connectors, to deliver the mechanical performance needed for ultra-deepwater moorings.

Splicing Technology

Polyester mooring ropes are a key component of deepwater and ultra-deepwater mooring systems. The mooring line is made up of one or more lengths of rope joined together by connectors. The longer the rope, the greater the number of connectors needed, including rope-to-rope, rope-to-chain and rope-to-wire connectors.

The rope is spliced to facilitate the connection. The quality of the splice is vital to ensuring the integrity of the mooring line. For example, in Fig. 1 the Gama 98 and Moduline sub-ropes are colour coded for identification purposes so that they have the same position throughout the rope, within each eye and are spliced to themselves.

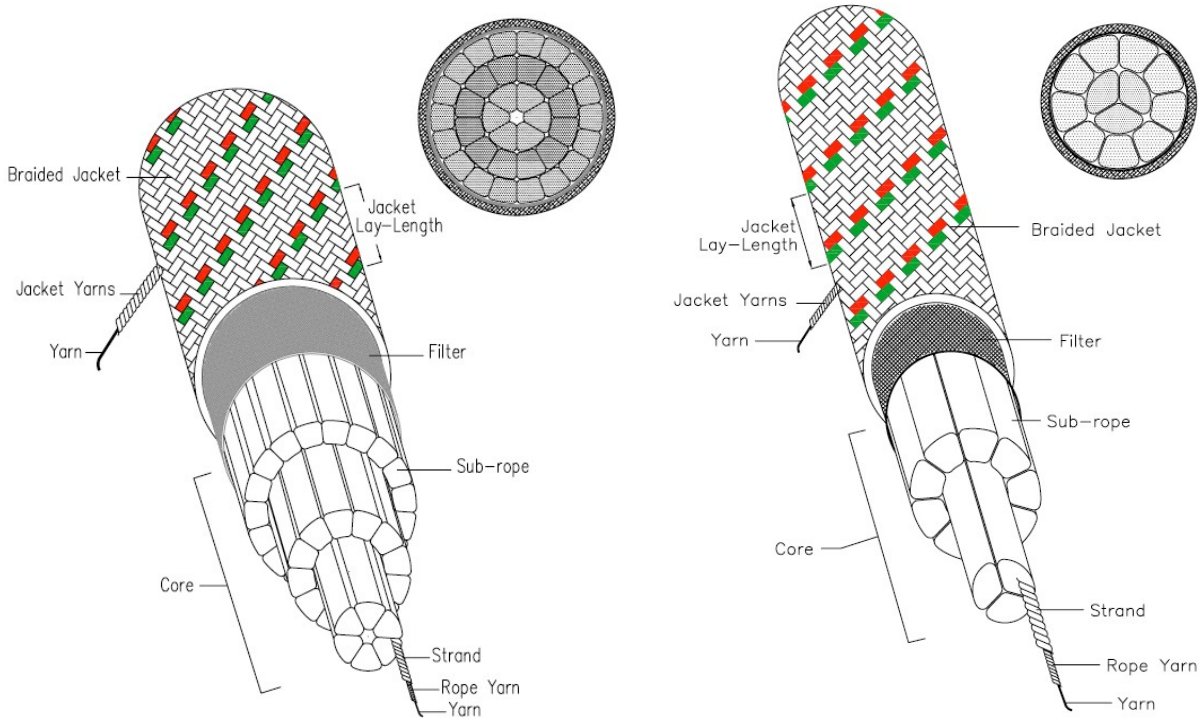


Figure 1 - (L) Moduline with multiple 3 strand sub-ropes and (R) Gama 98 comprising 12 hollow braid, 8-strand sub-ropes.

The evolution of deepwater rope splicing

The ideal splice

Deepwater rope construction involves multiple sub-ropes which are terminated either by hand splicing terminations or potentially with socket terminations. The eye splice is engineered for high efficiency strength realisation. To achieve this, each sub-rope is allocated a preset position around the eye so that the load is shared equally by all the sub-ropes. In the ideal splice each sub-rope is exactly the same length (Fig.2). In reality there will always be some variation.

The effect of length variation between sub ropes is an unequal loading on the shortest sub-rope in the eye, resulting in a shorter fatigue life (Table 1). Failure of the shortest rope initiates a domino effect as the next shortest rope it in turn takes an increasing load leading to catastrophic rope failure (Fig.3). It follows that the maximum break load of the assembled rope is governed by the length variability of each sub-rope within the rope.

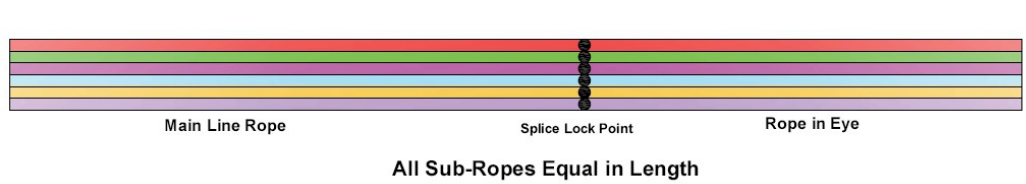


Figure 2 - Ideal Splice and Length Variation

Considered Individually as Sub-Ropes				
Sub-Rope Identity	Relaxed Sub-Rope Length	Sub-Rope Ext to Break	Length at Break	Length Variation
1	250	25	275	100%
2	260	26	286	104%
Considered Within a Tether Assembly				
1	250	275	25	100%
2	260	275	15	58%

Note: Above figures are based on Polyester having an extension to break of 10%.

Table 1 - Sub-Rope Length Variation within a Tether Assembly

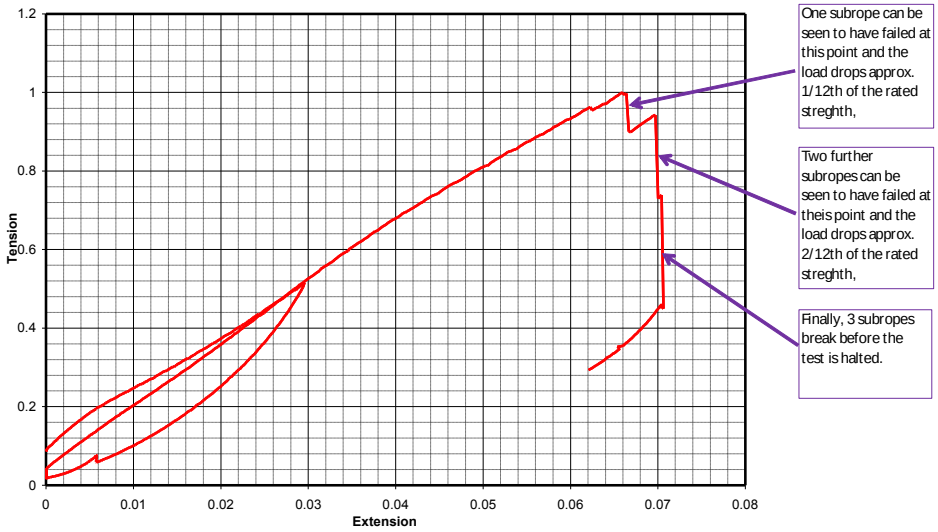


Figure 3 - the effect of poor splice geometry.

In the table above, the length variation is not only caused by poor geometry in the splice but also by differential back tension of sub-ropes during tether manufacture. This problem is compounded when using high modulus products such as High Modulus Polyethylene (HMPE), Liquid Crystal Polymers (LCP) and Aramids, especially where the fibers do not creep to allow for equalisation of loading.

Having established that the ideal splice requires equal length and tensions, let us now consider some splice design issues.

Type 1 splice

In Type 1 splicing the outer sub-rope stays on the outside and follows the longest path, conversely the inner sub-rope has the shortest path around the eye (Fig.4). This design has all the sub-ropes maintaining the same angle of attack in the rope structure to minimise cross-over.

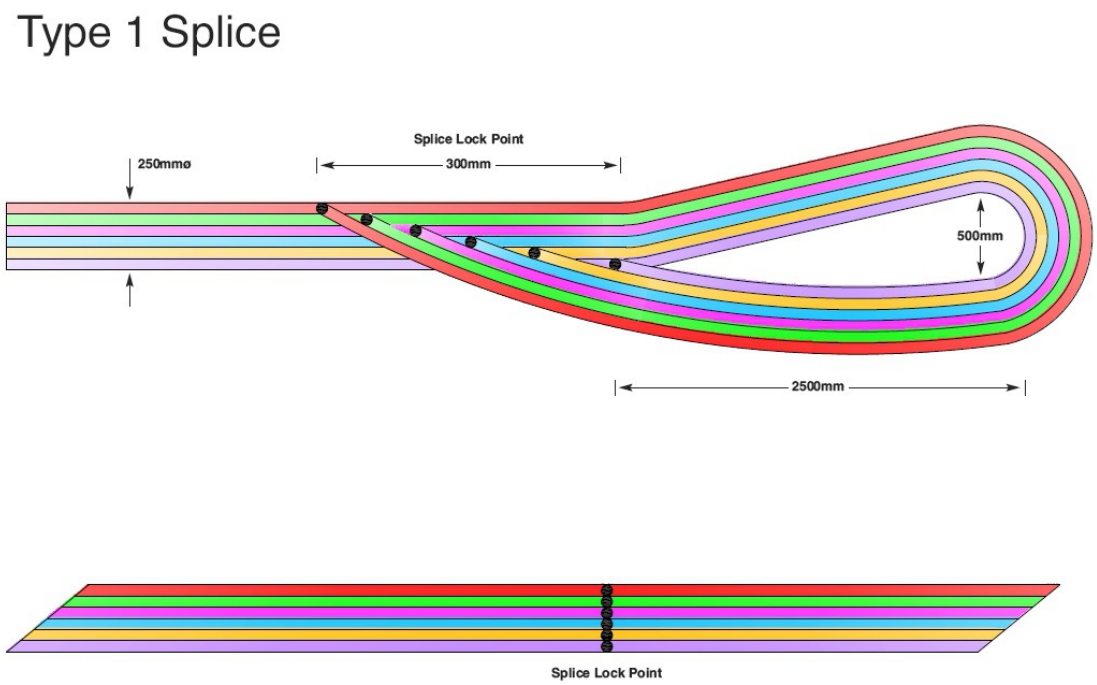


Figure 4 - Type 1 splicing

The different “lock-points” result in length variation in the main sub-rope length. When there is (say) 1,000m between splices, a few centimeters length variation is negligible, but in an insert or test piece with only 2-3 meters of rope between the tail of the splice this length variation is several percent and becomes the weakest point of the rope. This length variation can be reduced by having opposing direction of splices for the left and right hand splices of an assembly.

The load in each leg of the eye (to the right hand side of the lock point) is only 50% of the load to the left of the lock point, as the load is shared between the two legs of the eye, so some length variability should be acceptable. The optimum splice design is one where all sub-ropes in the tether fail simultaneously between the splices.

Type 2 splice

In Type 2 splicing the splice “lock” points are on the same line across the tether (Fig.5). All sub-ropes between the splices should now be the same length (assuming equal tension during manufacture).

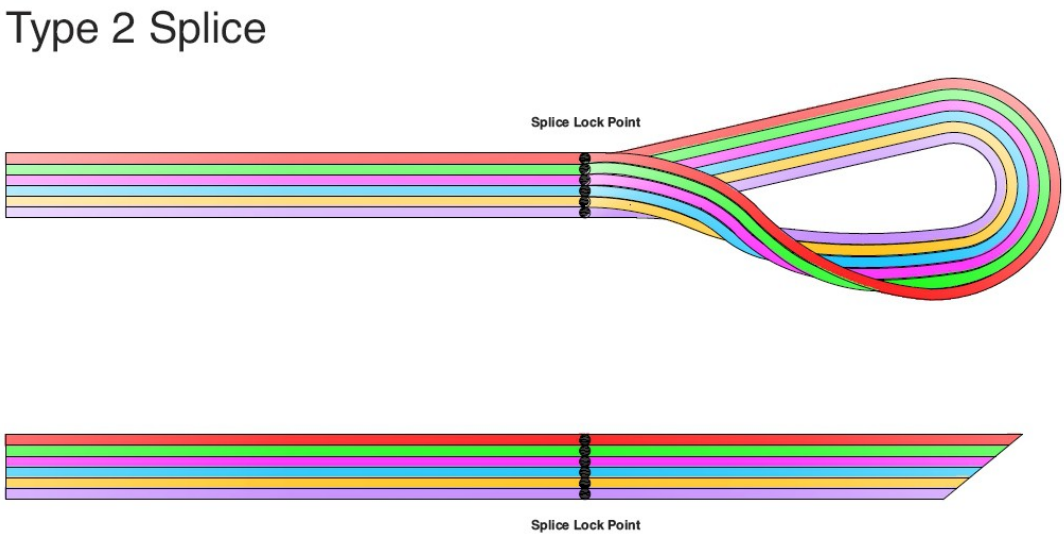


Figure 5 - Type 2 splicing

There is an increase in "cross-over" as sub-ropes pass through the tether structure. Misalignment will result in high abrasion and poor fatigue life. The outer sub-ropes are still longer than the inner sub-ropes. For this reason, it is essential that the fatigue test is maintained as a Type Test within the classification society rules, to ensure that a splice design however efficient does not create high internal abrasion and result in a short fatigue life. However, this should only be necessary on the largest size rope to be qualified, providing the splice geometry does not change for smaller ropes.

The splice will be much thicker than Type 1 at the localised area where all the sub-ropes interface. Note that increasing the D;d ratio of thimble bearing radius to rope diameter has reduced the length variation between inner and outer sub-ropes. Remember that the eye only sees 50% of load compared to the main line, thus 8% length variation can be considered as equivalent to 4% in the main tether (Table 2).

MBL		4200 kips		1907 Tonne								
Bottom of Groove diameter =				860			Each subrope MBL				183	
Rope diameter =				254			Aggregate Strength				2196	
Eye diameter =				270			Average Strength				2050	
D;d ratio =				3.19								
Jacket Thickness				9			Average extension at Break				10.75%	
Depth per layer when compacted				48								
Contact Arc				202	degrees							
Sub rope Layer	Subrope Radius		Bearing Length over 202 degrees	Effective sub-rope length to splice lock	Effective sub-rope length to splice lock at break (10.75% Ext)	Variation in length to break	Relative variation in length at break	Relative Variation in length at break load	predicted sub-rope Failure load	predicted Tether Failure load	ACTUAL AVERAGE TETHER BREAK LOAD	PREDICTED VERSUS ACTUAL VARIATION
1	462		1629	6629	7341	713	0	0.00%	183	2196		
2	510		1798	6798	7529	731	18	0.25%	179	2145		
3	558		1967	6967	7716	749	36	0.50%	175	2095		
4	606		2136	7136	7904	767	55	0.74%	170	2044	2050	0.29%

Table 2 - example calculation of a Type 2 splice showing the close correlation between theoretical strength based on length variation compared with full scale testing.

Type 3 splice

For Type 3 splicing in order to achieve equal length in all sub-ropes it is necessary to either put 180° twist into the rope within the eye before starting the splice or, as shown here, have a high degree of internal cross-over to the splice lock points (Fig6). Neither of these options has been shown to be successful because of the effect of poor geometry leading to increased internal abrasion. (See comment regarding fatigue testing under Type 2 splice.)

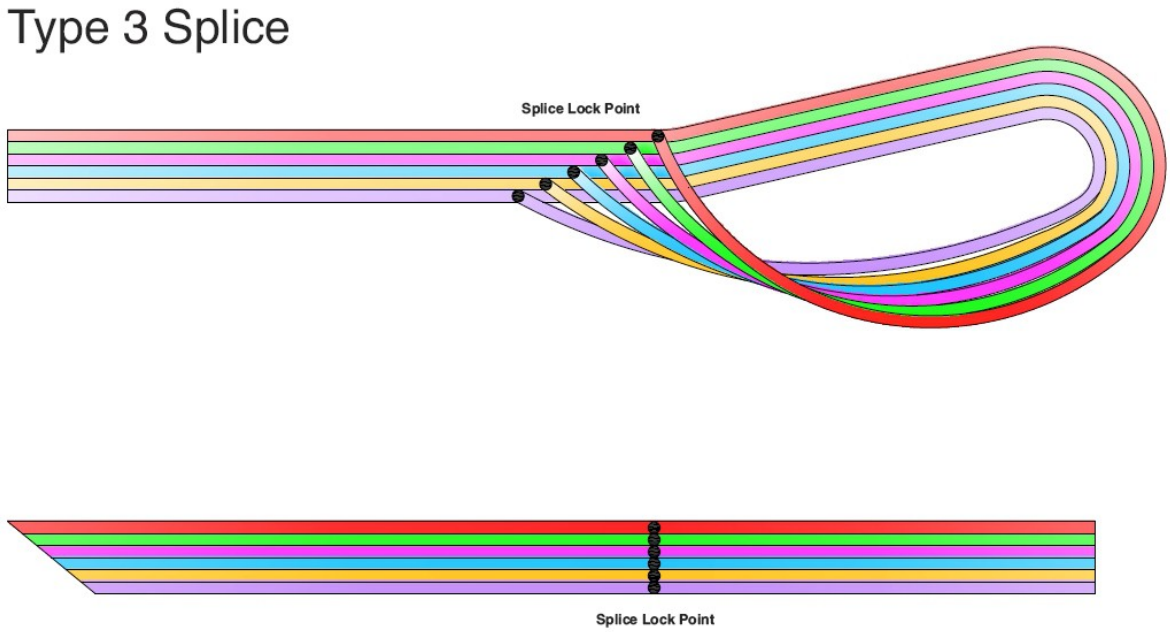


Figure 6 – Type 3 splicing

Type 4 splice

Type 4 splicing is a simple and effective way to minimise length variation in both the main line and eye by splicing the sub-ropes into "Pairs".

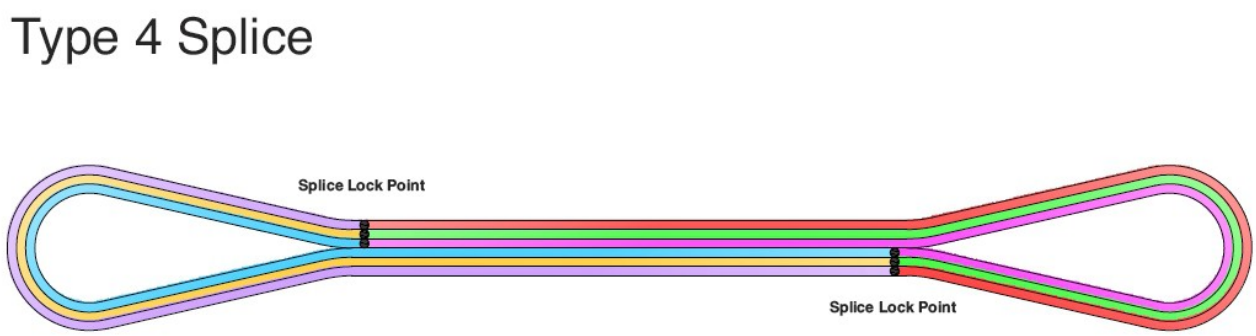


Figure 7 - Type 4 splicing

The benefit is that any length (or tension variation) is spread over 2x lengths of the tether. This method is also cheaper to fabricate as only 50% of the number of sub-ropes splices are needed (only three joints at each end instead of six in the case of a full eye that is spliced at each end. (Our example uses just six sub-ropes – in reality there are many more sub-ropes.)

The downside of this type of splice is that should the tether be accidentally damaged, the endless loops mean that for each damaged sub-rope, two lines are effectively removed from service, doubling the severity of the damage. A further problem is that each leg of the eye is now seeing 100% of the tether load, rather than 50% of the load for a conventional eye splice. For these reasons we are not in favour of this type of splice

Type 5 splice

In a Type 5 splice to reduce length variation as the multiple sub-ropes go round the cylinder or thimble roll, the most effective splice would be to have all the sub-ropes spread out in a single line, so they all have the same path lengths (Fig.8). Unfortunately this would result in a thimble or pin on a shackle or H-link fitting that was very wide and subject to enormous bending moments.

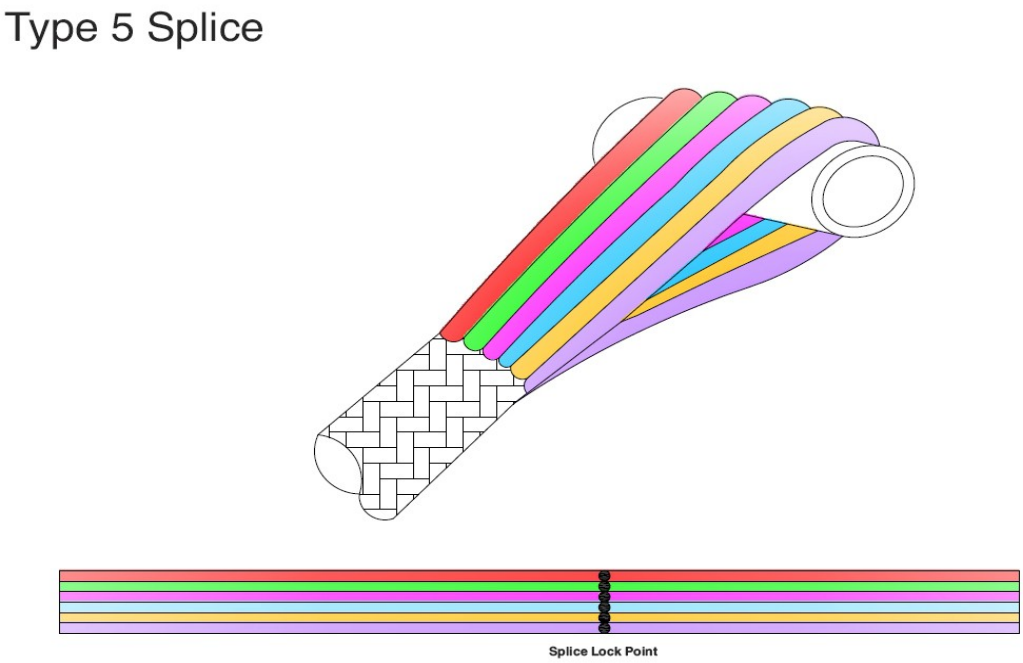


Figure 8 - Type 5 splicing

The type 5 shown here is with six sub-ropes in a single layer thimble. In practice we would have 12 sub-ropes and arrange the sub-ropes in a 6 x 2 layer configuration. This layout may appear strange when compared to a multiple layer thimble but we are minimising compression damage and length variables. This is the design adopted for the Thunder Hawk floating production unit (FPU) in the Gulf of Mexico.

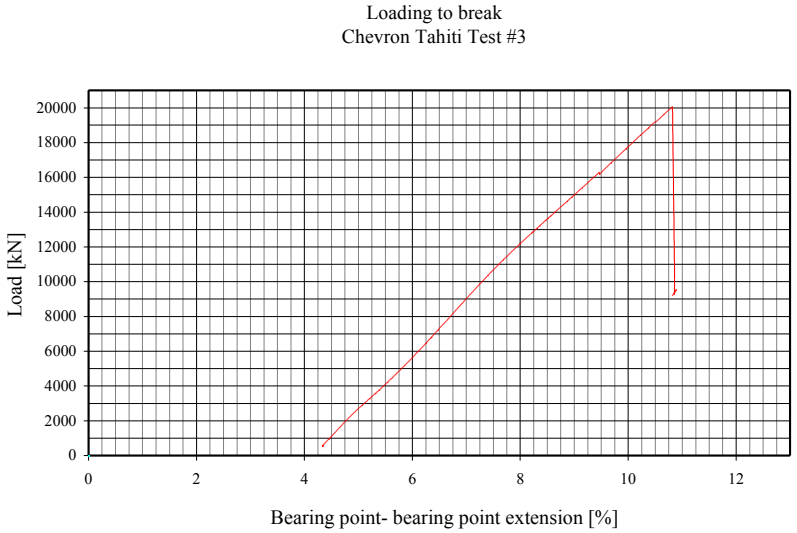


Figure 9 shows an example of a well balanced Type 5 splice with simultaneous failure of all sub-ropes.

Rope Length Accuracy

We have spoken a lot about the need for rope length accuracy within the splice to guarantee all sub-ropes work together to maximise ultimate breaking strength. Overall length accuracy is just as important to the client so that the top chain length can be minimised. A 0.5% line length “safety margin” in the top chain may be worth millions of dollars. Accurate rope length measurement enables significant project savings. A 50m top chain length saving per line on a 12 leg mooring system equates to savings of approx. $700,000 with R4 chain, and nearly $1M for Grade 5 chain.

To ensure length accuracy, ropes for deepwater tethers are manufactured under a machine tension of approximately 1 tonne back tension.



Figure 10 - Rope measurement system capstan holds rope under tension.

A rope Length Measuring System (LMS) for length measurement under a controlled tension is used (Fig.10). The rope is pre-tensioned to 1% MBL (current limit 20 tonnes) for length measurement in 75m (260ft) increments. Prototype testing always starts from the same reference tension of 1% MBL. Length accuracy is achieved with a laser gun and mirror which is calibrated to 75m ±3mm (260ft ± 0.12 inch). The rope is marked at each 75m (260ft) increment and the marks, numbered sequentially (1=75m (260ft) ; 2=150m (520ft); etc), are recorded by digital camera, thus minimizing the risk of human error. Feedback from recent projects such as Tahiti, Thunder Hawk, and a recent FPSO project, where the length of rope was double earlier deepwater projects, has confirmed the rope and system's accuracy.

Length and Break Strength Test Limitations

All synthetic mooring ropes are subject to fluctuating loads; therefore, tension-tension fatigue performance is an extremely important property. At present the maximum capacity within Europe is a test machine rated at 2,500 mT (5,500 kips). Taking into account the 'Average – 2 standard deviations' to obtain the rope's 'Rated Strength', then the maximum break strength that can currently be tested is approx. 2,400 mT (5,200 kips).

As the mooring industry continues to drive up the performance of mooring lines, so it is inevitable that either a bigger break strength test machine is needed or an alternative way of certifying ropes at loads beyond physical testing capacity is required. At present the typical break strength requirement for a deepwater FPU is 4000kips (1,907mT). This will increase as production moves to ultra-deepwater or to Arctic conditions with ice loading factors. Using polyester yarns the mooring industry can produce a rope of approx. 2,750T (6,000 kips) Minimum Breaking Load (MBL) without modification to the rope manufacturing plant, and 4,500T (9,900 kips) MBL in High Modulus Polyester (HMPE).

Maximum rope length is a function of the maximum reel weight and the linear weight of the rope which is required to meet the MBL dictated by the required breaking load (Table 3). Typical production lengths capacities vary dependent upon the take-up

reel capacity, for example.

Tether Strength	Length
800T	4,000m (13,000ft) (80T weight of rope) increasing to 5,000m (16,404ft) (100T weight of rope)
2,000T	1,700m (5,577 t) (80T weight of rope) increasing to 2,100m (6,890ft) (100T weight of rope)

Table 3 - simply upgrading a reeling machine can significantly increase the available rope length per reel.

Rope Raw Materials

Deepwater mooring lines are made from a range of synthetic polymer materials. The elasticity of a mooring line is important. It is a measure of the line's capacity to stretch under load. The higher the elasticity, the greater the line will stretch and absorb higher dynamic loads. The elasticity of a mooring line primarily depends upon the following factors: material and construction, length and diameter.

Current deepwater mooring line materials

Polyester - polyester rope tethers are made from high efficiency sub-rope cores laid parallel within an outer braided jacket. Each sub-rope is computer monitored during tether manufacture to ensure all sub-ropes have equal tension and length. Typically, Gama 98 deepwater mooring ropes comprises 12 sub-ropes, each sub-rope being of a long lay length 8 x 1 construction, which gives a 100% torque free rope.

The fatigue life of polyester rope is typically quoted as being approximately 80 decades superior to steel wire rope. The tether normally becomes up to 10% stronger during initial cycling as the molecule chains in the individual yarns straighten out under constant cyclic loading before losing strength and returning to initial Minimum Breaking Load after approximately 30% of the fatigue life.

High tenacity polyester offers high tensile strength, high modulus/low shrinkage, high tenacity (> 9 grams/denier), low elongation at break, high dimensional stability/low creep and high durability/low fatigue. The material is already used in some MODU moorings but not in permanent moorings due to concerns over creep. However, in the drive for deeper mooring systems there are rope concepts involving high tenacity polyester which create a hybrid combination mooring system.

Alternative potential deepwater mooring line materials

High performance fibers such as Aramids and HMPE are characterised by very high stiffness. This enables lighter and smaller diameter ropes; however, the stiffness translates into higher fatigue loading on other line components. Creep is an issue for HMPE fibers which is directly proportional to operating temperature and mean load. Whilst Aramid fibers suffer from reverse bend fatigue necessitating a minimum loading requirement on the leeward lines. These “shortcomings” can be overcome with appropriate design allowance.

There are a number of new polymers under evaluation as potential ultra-deepwater rope materials, these include:

Liquid Crystal Polymer (LCP) - LCP fibers are five times stronger per unit weight than steel, and retain their strength over a broad temperature range. They show no measurable creep under load at up to 50% of threadline breaking point, and exhibit good fiber-to-fiber abrasion resistance with correct coating applied. Compared with Aramid they perform better in tensile strength tests.

Polyethylene Napthalate (PEN) – hybrid polyethylene – is not as stiff as high modulus polyethylene but has the benefit of polyester-like stability**.**

In general high performance fibers are smaller in diameter and have a lower mass/m than polyester, making the ropes easier to handle and with a smaller winch storage capacity for a given rope length. However it should be borne in mind that abrasion damage tends to increase as wear occurs over a smaller contact area.

Another practical issue when selecting materials of the same stiffness for a mooring rope is that longer lines allow greater surface motions. A 2,000m line may allow 40m of vertical movement, whereas a 3,000m line would allow 60m under the same environmental conditions. This translates to greater horizontal offsets which may exceed riser limits. Stiffer materials or hybrid mooring systems will be required to compensate for the longer line lengths.

On-going areas of mooring line research and development

In addition to developments in rope splicing technology, as oil and gas operations move into deepwater further offshore, other factors that have a bearing on the rope's deployment and performance in-service are also being researched.

Improved cut resistance

Improved cut resistance of jackets is a high priority to minimise damage from fishing trawlers and so preserve the engineering integrity of the rope. Although the problems tend to be localised, it needs to be tackled to enable the development of oil fields in high risk zones.

Improved termination designs between rope and rope or rope and chain or wire

As the mooring line goes deeper so more connections are needed. Reducing the number of connectors by increasing the length of continuous rope between connections is the preferred route, however, there are not enough vessels capable of handling very long lengths of rope and these vessels tend to command high day rates. To use more readily available vessels with lower day rates typical restricts lengths to approximately 3,280ft (1,000m).

H-link, Pearlink and Platelink connections are labour-intensive, and time consuming to assemble offshore. Moreover, they are prone to being weakened by the bending moments experienced when deployed over the mooring boat's stern roller. This is less of a problem for short term MODU drilling moorings, but is an area of concern for long-term, 30 year, deepwater moorings.

Drawing on the Type 5 splicing methodology, an improved mooring rope connector has been developed to meet the following requirements:

higher engineering integrity than current plate links and thimbles connectors
smaller and lighter than current connectors for the same MBL
safer and easier to assemble offshore, whether vertically or horizontal
easier to run and retrieve across stern rollers and on anchor handling vessels.

The connectors are based on an improved rope splicing design. In place of the single, large eye splice used with thimble connectors, for example, the connector features a more compact eye splice. This enables the splice to be closer to the 'ideal splice' design with sub-ropes the same length, making it more compact, and thus stronger, than a single large eye splice.

Offshore mooring connections can be difficult and sometimes hazardous task. In addition to a better splice, the connectors offer a range of make-up options to provide safer connections that improve connector handling during line installation.

Three types of connectors have been developed: Clam, Snap and Link, for rope-to-rope and rope-to-chain connections.

In each case the connector design relies on the rope being spliced into a forged steel, sub-connector during rope manufacture. These are subsequently secured within the connector during make-up offshore. This has clear practical benefits in terms of the ease and speed of mooring line deployment, allowing the full connector to be assembled in half the time of conventional connectors, according to trials of the new design rope connectors.

• Clam – fiber rope to fiber rope (R2R) and fiber rope to chain (R2C): spliced rope sub-connectors enclosed within clam shell case. The rope-rope clam connector works by taking the rope end splices integrated with the sub-connector and inserting them into the clam connector which is then bolted together to make the rope to rope mooring line connection.

• Snap - fiber rope to fiber rope (R2R): spliced ropes integrated with the connector's two halves during rope manufacture and snapped together offshore.

The snap connector (Figure 11) uses proven, ball and taper technology to allow the end of each rope to be pushed and securely held within the connector body. This type of connector is designed to allow the rope connection to be made using a deck crane.

• Link – fiber rope to fiber rope (R2R): spliced ropes integrated with connectors (female clevis head and male padeye). The connector is joined using a pin.

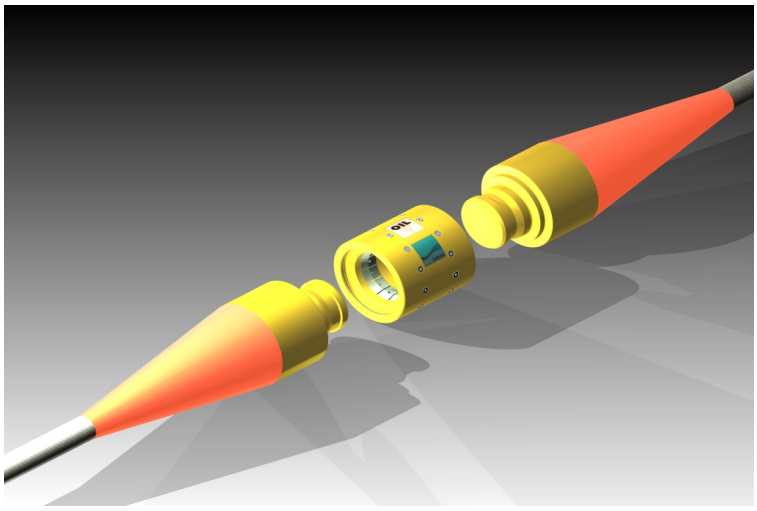


Figure 11 - shows the Snap connector for rope-to-rope connections

Both the Snap and Link connectors are designed to be made up by hanging them over the side of the mooring line installation vessel with the rope in the water. The Snap is held vertical to the water while the Link is held horizontal to the water during the rope / chain connection and then lowered into the water.

Higher integrity sand barriers

Filter elements are used between jacket and sub-rope cores to prevent sand particles getting between the sub-ropes and causing abrasion damage. The filters can be either air or water filters. Air filters are good at preventing particle ingress but also trap air in the rope;

Water filters are effective in filtering out particles greater than 5 microns whilst allowing free flooding of the rope but must be handled with care. Filter systems can be provided to allow for ropes to be pre-installed on the seabed prior to hook-up.

For Drilling / MODU vessels, higher integrity sand barriers are now available which will allow ropes to be pre-laid on the sea bed ahead of the surface production arriving on site. By improving the sand barrier design they can also be used for longer term deepwater moorings, enabling the mooring lines to be laid in advance, and by smaller vessels, when sea conditions are at their most suitable. This will address a number of deepwater mooring issues such as the shortage and high cost of installation vessels, and poor weather delaying traditional mooring line installation.

The Future for Fiber Rope Tethers

The future of deepwater and ultra-deepwater moorings will rely on the availability of longer, stronger, lighter and more robust fiber rope tethers. Although the ability to install longer lines from a singe reel will be possible with smaller diameter, higher modulus rope, there will still be the need for rope connectors.

The development of lighter and stronger connectors looks set to provide the blueprint for future rope connector developments where the focus will be on composite material construction, lightweight connectors that allow the 'ideal splice' approach and more closely complement the rope's mechanical characteristics.

Taken together the rope and connector developments reviewed in this paper will shape future deepwater mooring line make-up and deployment methodology. Until recently the US Department of Interior’s Minerals Management Service (MMS), Gulf of Mexico OCS Region had forbidden polyester ropes being laid on the seabed ahead of mooring. MMS has now approved the pre-laying of polyester rope on the seabed ahead of short term MODU moorings, where the rope is brought ashore for inspection.

The opportunity to pre-lay deepwater mooring lines on the sea bed many months ahead of installation will change the mooring process scenario significantly. By pre-installing the anchors, mooring connector and rope mooring line, mooring installations can be handled by smaller, lower cost anchor handling vessels months ahead of connection and at a time best suited to the local weather conditions.

Finally the current practice of loading each tether to approx. 40% of MBL for 3 hours when installing the tethers to minimise any bedding in creep, and re-tensioning, means that we have to predict the installed length, taking into account this pre-tensioning performed offshore. This is a costly exercise. As ropes get stronger, pre-tensioning to 40% MBL using higher bollard AHVs, or bigger crane barges or cross-tensioning becomes more difficult and dangerous. As a result we are developing tools that make it easier to better predict and calculate the effect of bedding in creep. This will allow us to calculate the maximum offset for the minimum line pre-tensioning. For example, it may only be necessary to tension to 20% of MBL for 1 hour, rather than the current industry norm of 40% MBL for 3 hours.

This paper has been prepared by the authors as part of their service to the OTC. Any views expressed are the authors but neither they nor their respective employers, Offspring International Limited, and Lankhorst Ropes S.A., shall be liable for any reliance on its contents.