Zarga's rope inspection certificate 29 August 2008

Certificate no: GLS 0834143

Lloyd's Register

H-16-4-(2)

Project: Samsung Heavy Industries
O.No A1486-001752

Client: Bridon Coatbridge Ltd

Office: Glasgow

Clients Order Number: E1004394

Date: 29 August 2008

Order Status: Complete

Inspection Dates

First: 29 August 2008

Final: 29 August 2008

This certificate is issued to Bridon Coatbridge Ltd to certify that at their request the undersigned Surveyor to Lloyd's Register EMEA did attend at their works at Greenhill Industrial Estate, Coltswood Road, Coatbridge, ML5 2AG on the above date for the purpose of examining the items listed below manufactured against Sales order number E1004394
Item/Part: WRG006 Quantity: 2 off
Description : 22 x 275 metre length Mooring Line. Bridon Steelite Xtra Brand UHMPE Fibre Rope. Superline circular braided construction comprising a polyester / supermix abrasion resistant braided jacket over a central UHMPE fibre load bearing core Rope supplied with a 2.5 metre cloth protected eye spliced at one end, other end plain.
Max 44mm diameter Minimum Break Load : 137 tonnes.
Scope of survey , Witness yarn realisation testing on selected sample of rope to determine rope strength = 151.47 tonnes
Endorse test report number : 25080802 , check calibration status of test equipment - satisfactory
Made to the order of Samsung Heavy Industries, 530 , Jangpyung-Ri , Sinhyun-u , KojeCity , Kyungsang Nam-Do 656-710 , Korea on their purchase order number A1486-001752.
In view of the above scope of survey now held with satisfactory results it is accordingly certified that the items described above are considered to have been manufactured and tested in accordance with the manufacturer's specifications and meet Bridon Coatbridge Ltd order acknowledgement descriptions.

[redacted] Glasgow Office Lloyd's Register EMEA Lloyd's Register

[redacted]
Surveyor to Lloyd's Register EMEA

A member of the Lloyd's Register Group

Annex B

Marlow Ropes *Steelite Superline Xtra* quality assurance test sheet

Superline Steelite Xtra with a 3 Strand Core

1.0 Scope

This specification describes the methods used to determine the breaking load of Superline Steelite Xtra with a 3 strand core in the nominal diameter range 40 to 44 mm.

2.0 Material

Superline Steelite 12 Xtra ropes with a 3 strand core comprise of Dyneema SK75 core and a sheath that can be made from any synthetic fibre.

3.0 Construction

The core comprises of a single 3-strand core while the sheath can be made from 16, 24 or 32 plaits and plaited in either 'one strand under two strands and over two strands' or 'one strand under one strand and over one strand' weave pattern.

4.0 Strength Test Methods

Two methods are available to assess rope-breaking strength. Unless specified all test variables and options shall be deemed to be at the manufacturer's discretion. Tests shall be conducted in an ambient atmosphere except in cases of dispute, when the test piece/s shall be placed in an atmosphere specified in EN 20139 for at least 48 h, immediately before testing. Test specimens may be subjected to a pre-loading stabilising routine.

4.1 Rope Destruction

4.1.1 Mounting the Test Piece in the Testing Machine

Each test piece of the rope will have an eye spliced into each end. Each eye of the test strop shall be placed around a bollard of at least twice the rope diameter. Load the rope to a reference load equal to

$$\text{Diameter (mm)}^2/8 \qquad \text{...(kgs)}$$

From the end of the last core splice tuck in each splice mark the rope at a distance of three times the pitch of the core. Should fracture occur in the unspliced rope between these marks then the break load achieved is considered as a rope break. If fracture occurs outside these marks, that is, in the area of the splice, then the splice is considered to have affected the break load and provided the break load is at least 90% of the rated minimum break load of the rope it will be deemed to have met this requirement.

4.2 Yarn Realisation Test Method

4.2.1 Procedure

The procedures laid down in BS EN 919: 1995 Annex B shall be generally followed with the following alterations:

The yarn samples for the realisation test will be taken at random from a sample of rope or from yarn spools of the same batch as that used to make the rope. The number of yarns tested shall be at least eight.

The rope breaking load shall be calculated using the following formula:

$$\text{Break Load}_{ROPE} = (\text{Average Break Load}_{YARN} \times \text{No.Yarns} \times \text{Realisation Factor}_{YARN})$$

4.4 Table of Realisation Factors

Nominal Diameter (mm)	Nominal Mass (kg/100m)	Min. Break Load (t)	Realisation Factor
40	85.3	113	0.998
44	102	127	0.998

In some instances the minimum break load required by the customer maybe different from that specified by Marlow.

Authorised by... [redacted]

Date October 31st 2003

Bridon’s high modulus synthetic fibre rope manual

High Modulus Synthetic Fibre Rope Manual

BRIDON

BRIDON International www.bridon.com Part of the FKI Group of Companies

South Road, Hailsham, East Sussex, BN27 3JS Tel +44 (0)1323 444777 Fax +44 (0)1323 444744
Registered in England Number 416671 Registered Office: Falcon Works, Meadow Lane, Loughborough, Leicestershire, LE11 1ZF

Table of Contents

This document is issued for guidance purposes only to be used at the owner's own risk. No responsibility is accepted by Bridon for any consequence whatsoever resulting directly or indirectly from compliance with or adoption of guidance contained within this document.

Introduction to High-Modulus Synthetic Fibres

The term "High-Modulus Synthetic Fibre Rope" & "Ultra High-Modulus Synthetic Fibre Rope" generally refers to ropes made from High-Modulus fibres such as Aramid and High-Modulus Polyethylene (HMPE or UHMPE). These fibres are much stronger than conventional synthetic fibres such as nylon, polyester and polypropylene. Aramid and HMPE have been used successfully as mooring ropes on large tankers for over fifteen years.

Aramid Fibres

Aramid fibre typically has high strength and low stretch. It does not creep. It does not melt but chars at high temperatures. Normally Aramid fibre mooring lines are produced in 3, 4, or 6 strand laid constructions. Aramid fibre is not suitable for use in large braided or plaited lines. Aramid ropes do not float; they have good cut resistance but only fair abrasion and UV resistance. They are typically covered (jacketed) with some synthetic fibre, such as polyester, to increase the abrasion and UV resistance.

Aramid is susceptible to axial compression fatigue that occurs when tightly constrained fibres are forced into axial compression. Such problems may be avoided with proper attention to rope and termination design. It is important to ensure that the correct diameter to diameter ratio is implemented.

High & Ultra High-Modulus Polyethylene (HMPE & UHMPE)

High & Ultra High-Modulus Polyethylene (HMPE & UHMPE) are manufactured fibres with high strength per weight ratio, low stretch characteristics and good UV resistance. HMPE fibres have very good fatigue properties (tension, bending, abrasion and cut resistance) but limited temperature resistance (melt temperature 150°C). HMPE fibres are used in the manufacture of a variety of rope constructions including 4 strand, wire rope lay, parallel, plaited and braided.

HMPE fibre is less dense than water, and thus floats. With its relatively low melt point, care should be taken not to expose HMPE ropes to high temperatures or heat sources. HMPE does not suffer from axial compression, has a low coefficient of friction and has good abrasion resistance.

South Road, Hailsham, East Sussex, BN27 3JS Tel +44 (0)1323 444777 Fax +44 (0)1323 444744
Registered in England Number 416671 Registered Office: Falcon Works, Meadow Lane, Loughborough, Leicestershire, LE11 1ZF

Introduction to Bridon Steelite Ropes

Bridon Steelite ropes are lightweight high strength fibre ropes manufactured using Dyneema high modulus polyethylene (HMPE/UHMPE) fibre manufactured by DSM. Steelite ropes are usually supplied in three different constructions:-

Steelite 8 & Steelite 8 *X*tra
Conventional 8-Strand Multiplait construction with square profile and fully impregnated with polyurethane for increased abrasion resistance. The rope is manufactured from 100% Dyneema HMPE fibre (Steelite 8) or Dyneema UHMPE fibre (Steelite 8 *X*tra). The rope is torque balanced, flexible and floats on water. The elongation to break of a used rope is ~4%.

Steelite 12 & Steelite 12 *X*tra
12-strand plaited construction ropes but with a firm round profile, again fully impregnated with polyurethane for increased abrasion resistance. The rope is manufactured from 100% Dyneema HMPE fibre (Steelite 12) or Dyneema UHMPE fibre (Steelite 12 *X*tra). The rope is torque balanced, flexible and floats on water. The elongation to break of a used rope is similar to 8-strand.

Steelite Superline & Steelite Superline *X*tra
This rope is constructed from a circular outer braided jacket surrounding a low twist core of either a Single 3-Strand, Multiple 3-Strand, 6-Strand or 12-strand construction. The core is designed to carry the load whilst the outer cover provides abrasion protection. The elongation to break of a used rope is ~2.5%
Bridon Superline circular braided construction ropes, offer probably the most efficient strength translation of all fibre ropes. The quoted strength is dependant entirely upon the construction and material of the central cores. The braided outer strands of the cover are highly twisted to provide added resistance to abrasion.

Steelite ropes can offer significant advantages to the marine market place over both conventional synthetic fibre ropes and wire. The low weight and buoyancy make the rope very easy to handle. HMPE has a very good resistance to abrasion when compared to other fibres and has proved to be very durable. Low elongation to break can be very desirable for some applications and it also means that the lashback energy is lower than that of most ropes, an important safety consideration. Another potential advantage of Steelite ropes is that when used as an alternative to wire they can save on maintenance costs. Steelite ropes do not require regular greasing and do not damage fairleads or other deck equipment.

Installing High-Modulus Synthetic Fibre Ropes

This section addresses new ships, but the concerns apply equally to existing ships. However, any mooring equipment that utilises High-Modulus synthetic fibre mooring ropes should already be in good condition. During the design and selection of mooring equipment for new ships which are intended to be outfitted with High-Modulus synthetic fibre mooring ropes it is recommended that the rope supplier/manufacturer is consulted to determine the optimum mooring equipment design. Fairlead design and surface quality in particular can have a significant impact on the life expectancy of High-Modulus synthetic fibre mooring ropes.

Chafe Protection

To avoid chafing damage to High-Modulus synthetic fibre mooring ropes, all contact surfaces should be smooth and free from snags. Fairleads and rollers should be clean and smooth. All rough surfaces must be welded up and polished. All painted surfaces should be free clean and smooth and any flaking areas should be smoothed over as soon as possible. Roller fairleads should be well maintained and able to roll. Once the fairleads and chocks have been fully repaired, only light grinding will be needed. This grinding should be to such a standard that it eliminates any barbs, sharp edges, or other significant irregularities. The use of steel wire mooring ropes on contact surfaces such as fairleads and rollers which are intended for use with High-Modulus synthetic fibre mooring ropes may cause damage and is not recommended.

Some operators have utilised chafing gear, after extensive surface smoothing, as part of an implementation process prior to a ship receiving a new synthetic line. Chafe protection will prolong service life for all types of rope. Successful chafe guards have been made from both polyester tubular cloth and also High-Modulus synthetic fibre tubular cloth. This approach to chafe protection allows a synthetic mooring line ease of movement due to its inner braided liner. The outer cover minimises the overall guard movement due to its frictional characteristics. Chafe gear should be employed as recommended by the mooring line manufacturer.

Mooring Winches

High-Modulus synthetic fibre ropes are commonly used on winches in the same way as steel wire ropes. If steel wire rope is substituted with a larger diameter High-Modulus synthetic fibre rope then it may not be possible to stow the same length on the winch stowage drum.

Some High-Modulus synthetic fibre ropes have a lower coefficient of friction than steel wire ropes and consequently more turns on the tension drum may be needed to compensate for loss of grip. Lower coefficient of friction High-Modulus synthetic fibre ropes also have a tendency to “bury” under tension, therefore more than one layer of turns on the tension drum should be avoided where possible. To compensate for the load having been shifted closer to or further from the centre of the tension drum the winch brake rendering setting may have to be readjusted.

There are many applications where Steelite ropes are successfully used on winches. The following points concerning the installation and operation of these ropes have been collated from direct experience with these applications.

- Winch barrels should be smooth and flat. Drums that have become grooved from previous use of wire rope can damage the fibre ropes.
- Ensure that no twist is induced into the rope when installing the rope onto the winch. This should be done by mounting the new rope on a turntable or reel stand prior to reeling onto the winch.
- The rope should be wound onto the winch as tightly as possible ensuring proper packing and layering. This particularly applies to the lower layers. When installing Steelite ropes onto tug winches, for instance, it is recommended that the entire line is passed out to a bollard on shore and the rope is wound in under a high tension maintained by the tugs propulsion units. Proper packing can be achieved by controlling the angle of the tug to the line. This process can be repeated when necessary.
- When reeling the rope on or off a winch ensure that the rope does not pass over rough surfaces, sharp edges or other obstacles that may damage the rope.

- Winches with split barrels are very effective at reducing the risk of the rope burying into lower layers. They are particularly popular for mooring applications. It is extremely important, however, that a sufficient number of wraps are maintained on the working part of the barrel to prevent slippage occurring into the storage section. If this happens the rope may be damaged on the separator flange and burying in the storage section can occur.

  It is recommended that a minimum number of 8 wraps are maintained on the working part to prevent slippage.

- The service life of Steelite ropes can be extended by end-for-ending them to vary regions of highest wear. Any damage to the outer braided cover should be repaired at the earliest opportunity by seizing with a heavy duty pre-stretched polyester cord. The procedure for which is covered later in this document.

Roller Fairleads
Roller Fairleads should be free from snags and rough edges. All rollers should be well maintained and able to roll easily. A failure to do this can cause increased abrasion of the rope, and in some cases, can cause more serious damage when the rope passes over a non rotating roller. The friction created when this occurs can create high temperatures that are transferred to the rope.

Mooring Pendants (Tails)
To provide additional elasticity and to reduce shock loading, synthetic fibre mooring ropes may be fitted with a mooring pendant (tail) at the shore end. Traditionally the connection between the primary mooring line and synthetic pendant has been with a "Mandal" or "Tonsberg" shackle. Aramid ropes are susceptible to axial compression fatigue due to tight radius bends and care should be taken to follow the manufacturer's recommendations when choosing the connection to the pendant.
If the manufacturer recommends it is appropriate, a synthetic pendant can be attached directly to a High-Modulus rope by interlocking the eyes using a "cow hitch" (Figure 1). The use of "cow hitches" is not recommended for connecting mooring pennants to Aramid on account of "axial compression".

Figure 1 - "Cow Hitch"

Factors Affecting Rope Life

Selecting the correct rope for an application involves the evaluation of all the factors which combine to influence the life of the product.

Rope Strength
Selecting the strongest rope for any given size will reduce the work the rope has to do in service. The load applied to a stronger rope will represent a lower percentage of the overall rope strength and will therefore mean the rope working less hard which in turn will increase its life.

Extension
A rope with a low extension under load can give better control, however shock loading applied to this rope can result in failure without warning, even with a rope which appears to be in good condition. Ropes which have a very high extension under load can lead to problems where the ropes run over guides as there will be more movement and therefore increased abrasion.

Working Loads
Working Loads are the loads that the rope will see in normal use. These loads are expressed as a percentage of the break strength of the rope when new. The factor by which the break strength is reduced to give the working load will vary according to the application to which the rope will be put. A general rule is that the working load of a rope should not exceed 20% of the new rope break strength.

Ropes which are greatly overloaded or subjected to high shock loads can suffer from fatigue damage which is not readily visible and this can lead to the rope breaking under normal working load.

Shock Loads
A shock load is considered to be any sudden change in load from a relaxed or low load situation to a high load situation. Any load which exceeds the normal working load by more than 10% is considered to be a shock load. Synthetic fibres have a memory and can retain the effects of being overloaded or shock loaded. This can result in a later failure of a rope while still within its working load limits.

Bending
Rope strength decreases substantially and can lead to premature damage or even failure if the rope is stressed around a sharp bend. A very sharp bend will mean that only a small percentage of the rope's fibres will be taking the full load whilst the remainder of the fibres are in compression.

Sheave diameters should always be in excess of five times the rope diameter but in some instances this can be up to twenty times the rope diameter depending on the material and construction of the rope.

Terminations
Ropes should always be spliced in accordance with the manufacturers recommended instructions. Correct splices will achieve between 90% and 100% of the rope strength when new.

The easiest way to terminate a rope is with a knot but this is not the most effective since in a knot the rope is bent around a very small diameter of one to one as it is bent around itself. Any knot will reduce the rope strength and with some knots this can be up to a 50% reduction.

Storage
Ropes should be stored in a clean dry situation out of direct sunlight. The ropes should be stored off the floor to allow a free flow of air. The ropes should be kept clear of direct heat.

Never store rope in the vicinity of chemicals of any type.

Never store ropes or run ropes over concrete or dirty floors or rough ground as dirt and grit picked up by the rope is likely to work its way into the strands and can then cut the fibres as the ropes are worked.

Coiling

Although Braided and Plaited Ropes can not be hockled they can have excessive twist imparted by improper handling and the best method would be to coil in a figure 8 fashion. This method avoids putting twist into the line in either direction and will ensure that the line runs freely when being deployed.

South Road, Hailsham, East Sussex, BN27 3JS Tel +44 (0)1323 444777 Fax +44 (0)1323 444744
Registered in England Number 416671 Registered Office: Falcon Works, Meadow Lane, Loughborough, Leicestershire, LE11 1ZF

Maximising Steelite Rope Service Life

All synthetic fibre ropes are more prone to damage than wire ropes if they are handled in the same manner. Correct installation procedures and preparation of deck gear are extremely important to ensure maximum service life. It is quite likely that crews will have little or no experience with this type of fibre rope so whenever possible they should be given a thorough briefing on all operating characteristics and handling procedures before the ropes are used.

The following recommendations should help the crew to realise the full potential service life of these ropes.

- All surfaces that the rope comes into contact with should be as smooth as possible. The rope must not be allowed to run over sharp edges. All scoring and grooving of equipment should be repaired before installation. Any equipment that has previously been used with steel wire should be checked for this type of damage and repaired.
- All deck equipment and fairleads should be dedicated to fibre ropes. Steel wires must not be allowed to run over the same surfaces as fibre ropes.
- Special consideration should be given to ropes that run through acute angles. The strength of a rope is affected by the angle it turns through and the ratio of rope radius to bend radius.
- Rollers should be used whenever possible to increase rope lifetime.
- Steelite ropes have low extension characteristics, similar to that of wire rope, so for some applications it may be necessary to consider using the rope in conjunction with a fibre spring.

Inspection and Retirement Criteria

Inspection Frequency
Each High-Modulus synthetic fibre mooring rope should be examined after use for indications of localised damage such as cuts and abrasion. Particular attention should be given to splices and portions of the rope in contact with fairleads. The entire length of each rope should be inspected in detail at least once every year for indications of general deterioration as well as localised damage. Inspection and retirement criteria can be developed by following a programme of periodically removing short specimens of rope, including splices, and performing break testing to determine residual strength.

Retirement
There are no definitive rules for the discard or retirement of fibre ropes. Ropes should always be retired before their strength is reduced to a dangerously low level where the rope is likely to break in service.

There are so many variables that affect rope life that only a continuous process of examination, during and after each use by a competent person, will give them the ability to retire the rope before it reaches a critical point.

Many factors affect the life of a rope in service and all must be taken into consideration in assessing the remaining rope life. Factors such as load history, abrasion, bending radius, chemical attack all need to be considered when assessing retirement criteria.

Abrasion
When a rope is first put into service the outer filaments will quickly take on a furry appearance. This is a normal occurrence as the surface filaments break due to slight abrasion in service. This furry surface however acts to protect the underneath fibres in the rope construction.

This surface abrasion needs to be examined regularly to ensure what is a normal occurrence is not mistaken for more serious damage being caused to the rope by other means. A rope left lying in the water for instance will suffer from water wash, this is where the action of the sea works the rope continuously under very low load, which results in flex fatigue which also causes fibre damage and furring. Another cause of abrasion can be from rust build up on untreated surfaces.

Abrasion can also occur between strands and yarns in a rope and therefore a rope should be opened up, where this is practical, to inspect for internal wear. One of the signs to look for is powdered fibre which is indicative of internal wear and will indicate a reduction in rope strength.

Glazed Areas
Ropes can be damaged by heat and on the surface this is indicated by glazed areas where the fibres have melted together. The strength loss can be much greater than the surface appearance would indicate.

Inconsistent Diameter
Ropes should be inspected for inconsistency in diameter which can be either increases or reductions. With ropes which have separate core and sheath constructions inconsistency in diameter can indicate internal damage from overloading or shock loads and can indicate that a rope needs to be replaced.

Discolouration
All ropes become dirty in use but patches of discolouration along a ropes length need to be investigated in order to determine the cause as this could indicate chemical contamination.

Stiffness
Localised areas of stiffness along a rope normally indicate that the rope has been subjected to shock loads and the rope should be considered for retirement.

BRIDON International www.bridon.com Part of the FKI Group of Companies

South Road, Hailsham, East Sussex, BN27 3JS Tel +44 (0)1323 444777 Fax +44 (0)1323 444744
Registered in England Number 416671 Registered Office: Falcon Works, Meadow Lane, Loughborough, Leicestershire, LE11 1ZF

Pulled and Cut Strands
Especially in Braidline (Double Braided) Ropes an occasional pulled or cut strand will have very little detrimental effect on the strength of the rope. However this damage is usually caused by localised external forces, which very rarely damage only one strand, and therefore the cumulative effect of the damage needs to assessed.

Temperature
Heat can be very detrimental to the strength of Man Made Fibre Ropes. Heat can be the result of friction and the greater the friction the higher the temperature that can be achieved. High temperatures can be achieved when surging rope on capstans or running over non-moving sheaves or rollers. Different rope constructions and fibre types will have different coefficients of friction under new and used conditions and this needs to be taken into account if heat build up is a problem.

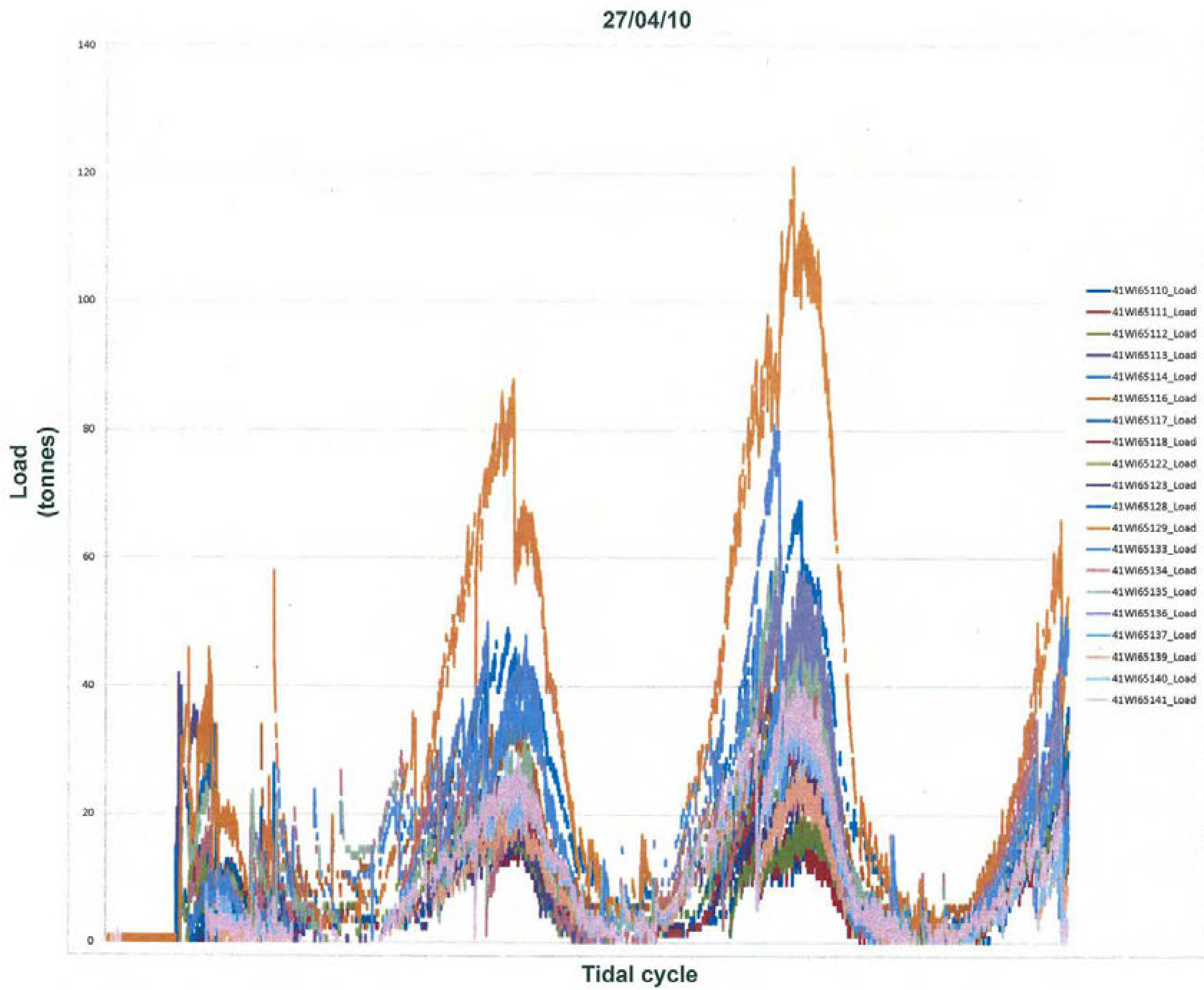
Never allow ropes under tension to rub against one another as this can result in excessive heat build up that can cause the ropes to fail.

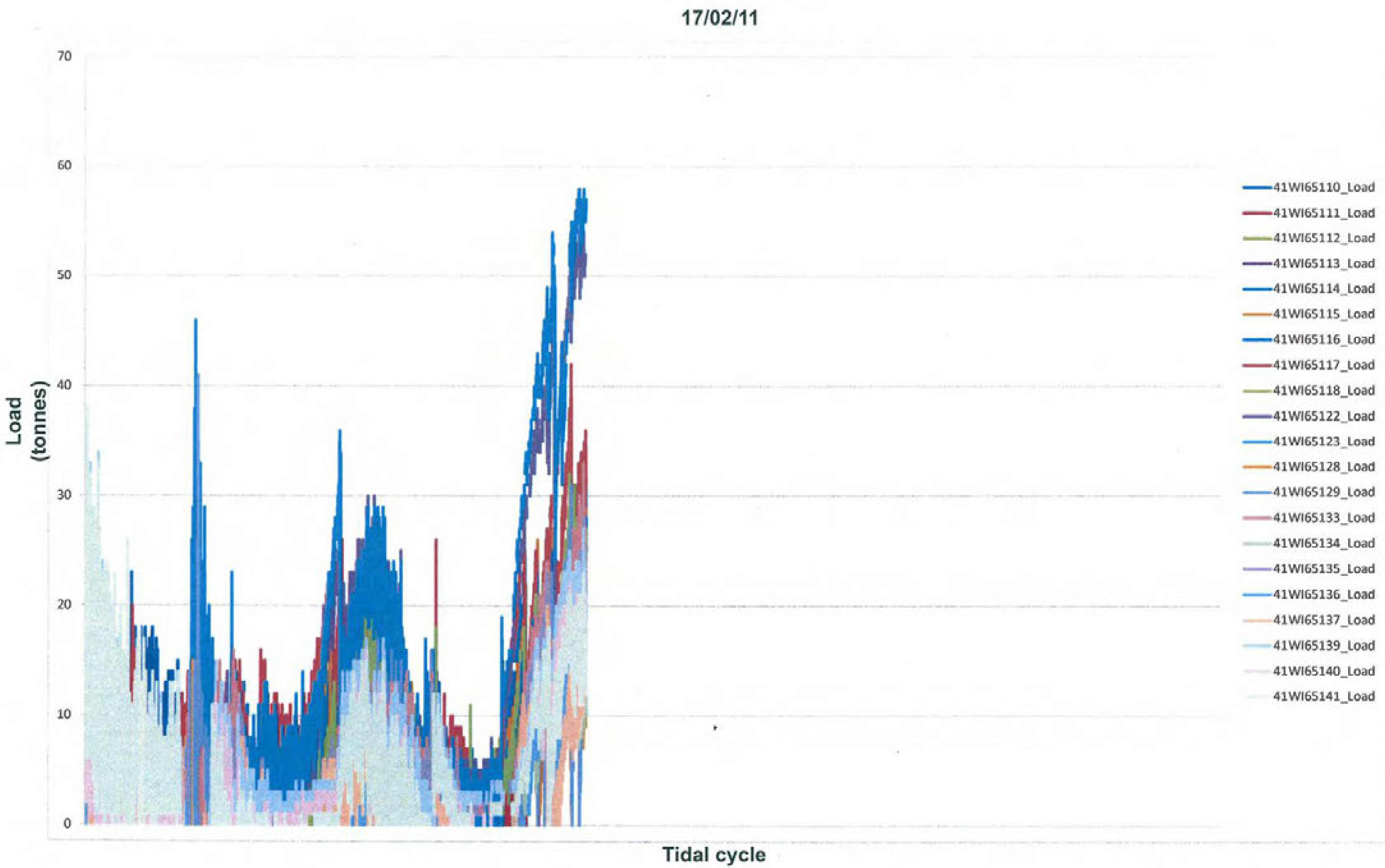
Never allow ropes to come into contact with hot surfaces or be in the vicinity of welding equipment, as these can be the cause of rope failures.

History of the failed mooring line

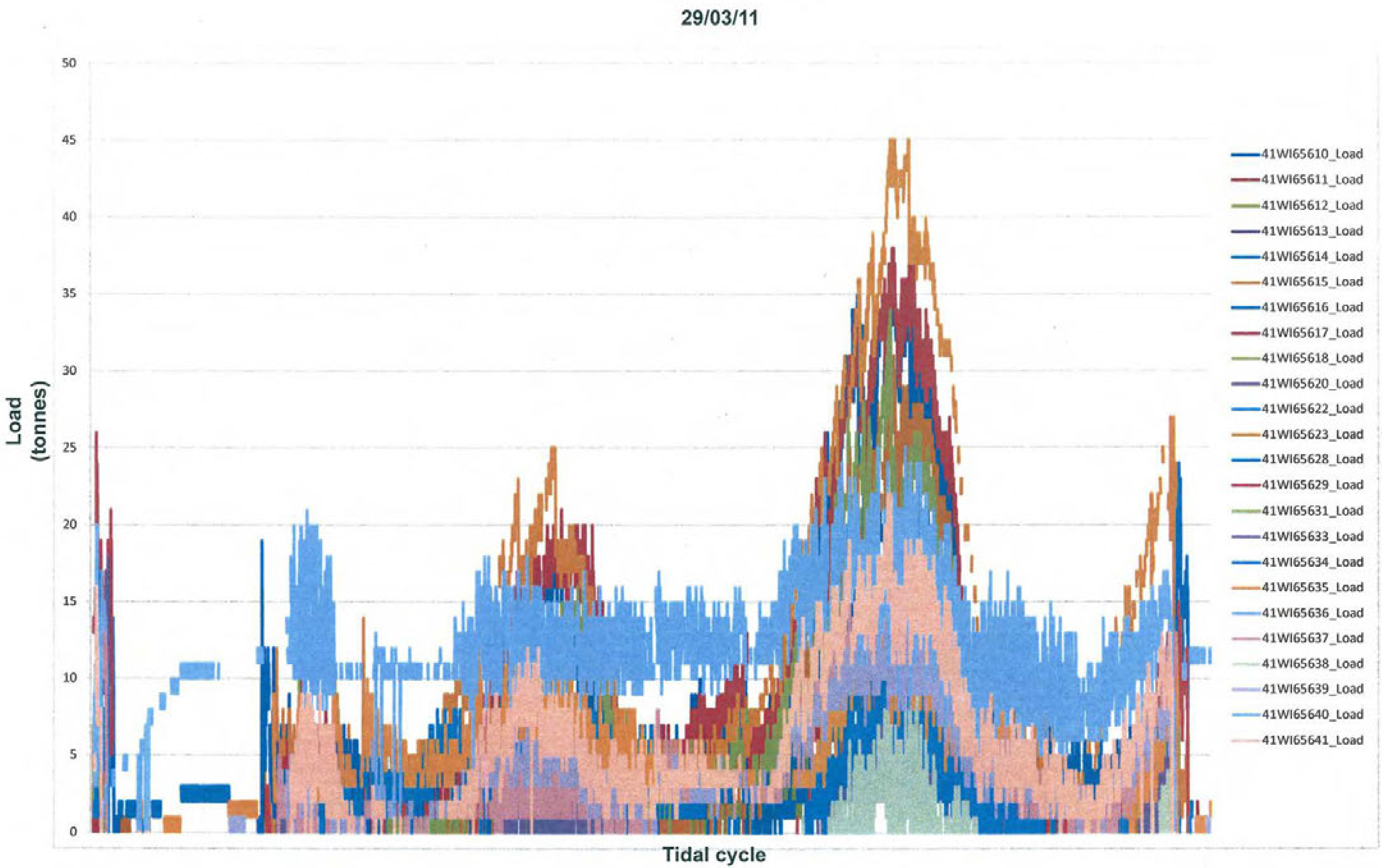
Voy No	Place/ Berth/ side alongside	Date	service	Max Weath
	Rope used as Head line on Stbd winch Position C with 11m nylon tail			
1	Ras Laffan No.4 / Port side	05.04.2010 to 09.04.2010	56.4	NW x 3
1	Milford Haven No.2/ Stbd side	27.04.2010 to 29.04 .2010	43.5	SW x 3
2	Ras Laffan No.4 / Port side	18.10.2010 to 20.10.2010	50.75	NW x 2
2	Milford Haven No.2/ Stbd side	06.11.2010 to 07.11.2010	33.9	NW x 3
3	Ras Laffan No.5/ Stbd side	07.12.2010 to 09.12.2010	50	NW X 2
3	Canaport/ Port Side	31.12.2010 to 02.01.2011	34.9	NE x 3
4	Ras Laffan/ No.4/ Port Side	29.01.2011 to 30.01.2011	39.75	SE x 3
4	Milford Haven/ No2. Stbd	17.02.2011 to 18.02.2011	33.35	S x 3
5	Ras Laffan/ No.4/ Port Side	11.03.2011 to 12.03.2011	37.8	E x5
5	Milford Haven/ No1. Port side	29.03.2011 to 30.03.2011	34.1	SE x 5
6	Ras Laffan/ No.6/ Stbd Side	14.04.2011 to 16.04.2011	38.6	NW x3
6	Milford Haven/ No.2/ Stbd side	04.05.2011 to 05.05.2011	29.8	SE x 5
7	Ras Laffan/ No.5/ Stbd side	22.05.2011 to 24.05.2011	37.75	NW x4
	Rope still used as Head line on Stbd winch Position C but changed to 22m Euroflex tail			
7	Milford Haven/ No. 2 Port side	14.06.2011 to 15.06.2011	32	NE x 3
8	Ras Laffan/ No.5/ Stbd side	12.08.2011 to 14.08.2011	48.8	NE x3
8	Milford Haven/ No.1 Stbd side	02.09 2011 to 03.09.2011	31	S x4
9	Ras Laffan/ No.6/ Stbd Side	15.10.2011 to 17.10.2011	41.1	NW x4
9	Milford Haven/ No.1 Port side	05.11.2011 to 06.11.2011	33.2	NE x 4
10	Ras Laffan/ No.5/ Stbd side	29.11.2011 to 30.11.2011	39.3	NW x4
10	Jiangsu/ No.1/ Port side	17.11.2011 to 19.12.2011	44.5	NW x2
11	Ras Laffan/ No.4/ Port Side	22.01.2012 to 23.01.2012	36.9	NW x4
11	Chita/ L2/ Stbd side	10.02.2012 to 12.02.2012	46.9	NW x5
12	Ras Laffan/ No.6/ Stbd Side	02.03.2012 to 04.03.2012	56.3	NW x6
12	Isle of Grain/ No.8/ Port side	23.03. 2012 to 24.03.2012	34.1	E x3
13	Ras Laffan/ No.5/ Stbd side	09.04.2012 to 11.04.2012	37.4	NW x3
13	Isle of Grain/ No.8/ Port side	02.05.2012 to 03.05.2012	34.4	W x4
14	Ras Laffan/ No.5/ Stbd side	19.05.2012 to 21.05.2012	47.25	NW x3
14	Milford Haven/ No.2/ Port side	07.06.2012 to 05.06.2012	53.9	WSW x8
15	Ras Laffan/ No.4/ Port Side	08.07.2012 to 10.07.2012	38	NW x4
		Used as Head rope	1175.65 hrs	
	Rope used as Aftermost Spring line on winch Position F with 22m Euroflex tail			
34	Ras Laffan/ No.4/ Port Side	18.11.2014 to 19.11.2014	28.1	NW x7
34	Jiangsu/ No.1/ Port side	06.12.2014 to 08.12.2014	40.5	NW x4
35	Ras Laffan/ No.5/ Stbd side	08.01.2015 to 10.01.2015	26.6	NW x5
35	Kawagoe/ No.1/ Stbd side	27.01.2015 to 25.01.2015	44.9	WNW x5
36	Ras Laffan/ No.4/ Port Side	12.02.2015 to 13.02.2015	27	NW x4
		Used as Fwd spring	167.1 hrs	
		Rope total usage	1342.75 hrs	

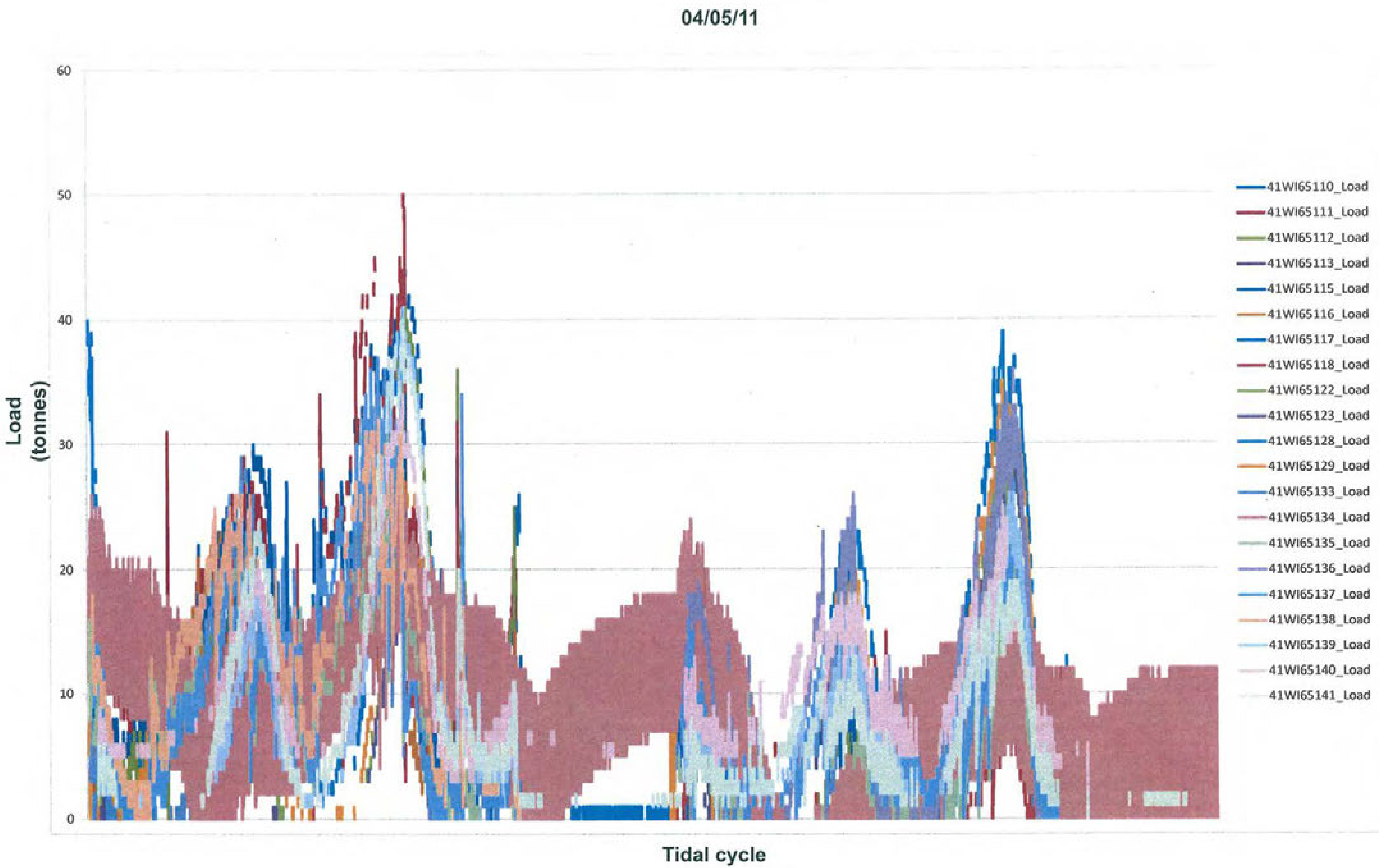
Zarga hook load history 2010-2012 at South Hook LNG terminal


27/04/10
140
120
100
80
60
40
20
0
Load
(tonnes)
Tidal cycle
41WI65110_Load
41WI65111_Load
41WI65112_Load
41WI65113_Load
41WI65114_Load
41WI65116_Load
41WI65117_Load
41WI65118_Load
41WI65122_Load
41WI65123_Load
41WI65128_Load
41WI65129_Load
41WI65133_Load
41WI65134_Load
41WI65135_Load
41WI65136_Load
41WI65137_Load
41WI65139_Load
41WI65140_Load
41WI65141_Load

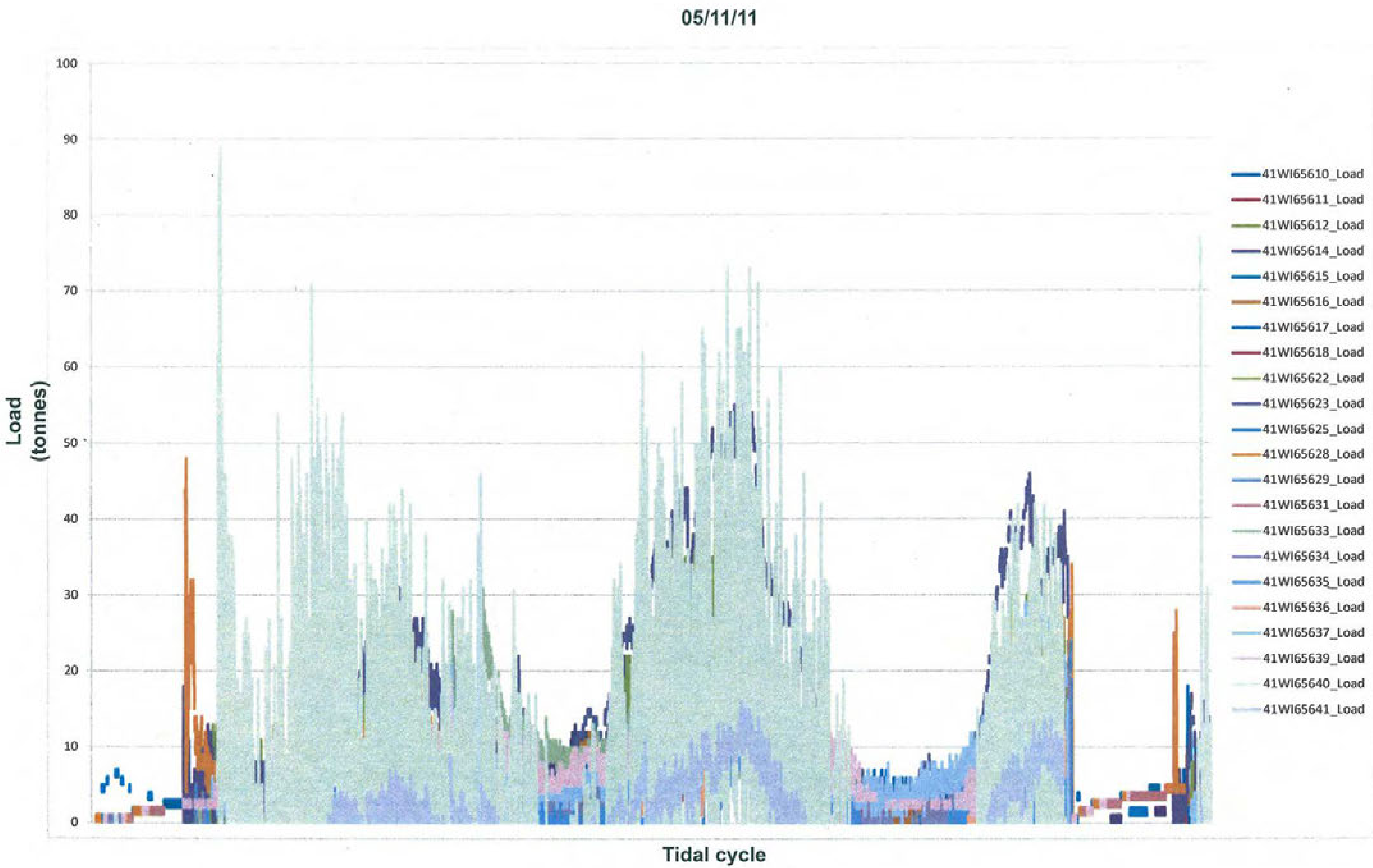


17/02/11
Load (tonnes)
70
60
50
40
30
20
10
0
Tidal cycle
41WI65110_Load
41WI65111_Load
41WI65112_Load
41WI65113_Load
41WI65114_Load
41WI65115_Load
41WI65116_Load
41WI65117_Load
41WI65118_Load
41WI65122_Load
41WI65123_Load
41WI65128_Load
41WI65129_Load
41WI65133_Load
41WI65134_Load
41WI65135_Load
41WI65136_Load
41WI65137_Load
41WI65139_Load
41WI65140_Load
41WI65141_Load


29/03/11
Load (tonnes)
0
5
10
15
20
25
30
35
40
45
50
Tidal cycle
41WI65610_Load
41WI65611_Load
41WI65612_Load
41WI65613_Load
41WI65614_Load
41WI65615_Load
41WI65616_Load
41WI65617_Load
41WI65618_Load
41WI65620_Load
41WI65622_Load
41WI65623_Load
41WI65628_Load
41WI65629_Load
41WI65631_Load
41WI65633_Load
41WI65634_Load
41WI65635_Load
41WI65636_Load
41WI65637_Load
41WI65638_Load
41WI65639_Load
41WI65640_Load
41WI65641_Load



04/05/11
60
50
40
30
20
10
0
Load (tonnes)
Tidal cycle
41WI65110_Load
41WI65111_Load
41WI65112_Load
41WI65113_Load
41WI65115_Load
41WI65116_Load
41WI65117_Load
41WI65118_Load
41WI65122_Load
41WI65123_Load
41WI65128_Load
41WI65129_Load
41WI65133_Load
41WI65134_Load
41WI65135_Load
41WI65136_Load
41WI65137_Load
41WI65138_Load
41WI65139_Load
41WI65140_Load
41WI65141_Load


05/11/11
Load (tonnes)
100
90
80
70
60
50
40
30
20
10
0
Tidal cycle
41WI65610_Load
41WI65611_Load
41WI65612_Load
41WI65614_Load
41WI65615_Load
41WI65616_Load
41WI65617_Load
41WI65618_Load
41WI65622_Load
41WI65623_Load
41WI65625_Load
41WI65628_Load
41WI65629_Load
41WI65631_Load
41WI65633_Load
41WI65634_Load
41WI65635_Load
41WI65636_Load
41WI65637_Load
41WI65639_Load
41WI65640_Load
41WI65641_Load

Bridon comments in response to the condition of *Al Ghuwairiya* mooring lines

Bridon comments in response to the condition of the Al Ghuwairiya mooring lines

15 December 2009

General Rope Comments
After a full review of the photographs it is clear that the ropes have seen some heavy loads during the port call at South Hook however in general the rope condition is consistent with what we would expect to see from the lines.

The ropes are manufactured from a HMPE fibre core that will stiffen during normal mooring operations. This is nothing of concern as long as the rope has not fused. This can be checked by had working the ropes to get them soft again. A rope that is heavy fused will soften after being worked.

The HMPE core is covered in a self amalgamating tape that is used to bond the cover and core together. This is not a strength member and may on occasions may ‘extrude’ through the jacket when the ropes are exposed to a high percentage load [this is the white ‘plastic’ material that can be seen through the jacket on some of the photographs]

The jacket is non-loading bearing and is manufactured from a blend of high tenacity polyester and Supermix yarn which is a polyester / polypropylene mix. This jacket is designed to offer a higher coefficient of friction and the combination of the polypropylene and polyester offer a sacrificial medium for abrasion and fusion damage as the polypropylene element melts first stabilizing the temperature of the whole rope.

Port / Mooring Comments
As mentioned, we are in dialogue with a number of LNG operators using the same or very similar mooring lines to yourselves. We have a number of breakages that have occurred with ours as well of other manufacturer’s lines which have parted under conditions which the operators would not have expected. From general comments made by you and indeed other operators it would appear that the mooring loads being experienced are greater than we would have expected and indeed in some cases even exceed the maximum recommendations of guidance notes issued by OCIMF and the Nautical Institute.

Our recommendations are that the working load should not generally exceed 20% of the new rope break strength. This equates to 27.4 tonnes based on our break load of 137 tonnes. OCIMF recommends that the safety factor for mooring loads should not exceed 50% of MBL i.e.: 68.5 tonnes, while we are aware that the brake on your winch is set at 60% which again follows OCIMF recommendations, at 82.2 tonnes

It should be noted that while neither of these indicated loads exceed the minimum break load of the rope, the breaking load is based on a single break test without fatigue considerations.

If, as it would appear to be indicated, the nominal working load and frequency is greater than first indicated particular in the more exposed ports, then it has to be accepted that the fatigue life of the ropes will be reduced and certainly taking the ropes to 50% of their rated break load or indeed exceeding this as indicated with one winch brake actually rendering then this will have a more dramatic effect of service life and rope damage. It should also be noted that high shock loads can have a large detrimental effect of rope service life as the rope can develop a plastic memory which can subsequently cause the rope to part under normal conditions later in its service life.

STASCo LNG mooring line failures 2010-2015

Mooring line failures during 2010

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1	10/5/2010	Stern	Bridon Steelite Xtra Jacketed	South Hook	Line parted during discharge operations Rope sent to Bridon
2	14/5/2010	Forward breast	Bridon Steelite Xtra Jacketed	South Hook	Wind: Southerly 15kts; Line load: 47 tonnes Rope sent to Bridon
3	31/8/2010	Forward spring		South Hook	Wind: 10kts Tidal stream 1kt
4	31/8/2010	Forward spring		South Hook	Wind: 10kts Tidal stream 1kt
5	16/9/2010	Forward breast	Bridon Steelite Xtra Jacketed	South Hook	Wind: 20-22kts @280 degrees Line load:<20 tonnes Rope sent to Bridon
6	25/10/2010	Aft spring	Bridon Steelite Xtra Jacketed	South Hook	Wind: 28-32kts @ 160 Line load: 27 tonnes
7	25/10/2010	Aft breast	Bridon Steelite Xtra Jacketed	South Hook	Wind: 28-32kts @ 160 Line load: 27 tonnes
8	4/11/2010	Aft breast	Bridon Steelite Xtra Jacketed	South Hook Berth 2	Line load: < 20-25 tonnes
9	4/11/2010	Aft breast	Bridon Steelite Xtra Jacketed	South Hook Berth 2	Line load: < 20-25 tonnes
10	14/11/2010	Aft breast	Bridon Steelite Xtra Jacketed	South Hook	Wind: Westerly 11kts Tide: slack

11	19/12/2010	Aft breast		South Hook	Wind: 6kts on port bow Tide: High 5.5m 0.8kts at stern Dolphin 'C'

Mooring line failures during 2011

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1	3/2/2011	Aft breast	Bridon Steelite Xtra Jacketed	South Hook	All crew were clear and no personel were hurt
2	19/3/2011	Forward breast	Bridon Steelite Xtra Jacketed	South Hook	AS per OPTIMOOR, the rope parted was no.15 going to dolphin 'C'
3	2/4/2011	Aft breast	Bridon/Lankhorst Jacketed	South Hook	Line parted unberthing Break: outboard of the fairlead, at about 1-2m from the eye
4	4/5/2011	Aft breast	Bridon Steelite Xtra Jacketed	Elba Island, USA	Wind: 20-22kts @300 degrees Line load: 10 tonnes Break: 12-15m out of the split drum in the direction of the roller fairlead on the poop deck
5	18/6/2011	Aft breast	Bridon Steelite Xtra Jacketed	Isle of Grain, UK	During unmooring operations
6	15/7/2011	Aft breast	Bridon Steelite Xtra Jacketed	Canaport, Canada	N/A
7	18/7/2011	Aft breast	Bridon Steelite Xtra Jacketed	South Hook	Wind: 25kts WNW from Port quarter

					Sea: 0.3 – 0.5m During mooring
8	28/7/2011	Aft breast		GATE, Rotterdam	Line load: 25 tonnes
9	28/7/2011	Aft stern		GATE, Rotterdam	Line load: 15 tonnes
10[1]	3/9/2011	Aft breast	Bridon Steelite Xtra Jacketed	South Hook	Line load: 38 tonnes
11	12/10/2011	Forward spring	Bridon Steelite Xtra Jacketed	South Hook	Wind: 240 degrees, slight Line load: 20 tonnes Break: 35m from pendant eye
12	18/11/2011	Aft breast	Bridon Steelite Xtra Jacketed	Canaport, Canada	Wind: 18 – 25kts NNW Break: 5m from winch tension drum
13	30/11/2011	Aft breast	Bridon/Lankhorst Jacketed	Jiangsu, China	Exposed berth. Rough weather

Mooring line failures during 2012

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1	19/1/2012	Stern	Bridon Steelite Xtra Jacketed	Futtsu, Japan	Line load registered 5 tonnes. Mooring party began adjusting to the required tension (10 – 15 tonnes) when the line parted near the eye.

[1] Zarga

2	9/3/2012	Aft breast	Bridon Steelite Xtra Jacketed	N/A	Parted just before departure
3[2]	24/3/2012	Aft breast	Bridon Steelite Xtra Jacketed	Isle of Grain	Break: 7m from eye. During port stay, all mooring lines were in high tension from 10 – 30 tonnes which was port requirement due to high tidal difference and current
4	15/5/2012	Forward spring	Bridon Steelite Xtra Jacketed	Elba Island, USA	Line load: 30 tonnes
5[3]	8/6/2012	Stern	Bridon Steelite Xtra Jacketed	South Hook	Wind: Westerly increasing 35-40kts, gusts to 45-50kts at stern Line load: 40 tonnes
6[4]	8/6/2012	Stern	Bridon Steelite Xtra Jacketed	South Hook	Wind: Westerly increasing 35-40kts, gusts to 45-50kts at stern Line load: 28 tonnes
7	23/7/2012	Aft breast	Bridon Steelite Xtra Jacketed	Jiangsu, China	Parted after completion of discharge just inside the roller fairlead, 51.5m from eye. Line load: 6 tonnes
8	20/9/2012	Aft breast	Bridon Steelite Xtra Jacketed	Ras Laffan	Wind: <10kts Line load: <10 tonnes

[2] Zarga
[3] Zarga
[4] Zarga

Mooring line failures during 2013

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1	10/1/2013	Aft breast	Bridon Steelite Xtra Jacketed	N/A	Line load: ~10 tonnes
2	27/1/2013	Forward spring	Bridon Steelite Xtra Jacketed	Isle of Grain	During discharge operation Line load: 40 tonnes
3	25/3/2013	Aft breast	Bridon Steelite Xtra Jacketed	Isle of Grain	During unmooring, rope broke without warning. Crew positioned out of snap back zone.
4	4/5/2013	Aft breast	Bridon Steelite Xtra Jacketed	Ras Laffan	Wind: Gale force >40kts
5	27/9/2013	Aft breast	Bridon Steelite Xtra Jacketed	Ras Laffan	During mooring operations Line load: slight to medium strain

Mooring line failures during 2014

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1[5]	25/5/2014	Aft spring	Bridon Steelite Xtra Jacketed	Ras Laffan	During berthing. Vessel position adjusted using the aft springs and winches.

[5] Zarga

2	01/7/14	Forward spring	Bridon Steelite Xtra Jacketed	South Hook	During unmooring operation. Subsequent ropes inspection found second spring had sustained jacket damage.
3	10/9/2014	Forward breast	Bridon Steelite Xtra Jacketed	Ras Laffan	During berthing. Line load: ~10 – 15 tonnes

Mooring line failures during 2015

No.	Date	Mooring line failure	Rope manufacturer(s) and rope type	Port	Notes (abbreviated)
1[6]	2/3/2015	Forward spring	Bridon Steelite Xtra Jacketed	South Hook	Wind: 30kts WSW gusting 38kts Line load: 24 tonnes. 3/O injured
2	22/6/2015		Samson Jacketed		Line load: 10 – 15 tonnes
3			Bridon Steelite Xtra Jacketed		
4			Bridon Steelite Xtra Jacketed		

[6] Zarga

Shading:

Instances of more than one failure while alongside	
Similar previous incident on board *Zarga*	

HMPE Users Group report 2011

Tension Technology International Ltd

69 Parkway, Eastbourne, East Sussex, BN20 9DZ, United Kingdom
Tel: +44 (0) 1323-504 167**Fax**: +44 (0) 1323-509 770   www.tensiontech.com

HMPE USERS GROUP

LNG Mooring Line Failures

FINAL REPORT

Ref: TTI-CB-2011-821-R

Date	Rev.	Description	Prepared by	Authorised by
19 Oct 2011	1	Final	[redacted]	[redacted]

Report submitted to:

Contact	**Organisation**
[redacted]	BG LNG Services, LLC
[redacted]	Bridon International Ltd
[redacted]	BP Shipping
[redacted]	DSM Dyneema B.V.
[redacted]	Marangas
[redacted]	Milford Haven Port Authority
[redacted]	NYK LNG Ship Management
[redacted]	Nigeria LNG
[redacted]	OCIMF
[redacted]	OSG GAS (LNG Group)
[redacted]	Qatargas Operating Company Limited
[redacted]	Samson
[redacted]	Shell Shipping Technology
[redacted]	South Hook LNG Terminal Company Ltd

Distribution:

The obligations of the applicable Non-Disclosure Agreement including any documentation generated by Tension Technology International as part of the project shall continue until five years from the end of the final HMPE Mooring Line Failures Users Group meeting of 16th September, 2011.

CONTENTS

1 Executive Summary

The conclusion of this study is that the overriding reason for premature failures of HMPE ropes from 2007, is that the HMPE material content in some of the designed ropes has been optimised for strength and is no longer sufficient to counter virtually all potential failure mechanisms. This is due to the increase in use of LNG terminals where harsher conditions are more frequently encountered than prior to 2007 where no known failures have been reported.

Many failure mechanisms were found during used rope examinations showing that there is no single failure cause. This is attributed to the variety of loading scenarios and circumstances that occur, their duration and order in which they occur. Different conditions in a different order would find the rope breaking down in a different manner.

The most dominant type of failure was well clear of fairlead at low loads, most likely due to prior higher loading causing fatigue damage, combined with low material content, leading to later failures in tensile, abrasion and creep.

Tail elasticity is very important in reducing line loads. Nylon is approximately twice as compliant as polyester and polyolefin so serious consideration should be given to deploying 11 m nylon tails at sheltered berths and 22 m nylon tails at exposed berths to reduce peak line loads in any situation and extend line life.

Sections 13 and 14 detail a number of recommendations aimed at reducing line failure rate.

2 Discussion

A number of HMPE mooring line failures on LNG carriers have been observed in recent years. The failures are predominantly at relatively new and exposed ports where the environmental conditions are harsher than that typically encountered previously in service, and so some failures might be expected. Failures have tended to be in the more heavily loaded breast lines; however, this is not always the case, some ropes failing at modest loads, located randomly along their lengths. The failures have occurred both in used and relatively new lines and continue to occur.

An HMPE Users Group was started in February 2011 to investigate the reasons for these failures and to provide recommendations for reducing the failures' incidence in this application in the future.

It should be noted that vessel sizes have increased, but this does not put more loading on the lines for the following reasons: Mooring analyses conducted at the ship design stage have to verify that the line loading to OCIMF 60 knot wind (and current) does not exceed 50% for HMPE mooring lines. The Q-Flex and Q-Max both have much larger volume of LNG but may use stronger ropes typically 137 tf MBL compared to around 127 tf MBL for the 122,000cm to 177,000cm LNG conventional vessels and will use up to 20 lines instead of 16 or 18 on the conventional LNG vessels. It should also be noted that the mean loads due to wind and current are not as damaging to the HMPE ropes as the wave induced vessel motions, which can place a very large tension range on the moorings. Wind and current forces are not cyclical. For a given wave height, the larger the length and beam of the vessel, the lower the motions. Therefore, a larger vessel will have smaller motions and hence smaller induced load range in the HMPE moorings.

There has been a variety of failure modes observed in the ropes returned to the User Group. Some have been mixed mode of failure including effects of applied rope twist, internal abrasion, tensile overload and creep.

Of major concern are the failures that occurred mid-span between vessel and hook, under very low load. These are not isolated failures; several such well-documented failures have now been submitted to the User Group. These did not show any significant internal wear or damage. Some of these rope failures had the distinct appearance of a creep-induced mechanism.

It appears that the Bridon ropes have failed due to a combination of tensile overload/creep dominated failure process. This is likely due to lower HMPE content. Bridon ropes made from a much earlier period in 2002, well before this high occurrence of failures since 2007, have not had any failures. Bridon ropes from this earlier period on BP Trader class vessels have reached 9 years' service and up to 7,000 mooring hours. The Trader class has not visited so many ports with high occurrence of wave-induced motions, so this is the likely explanation.

The few Samson rope failures have all been at very high load and as no samples for examination and testing have been submitted, it is not possible to provide a failure mechanism. What is clear is that these ropes at such a young stage of life should not fail under short duration loading at 80 tonnes when compared to the excellent high loading performance either in tension-tension fatigue tests or the OCIMF TCLL (thousand-cycle load level).

In the advent of new ships and new terminals, purchase specifications were based on successful experiences with HMPE lines used in the oil tanker sector. It is now apparent that exposed berths and the corresponding environmental conditions did not receive the high level of scrutiny that we now know is paramount to developing a mooring application. This needs to be addressed to prevent future failures. Although different constructions have changed over time, the quantity of HMPE in any given rope construction has not changed. This implies that some of the failures may have been due to vessels trading at more exposed ports.

3 Introduction

A number of HMPE mooring line failures on LNG carriers have been observed in recent years. TTI have conducted some small studies for individual Vessel Owners, Ship Management Companies and Operators mainly through analysis of visual and tensile properties observed from failed rope specimens returned to the laboratory at TTI Testing Ltd. This work while revealing useful information has not provided a definite consensus on the failure mechanisms.

As a result, companies that were known to have experienced these failures along with other assumed interested parties were invited with the aim of pooling resources to investigate the reasons for these failures and to provide recommendations for the use of HMPE ropes in this application in the future.

The project ran from the kick-off meeting on the 3rd February, 2011 until the final meeting on September 16th, 2011.

The companies that were part of the study are:

- BG LNG Services, LLC
- Bridon International
- BP Shipping
- DSM Dyneema B.V.
- LNG Nigeria
- Marangas
- Milford Haven Port Authority
- Nigeria LNG
- NYK LNG Ship Management
- OCIMF
- OSG GAS (LNG Group)

- Qatargas Operating Company Limited
- Samson
- Shell Shipping Technology
- South Hook LNG Terminal Company Ltd

4 Scope of Work

The original work scope of the group was to:

- Collate all available information on rope failures
- Focus on five ex-service rope failures for which very complete data (environmental, hook loads etc.) is available for review:
- Examine rope samples to determine fatigue mechanisms and residual strength based on a good knowledge of the rope usage.
- Using Optimoor with the environmental data, loads can be modelled to see if they match the load at failure and provide more insight into the cause of failure. This has already been accomplished for another recent project where field measured loads matched Optimoor modelled loads when taking into account cyclic stiffness (ref 1).
- Using wave occurrence data and the modelled mooring line loads, the fatigue life can be determined and compared with operational history provided by the members of the study.

The work scope was modified to spend more time on data collation and management of circumstances surrounding rope failures and less time on Optimoor modelling.

5 HMPE Mooring Line Ropes

The Bridon/Marlow ropes are termed as such because the original manufacturer of these ropes was Marlow Ropes who went into receivership in November 2005. Bridon International subsequently purchased the marine and offshore assets in January 2006, which included manufacturing equipment, IP and order book.

A description of the following rope types featured in this study is:

5.1 Samson – 12 Strand Single Braid

12 Strand single braid is a floating torque free 12-strand single braid manufactured from Dyneema SK75 HMPE (see fig. 1). It is coated with a Samthane coating that enhances the abrasion and cut resistance

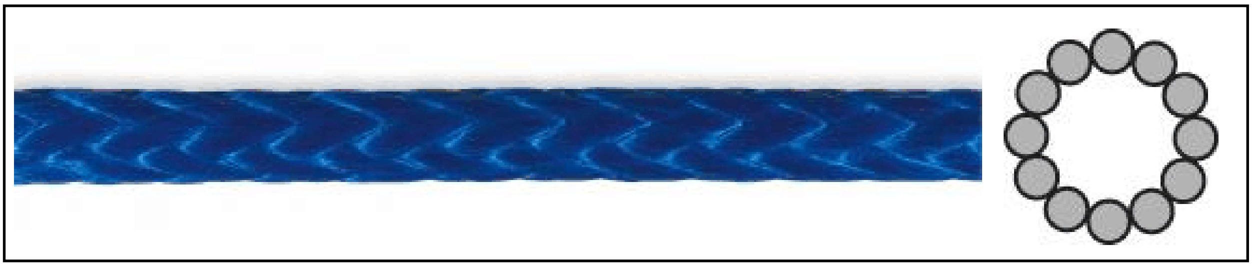


Figure 1: 12 Strand single braid

5.2 Samson - Core with Jacket

Samson "core with jacket rope" comprises of a load-bearing 12 strand braided core manufactured from Dyneema enveloped in a polyester braided jacket complete with a performance enhancing coating see figure 2.

Figure 2: Samson Core with Jacket

5.3 Bridon/Marlow – Core with Jacket

Bridon/Marlow "core with jacket rope" comprises of a load-bearing core manufactured from Dyneema SK75 in one of three constructions – a single 3 strand hawser laid core, a single 6 strand wire laid core or a single 12 strand plaited core (see fig. 3). In each case enveloped in a 32-plait polyester or polyester /polyolefin braided jacket. A thin intermediate synthetic rubber tape to reduce core to cover slippage may also be present.

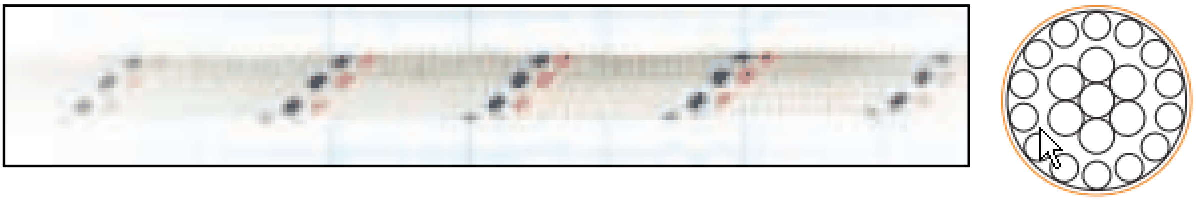


Figure 3: Bridon/Marlow Core with Jacket

5.4 Koronakis - Core with Jacket

Koronakis "core with jacket rope" comprises of a load-bearing non-rotating core manufactured from Dyneema and enveloped in a polyester braided jacket, see figure 4.

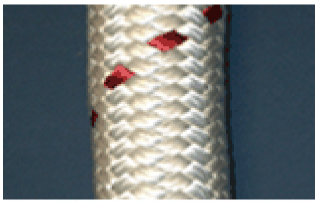


Figure 4: Koronakis Core with Jacket

5.5 Basic Technical Data

Some basic technical data associated with the ropes under consideration is shown in table 1.

Manuf.	Trade Name	Construction	Dia (mm)	HMPE Mass (g/m)	Minimum Spliced Break Load (tf)
Samson	12 Strand single braid	12 Strand braid coated with PU	40	[1]873	116
Samson	Core with Jacket	12 Strand braided core coated with PU & encased in a polyester jacket	44	701	125
Bridon/ Marlow	Core with Jacket	3/6 strand twisted or 12 strand braided core encased in a polyester based jacket	40/44	627	114
[2]Koronakis	Core with Jacket	Load-bearing core encased in polyester jacket	42	1296 (incl. jacket)	130.7 (assumed unspliced)

Table 1: Rope Properties

[1]Originally data supplied by Samson was 926 g/m

[2]Unable to contact Koronakis to confirm details, data taken from website

The Samson 12 strand single braid rope has 38% more HMPE than the Bridon rope. This will have a significant benefit in resisting failure for all modes bar heat dissipation, should that be considered a failure mode in this application. The mistake should not be made though that the Bridon/Marlow ropes are under strength. A rope construction with a core and jacket does not require the core to be externally abrasion or snag resistant, this means that twist levels and braiding angles of rope components can be very low since there is a jacket to protect against external abrasion and snagging. The lower the twist levels and braiding angles the higher the strength. In the case of the 12 Strand single braid where there is no jacket, then any damage to the exterior of the rope reduces rope strength. To provide a robust rope construction where there is no jacket, twist levels and braiding angles have to be significantly higher and this reduces component strength efficiency and therefore rope strength. Coatings can also be applied to improve rope durability. Both Samson rope types benefit from this but not the Bridon/Marlow rope.

Unused Bridon/Marlow rope samples were returned from one of the BG vessels in 2010 and assessed for unused break load where they were deemed satisfactory in this respect.

Samson also have an HMPE core with jacket rope used in this application that has 12% more HMPE than the Bridon/Marlow one.

Low twist and braiding angles also provide longer lifetimes in tension – tension fatigue, this design of core being widely used in offshore mooring. What might be a minor effect but worth mentioning is that the lower twist and braiding angles result in less constructional stretch (as opposed to material stretch). This means that the core with jacket ropes would be less extensible. However, this effect is most apparent when new and as the rope beds in the stretch of the two rope types (single braid and core with jacket) would converge.

The resistance to virtually all potential failure mechanisms however will increase with an increase in HMPE material of the Samson 12 Strand single braid and Samson core with jacket rope over the Bridon/Marlow core with jacket rope.

Rope masses depend on their method of determination. Variances in tension under which the mass is measured, applied finishes/coatings, constructional take-up and whether the sample has seen previous loading will all have an effect on the linear density. TTI have not verified any of the rope masses stated.

6 Pre HMPE User Group Failure Analyses

Summaries of investigations on failed ropes conducted previously by TTI and commissioned by members of the User Group are made accessible to the Group:

6.1 BG HMPE failures – Methane Shirley Elisabeth and Methane Jane Elisabeth

Two Bridon core with jacket rope failures from Methane Shirley Elisabeth and Methane Jane Elisabeth were investigated. The ropes were reported to have failed at loads as low as 6-8 tonnes and up to around 30 tonnes.

Key findings from those studies are as follows:

- The strength of the rope textile yarns had been severely reduced adjacent to the failures of the pair of ropes from the Methane Shirley Elisabeth with a residual textile yarn tenacity being about 40% of that expected of new yarn. About three metres away from the fail zones of the ropes investigated, the residual tenacity was found to have risen to about 60% of the expected value. In the one case where a rope could be sampled about twenty metres from the fail zone, the residual tenacity was found to be 93% of the expected value.
- Thus, a severe and unacceptable loss of tensile properties of the textile yarns adjacent to both failures has been measured, especially considering the short service history - around 1.5 years old. In addition, at a distance away from the fail zones, a loss of tenacity was also found, though it was not as severe.

A short testing programme to compare the creep properties of textile yarns adjacent to and remote from one of the rope failures supported the results gained from tensile testing, in that there was virtually no creep rupture life remaining in yarn adjacent to the failure.

6.2 BG Methane Heather Sally

A Bridon rope failure from Methane Heather Sally has been investigated. Findings are as follows:

- The strength of the rope textile yarns had been severely reduced adjacent to the failure with residual textile yarn tenacity being about 40% of that expected of new yarn.
- About 4 metres away from the fail zone, the residual tenacity was found to have risen to about 50% of the expected value. The residual tenacity of yarns from a new rope was found to be better than 90% of that expected of a reference yarn.
- Thus, a severe and unacceptable loss of tensile properties of the textile yarns adjacent to the failure has been measured. In addition, at a distance away from the fail zone, a loss of tenacity was also found, though it was not as severe.
- Whilst the jacket was quite dirty, the general external appearance of the ropes does not suggest that handling and conditions in use have played a major part in the loss of strength. Internal inspection did not show strand-strand or yarn-yarn abrasion damage at a level that would explain the failure.

- Of key importance was that three ropes failed mid-span between hook and fairlead so this is not an isolated incident.

From these rope failures and other LNG HMPE rope failures some typical failure modes are shown in the photographs below.

Figure 4: Typical modest abrasion, complex shear/torsional forces induced failure, BG vessel Methane Shirley Elisabeth

Figure 5: Typical wear, bending and final creep failure, British Sapphire

Figure 6: Mixed mode failure, Methane Shirley Elisabeth

6.3 LNG Nigeria River Orashi at Bilbao

This series of failures of Bridon core with jacket rope on the LNG Nigeria vessel River Orashi at Bilbao in 2011 was conducted by BW Fleet Management and DNV. The key reason for failure was attributed to a sawing action of the rope in a fairlead caused by first order vessel motions of the vessel during high swell. Figure 7 shows three positions on the rope core where cutting/abrasion damage has occurred due to the motion of the vessel in the fairlead. One cut is under the jacket as circled.

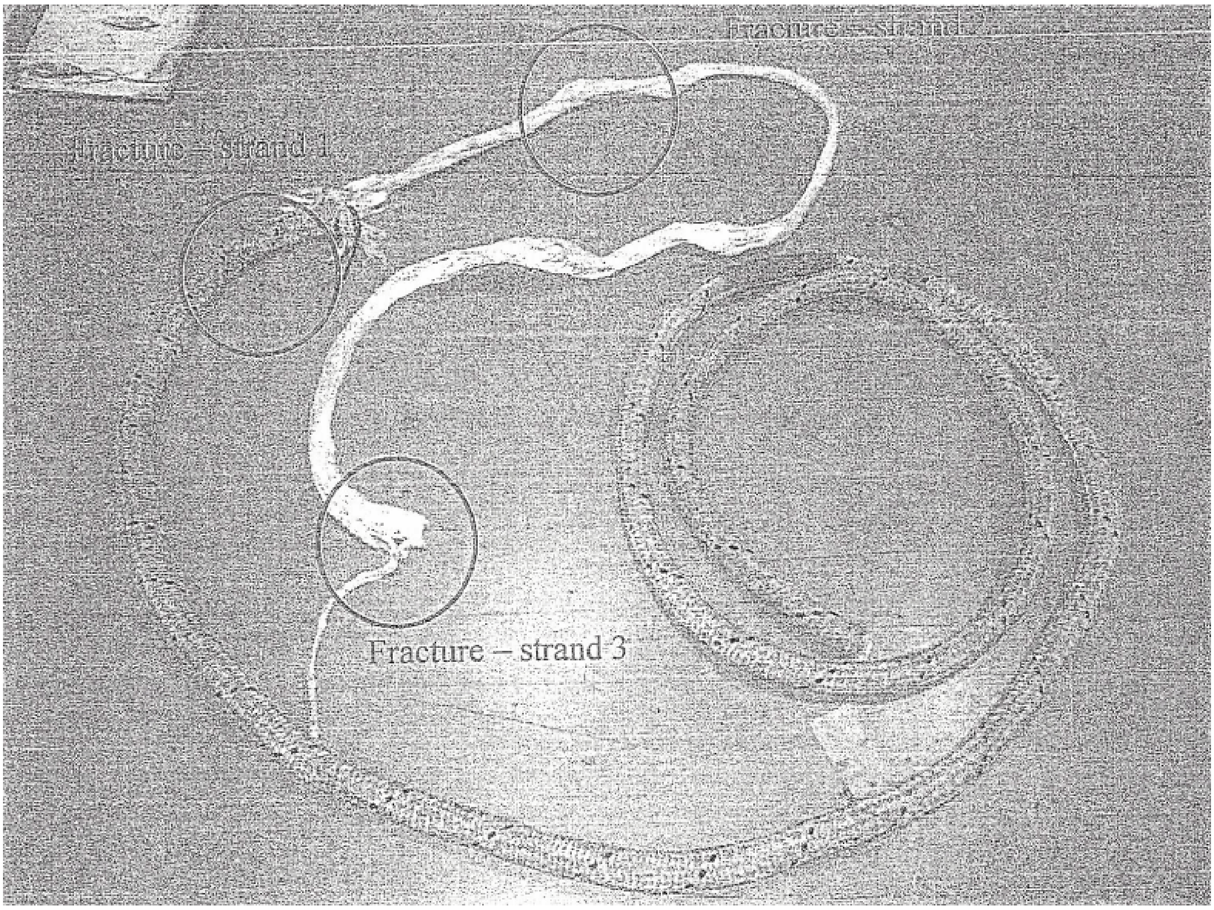


Figure 7: Sawing action at fairlead

6.4 British Sapphire

Several ropes (ref 16) failed on the tension drums and fairleads at Dahej due to long period swell causing high vessel motions. Several locations along the length were tested for yarn residual strength and the calculated rope strength was around 80-90%. A typical failed end is shown in figure 5 which appears to be a wear/bending aggravated creep dominated process in the final failure.

7 Pre HMPE User Group – Analyses of Intact Rope

7.1 BP Innovator

Two 3-metre lengths of rope were submitted for investigation to TTI Testing, from the vessel British Innovator. The test certificate showed they were 2002 manufacture from Marlow Ropes.

Both ropes were inspected visually before being unravelled to permit tensile testing of their constituent textile yarns.

The visual inspection found the ropes to be in reasonable condition, given they had been deployed for about 7 years and had an estimated 3000 hours of mooring service. Internal inspection found the rope strands to be in reasonable condition, with no significant evidence of strand/jacket abrasion damage or strand/strand abrasion damage.

Microscopic investigation found the filament diameters to be in line with that expected - about 17 microns.

Tensile testing of textile yarns from both rope samples did not reveal any evidence of loss of performance other than that expected for a 'used' rope.

A brief study of the creep resistance of the textile yarn of one of the rope samples did not reveal any evidence of a loss of creep life.

The ropes were estimated to have lost only 5% of their new strength.

8 HMPE User Group – Analyses of Intact Rope

Two operationally intact ropes were made available for analysis. They were from the BP Trader and Qatargas.

8.1 BP Trader

BP supplied TTI with a length of Marlow core with jacket rope for analysis from the BP Trader. This rope has 6,993 hours of logged use from November 2002 to June 2011 and was a breast line. A break test conducted at Bridon reached 105 tf, which is 92% of new spliced MBL.

The tenacity values of the textile yarn were comparable to that expected of new textile yarn.
The results support the reported field performance and used rope break test, in that no problems with either rope had been observed.

8.2 Qatargas

A delivery was received from Qatargas that comprised a section containing an eye and a length of rope from the same line from the winch end. Rope was tested from just below the eye splice and from the winch end.

Generally, the tenacity values of the textile yarns were close to the expected value for 'new' yarn and support the fact that the ropes had not had any performance problems in use.

9 HMPE User Group – Analyses of Failed Ropes

9.1 Overview of testing

The testing conducted by TTI has been on used ropes which had failed and used ropes that had performed satisfactorily. The failed ropes were divided into two types, depending on the location of the failure. The first type was where the failure was very close to the bottom of an eye splice and the second type was where the rope had failed between the eye and the vessel fairlead.

The objective of testing was to establish the residual physical properties of the textile yarns from which the ropes were made and to look for changes that might contribute to the better understanding of the problem. The physical testing of the ropes was performed on constituent textile yarns, and the textile yarns were selected from the inner rope yarns of strands. From inner rope yarn, inner textile yarns were then retrieved for testing. The selection of these yarns was done to avoid as much as possible measuring any loss of performance due to abrasion damage.

The testing performed was as follows:

a) Visual inspection of the ropes and their failures
b) Establishing the linear density of textile yarns
c) Measuring breaking load and breaking extension

d) Calculating tenacity for the textile yarns for comparison between samples and also with the expected 'new' value for tenacity
e) Creep testing was performed both at TTI and at an independent laboratory.
f) Optical and scanning electron microscopy was also performed.
g) Testing was conducted to investigate the crystallinity of different samples and also to investigate their thermal stability

The ropes analysed that had failed adjacent to the eye splice were labelled

- Q/OSG/Ras Laffan
- NYK'AU/Ras Laffan

The ropes that had failed away from the eye splice were called

- CRN0205 rope 1
- CRN0205 rope 2

10 Data Trending Analysis of Known Failures

Separate to this report an electronic Excel spreadsheet file is provided that details key data on known failures of HMPE mooring lines used on LNG carriers that have been provided for use in this group. This data has been provided by BG, DSM, K Line (non-members), LNG Nigeria, OCIMF, QatarGas and Teekay (non-members).

The following discussion is presented after analysing the data in order to find trends and significant occurrences. There were suspected anomalies and duplications in the data and best judgement was used in interpretation. Of particular note were the stated use of nylon tails for Q-Flex vessels in one spreadsheet and the same failure occurrences citing a polypropylene/polyester blend. As the latter reference provided trade name and diameter, it is assumed to be the correct tail material. Nylon is often used synonymously for synthetic. Nylon will have approximately twice the elasticity of a polyolefin (polypropylene/polyethylene)/polyester blend. Where failure loads are given as a range the mid load has been used for trending.

We know there are many more failures than have been included in this study because in the course of normal business every LNG operator/management company/owner asked has experienced at least one HMPE line failure in this market sector. These companies normally do not want to get involved at this level perhaps because they have moved back to wire or they do not have the data surrounding the failure to make reporting it in detail of much value.

10.1 Date of First Recorded Failure

The first recorded failure was on 27th April, 2007. Prior to this, we have no records of any HMPE LNG lines breaking in service. This is a significant milepost because it suggests that assuming rope constructions and fibre remain unchanged then there are one or more other changes connected with the use of these ropes that are causing or contributing to their failing in service. This means that any proposed contributory factor that existed prior to 2007 is unlikely to be the main cause or part of the main cause otherwise breaks would have occurred prior to 2007.

Discussion with three Bridon personnel who worked for Marlow Ropes from 1990 until January 2006 when Marlow was dissolved cannot recall a single HMPE LNG line failure or other vessel type HMPE mooring line failure.

10.2 LNG Carrier Type

LNG vessel type can be separated into five types:

- Conventional prismatic tanked
- Conventional spherically tanked
- Q-Flex
- Q-Max
- Small vessels with < 100,000 m3 capacity

The distribution of failures across vessel type is shown in figure 8. The majority of vessels are of the Q-Flex type, which is larger than a conventional LNG vessel. This may not be significant as the trend in vessel sizing is to larger vessels. Q-Flexes and Q-Maxes were first built in 2007. Mooring analyses conducted at the ship design stage have to verify that the line loading to OCIMF 60 knot wind from all directions (and associated specified currents) with the vessel in the most wind exposed condition (ballast draft and highest water level) does not exceed 50% of MBL for HMPE. The Q-Flex and Q-Max have much larger volumes of LNG but may use stronger ropes up to 137 tf MBL compared to around 127 tf MBL for the conventional LNG vessels and may use up to 20 lines instead of typically 16, occasionally 18 in the smaller conventional vessels. It should also be noted that the mean loads due to wind and current are not as damaging to the HMPE ropes as the wave induced vessel motions, which can place a very large tension range on the moorings. For a given wave height, the larger the length and beam, the lower the motions. So a larger vessel will have smaller motions and hence smaller induced load range in the HMPE moorings. To support this, Bilbao note that they have no problems with Q-Flexes in swell but do with conventional vessels (see failures spreadsheet). Also, consider that the terminal with the highest reported number of failures, South Hook only accept Q-Flex and Q-Max vessels.

A breakdown into vessel type of the world LNG vessel population (ref 11) is:

13 Q-Max L 333 B 55 D27
32 Q-Flex L 303 B 50 D27
180 Conventional prismatic tanked L 276 B 46 D 26
107 Conventional spherically tanked L 268 B 43 D26
25 Small vessels with < 100,000 m3 capacity
357 vessels total

L, B, D = Typical Length, Breadth & Depth (m)

At the risk of trying to be unrealistically accurate with the data we have – Samson have provided 2135 lines and Bridon/Marlow 1360 lines. Dividing this total by 20 lines per vessel/yields 175 vessels. This figure does not allow for replacements of HMPE for HMPE, the supply to new builds that are not yet in service, those vessels that have changed back to wire and ropes supplied by other rope manufacturers.

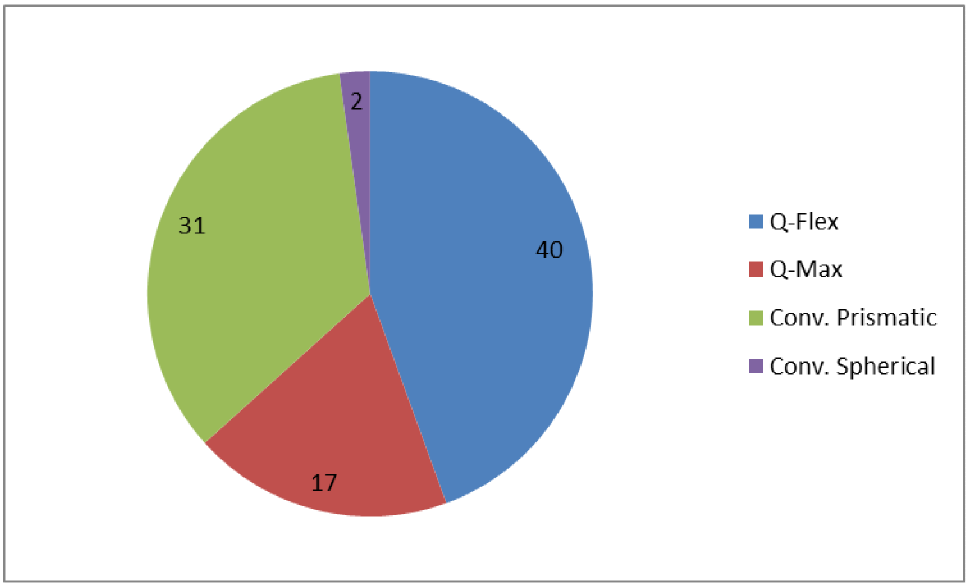


Figure 8: Vessel Type by Number of Failures

10.3 Terminals

The distribution of terminals at which failures were recorded is shown in figure 9. Some terminals have more than one jetty, these are grouped together under that the main terminal name because they were not always itemised individually in the spreadsheet. An example being South Hook, which has two jetties, is not divided into jetties one and two. Some of the geographical failure locations are given by country or continent and so are not included in this chart as they may represent two or more terminals.

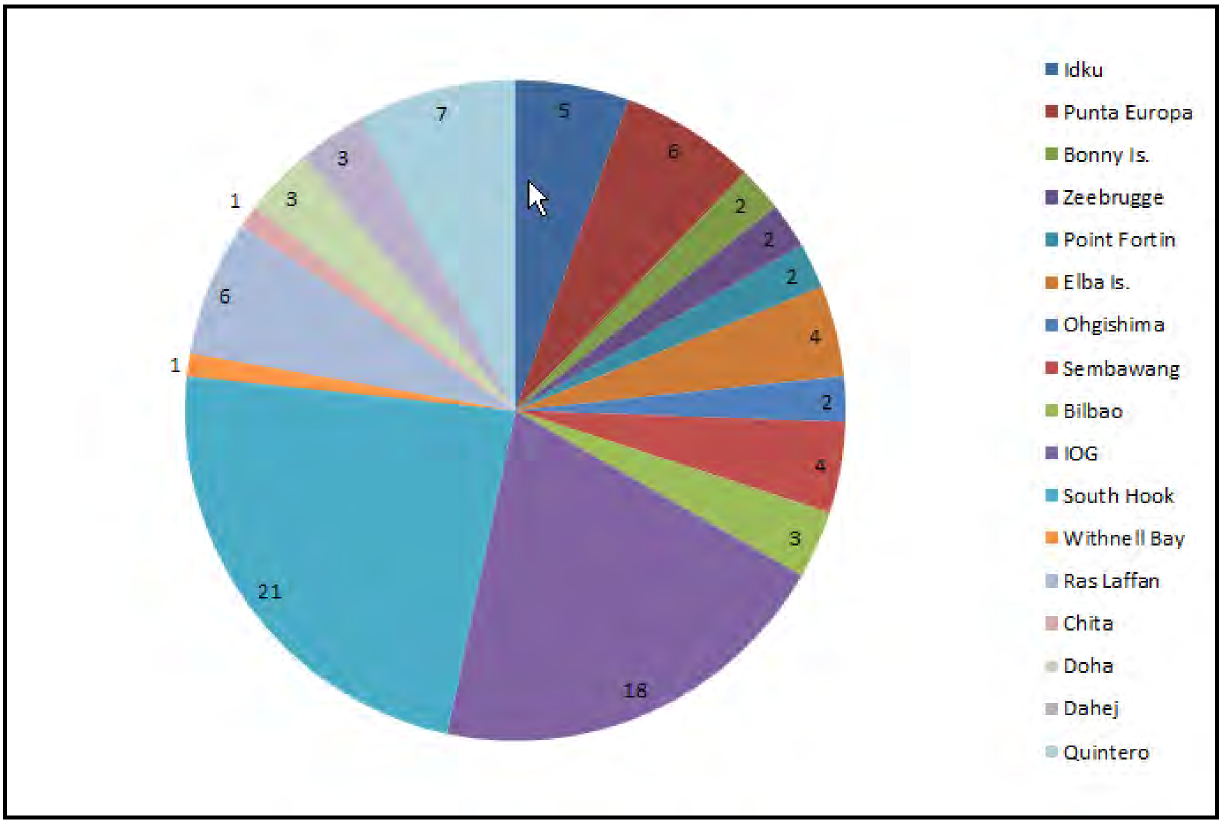


Figure 9: Terminals by Number of Failures

It is interesting to consider that four of the top five terminals with most failures – South Hook 21 failures (started trading 2009), IOG 18 (2005), Quintero 7 (2009) and Punta Europa 6 (2007) and Ras Laffan 6 (1996) (TTI believe the IOG was trading very slowly at first). Another interesting characteristic concerning these terminals is that South Hook, Quintero and Punta Europe are known for significant swell, IOG for high current and Ras Laffan for very high temperatures. Also, many of the Q-Flex and Q-Max trade between Ras Laffan and South Hook, so although ropes have failed at Ras Laffan, the damage may have been caused at a prior mooring in South Hook when affected by wave motions.

The population of LNG terminals (ref 12) is 122 worldwide. Within this there is more than one berth at some of the terminals.

10.4 Rope Manufacturer

Associating the rope manufacturer to the reported failures, the chart below shows that 92% are of the Bridon/Marlow manufacture, 5% Samson and 3% Koronakis. Bridon/Marlow has supplied 1,360 of these lines (68 vessels x 20 lines per vessel) through large shipbuilders' OEM contracts while Samson has supplied 1429 core with jacket and 706 12-strand single braid ropes. Data is not known for Koronakis and there are believed to be other rope manufacturers supplying ropes to this market sector.

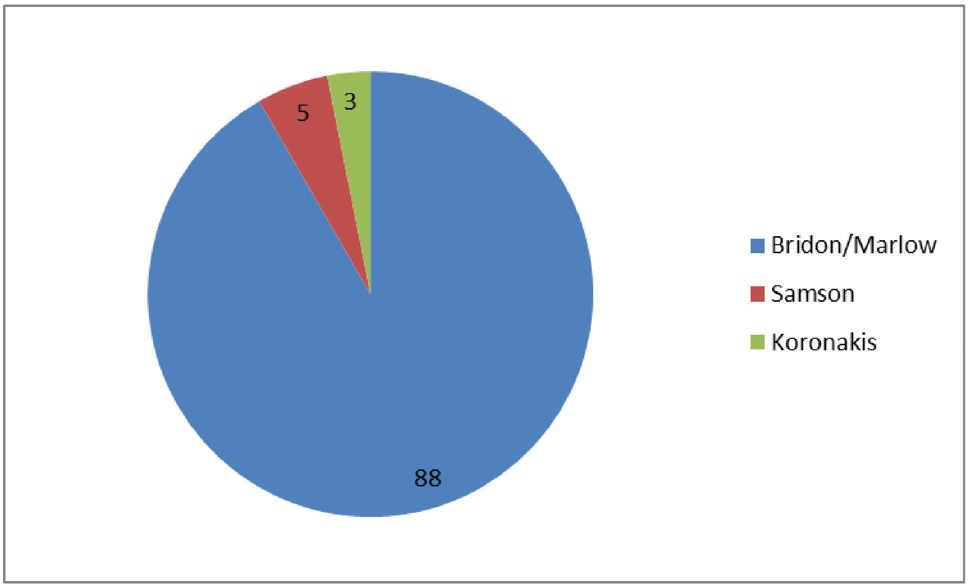


Figure 10: Rope Manufacturers by Number of Failures

10.5 Rope Construction Type

All rope constructions bar one listed in the rope failure spreadsheet are core with jacket type ropes. Note that the number of failures reported to this group is only part of the total number of HMPE rope failures in the LNG mooring application. An estimate based on information received from non User Group operators is that the number of total failures is twice what we are considering in this study.

10.6 Rope Lifetime

The usage of mooring lines is documented by users as numbers of mooring hours. This is the time spent when the vessel is moored and the hours not moored is not recorded as it is somewhat irrelevant, as the rope is stored on the drum during which time no tensile damage occurs. The average mooring hours of a failed rope was 1011 hours with a minimum of 62 and maximum of 1940 hours. This data should not be confused with the average lifetime of LNG HMPE mooring lines since an assumption is that not all of them fail, therefore their average lifetime may well be much higher.

10.7 Tails

Tail lengths used in this data set were either 11 or 22 m long. Tail material was polyester, nylon or a blend of polyolefin (mainly polypropylene) and polyester.

Figure 11 shows the distribution of both material type and length while figure 12 the distribution of just length and figure 13 just material types.

To reduce peak loads in a mooring system the elasticity of the system has to be increased. In sheltered berths, 11 m nylon for all line functions would be used to achieve this. At exposed locations, 22 m nylon tails would be used for all line functions except springs where normally but not always 11 m lengths remain. Vessel excursion should be checked if increasing mooring elasticity.

It is interesting that the most compliant tail being 22m nylon was only present in 5 of the 84 cases (see fig. 11). Where 11 m tails were used – 51 cases only 4 of them were nylon (see fig. 11) and just considering material type only (fig. 13) only 10 of the 85 failures were nylon. Polyester and pp/polyester mixed fibre rope tails have been preferred over nylon due to their much longer life. However, the reason for using nylon has largely been overlooked, and until recently when this high number of mooring line failures occurred, it was highlighted how important nylon was to keeping line loads down.

The benefit of nylon was proven from measured hook loads, which reduced by around a factor of three when compared to polypropylene tails (ref 1)

Furthermore, the recent Effective Moorings JIP showed the benefit of lower line loads and longer fatigue life in the main winch line when using nylon tails compared with polypropylene tails using Optimoor modelling software (ref 3 & 15).

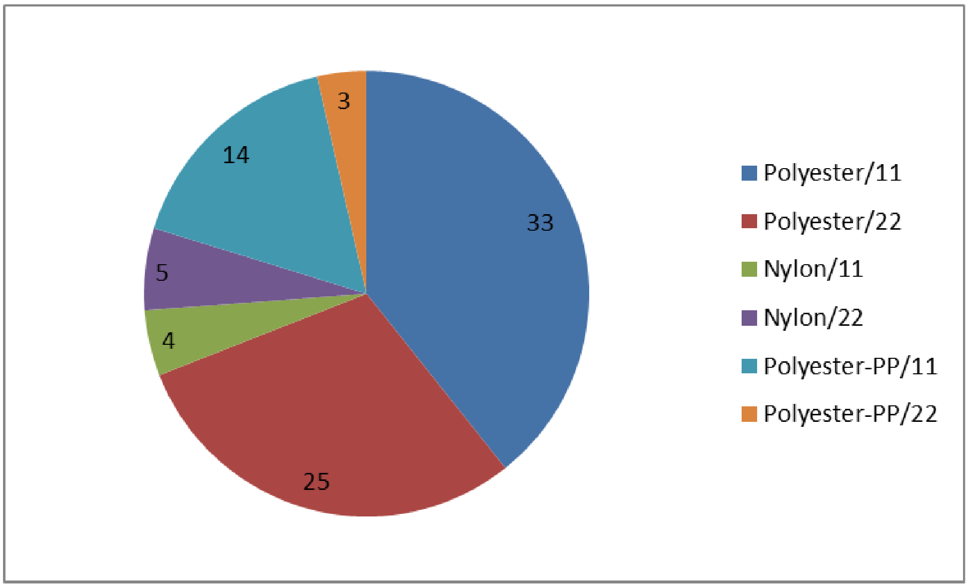


Figure 11: Tail Material & Length by Number of Failures

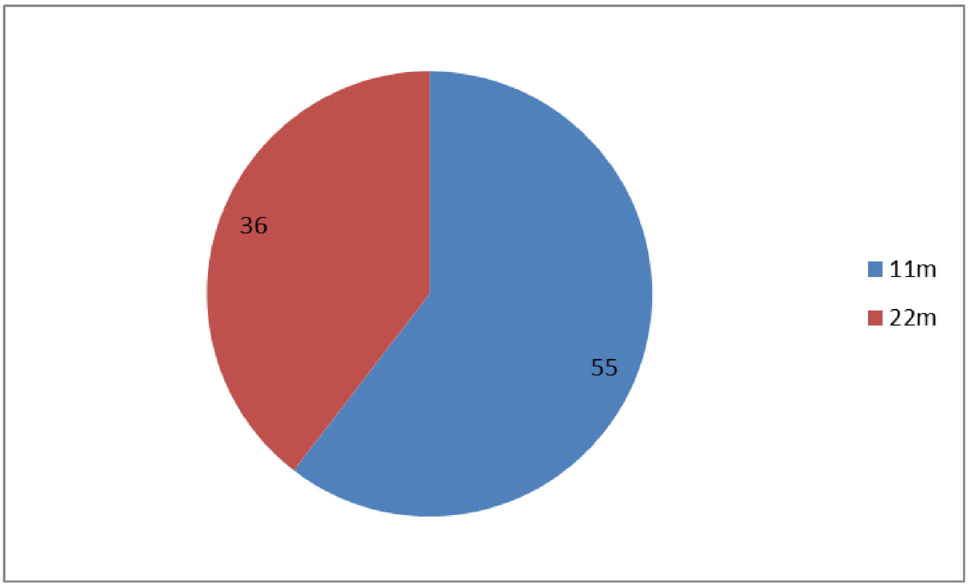


Figure 12: Tail Length by Number of Failures

Conclusion: the majority of line failures are in combination with either polyester or polyester/polyolefin blend, 11m tails

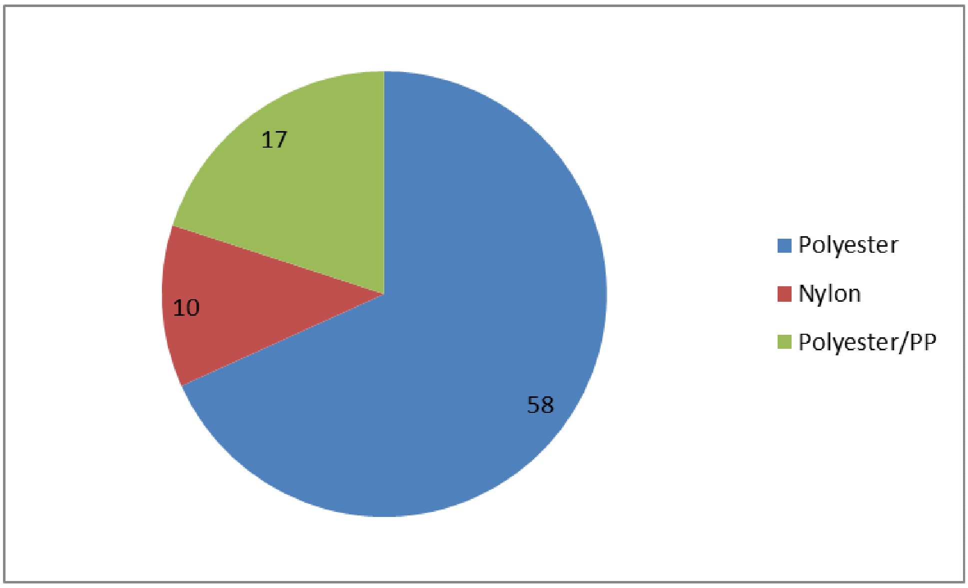


Figure 13: Tail Material by Number of Failures

10.8 Line Load at Failure

The distribution of failure loads is shown in figure 14, half of them are 20 tf or below representing 16% or below of the rope minimum break load.

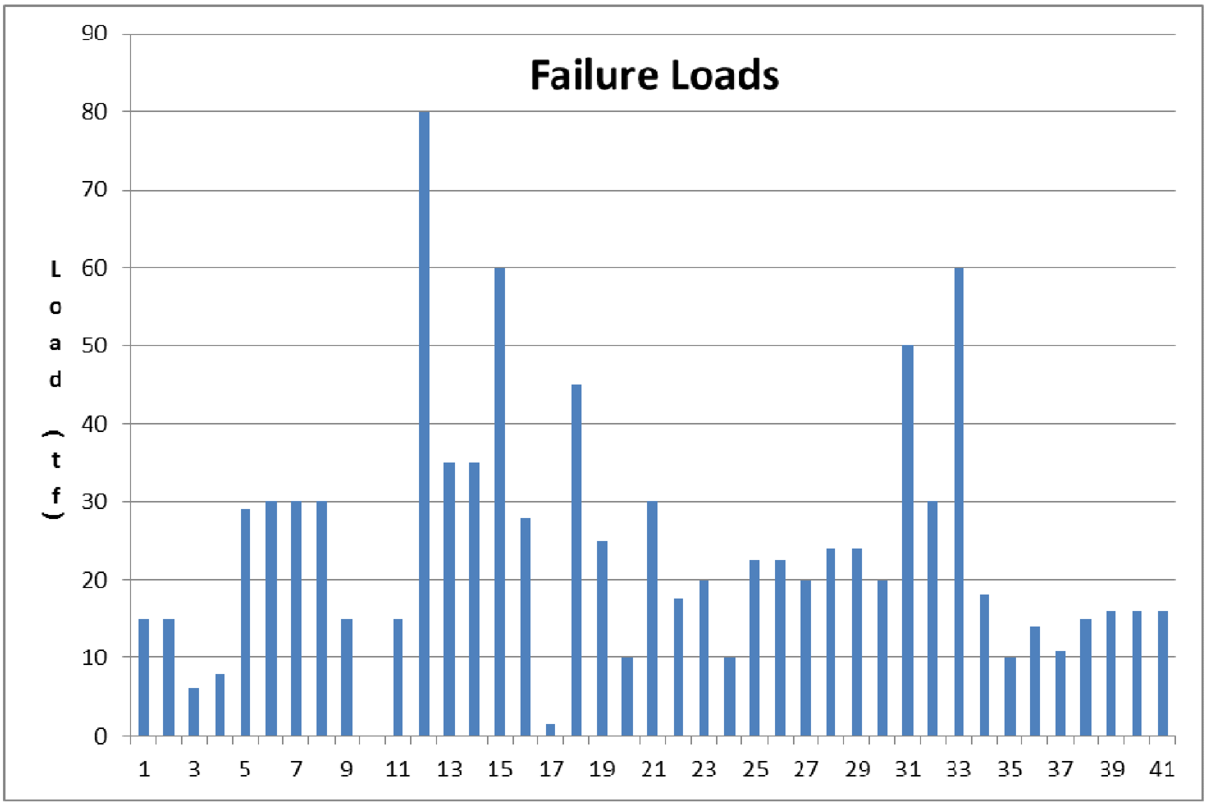


Figure 14: Failure Load by Number of Failures

10.9 Line Function

Of the 125 failures where line function was provided at least 70% were breast lines (at least 56% aft) and 19% spring lines. These values have to be considered against the proportion of each line type in a mooring. For example, a typical 16-line mooring will have 4 spring lines indicating 25% of all lines are springs. Similarly, approximately 25% of lines maybe head or stern lines and 50% breast lines. This data indicates that aft breast lines are failing at over twice the frequency than that of a randomly distributed line function.

10.10 Fairlead Type

Eighty-six % of the line failures occurred in vessels using panama fairleads and 14% in those using roller fairleads. Without knowing the proportion of each in service this only indicates failures maybe independent of OEM fitted fairleads. There is insufficient data for retro fitted nylon fairlead inserts. Laboratory test programs have shown that roller fairleads have a higher wear rate than either Panama or nylon lined Panama when the rope is running over the roller at an angle (ref 4). If the rope is running over the roller perpendicular then the wear is similar between nylon lined Panama and roller fairlead.

A report of an investigation of an HMPE rope established that wear was the cause of an unprotected Panama fairlead (ref 5).

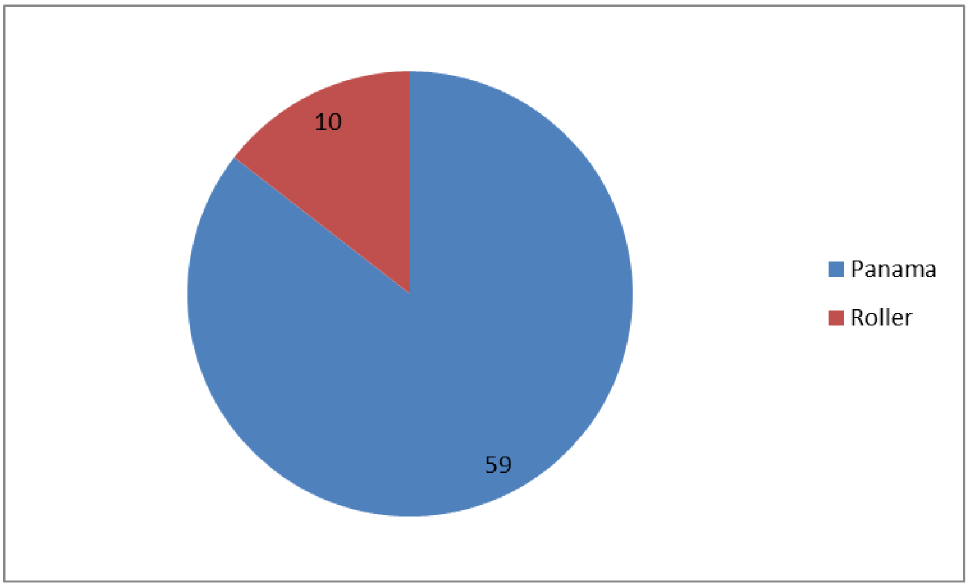


Figure 15: Fairlead Type by Number of Failures

10.11 Point of Failure on Line Length

The position along a line's length where failure occurred has been grouped into four areas;

- On-board between winch and fairlead
- In the fairlead
- Outboard between fairlead and end of splice
- Within the splice length itself.

The distribution is shown in figure 16. This appears randomly distributed across the groups. Consider that the splice region maybe around 5 m and that this is weakest point of the rope and should an unbiased break test be performed or a tension – tension fatigue test be undertaken then this is where the failure should occur. This may indicate that first order wave motion action in the fairlead is not a predominant factor. While the position of a section of rope may vary, from terminal to terminal modern LNG terminals are designed along similar lines so that mooring dolphins set back from the berthing line would be a similar length in the majority of terminals.

What is significant is that the bending and wear damage accumulation would be much higher in a fairlead or on the tension drum, compared to the end of splice location, which is only subjected to tension-tension cycling. Therefore, the very high number of failures outboard is very significant and strongly suggests that the abrasion mode (internal or external) should not be active in these cases.

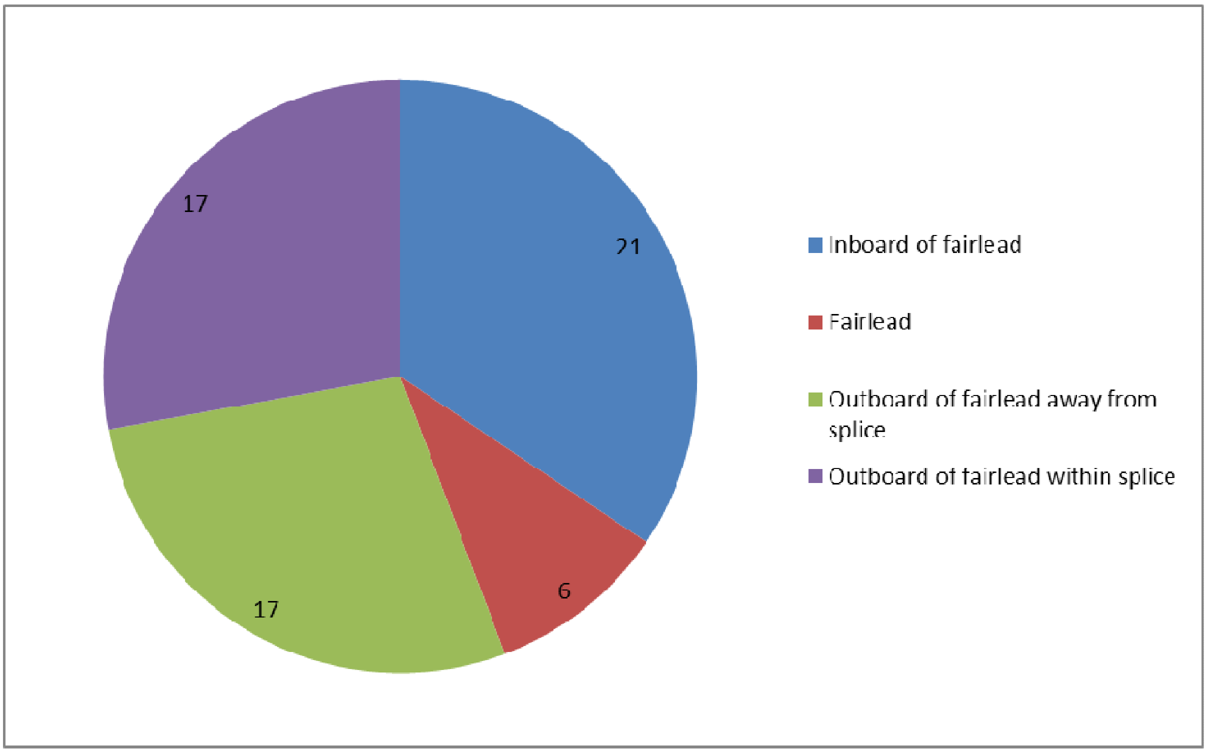


Figure 16: Position Along Line Where Broken by Number of Failures

11 Possible Failure Causes Discussion

11.1 User Induced

11.1.1 Twist

It is known that adding twist in either direction to a rope in service will decrease rope strength. For ropes with twisted load-bearing components such as the Bridon/Marlow core with jacket with a 3-strand or 6-around-1 core the effect on strength is small because the structure is already twisted and is therefore able to have that twist modified with minor effect on breaking load. For ropes with plaited or braided load-bearing components such as the Samson 12 Strand single braid, Samson core braid with jacket or the Bridon/Marlow core with jacket with a 12 strand core the effect on strength is more noticeable because the structure has not been formed using twist as the final process in manufacturing, but is not significant enough to be a primary factor in these failures.

The most significant reason against induced twist as a primary factor for these failures is why would failures occur from April 2007? Why would crews deploy ropes with twist in from this date on LNG vessels only? It is illogical. Mooring ropes have always been used with induced twist, undesirable though this is. This point is addressed later in the recommendations.

11.1.2 Environmental Conditions

Many of the failures are occurring in harsh environmental conditions through the rapidly growing LNG market. This has required a growth in LNG terminals that are being built in exposed locations because of the lack of suitable sheltered locations.

These environmental conditions may feature local wind generated waves, far off generated swell and/or high currents often coupled with large tidal range (up to 11 m from low to high).

Sheltered terminal moorings with just minor current and wind typically impart line loads of 15 – 20 % MBL and tend to apply themselves in a constant or gradually changing fashion. Significant swell such as seen at South Hook for example sees line loads up to 58% of line MBL. First order wave and swell motion are periodic meaning that the ropes are repeatedly cycled from as low as slack (0%) to 58% of MBL in this example.

11.1.3 Non-Optimization of Tails

The more elasticity in the mooring system the lower the peak loads. The only limitation to the amount of elasticity that a mooring system can have is the effect on vessel movement during the mooring, that is mainly the vessel surge (forwards/backwards movement along the jetty) and the outward sway (movement of vessel away from the jetty). It is unlikely in our experience that the difference between using a high elongation tail – nylon, would have practical disadvantages over the use of polyester, polyolefin (typically polypropylene and polyethylene) and blends of polyester and polyolefin in this respect. Therefore, at sheltered berths there is a technical preference for using only nylon over polyolefin or polyester tails from a line load perspective. The standard length for tails is 11 m and this is suitable for sheltered berths.

At exposed berths with first order vessel motions, there is more vessel movement for the lines to absorb so the same arguments apply regarding material. To reduce the peak loads TTI have done considerable work (refs 1, 3, 4) in proving and setting the standard for longer tails. The standard length for exposed terminal tails is 22 m for all line functions except the springs where either 11 or 22 m can be used (at the terminal’s discretion). Doubling tail length to 22 m does not double the vessel movement at berth. Typical increases in surge or sway are around 15%.

11.1.4 Overload

As far as the information in this study allows, all lines were deployed from winches. Theoretically, lines can occasionally be deployed from bitts. The difference for this discussion is it is impossible to overload a winch line as it has a winch render setting. This is typically set to 60% of the line MBL according to OCIMF MEG 3 (Oil Companies International Marine Forum, Mooring Equipment Guidelines Version 3) but in practice can vary above or below this value. Line attached to vessel bitts if overloaded can break, as there is no mechanism to prevent this. Winch lines, once the render limit is reached will slip and release line causing the vessel to increase its movement relative to the berth. The use of correctly maintained winches makes it impossible to overload a line assuming the line has the break load it is designed to have.

This makes line overload as a failure mechanism unlikely assuming winch brakes are working correctly unless the line has a reduced breaking load through current operating conditions or through being damaged from a previous mooring. Consider a South Hook failure (documented in the failures spreadsheet), of a Samson line at about 80 tf on a 137 tf MBL representing 58% of line MBL. Winch brakes were tested at 82 tf 5 months earlier (source 18/11/2009 at South Hook). However, friction through the fairlead could increase tension outboard by up to a factor 1.2, or 98t in this real case, so would explain higher hook tensions than the break setting. We could assume that a rope with over 40% strength loss would have exhibited visual signs of this at the point of being passed from ship to shore bollard and that if so would not have been used. If the rope was in acceptable visual external condition then it remains a mystery as to why it broke.

11.1.5 Dynamic Loading

TTI have seen video evidence of lines being cycled from slack condition to peak load in swell. This means that the application of load can occur very quickly over a few seconds. Laboratory testing of ropes for certification purposes will apply a breaking load over a period of a few minutes. Testing a rope very quickly reduces its ability to adjust its sub-components to converge to perfect load sharing and can reduce the ultimate break load. This effect would be much greater on a new rope than a used undamaged rope since bedding-in of the construction will not have optimised. A used damaged rope may require bedding-in to equally share load over a non or less damaged component. No evidence is offered for this being a contributory failure mechanism as testing resource was not available for this task i.e. full-scale dynamic test facilities, but it is mentioned for consideration.

11.1.6 Unequal Load Sharing

Two or more ropes performing the same function say aft breast ropes that have not been tended to correctly and therefore under different tensions will not share load equally and therefore put more stress under the more highly loaded. While this would be clearly a contributory factor in line failures we have to consider that this 'human' element would have been present long before the cut off point for failures in 2007 and cannot therefore be considered a primary reason.

11.2 Design Induced

11.2.1 HMPE Content

HMPE content in particularly the difference between the Samson ropes and Bridon/Marlow ropes is discussed in section 4.4.

11.2.2 Rope Construction

The rope construction in particular the load-bearing core of the Bridon/Marlow core with jacket rope is a single 12-strand braid, a single 3-strand hawser or a wire laid 6-around-1. These core constructions have been used by Bridon/Marlow ever since HMPE was commercially available from the late 1980s. The most significant reason against the construction (not mass) as a primary factor for these failures is why would failures occur from April 2007 when they have been deployed for 15 to 20 years previously for the same application across different market sectors?

This argument applies for the jackets of these ropes be they 24 or 32 plait polyester or polyester/polyolefin blends and for the layer of rubber tape applied between the core and the jacket.

11.3 Intrinsic

11.3.1 Heat

High ambient temperatures with or without additional heat generated within the rope through cyclic loading and/or through contact with a fairlead could lead to premature failures through hysteresis heating. Creep accelerates rapidly with temperature with all other conditions remaining the same. As a rule of thumb, a four-fold increase in the creep rate could be expected for every 10 degrees Celsius temperature change.

Temperature data supplied by [redacted]/Shell at Ras Laffan for an HMPE mooring line is shown in table 2.

Date	Time	Weather	Stowed on reel under canvas exposed to sun	Stowed on reel under canvas in shade	Flaked out on deck	Moored on tension drum	Moored on fairleads
11/06/11	1300	Sunny	50	47	64		
12/06/11	1300	Sunny				60	56

Table 2: Temperature data at Ras Laffan

11.3.2 [1]Creep

Residual creep life tests were conducted on textile yarns removed from the failed rope Q/OSG/Ras Lafan as shown in Figure 17. These indicate that the nearer to the in service failure point the less creep life remains. This suggests that the more highly a rope is used regarding time under load and temperature then consumption of its finite creep life occurs. This is a known characteristic of HMPE and to a greater or lesser extent in any visco-elastic material used in rope manufacturing.

However, the loss in creep life could result from the service conditions and other fatigue mechanisms and due to the failure itself. It should be noted that the sample taking at a position 15 m from the failure is well clear of the failure and it is not expected that the yarn would have been affected by the rope breakage.

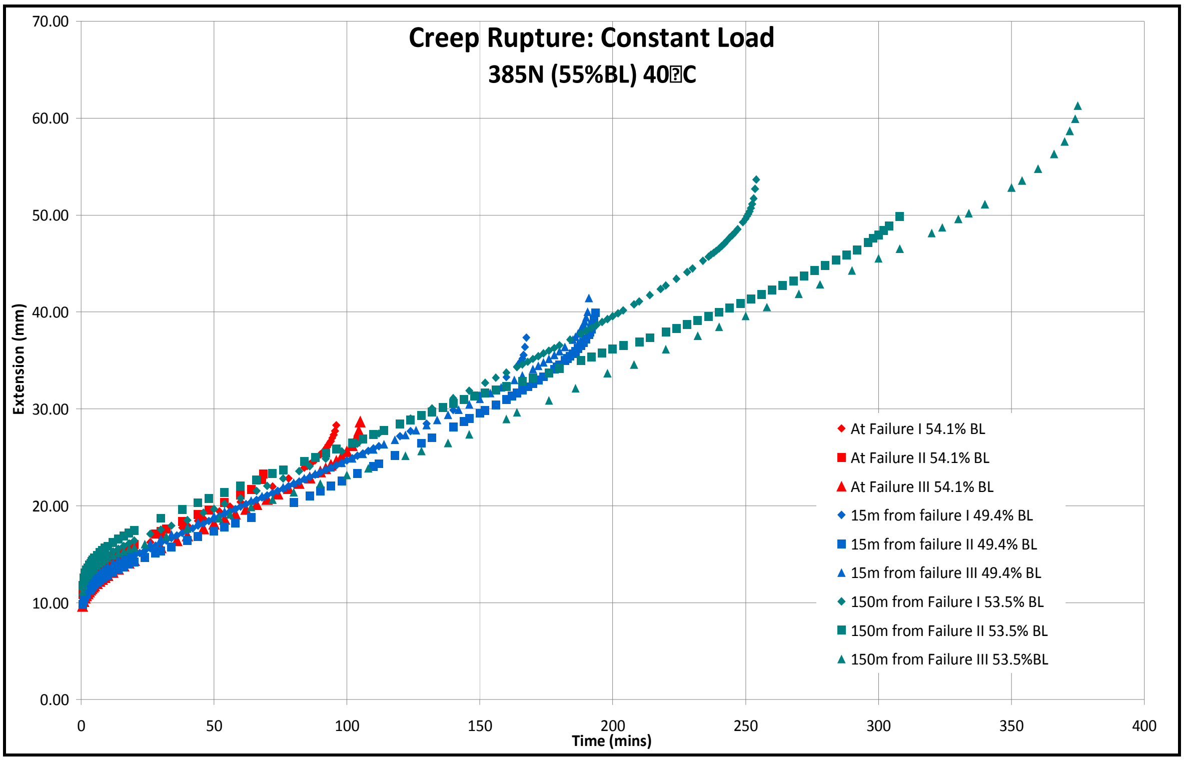


Figure 17: Textile yarn residual creep life for different distances from rope failure (TTI)

A second series of tests were performed from the same rope samples at ERA. ERA is an advanced technology consultancy with expertise in synthetic fibre creep measurement. The results of the ERA tests mirror the ones performed at TTI see figure 18.

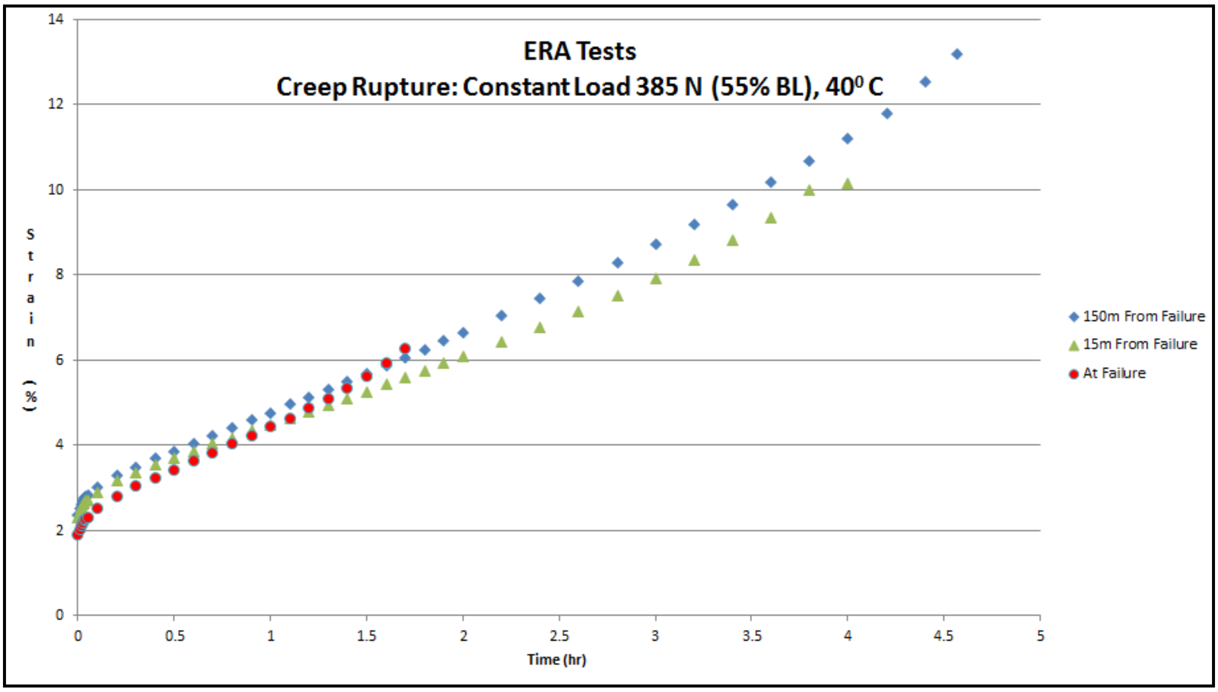


Figure 18: Textile yarn residual creep life for different distances from rope failure (ERA)

Creep response is characterised by three periods of length change activity termed regimes I, II and III. Regime I is early change in length and mainly due to non-creep elongation characteristics. In figure 18 it is the strain response up to approximately 0.2 hours. Regime II is predictable creep, linearly proportional to time and can be considered as a safe area (in terms of the service life for the user) of the creep curve to be in. For the blue line in figure 18 the end of regime II is about 3.5 hours. Regime III is the non-linear with time post regime II change in length response leading to failure. The data presented in figures 17 and 18 may show that the nearer the failure point where samples are removed for the creep test, the more regime II creep has been consumed. All three plots in each of these graphs show similar creep rate for the regime II sections of the curve indicating that regime III has not yet been reached.

[1]*Creep is the tendency of a solid material to slowly move or deform permanently under the influence of stress. It occurs as a result of exposure to high levels of stress. Creep is more severe in materials that are subjected to heat for long periods. Creep always increases with temperature. The rate of this deformation is a function of the material properties, exposure time, exposure temperature and the applied stress. Depending on the magnitude of the applied stress and its duration, the deformation may become so large that a component can no longer perform its function resulting in the failure of the rope. Rope creep is usually of concern when evaluating ropes that operate under high stresses or high temperatures. Creep is a deformation mechanism that may or may not constitute a failure mode. Moderate creep is sometimes welcomed because it relieves tensile stresses and leads to better rope component load-sharing.*

For the rope end user there are two key properties of creep, namely creep strain and creep rupture. Creep strain is the non-recoverable increase in length and creep rupture is the failure that occurs after a period of time with an applied load.

For creep data and illustrations of creep life on Samson's 12 Strand Amsteel Blue see ref 13.

11.3.3 Internal Abrasion

Internal abrasion is damage caused internally by rope components rubbing and sliding against each other during the loading and unloading of a rope in cyclic loading. In the returned failed rope sections, TTI found no evidence of strand-strand or yarn-yarn abrasion damage at a level that would explain the failures.

11.3.4 External Abrasion

This is the mechanism of damage to the outside of the rope due to contact with abrasive or static surfaces such as rough fairleads or static rolling components.

11.3.5 Hysteresis Heating

The generation and dispersion of heat within a rope due to cyclic loading will mean that layers of rope yarns and strands can be at different temperatures simultaneously and so have different properties such as strength elongation and creep rate meaning that load sharing is skewed. Work done by TTI indicates in practice that this is not a major cause of rope failure and TTI have found no significant evidence that this might be occurring.

11.3.6 Axial Compression

Axial compression and resulting kink bands are known to damage fibres and will result from ropes going into compression during a loading cycle where the minimum load is the rope in a slack or near slack condition. HMPE is known to have excellent resistance to this phenomenon and no evidence is found of this in the investigations carried out in this study.

11.3.7 Structural Effects

Structural effects include any mechanism by which length/path imbalances are introduced into the yarns/strands, which make up a rope. This could be bending, handling, rope manufacturing, splicing, core/cover interaction. There was evidence of some structural damage, which would have had some contribution to reducing rope strength. In particular DSM observed constructional damage such as length difference, hockles, and strand distortion on failed rope samples they analysed.

The Bridon/Marlow core with jacket rope has very high strength efficiency meaning the ratio of strength to HMPE mass is very high (possibly the highest in the market place). Suggestions that length variance in the manufacturing of these ropes leads to poor load sharing of these ropes does not match test data at hand. With such high strength efficient ropes the most significant area where this would show up is in break strength testing of unused ropes. As stated elsewhere in this report three unused ropes were returned from one of a User Group member's vessels and break tested. There was no evidence of under strength rope. As a rope is used through time, length differences will converge to zero because of the beneficial properties of creep that coverage component lengths to equal and load sharing to an equilibrium position. So a rope with poor load sharing is much more at risk when brand new than when it has seen service.

The impression of poor load sharing can be provided by high loading, loading around bends and with twist in the rope.

A quantitative measure of length variance can easily be measured on rope samples. Computer models such as TTI's Fibre Rope Modeller can determine the effect of any manufacturing variance of any rope component on tensile and fatigue properties.

12 Failure Hypothesis

12.1 Bridon/Marlow Core with Jacket

- Several HMPE failures have occurred at very low load in benign mooring conditions
- Low residual strength and low residual creep life of the textile yarns conducted by TTI has been measured on some failed rope samples from the Bridon ropes
- Low residual strength of several rope tests has been reported
- Several photographs of failures indicate mixed reasons for failures, abrasion, tensile, shear/torsion and creep
- The mid-span failures between vessel and hook showed negligible to mild internal abrasion and no other forms of damage visible to the naked eye.

The failures with Bridon/Marlow core with jacket rope appear to have been caused due to the design of these ropes being optimised for strength resulting in lower HMPE content when compared to the Samson ropes. This factor may have been exacerbated by structural and wear mechanisms (not outboard failures). With hindsight, the increase in the number of operational exposed LNG terminals since 2006 called for a more tensile tolerant rope than was successfully used prior to 2007.

12.2 Samson 12 Strand single braid

In summary, the results so far for the Samson 12 Strand single braid:

- The failure of Samson ropes at South Hook were at very high load around 58% of MBL
- Calculations of tension-tension fatigue life for the duration of the bad weather at South Hook confirm that this mechanism was not a contributory factor unless exacerbatory factors are involved such as heat generation within the rope
- OCIMF TCLL shows these ropes should not fail under short term very high loading

Some of the rope failures may have been associated with prior high loading at exposed ports, with high vessel 1st order wave induced motions, exacerbated by short 11m tails. Recent studies (ref 2) have shown that to reduce loadings to safe working loads, 22m nylon tails are essential.

12.3 Samson Core with jacket

One failure with the Samson core with jacket rope has been noted. TTI have not received any samples of this construction. It has signifcantly lower HMPE mass than the Samson 12 strand braid but not as low as the Bridon/Marlow core with jacket rope. It also has a performance enhancing coating.

12.4 Other Pertinent Findings:

- All the recent failures were with ropes no older than 1-3 years and up to 1940 mooring hours service, with the exception of BP Innovator at 8 years old and around 3000 mooring hours and BP Trader, 9 years old and 7,000 mooring hours both without failure.
- No failures had been reported on the BP Trader class vessels of which BP Innovator and BP Trader are examples

As all the failed ropes (except Innovator) in this User Group study have not reached more than 1,940 mooring hours service, compared to expected 5000 hours life, it is not possible to say whether more failures will occur or not in the future with the Bridon or Samson rope.

For the BP Trader class vessel that had a total 7000 hours mooring service (and still going), 6% of time (430 hours) was spent at ports that suffer waves (Rovigo, Bilbao, AES Andres). It is not known what the wave climate was for these berths but the wind for each mooring was recorded as Beaufort 4, 4 at Bilbao, 2, 3, 3, 4, 2, 5, 3, 5, 3, 4 at AES Andres and 3, 4, 6 at Rovigo. The 2's to 4's would not generate any waves to cause vessel motions and so the time spent in 5 and 6 was very low.

13 Recommendations

13.1 HMPE Rope Procurement Specification

13.1.1 Currently the specification focuses on rope minimum break load. This is no longer enough. There needs to be sufficient HMPE content in the rope to increase the longevity of the rope should prolonged periods of high load and temperature occur in service. To determine the minimum HMPE content maybe per rope construction type further work needs to be considered.

13.1.2 Currently rope minimum break is allowed to be assessed for contract approval by testing sub-components of the rope and referring and calculating back to prototype samples sometimes made and tested many years previously. To remove the chance of changes from prototype to current production, actual rope break loads from the contract under consideration should be broken to prove MBL.

13.1.3 Standardised operating conditions should be established and creep performance modelled to establish acceptable creep and HMPE mass performance.

13.2 Alternative Grade HMPE

13.2.1 Lower creep grades of HMPE could be considered as the load-bearing material such as Dyneema SK78

13.3 Other Materials

13.3.1 Other high performance materials could be considered for LNG mooring lines such as aramid and liquid crystal polymer.

13.4 Rope Coatings

13.4.1 Rope coatings for both single braid and core jacket constructions can enhance service life by reducing internal and external abrasion, dissipating heat and improving fatigue life. The Samson ropes featured in this report both make use of performance enhancing coatings.

13.5 Computerised Mooring Analysis for Ship-Shore Compatibility

13.5.1 Investigation should be carried out to ensure where local conditions are known that computerised mooring analysis is performed to these conditions rather than the standardized OCIMF environment of 60 knot wind speed form all directions and current up to 3 knots from selected directions.

13.5.2 Where local environments are not known for a terminal, consideration should be given to obtaining them and following advice in 13.5.1.

13.6 Tails

13.6.1 At terminals where significant waves, swell and/or current is present the use of 22 m long nylon tails is advised for all positions other than springs which remain at 11 m as a minimum requirement. The option for longer tails including for springs is also an option for higher wave height and/or longer wave period. This means that tails made from other materials such as polyester, polyolefin (e.g. polypropylene, polyethylene) and combinations of materials should only be used with good reason such as unacceptable vessel movement, lower wave height and/or lower wave period.

13.6.2 At sheltered berths where there is no significant waves, swell and/or current the present practice of 11 m tails in nylon, polyester, polyolefin (e.g. polypropylene, polyethylene) and combinations of these materials is fine.

13.6.3 At terminals where significant waves, swell and/or current is present consideration should be given to using more winch lines than may normally be deployed. The standard mooring arrangement utilizes 16 lines for conventional LNG vessels and up to 20 for Q-Flex and Q-Max vessels. If additional winch lines are available then these can be used to reduce the mean load per line in any given environment.

13.7 Rope Inspection

13.7.1 Periodically inspect ropes and do so after mooring at terminals where significant waves, swell and/or current were present. Such methods are described in OCIMF MEG 3 and the Cordage Institute International Guideline CI 2001 – 04 Fibre Rope Inspection and Retirement Criteria. Particularly attention should be paid to ropes with jackets for internal damage, which is difficult to detect. Such indicators are reduction in rope diameter unusual profile and bulges.

13.8 Chafe protection

13.8.1 At terminals where significant waves, swell and/or current is present, consideration to chafe protection maybe applied to the section of rope undergoing rubbing in the fairleads due too vessel motion. Retrofit nylon liner inserts should also be considered.

13.9 Operational Service Records

13.9.1 Complete service records of all mainline ropes and tails should be kept (ref 14) to include

- Trade name, manufacturer, MBL, certification record, deployment date, significant events such as end-for-ending, repairs and inspection record
- Berths visited, mooring time, temperature, wind, wave, swell, current

13.10 Line Tending

13.10.1 Consideration should be given to improving line tending to equalize line loading in shared mooring functions such as a group of aft breast lines for example.

14 Recommendations Outside the Scope of the HMPE Users Group

14.1 HMPE Rope Content

14.1.1 Minimum HMPE content per generic rope construction needs to be established so that sufficient life is demonstrated with the range of environmental conditions typically met in LNG moorings.

14.2 Full Scale Testing

14.2.1 It is recommended that full scale laboratory testing be conducted to simulate exposed location service conditions to assess the safe lifetime of these ropes.

14.2.2 To ensure the creep mechanism is properly accounted for in such testing, the duration of loading has to be of sufficient timescale and reflect operating temperatures and load levels. For example, say a typical expected rope life is 5000 hours, then 20% of life is 1000 hours, which equates to 42 days in a test machine, which is not unrealistic.

14.3 50% MBL Load Limit

14.3.1 Reduce HMPE line load limit from 50%. This would require vessels to use either more mooring lines or larger ones. Logistically this may not be possible.

15 References

1. Banfield S.J., Flory J.F., Effects of Fibre Rope Complex Stiffness Behaviour on Mooring Line Tensions With Large Vessels Moored In Waves, Oceans 2010.

2. OCIMF – Guidelines for the Purchasing and Testing of SPM Hawsers, First Edition Sept. 2000

3. Joint Industry Project, Develop Effective Moorings for Tanker and Gas Carrier Terminals Exposed to Waves, final report Mooring Analyses & Safe Mooring Practices for Exposed Terminals, rev 1 dated 17/11/2006.

4. Joint Industry Project, Operation of Wire and Fibre Ropes Over Ship's Fairleads, final report TTI-IMLR-2009-626, Tension Technology International, dated 23/11/2010.

5. BW - DNV LNG HMPE Mooring Line Failure – LNG Nigeria

6. Consolidated summary report of testing conducted by TTI on ropes for the User Group HMPE rope study – Jeff Nichols, TTI Testing Ltd

7. DSM Dyneema - Investigation report broken LNG line Heather Sally, TTI, BG

8. DSM Dyneema 20091113 - Investigation report from broken MaranGas line – TTI

9. DSM Dyneema 20110825 - Investigation report from broken K-line rope – TTI

10. HMPE LNG Failures Spreadsheet – BG, QatarGas, Shell, Samson, OCIMF

11. http://shipbuildinghistory.com/today/highvalueships/lngactivefleet.htm

12. http://www.lngwebinfo.org/pagesmain/home/default.aspx

13. 12-Strand Amsteel Creep Predictions – TTI Using Samson Ropes Published Data

14. Operational Data Required for Studying HMPE Mooring Line Behaviour

15. DSM 150kcm LNG exposed terminal report rev3

16. Examination and tensile testing to determine residual strength of Steelite mooring lines from British Sapphire Gems class for BP Shipping ref: TTI-SJB-2009-609-R

TTI Inspection and test report on failed HMPE mooring line

TTI Testing Ltd

Unit 2, Hithercroft Road, Wallingford, Oxfordshire, OX10 9DG, UK

www.tti-testing.com

Inspection and Test Report on Failed UHMPE LNG Mooring Line

Reference number TTI-JSM-2015-5147

Date	Rev.	Description	Prepared by	Authorised by
01/07/2015	0	First issue to client	[redacted]	[redacted]
20/07/2015	1	Clients comments incorporated	[redacted]	[redacted]
03/09/2015	2	Detail of mooring rope and tail history updated.	[redacted]	[redacted]

Distribution:

TTI Testing Ltd (author, file)

MAIB

Attention:

[redacted]

Contents

1 Introduction

Tension Technology International Ltd (TTI) and its partner company TTI Testing have been approached by the Marine Accident Investigation Branch (MAIB), to assist in the examination, analysis and testing of a UHMPE [Ultra High Modulus Polyethylene] mooring line that failed during the mooring operation of the LNG Tanker 'ZARGA' alongside the Milford Haven LNG Terminal on 2nd March 2015.

This document presents methodology, results, discussions and conclusions of the visual inspection, yarn and sample break load tests, high speed camera work and and fibre fracture morphology gained through scanning electronic microscope examinations that were carried out by and on behalf of TTI Testing.

2 Mooring Line and Tail Details

The mooring line was manufactured by Bridon International and was supplied as a new line to the shipyard in October 2009. Bridon works order E1004394, and Lloyds certificate reference GLS 0834143 refers [1]. The mooring line specification is noted as follows:

Part Code: WRG006 – 275 metre length mooring line. Bridon Steelite Xtra brand UHMPE fibre rope. Superline circular braided construction comprising a polyester/Supermix abrasion resistant braided jacket over a central UHMPE fibre load bearing core. Rope supplied with a 2.5 metre protected soft eye spliced at one end. Other end plain. Maximum Diameter 44mm. Minimum Breaking Load: 137 tonnes.

The actual realised break strength shown on the certificate is 151.47 tonnes having been tested in general accordance with ISO 2301 [5].

The rope was first used as a head line on the starboard winch position C, from April 2010 and was used with the original 11 metre x 84mm nylon tails. Initially during the investigation it was believed that these tails were changed out after two mooring however subsequent evidence [11] provided in August 2015, confirmed that a total of 13 mooring operations were completed with these tails until these were changed out in May 2011, to 22m x 88mm Polyester/Polyolefin tails.

Following the tail change out a further 16 mooring operations were completed up to 10th July 2012, after which the plain end of the rope is understood to have been spliced by a Bridon engineer and the rope was end for ended.

In November 2014, the rope was end for ended again to the original eye end and the line was moved to the aftermost spring line winch position F. The rope was used for a further five full moorings up to February 2015, with the line parting during the mooring deployment on the 2nd March 2015.

In total the mooring line had been used on this end for a total of 1342.7 hours [1175.6 hours as a head rope and 167.1 hours as a spring line].

In addition to the mooring line, the mooring tail from the incident was also subsequently supplied to be used in the additional slow motion tests. The mooring tail details are noted as follows:

22 metre long. Nominal 88mm diameter Strong 8 rope [50% polyester/50% polyolefin] with jacketed eyes 1.0m and 2.0m at each end. Minimum Break Load: 190 tonnes.

The tail was manufactured by D. Koronakis, Greece in July 2012. Certificate PIR1207686/2 refers [2].

3 Visual Inspection

Initial visual inspection of the mooring line was conducted at TTI Testing's Wallingford premises on the 14th April 2015, and was witnessed by representatives of MAIB, Shell International and Marshall Islands State Flag.

The coil and paper work were first verified to ensure that the received rope was the correct line. The coil packing was then removed and the first section of rope was removed which contained the shore side parted end.

3.1 Shore Side Parted End

The section was then laid out in 20 metre bits so that an estimated length could be obtained [Figure 3.1.1]. A length of approximately 57 metres was confirmed.

It was also confirmed that this length included the original factory spliced eye end. This was indicated by the fact that the splice had a factory only finish overbraid and the original polyester cloth protection was still present [Figure 3.1.2].

A visual inspection along the total length was carried out to determine if there was any additional damage and the rope was flexed to see if any sections were hard and inflexible. No evidence of abrasion damage to the jacket or internal rope hardening could be identified other than the failure and a short section of green paint which was observed on the jacket for a distance of approximately 1 metre at a distance of 22.3 metres from the failed end [Figure 3.1.3]. This was likely to have been transferred onto the rope while being worked around a fairlead at some point during a previous mooring.

Having established that there was no further visual damage to the section apart from the failed end a brief visual inspection of the failure was carried out.

The failure had a number of matted and irregular strand sections typical of a tensile failure however a lack of significant or indeed any recoil in the strands and only a small amount of yarn fusion damage indicated that the rope had broken at a relatively low value which is consistent with the reported low hook load at failure of approximately 24 tonnes + frictional losses, so approximately 28/29 tonnes [Figure 3.1.4 – 3.1.6].

Following visual inspection it was then agree to identify and remove sections from the line for further investigation and testing. The failure end and 1.5 metres down the line were marked for removal and labelled '5147 MAIB Shore End Failure'.

From this section a further 3 metre section was marked immediately after for removal as the shore side residual strength inspection sample. This would also be used for SEM yarn samples if deemed necessary.

A 25 metre section was now also identified for removal for subsequent splicing into a full rope break test sample. This was originally proposed to be placed immediately after the residual sample however a section of paint had been identified as noted earlier. This section was moved 6 metres further down the line to ensure that the painted section fell within the segment to be removed. Both the residual sample and the spliced section were marked with similar labels '5147 MAIB Shore End. Yarn Realisation Sample' and 5147 MAIB Shore End.

Following removal of the sample sections the remaining shore end rope was packed onto a pallet and moved to one side clear of the inspection area.

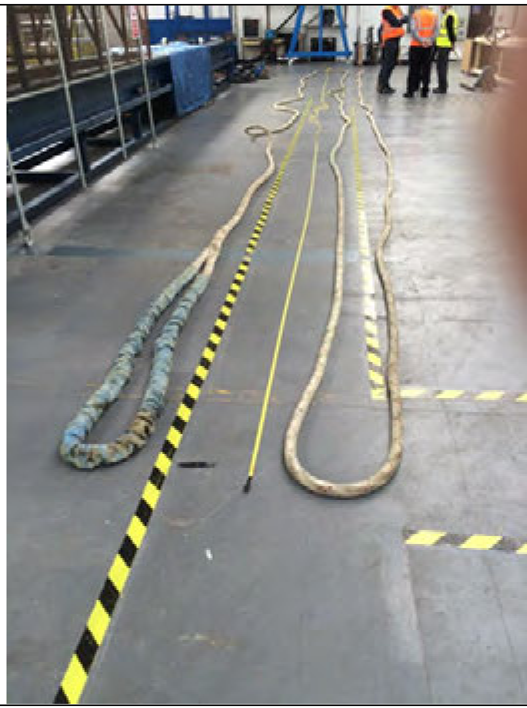


Figure 3.1.1 – Sample laid out

Figure 3.1.2 – Factory finished eye and splice

Figure 3.1.3 – Green paint on rope

Figure 3.1.4 – Shore end failed end

	
Figure 3.1.5 – Matted and fused ends of failure	Figure 3.1.6 – Lack of strand or jacket recoil

3.2 Vessel End Section

As with the shore side section, the vessel end rope was laid out in 20 metre sections to ascertain the approximate rope length. The original rope supply length was 275 metres with an eye at one end only. As the rope had been spliced with a new eye on the plain end in 2012 the expected total length of the mooring line prior to failure would have been expected to be the region of 267 metres. While not forming part of the investigation scope it was noted that the vessel end section measured approximately 210 metres and allowing for the shore end at 57 metres, it can be concluded that the rope had been supplied to length.

Having laid the rope out and confirming that this section included the newer splice which had been spliced on board by a splicing engineer from Bridon, a similar visual inspection and flexibility check of the entire rope length was carried out. As with the shore side section the condition of the rope was generally considered as being in very good condition with only minor discolouration to the jacket which would be typical of a rope of this age. Abrasion to the jacket was minimal and there were no evidence of any stiff or hard areas within the rope length [Figure 3.2.1 – 3.2.2].

Having reviewed the rope length a visual inspection of the failed end was carried out and it was noted that this section was much cleaner and intact compared to the shore end. The failure was fused over a section of approximately 400mm with some of the strands heavily fused but tapering to the point of failure [Figure 3.2.3].

This type of 'tapered cone' in the failure area has been seen before and therefore would not indicate an unusual failure mode other than tensile failure. This end would have stayed on board the vessel following failure and therefore would have stayed intact while the shore end section having exited the vessel, fell into the water and would have been subjected to some wave and tidal movement until recovered which may have led to the breakdown and matting of the fibres in the failure zone.

As with shore end there was a lack of recoil in the strands and only minor recoil in the jacket consistent with a relatively low break load [Figure 3.2.4 – 3.2.6], however looking at the end of the failure there appeared to be some uniform straight yarn ends which would be unexpected in a pure tensile failure.

As with the shore side section, a number of sample were then identified for removal from the line for yarn realisation, break load testing and possible SEM imaging on the yarn.

Sample 1, was taken to include the failure and was 3 metres long. Sample 2 was taken immediately after this and was again 3 metres long taken for yarn realisation and possible SEM testing. Sample 3, immediately following this was 25 metre long and was taken for the spliced strop testing.

Three further sections of rope were removed. Sample 4, a 25 metre section taken 14 metres from the remaining eye at the winch end. Sample 5, a 25 metre section taken from a position that was approximately in the middle of the rope and sample 6, a 3 metre section taken adjacent to sample 5 to be used for realisation and possible SEM testing.

Each sample section was individually labelled as a vessel end section and the rope sections were removed. The remaining rope was repacked and secured.

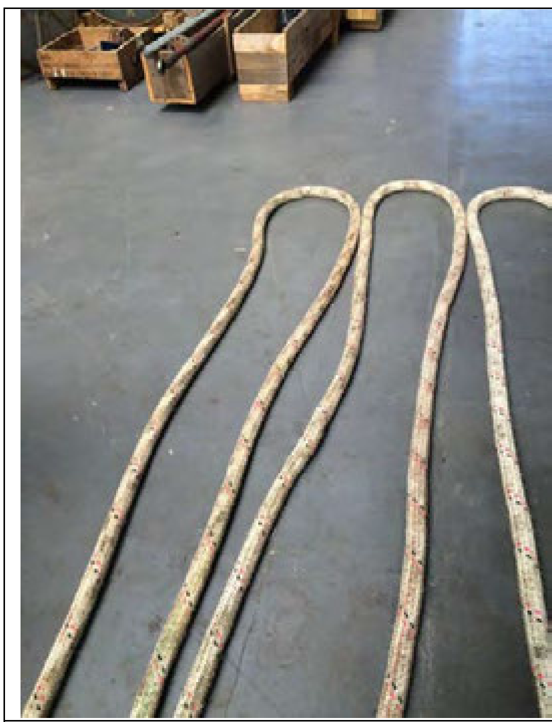


Figure 3.2.1 – Vessel end rope section laid out

Figure 3.2.2 – Vessel end rope section laid out

Figure 3.2.3 – Vessel end failure

Figure 3.2.4 – Vessel end failure – minor jacket recoil

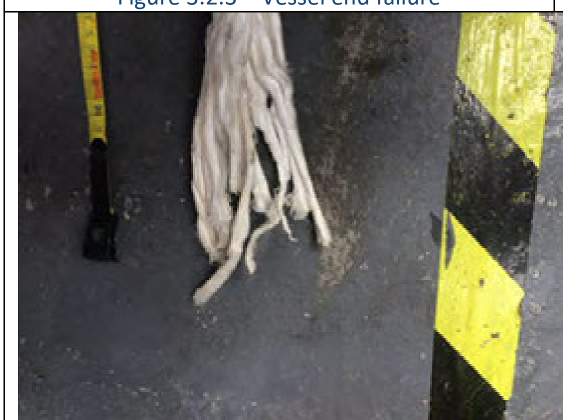


Figure 3.2.5 – Vessel end failure

Figure 3.2.6 – Vessel end failure

4. Examination of Realisation Test Samples, Strand Removal and Yarn Test Results

Following removal of the three samples for yarn realisation testing the individual samples were placed on the examination table for dissection.

The Bridon Superline design supplied utilises a large single 3-strand load bearing UHMPE core with a polyester/Supermix abrasive resistant jacket. The core is additionally wrapped in a self-amalgamating tape which assists in bonding the cover to core. The reason for applying this is due to the different coefficient of friction properties of the cover and core materials and by applying the tape the manufacturer ensures that a bond exists between the two materials, however this also means that the jacket particularly in a used rope can be difficult to remove without disturbance to the outer core yarn. To ensure that disturbance was kept to a minimum a large Swedish fid was pushed between the core and jacket which was then progressively cut back in small sections. Small wraps of electrical tape were placed around the core as the jacket was removed to ensure that the core rope construction remained intact.

4.1 Yarn Realisation Samples

The shore end section was dissected first, however within 200mm of the initial jacket being removed a number of yarn sections approximately 50~80mm in length were seen to separate from the main yarn bulk in one strand. It was also noted that the yarn in all strands exhibited moderate to severe 'kink bands' which were evident throughout the entire length at regular intervals of 100-150mm [Figure 4.1.1]. Further investigation revealed that in total 12 core yarns had suffered failure in this same area.

The ends of each strand were taped and the entire jacket from the 3 metre sample was removed.

A yarn count of each strand was conducted and the total number of yarns was confirmed as being 32 yarns per strand, configured as 17 outer yarns and 15 inner yarns. This gives a total rope count of 96 yarns per rope.

ISO 2307 [5], gives guidance on the realisation method that can be used to determine rope strength by breaking individual rope yarns and multiplying the average break result by the number of yarns in the rope. This is then multiplied by a realisation factor to give the full rope break strength. While this method is intended for new rope, it can be applied for used rope as well, as long as consideration is given to rope condition. The standard calls for a minimum of 15 yarns to be tested for 3 and 4 strand rope of which a minimum of 3 yarns should be taken from the core. To allow for the larger coefficient of variation we usually see in used rope it was suggested a larger number of yarns would be tested.

In this instance it was decided to test 12 yarns from each strand of which two would be taken from the core, giving a total of 36 yarns to be tested. This represents 37.5% of the total rope yarn, as opposed to 15.6% required as a minimum in the standard.

The strand where acute yarn damage had been noted was put to one side and one of the other two strands were then taken to the yarn test bed table for removal of yarns for testing.

The strand was laid out and the outer and inner yarns were removed. The outer yarns were then loosely laid out on the table and 10 yarns were randomly selected for break testing. The results of the residual tests can be found in section 4.2.

Following testing of the outer yarns, the inner core yarn was similarly laid out, however at this stage an observation of the number of 'kinks' within the sample length was also made. This was noted as being 22 within a measured section of 2.7 metres, correlating to the previously noted frequency of bands.

The two strands plus the third strand which was placed to one side and included the broken yarns [once a count of the broken yarns had been made] were all tested and as noted results can be found in section 4.2.

Following testing of the Shore Side sample both the vessel end and middle yarn realisation samples were dissected in a similar manner to the shore end sample. While no additional yarn breaks were noted in either sample, there was evidence of 'kink bands' in both sections. Results for residual tests on these samples can be found as noted above in section 4.2.

Supplementary Note

Following identification of the yarn failures within the strands on the shore side sample and the severe 'kink bands' noted in the other original samples removed, a number of additional sections of the rope were visually inspected throughout the rope length. Further yarn failures and damage to yarn were seen, consistent with what would be expected from axial compression fatigue. Section 6 includes photographs of these visual inspections. Sections 8 and 9 discusses the evidence and causes of axial compression fatigue in greater detail.

Figure 4.1.1 – Original Shore side sample – yarn failures

Figure 4.1.2 – Original Shore side sample - Multiple yarn failures in core yarn of one strand

Figure 4.1.3 – Original Shore Side Sample - kink bands noted in both inner and outer yarn

Figure 4.1.4 – Original Shore Side Sample - Kink band frequency measurement

4.2 Yarn Residual Strength Test Results

4.2.1 Yarn Tests

As noted in section 4.1. Three samples were selected for yarn realisation testing. One each from either side of the failure and one from a mid-section of the rope. Each sample had 12 yarns removed from each of the three strands. 10 outer yarns and 2 inner yarns. These were randomly selected and tensile tested on the Testometric machine [Figure 4.2.1.1]. Testing was conducted in general accordance with ISO 2307 [5]

Tables 4.2.1.2, to 4.2.1.4 shows the results of the break tests on the three samples, with mean, standard deviation [SD] and coefficient of variation [CV].

Figure 4.2.1.1: Testometric test machine

Sample 1 - Shore Side - 1.5 metres from break				
	Yarn	Strand 1	Strand 2	Strand 3
		Break Load - N	Break Load - N	Break Load - N
Outer	1	12773	11233	14021
	2	12607	11584	14456
	3	14061	13811	12921
	4	13272	10204	12768
	5	11730	12811	11022
	6	12809	12067	13203
	7	12827	12376	13846
	8	13341	9887	13275
	9	13597	12317	12459
	10	12340	11613	12407
Inner	1	11627	11964	10658
	2	11150	9185	10447
	Mean	**12678**	**11588**	**12624**
	SD	**856**	**1303**	**1311**
	CV	**7%**	**11%**	**10%**

Table 4.2.1.2: Sample 1 – Shore Side Sample

Sample 2 vessel end - 3 metres from break				
	Yarn	Strand 1	Strand 2	Strand 3
		Break Load - N	Break Load - N	Break Load - N
Outer	1	8997	8594	10970
	2	8606	9241	9726
	3	8505	8745	8756
	4	9158	8844	9892
	5	8770	7357	9160
	6	8171	9840	9225
	7	8600	9275	10890
	8	8593	8622	9259
	9	9584	9725	8002
	10	10204	10821	7612
Inner	1	6587	7050	6713
	2	8639	7866	9455
	Mean	**8701**	**8832**	**9138**
	SD	**861**	**1067**	**1247**
	CV	**10%**	**12%**	**14%**

Table 4.2.1.3: Sample 2 – Vessel Side Sample

Sample 3 vessel end - ~ middle of rope				
	Yarn	Strand 1	Strand 2	Strand 3
		Break Load - N	Break Load - N	Break Load - N
Outer	1	13130	12652	15057
	2	14195	12953	13826
	3	14104	13597	14045
	4	14226	13710	15265
	5	14069	13574	14164
	6	13760	13385	14358
	7	13369	13322	13432
	8	14484	14003	13298
	9	14110	13027	14146
	10	13579	14425	13323
Inner	1	11860	13482	12798
	2	13052	12671	12421
	Mean	**13662**	**13400**	**13844**
	SD	**729**	**524**	**845**
	CV	**5%**	**4%**	**6%**

Table 4.2.1.4: Sample 3 – Mid-Section Sample

4.2.2 Residual Yarn Strength

Table 4.2.2.1 shows the calculation of residual rope strength for sample 1, the shore side section. This gives a result of 79% residual strength adjacent to the break. The coefficient of variation [CV] was 10% across both samples indicating uniform degradation across the sample tested. A larger CV would be expected in ropes which have experienced higher abrasion or yarn damage.

Table 4.2.2.2, shows the results achieved in the section of rope adjacent to the failure on the vessel side. Significantly here the residual strength is lower at 57% indicating that the yarn has degraded here significantly.

Table 4.2.2.3, shows results for the sample taken from the middle of the rope which unsurprisingly gives the best result out of the three samples with 88%. It should also be noted that the CV is much lower at 5%, indicating that the yarn degradation here was minimal.

Sample 1 - Shore Side - 1.5 metres from break - Rope Residual Strength					
		Strand 1	**Strand 2**	**Strand 3**	**units**
Mean		**12678**	**11588**	**12624**	
SD		**856**	**1303**	**1311**	
CV		**7%**	**11%**	**10%**	
Overall Mean				**12296**	**N**
SD				1250	
CV				**10%**	
Yarns / Rope				96	
Realisation Factor				0.998	
Calculated MBL				1178.1	**kN**
Original MBL				1485	**kN**
% Residual Strength				**79%**	

Table 4.2.2.1: Sample 1 - Shore Side Sample – Rope residual strength results

Sample 2 - Vessel end - 3 metres from break - Rope Residual Strength					
		Strand 1	**Strand 2**	**Strand 3**	**units**
Mean		**8701**	**8832**	**9138**	
SD		**861**	**1067**	**1247**	
CV		**10%**	**12%**	**14%**	
Overall Mean				**8890**	**N**
SD				1056	
CV				**12%**	
Yarns / Rope				96	
Realisation Factor				0.998	
Calculated MBL				851.8	**kN**
Original MBL				1485	**kN**
% Residual Strength				**57%**	

Table 4.1.2.2: Sample 2 – Vessel End - Rope residual strength results

Sample 3 - Vessel end - ~ Middle of rope - Rope Residual Strength					
		Strand 1	Strand 2	Strand 3	units
Mean		13662	13400	13844	
SD		729	524	845	
CV		5%	4%	6%	
Overall Mean				13635	N
SD				715	
CV				5%	
Yarns / Rope				96	
Realisation Factor				0.998	
Calculated MBL				1306.4	kN
Original MBL				1485	kN
% Residual Strength				88%	

Table 4.2.2.3: Sample 3 – Vessel end – Middle - Rope residual strength results

Following further investigation it was noted that the inner yarns in the strand exhibited more severe 'kinks' to that of the outer yarns. During realisation tests a coloured marker was used to identify each kink band and significantly the yarn failure points coincided with these 'kink' zones in almost all cases in both inner and outer yarns.

As the rope break load is a function of both inner and outer yarns it was decided to conduct a further yarn realisation test using a section of the shore end rope. This was taken within 5-10 metres of the failure end. As with the previous three tests 12 yarns in total per strand were tested however instead of using 10 outer yarns and 2 inner, this time the yarns were split at 6 inner and 6 outer yarns. The results of these tests are shown in tables 4.2.2.4 and 4.2.2.5. Significantly it is noted that the CV has increased from 10% to 26% while the residual break load has decreased from 79% to 61%. Significantly the CV for the outer yarn is low at 6% while the inner yarn is 20%. In addition there is a 36% difference in retained strength between the inner and outer yarns indicating that the rope strand yarns are not uniformly degrading.

Sample 4 Shore End ~ 5-10 metres from break				
	Yarn	Strand 1	Strand 2	Strand 3
		Break Load - N	Break Load - N	Break Load - N
Outer	1	11369	11920	11743
	2	12200	12654	10667
	3	10238	11716	11625
	4	11836	11687	11635
	5	9978	11658	12251
	6	11994	10691	11795
Inner	1	8989	7480	6137
	2	7239	5708	7229
	3	9266	9873	6103
	4	5972	6544	6243
	5	8456	5009	8627
	6	6047	9452	7427
	Mean	9465	9533	9290
	SD	2218	2681	2549
	CV	23%	28%	27%

Table 4.2.2.4: Sample 4 – Additional shore end yarn samples

Sample 4 -Shore End ~ 5-10 metres from break - Rope Residual Strength					
		Strand 1	Strand 2	Strand 3	units
Mean		9465	9533	9290	
SD		2218	2681	2549	
CV		23%	28%	27%	
Overall Mean				9429	N
SD				2420	
CV				26%	
Yarns / Rope				96	
Realisation Factor				0.998	
Calculated MBL				903.4	kN
Original MBL				1485	kN
% Residual Strength				61%	

Table 4.2.2.5: Sample 4 – Additional shore end sample - Rope residual strength results

5. Dissection of Failure

Both ends of the failure were removed during the original visual inspection for dissection. The details of these are as follows.

5.1 Shore End Failure

As previously noted in section 3, the shore end failure had little or no recoil present in the jacket or strands which is usually indicative of a low load failure however the uneven nature of the strands and fused matted ends were consistent with that seen in a tensile failure [Figure 5.1.1].

Figure 5.1.2, shows the failed end against a blue background and while there are some uneven and matted strands it was noted that there were a number of sections that appeared to have regular square ends similar to what would have been observed if yarns had been parted at a 'kink band' similar to that observed during dissection of the yarn realisation samples. Figure 5.1.3, shows this in greater detail with a number of yarns having regular tips [possible 'kink band' failure] while others have a matted irregular tip [tensile failure]. A pure tensile failure would have irregular yarn failures throughout.

Sections of both possible yarn failure modes were removed for SEM examination. Results of these can be found in section 8.

Figure 5.1.1 – Shore side failure end

Figure 5.1.2 – Shore side failure

Figure 5.1.3 – Shore Side failure – regular and irregular yarn failures

5.2 Vessel End Failure

The profile of the vessel end failure was distinctly different from the shore side in that the failed end appears fused and tapered over its length and while there are separated yarns at the end, the strands appear intact over much of their length [Figure 5.2.1. and 5.2.2]. There was again little evidence of recoil in the rope although some can be seen in the jacket indicated by the higher pitch angle close to the break.

Pulling the failed end apart, some inter-strand fusion was noted as the yarns appeared stuck together however a number of regular ends were also noted and these indeed were more regular and cleaner than the shore end sample. This may have been caused by the fact that the ship end would have remained on board and therefore would have been protected to some degree while the shore side end fell from the ship into the water and may have suffered some water wash through wave/current/tidal affects prior to recovery which may have separated the yarns out.

Figures 5.2.3 and 5.2.4, clearly show these regular yarn breaks and multiple ones were found through the failure. Again as with the shore break, sections of yarn were removed for SEM examination. Results can be found in section 8.

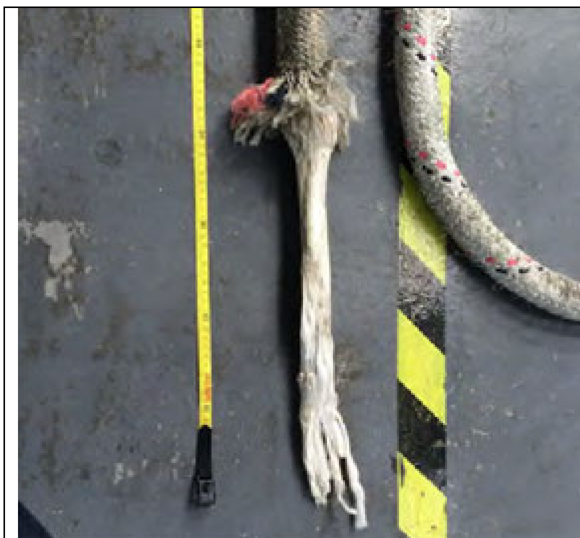


Figure 5.2.1 – Ship side failure end

Figure 5.2.2 – Ship side failure

Figure 5.2.3 – Ship Side failure – regular and irregular yarn failures

Figure 5.2.4 – Ship Side failure – regular yarn failure

6. Additional Visual Examination Sections

As noted 'kink band' distortion has been identified in all sections of the rope originally removed for inspection. Since the remaining potions of the rope were available for inspection, a number of other sections were dissected to identify the effects of the 'kink bands' and sections of yarn were identified and sent away for SEM imagining.

The following photographs shows evidence of yarn distortion and partial and full yarn failure particularly in the shore end sample. Figure 6.5 shows a partial failure at a kinkband, confirming the failure mechanism gives a regular end as shown in figure 6.6 where complete yarn breakage has occurred.

Figure 6.1 – Shore end sample

Figure 6.2 – Shore end sample – jacket removed

Figure 6.3 – Shore end – Outer yarns – kinks evident

Figure 6.4 – Shore end – inner yarns - single yarn failure and partial failure failures

Figure 6.5 – Shore end - partial yarn failure

Figure 6.6 – Shore end - failed end

Figure 6.7 – Vessel break end

Figure 6.8 – Outer yarns – All strands similar condition

Figure 6.9 – Vessel Break end - Inner yarns with moderate kinks

Figure 6.10 – Vessel end middle

Figure 6.11 – Vessel end middle – outer yarns. All strands with similar small kinks

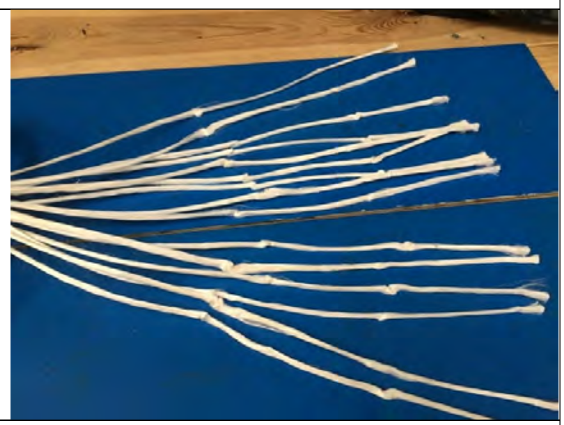


Figure 6.12 – Vessel end middle – severe kinks found in one strand

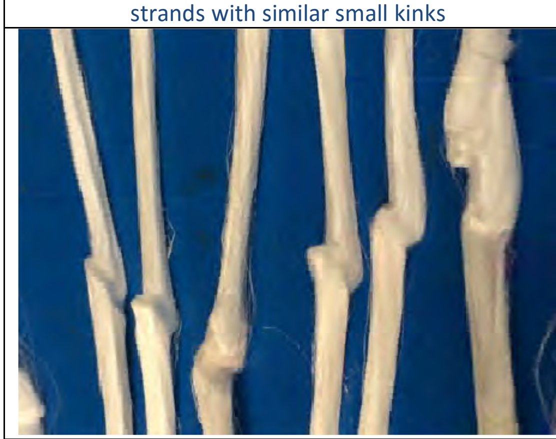


Figure 6.13 – Vessel end middle – severe kinks found but no evidence of yarn failure

Figure 6.14 – Winch end

Figure 6.15 – Winch end – outer yarns slight evidence of kinks developing – all strands similar

Figure 6.16 – Winch end – inner yarns showing moderate kinks developing – all strands similar

7 Break Load Test Samples, Tail and High Speed Camera Work

In addition to the realisation test sections, four 25 metre sections of the line were also removed for splicing into break load test strops. These were removed as indicated in section, 3.1 and 3.2. One from the shore side and three from the vessel end.

The sections were spliced into 10 metre test sections with a 0.5 metre soft eye spliced at each end. Splicing was conducted by a retired Marlow/Bridon splicer who had experience with splicing this type of rope during his service and the rope was spliced in general accordance with Bridon International splicing instructions for Superline Steelite HMPE mooring lines with a 3-strand core [8]. The only variation to the specification was that instead of the addition of a dummy braid or factory braided jacket over the splice, the jacket was secured into the splice tails and then wrapped with insulation tape. This is a common practice when testing ropes as generally they do not need the robust jacket fitted to in-service ropes and as the jacket has no strength requirement this would not have altered the strength achieved.

In addition to the sections of the mooring line, as previously noted the mooring tail used in the incident was also returned to TTI Testing for visual inspection and to be used during the break load testing of one section of mooring line. The tail and mooring section where joined via a cow-hitch arrangement similar to the method used to connect the tail and mooring in service and then both were tested in line. The purpose of this test was to capture the system in series load extension and also to film the break using industrial high speed cameras so that the dynamics of the break, rope reaction and energy could be modelled to understand how the mooring line and tail may have recoiled during the incident.

Some of this data was subsequently used in the non-linear finite analysis modelling conducted on behalf of Shell in respect to this incident.

Due to limitations in the test facilities here in the UK, the break tests were carried out at Mennens Dongen B.V., in the Netherlands. Mennens have a test bed length of 35 metres with a break load capacity of 14000kN and an available stroke of 4 metres. In order to ensure a suitable break with the tail included, the tail length had to be reduced from the original supplied length of 22 metres to 15 metres, giving a combined overall length of 25 metres.

In total four breaks were carried out. Three on just the mooring line and the final one with the combined mooring line and tail. All breaks were recorded with high speed cameras so that images could be obtained from a number of angles.

The samples were all pre-loaded into the test machine and were then cycled 20 times to 25 tonnes prior to taking the sample to break on the final cycle. The preloading operation helps to bed in the splice and rope construction. The new minimum break load for the rope has been taken as 151.47 tonnes minus 10% for splice efficiency equating to 136.23 tonnes or 1336.5kN

The break load results for the four tests are shown in table 7.1.

Sample	Description	Elongation – Measured test pin to test.	Break Load - kN	% Residual Strength
1	Shore end – 10mts from failure point	209mm / 2.09%	671kN	50.2%
2	Vessel end – adjacent to failure point	153mm / 1.53%	465kN	34.8%
3	Winch end – opposite end of rope to failure	267mm / 2.67%	847kN	63.37%
4	Middle of rope + 88mm Tail	1209mm / 4.84%	645kN	48.26%

Table 7.1: Break load test results and residual strength

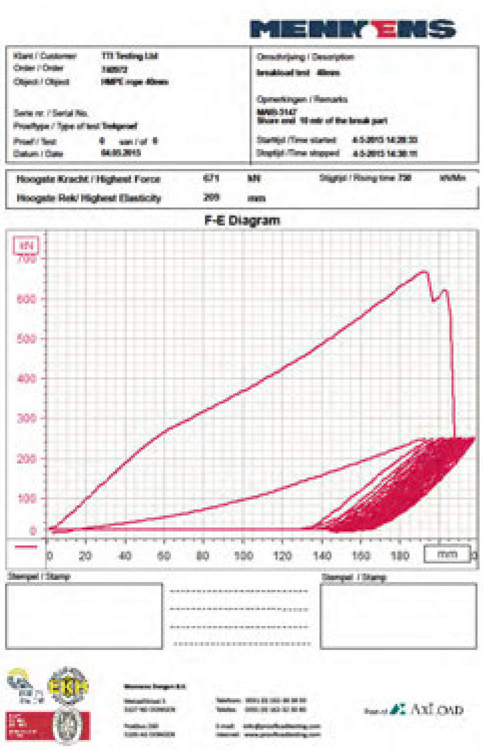


Figure 7.2 – Load extension curve for Sample 1

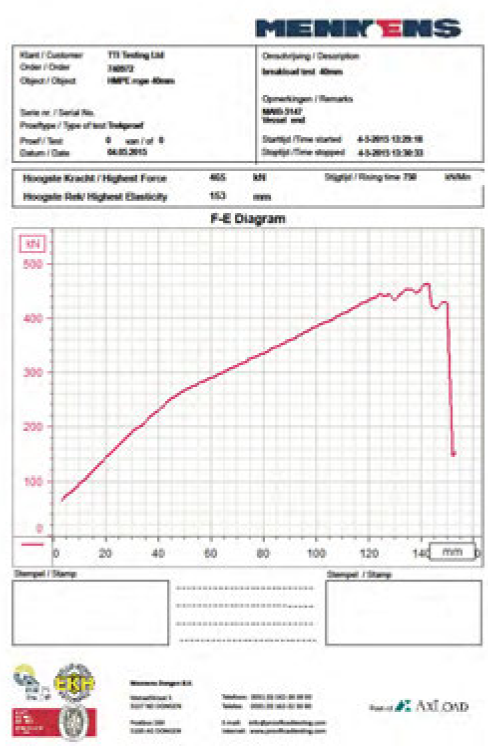


Figure 7.2 – Load extension curve for Sample 2

Figure 7.3 – Load extension curve for Sample 3

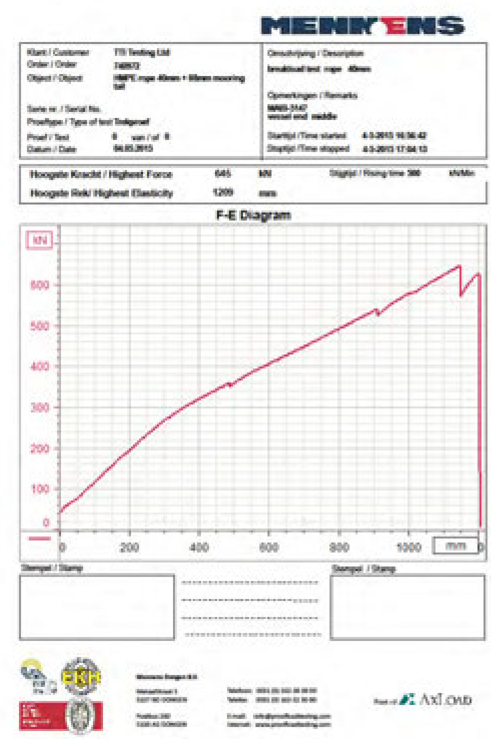


Figure 7.4 – Load extension curve for sample 4

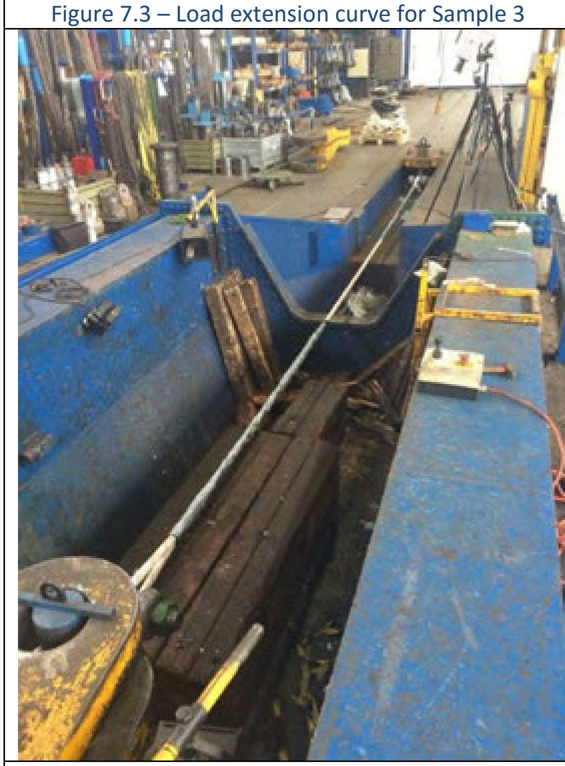


Figure 7.5 – Mooring line sample loaded in test bed

Figure 7.6 – Mooring line & tail assembly

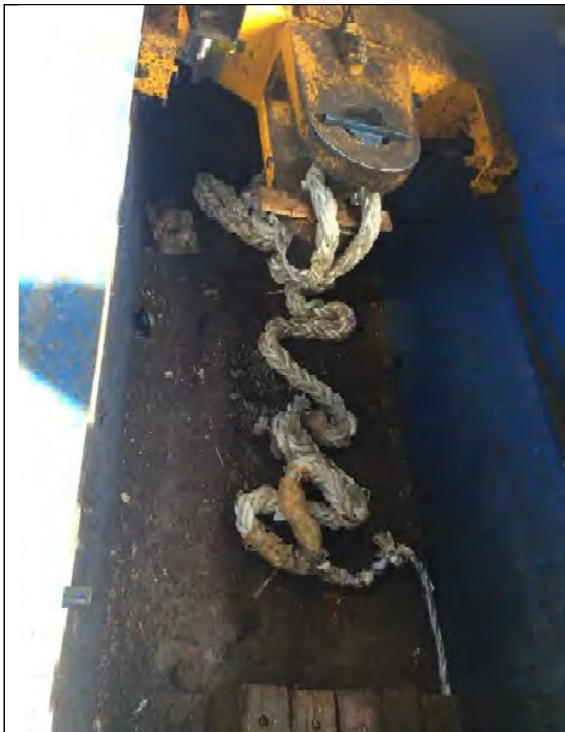


Figure 7.7 – Tail fully recoiled following test


Figure 7.8 – Mooring line section following test

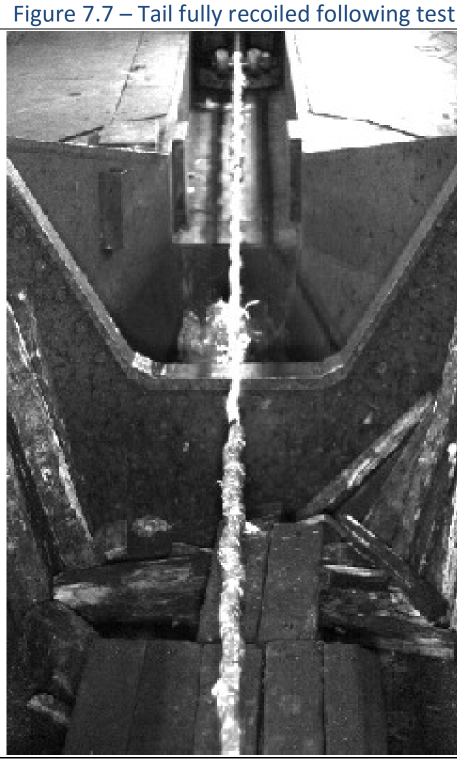


Figure 7.9 – High speed shot at break on mooring line

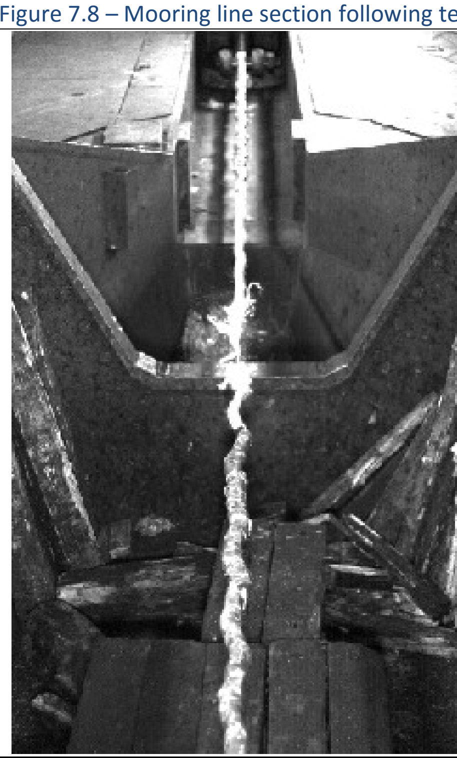


Figure 7.10 – High speed shot 0.01th second after 1st image

Figure 7.11 – Mooring line and tail – 1.04s

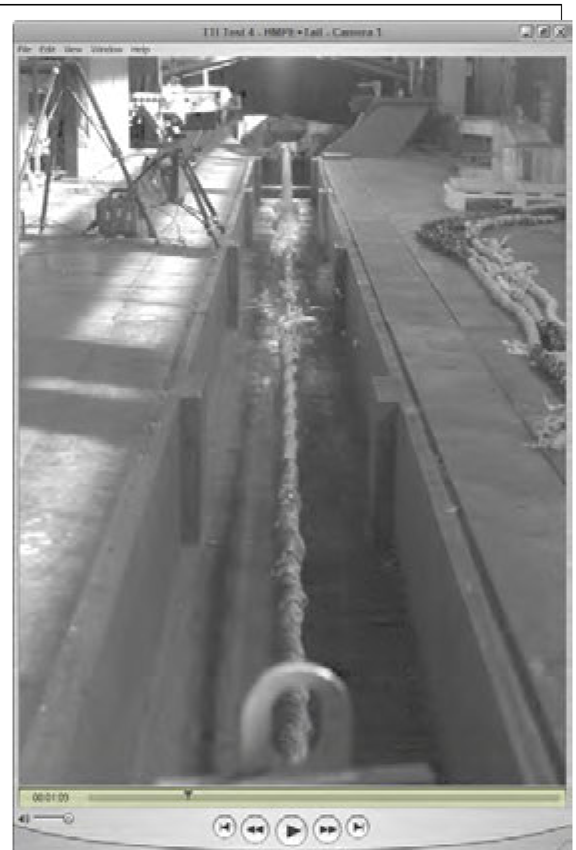


Figure 7.12 – 1.09s

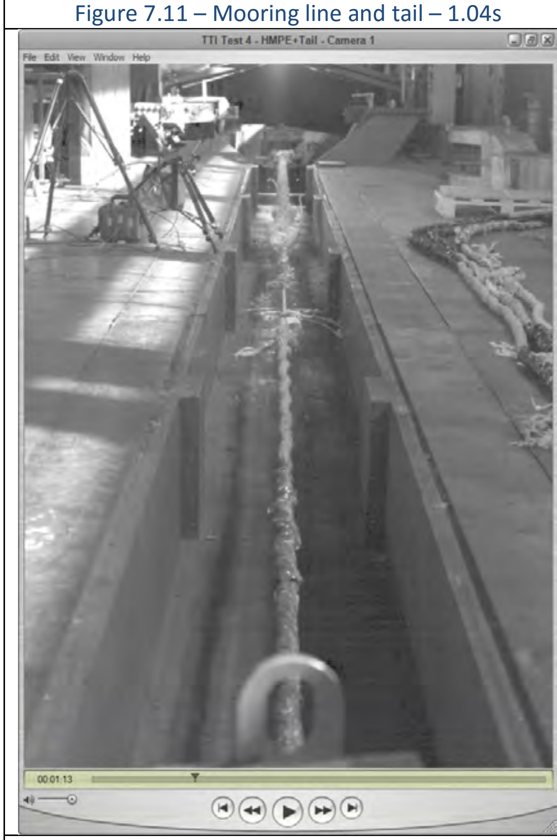


Figure 7.13 – 1.13s

Figure 7.14 – 1.46s

Figure 7.15 – 2.17s

Figure 7.16 – 5.18s – Tail completed recoil

Figure 7.17 – Mooring line and tail 0.44s

Figure 7.18 – 0.50s

Figure 7.19 – 1.20s

Figure 7.20 – 2.01s

Figure 7.21 – 2.42s

Figure 7.22 – 3.16s – Tail reaching full recoil

In addition to slow motion video real time Native video footage of all breaks was supplied via a Dropbox link and can be shared via request and approval through MAIB and TTI.

8 Scanning Electron Microscope [SEM] Images and Analysis

Following discovery of what appeared to be broken sections of yarn within the strands both within the failure and remote from the failure area, a number of sections of yarn were sent away for SEM imaging so that a closer inspection of the fibre fracture mode could be investigated.

The fractures visually seen and the severe kinkbands indicated that axial compression fatigue may have been a contributing factor to strength loss, however only clear SEM images showing distortion and filament fracture would confirm this. The 'Atlas of fibre fracture and damage to textiles' [7] is the most established reference guide identifying types of failure mode and fibre distortion.

Tensile failures in HMPE tend to be identified by axial splits in the filaments as the material is highly crystalline and oriented, while kinkband failures tend also to be splits these are normally also associated with a clear kink in the filament.

The results of the investigations into the yarns are shown below.

Figure 8.1 – Shore side Inner yarn, tensile failure

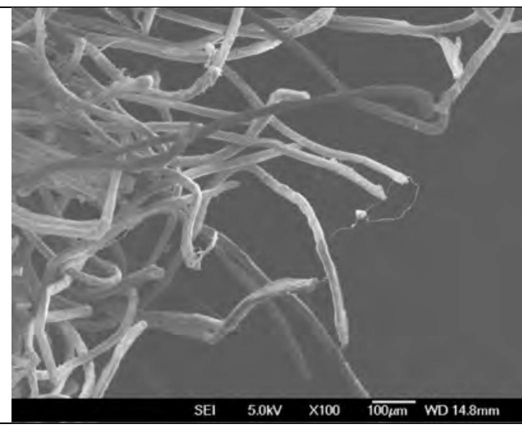


Figure 8.2 – Shore side Inner yarn filaments

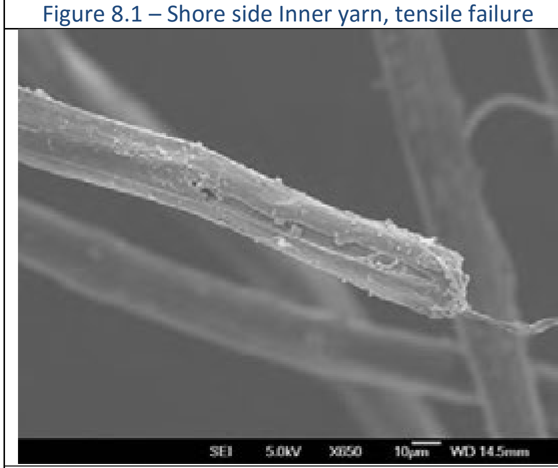


Figure 8.3 – Tensile failure

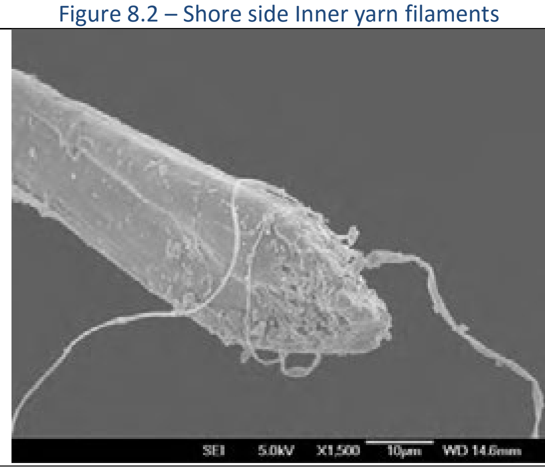


Figure 8.4 – Tensile failure

Figure 8.5 – Shore side possible kinkband failure

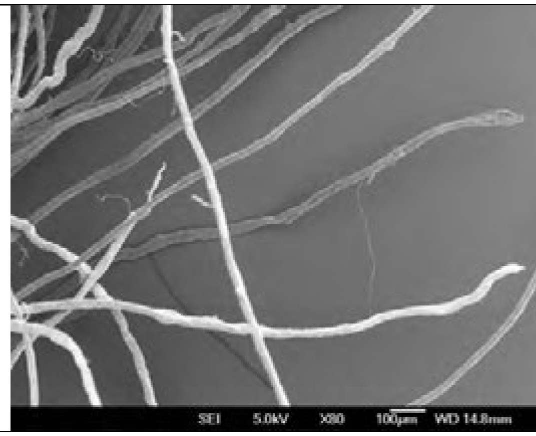


Figure 8.6 – Filament close up

Figure 8.9 – Kindband distortion to filaments

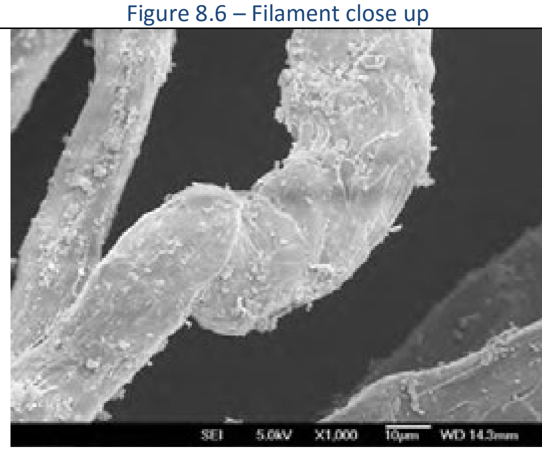


Figure 8.10 – Close up on distortion

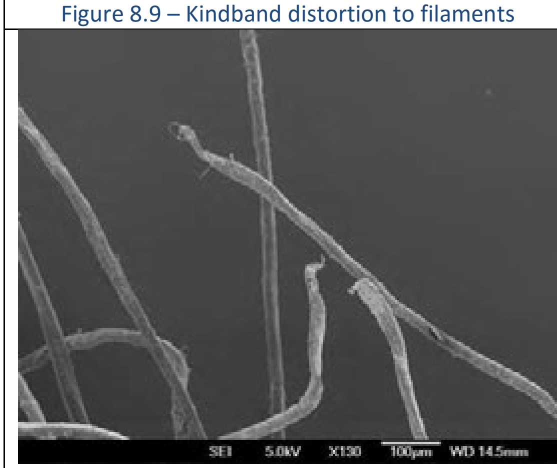


Figure 8.11 – Filament failure at kinkband

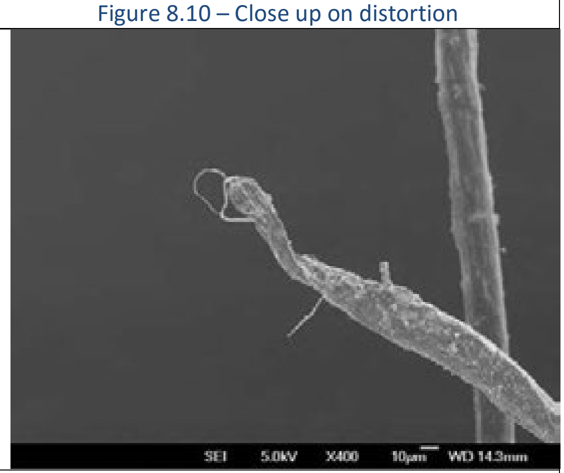


Figure 8.12 – Close up of filament failure

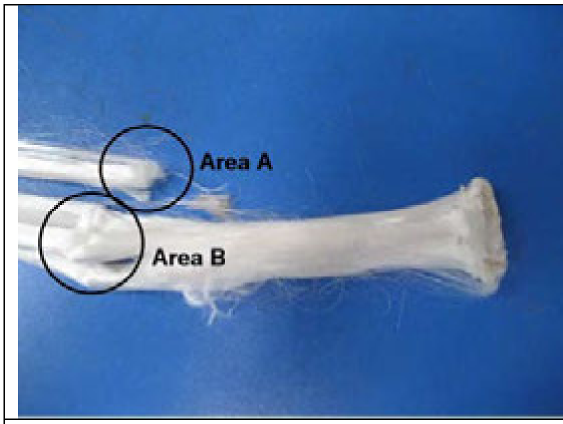


Figure 8.13 – Shore end inner yarn kinkbands

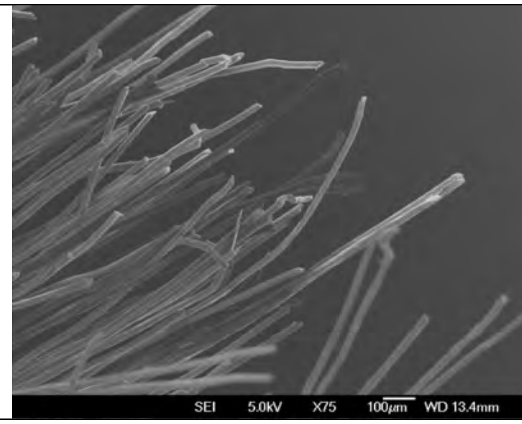


Figure 8.14 – Area A1 close up

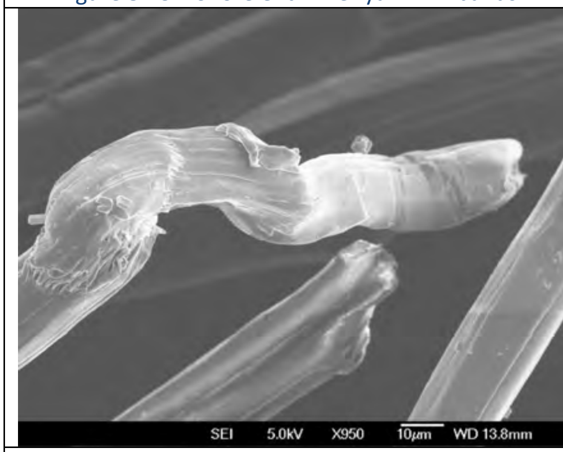


Figure 8.15 – Area A – Kinkband filament failure

Figure 8.16 – Area A – Kinkband filament failure

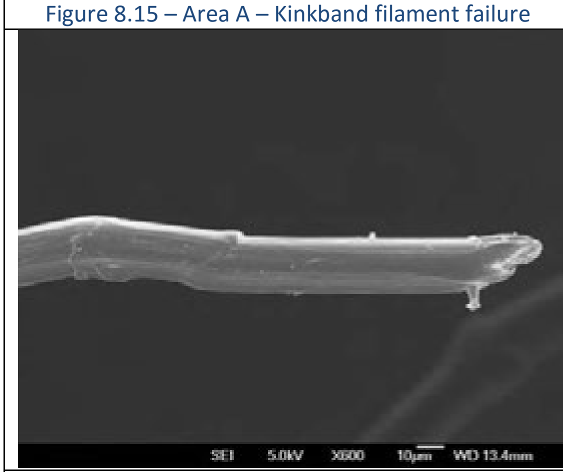


Figure 8.17 – Area A – Kinkband filament failure

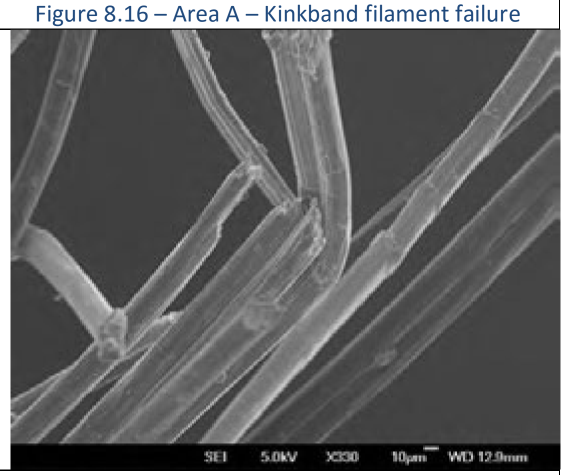


Figure 8.18 – Area B – Kinkbands and filament failure

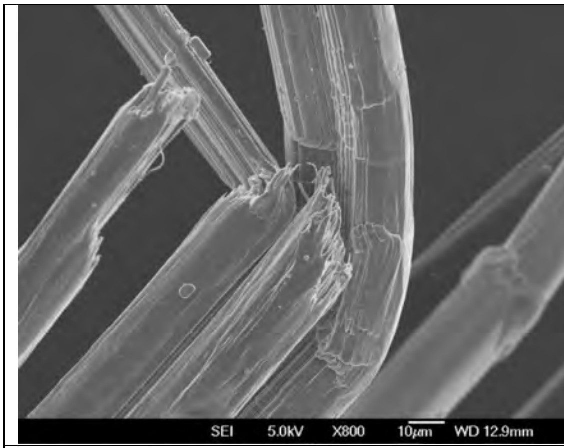


Figure 8.19 – Area B – Close up of bands and filament failure

Figure 8.20 – Area B – Kinkband

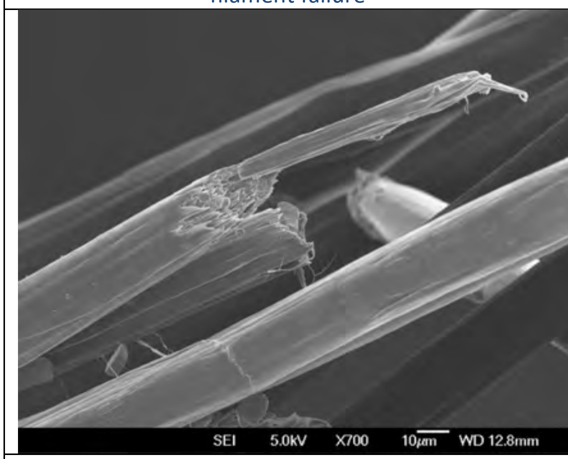


Figure 8.21 – Area B – Filament failure

Figure 8.22 – Area B – Filament failure


Figure 8.23 – Vessel end possible kinkband failure

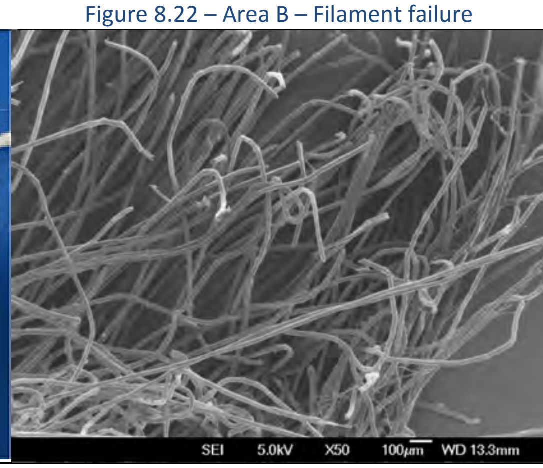


Figure 8.24 – Vessel end close up

Figure 8.25 – Filament failure

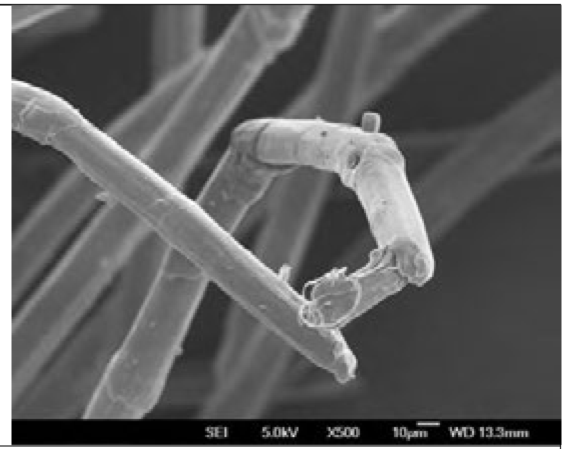


Figure 8.26 – Filament failure

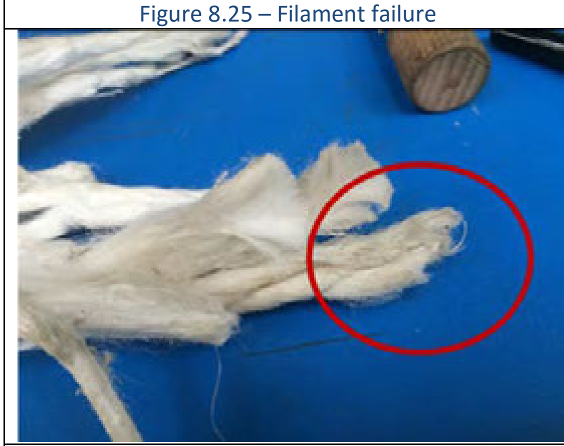


Figure 8.27 – Vessel end possible tensile failure

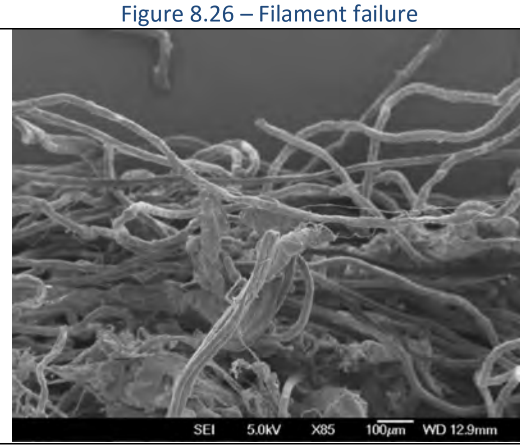


Figure 8.28 – close up of tensile failure end

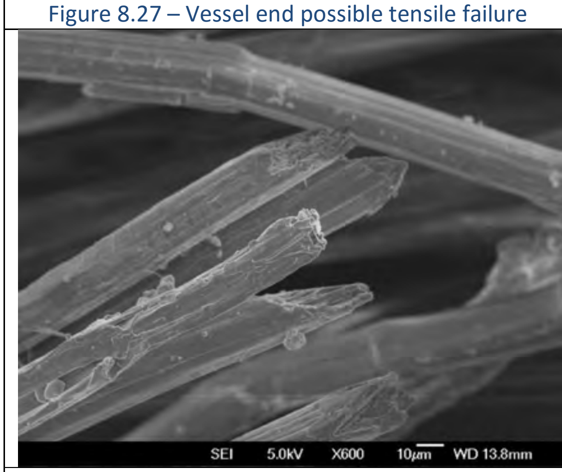


Figure 8.29 – Vessel end filament tensile failure

Figure 8.30 – Vessel end filament tensile failure

9 Discussions and Conclusions

9.1 Discussion

The initial visual inspection of the line appeared to indicate that the rope was in good condition considering its service time and had not suffered any mechanical damage up to the point of failure. The initial thoughts were that this rope had failed either due to localised mechanical damage or to tensile overload during the mooring or ship manoeuvring operations.

Dissection of the rope and indeed the parted ends however appeared to indicate that the rope and in particular the inner core yarns in the strands had suffered significant distortion and possible failure due to induced kinkbands commonly associated with axial compression fatigue. This is generally caused at low rope tensions when some yarns may go into axial compression while the tension is taken in other yarns. In fibre the presence of axial compression is generally identified by the presence of kinkbands which will be distributed through the affected rope length at relatively short distances as indicated in § 4.1. These bands may form in various degrees of severity through the rope length but the yarn will be most affected where it is restrained by adjacent rope elements that are still under tension or by induced axial compression as the rope passes over fairleads or other deck equipment while under tension. Jacketed ropes and in particular tightly braided jackets can also cause the rope core to go into compression.

The kinks themselves first manifest themselves as smooth curves however if the bending yield in the yarn filament is reached a sharp kink appears causing a molecular buckle within the yarn filaments and a sharp Z shaped kink is formed. After repeated cycling the fibre will fail. This failure can to the untrained eye have the appearance of a cut to the yarns as the failure will be short and uniform similar to a knife cut.

Previous testing carried out as part of the FIBRE TETHERS 2000 [9] work showed severe strength loss in aramids after 20,000 cycles, in HMPE after 200,000 cycles and polyester after 1,000,000 cycles. As the relative number of mooring hours the rope was used for was well below the 200,000 cycles indicated the cause is more difficult to define.

Regarding the residual break loads achieved as previously noted the realisation factor used by Bridon seems unrealistic given the variances achieved between the realised strength tables and the corresponding spliced break load values achieved. The Bridon factor of 0.998, suggests that there would be almost 100% transition between the yarn and rope strength. While the design uses a long lay three strand core which would undoubtedly achieve a high realisation it is improbable that such a high transition would be achieved given the normal manufacturing variances in twist and lay in the strand and rope construction. In our experience a factor of 0.85 would be more realistic and would bring the achieved realised break loads closer to the actual spliced strengths achieved although still a little high.

The following two tables show recalculated realised break loads for sample 4, Shore end, which used 6 outer and 6 inner core yarns. Table 9.1.1, looks at the result based on the suggested TTI realisation factor while table 9.1.2, uses the same calculation but with a reduction of the number of yarns in the rope from 96 to 84, representing the 12 broken yarns that were found in one strand location. While it should be appreciated that the yarns around would give some support to those broken yarns and may therefore reduce the strength loss, it does give an indication of the impact it could have.

Sample 4 -Shore End ~ 5-10 metres from break - Rope Residual Strength					
		Strand 1	Strand 2	Strand 3	units
Mean		9465	9533	9290	
SD		2218	2681	2549	
CV		23%	28%	27%	
Overall Mean				9429	N
SD				2420	
CV				26%	
Yarns / Rope				96	
Realisation Factor				0.85	
Calculated MBL				769.4	kN
Original MBL				1485	kN
% Residual Strength				52%	

Table 9.1.1 – Revised realisation factor only

Sample 4 -Shore End ~ 5-10 metres from break - Rope Residual Strength					
		Strand 1	Strand 2	Strand 3	units
Mean		9465	9533	9290	
SD		2218	2681	2549	
CV		23%	28%	27%	
Overall Mean				9429	N
SD				2420	
CV				26%	
Yarns / Rope				84	
Realisation Factor				0.85	
Calculated MBL				673.3	kN
Revised Original MBL				1485	kN
% Residual Strength				45%	

Table 9.1.2 – Revised realisation factor and reduction in rope yarns

The realisation calculations are for unspliced ropes and therefore a 10% reduction in accordance with ISO 2307 [5] would additionally be applied when comparing with the spliced break load section. The shore end spliced sample achieved a break load of 671kN. The revised realisation calculations give break loads of 692.4kN for table 9.1.1 and 605.97 for table 9.1.2. Given that the spliced sample may not have had the any broken yarns the break load calculated from table 9.1.1, correlates very closely with the actual spliced break load.

As noted in Section 2, it was initialling understood that the original 11 metre mooring tails were replaced with longer 22 metres after two moorings however subsequent evidence now provided [11] has confirmed that the tails were not actually changed until May 2011 and that the vessel had conducted a total of 13 mooring operations up to this point, 5 of which had been at Milford Haven. A review of the loading data from Milford and the location in the mooring of the section of rope that parted during the failure incident would appear to indicate that the rope had suffered a number of high load incidents during these first moorings at Milford and that the location of the failure section would have been in the vicinity to the fairlead and pedestal roller which may have caused localised high axial compression fatigue and degradation in the rope during these mooring operations.

Switching to the longer 22 metre tails has shown to reduce mooring line loads due to the increased compliance and this would have also have moved the section previously loaded inboard by 11 metres.

9.2 Conclusion

From the findings of the investigations it is clear that the rope has failed due to the effects of axial compression fatigue that has significantly reduced the yarn strength and therefore rope residual strength.

Kinkbands were observed throughout the rope length and were severest in the inner yarns around failure with evidence of fully and partially severed yarns, however it should be noted that these could have been caused during the failure incident as the rope would have gone into rapid compression following the failure.

It was initially thought that type of failure in a HMPE mooring line had not been observed before and would be considered unique however further review of rope failure data received as part of the HMPE User Group report [10] has highlighted other failures that could be attributed to similar axial compression fatigue degradation.

To date, HMPE is widely accepted in the industry as not being sensitive to axial compression fatigue with a number of international standards stating that it should not be considered when designing rope systems. Clearly something has occurred either in the application, material, rope design or use of mooring tail that has affected the rope and caused the failure. Further work to investigate the rope design and failure mode would be recommended but this goes beyond the scope of this report and will be forwarded under a separate proposal.

10 References

[1] Fibre rope certificate document Doc. GLS 0834143 dated 29th August 2008.

[2] Fibre rope certificate document PIR1207686/2 dated 27th July 2012.

[3] OCIMF Mooring Equipment Guidelines, 3rd Edition, Oil Companies International Marine Forum, London, Witherby Seamanship International, Livingston, UK, 2008

[4] Fiber Rope Inspection and Retirement Criteria, CI 2001-04, Cordage Institute, Wayne, PA, 2004

[5] BS EN ISO 2307:2010, Fibre Ropes – Determination of certain physical and mechanical properties, International Standards Organization, Geneva, 2010

[6] Handbook of fibre rope technology – H.A. McKenna, J.W.S. Hearle and N. O'Hear, The Textile Institute, Woodhead Publishing Limited, UK. 2004

[7] Atlas of fibre fracture and damage to textiles – 2nd Edition – J.W.S. Hearle, B Lomas, W.D. Cooke, The Textile Institute, Woodhead Publishing Limited, UK. 1998

[8] Superline Steelite 3 Eye Splice Method, AS Issue 4, Bridon International Limited, 2006.

[9] Fibre Tethers 2000 phase 1 report, Noble Denton Europe Ltd, National Engineering Laboratory and Tension Technology International Ltd, 10th February 1995

[10] HMPE User Group, LNG Mooring Line Failures, Final Report. Ref: TTI-CB-2011-821-R, Tension Technology International Limited, September 2010

[11] Copy of Mooring Rope History NEWEST. Xcel spread sheet STATSCO, 29th April 2015

MAIB Safety Bulletin SB1/2015

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

SAFETY BULLETIN

SB1/2015

July 2015

Extracts from The United Kingdom Merchant Shipping (Accident Reporting and Investigation) Regulations 2012

Regulation 5:
"The sole objective of a safety investigation into an accident under these Regulations shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of such an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

Regulation 16(1):
"The Chief Inspector may at any time make recommendations as to how future accidents may be prevented."

Press Enquiries:
020 7944 4312/3176

Out of hours:
020 7944 4292

Public Enquiries:
0300 330 3000

NOTE

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall be inadmissible in any judicial proceedings whose purpose, or one of whose purposes is to attribute or apportion liability or blame.

All bulletins can be found on our website:
https://www.gov.uk/government/organisations/marine-accident-investigation-branch

For all enquiries:

Email: maib@dft.gsi.gov.uk
Tel: 023 8039 5500
Fax: 023 8023 2459

Mooring line failure resulting in serious injury to a deck officer on board *Zarga* alongside South Hook LNG terminal, Milford Haven on 2 March 2015

Figure 1: *Zarga* alongside South Hook LNG terminal

MAIB SAFETY BULLETIN 1/2015

This document, containing safety lessons, has been produced for marine safety purposes only, on the basis of information available to date.

The Merchant Shipping (Accident Reporting and Investigation) Regulations 2012 provide for the Chief Inspector of Marine Accidents to make recommendations at any time during the course of an investigation if, in his opinion, it is necessary or desirable to do so.

In co-operation with the Republic of the Marshall Islands, the Marine Accident Investigation Branch (MAIB) is carrying out an investigation into a mooring line failure, resulting in the serious injury to a deck officer on board the Marshall Islands flagged Liquefied Natural Gas (LNG) carrier *Zarga* at the South Hook LNG terminal, Milford Haven on 2 March 2015.

The MAIB will publish a full report on completion of the investigation.

Steve Clinch

Chief Inspector of Marine Accidents

NOTE

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall not be admissible in any judicial proceedings whose purpose, or one of whose purposes, is to apportion liability or blame.

This bulletin is also available on our website: www.gov.uk/maib

Press Enquiries: 020 7944 4312/3176; Out of hours: 020 7944 4292

Public Enquiries: 0300 330 3000

BACKGROUND

On 2 March 2015, a deck officer on board the LNG tanker, *Zarga* **(Figure 1)**, suffered severe head injuries when he was struck by a mooring line that parted during a berthing operation at the South Hook LNG terminal, Milford Haven. The officer, who was in charge of the vessel's forward mooring party, was airlifted to a specialist head injuries trauma unit for emergency surgery.

Zarga was declared *all fast* alongside about 40 minutes prior to the accident and the attending tugs were let go. The vessel subsequently moved out of position in the gusty wind conditions during which time the mooring teams were fitting chafing guards to the lines **(Figure 2)**. As the tugs had already been released, the master instructed the officer in charge (OIC) of the forward mooring party to tension the forward spring lines to warp *Zarga* back into the correct position.

The OIC positioned himself aft of the forward springs' port-shoulder roller fairlead **(Figures 2** and **3)**, and positioned a second crewman forward of him in order to relay his orders to the winch operator. As the winch operator attempted to heave in on the springs, the winch repeatedly stalled and rendered[1]. After about 10 minutes, one of the spring lines began to rattle and creak, and then suddenly parted **(Figure 4)**. The section of the line between the break and the port-shoulder roller fairlead struck the OIC on his head as it whipped back before going overboard through the fairlead.

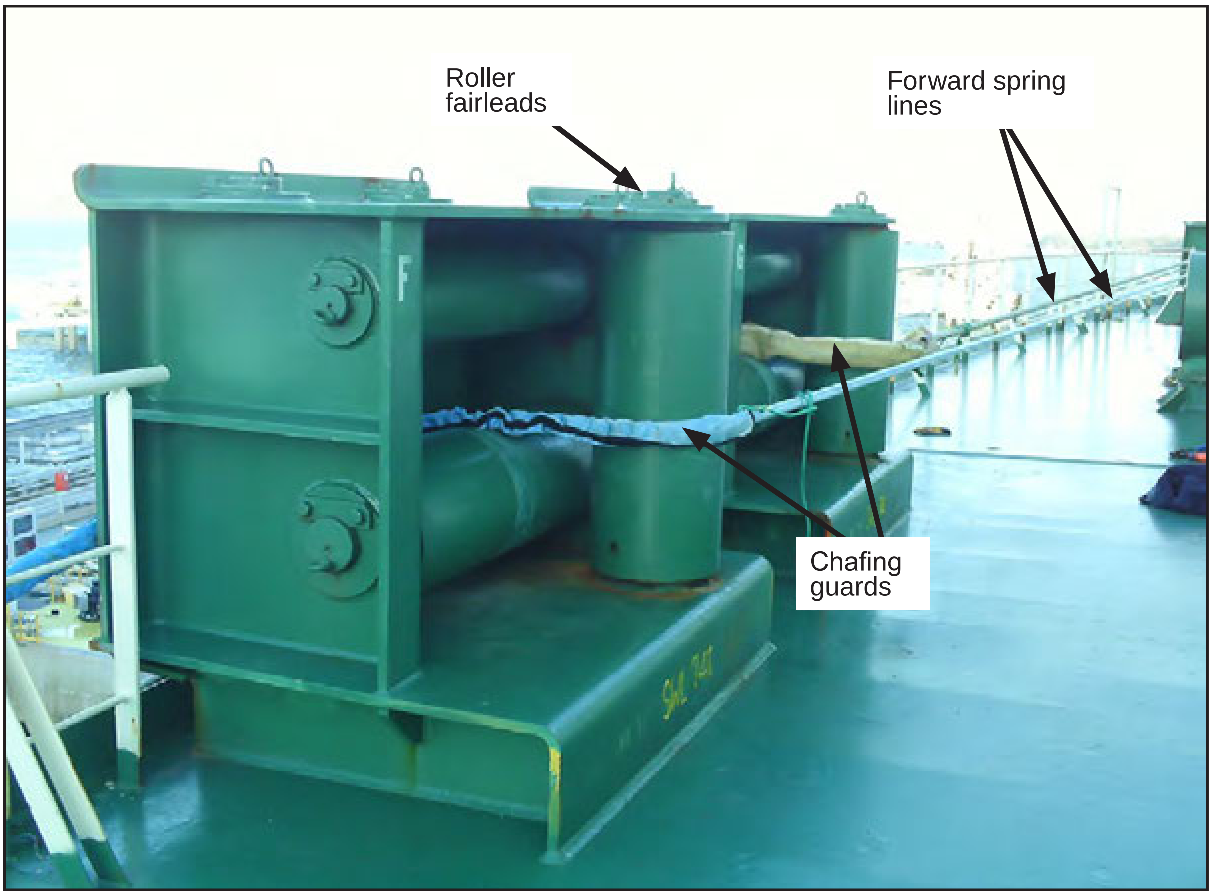


Figure 2: Port-shoulder roller fairlead

[1] Slipping under load

MOORING LINES AND WINCHES

The 5-year old mooring lines fitted to the vessel were 44mm diameter sheathed ultra-high modulus polyethylene (UHMPE) with a length of 275m and a minimum breaking load (MBL) when new of 137t. The outboard ends of the UHMPE spring lines were fitted with 22m long Euroflex (polyester/polyolefin) tails, which had an MBL of 190t. The section of the UHMPE spring line in use between the winch and the connection with the Euroflex tail was about 68m long. The split drum type mooring winch had a 30.6 tonne-force (tf) winding pull, rendered at a load of 34tf and operated at 15m/minute.

INITIAL FINDINGS

Elongation and snap-back

The amount a mooring line stretches depends on the elasticity of the material(s) used in its manufacture and the length under load. Elongation of the line introduces stored energy that, if suddenly released under load when the line parts, can cause the failed ends to recoil back towards their anchor points at high speed; this is referred to as snap-back.

Both wire and high modulus synthetic mooring lines have low elasticity and, consequently, are considered to have very little snap-back when they fail, and this is often considered to be an advantage over other types of synthetic line. However, although capable of handling high dynamic loads, low elasticity can make high modulus synthetic mooring lines prone to failure under peak dynamic loading.

On board *Zarga*, 11m tails were originally fitted to reduce peak dynamic loading, but these were replaced with 22m tails after peak dynamic loads were experienced that had led to a series of line failures. However, the 22m tails had much greater elasticity and this, and the routeing of the line, introduced a significant snap-back hazard to the outer section of the failed UHMPE mooring line. The danger of snap-back was identified in the vessel's risk assessments, but snap-back zones had not been marked on *Zarga*'s mooring decks. Because UHMPE mooring lines were fitted, the perception among members of the crew was that, in the event of a mooring line failure under load, the ends of a parted line would simply fall to the deck. In this case, the inboard section of the failed line recoiled a short distance towards the base of the winch.

Post-accident tests

Following the accident, the MAIB commissioned a series of tests and trials designed to measure the elongation and snap-back characteristics of the mooring lines used on board *Zarga*. When sections of the UHMPE rope were loaded to the point of failure the average maximum elongation was about 2% and minimal snap-back was observed. When the trial was repeated with the Euroflex tail[2] attached the elongation was significantly increased. Similar to the accident, it was the UHMPE section of the line that parted, and the failed end that was attached to the tail snapped back over 15m in less than 1 second. The other end of the UHMPE rope did not snap back.

Short video clips of these trials can be found on the MAIB website at https://www.gov.uk/maib-reports/safety-warning-issued-after-mooring-line-failure-on-board-lng-tanker-zarga-resulted-in-serious-injury-to-a-deck-officer.

The causes and contributing factors of *Zarga*'s mooring line failure are subject to an ongoing investigation and will be discussed in a full investigation report.

[2] The 22m tail was shortened to 15m to allow it to be accommodated within the test machine

Figure 3: Forward mooring party OIC at port-shoulder roller fairlead

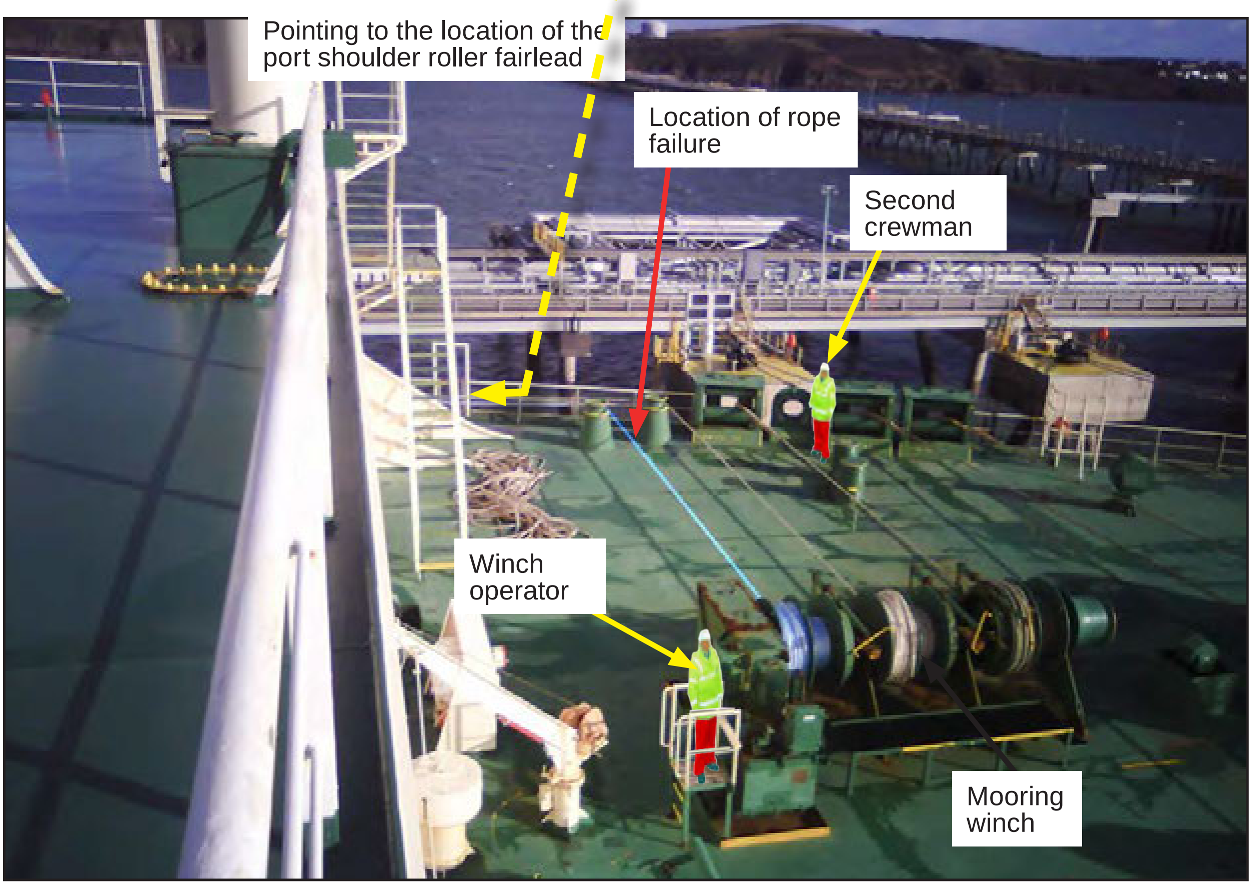


Figure 4: Port side forward mooring deck

SAFETY LESSONS

- When connecting synthetic tails to UHMPE, HMPE and wire mooring lines, the energy introduced due to the elasticity of the tails can significantly increase the snap-back hazard.
- Elongation is proportional to the length of tail. Increasing the length of the tail will increase the amount of elongation and hence the amount of energy that can be stored in the line when under load.
- Ship owners/operators should ensure that the type of lines and tails used for mooring lines are suitable for the task and that the dangers of snap-back are fully considered.
- Mooring teams should be aware of the potential for snap-back in all types of mooring line, and the probable areas on the mooring deck that are not safe when lines are under load.
- Mooring lines led around roller pedestals and fairleads can lead to potentially complex snap-back zones. Ship operators and masters should conduct their own risk assessments to ensure potential snap-back zones are identified, and are reviewed at regular intervals.
- Notwithstanding the ongoing investigation into the nature of the failure of *Zarga*'s spring line, where doubt exists on the continued use of a mooring line, the vessel operator should obtain guidance from the rope manufacturer on the conduct of detailed line inspections.

Issued July 2015

TTI Report on computer modelling and testing of HMPE Rope for axial compression fatigue – *Zarga* incident

TTI Testing Ltd

Unit 2, Hithercroft Road, Wallingford, Oxfordshire, OX10 9DG, UK

www.tti-testing.com

Report on Computer Modelling and Testing of HMPE Rope for Axial Compression Fatigue – Zarga Incident

Reference number TTI-SJB-2015-5167

Date	Rev.	Description	Prepared by	Authorised by
21/06/16	0	Issued to client	[redacted]	[redacted]
04/07/16	0	MAIB comments and clarification on realisation factor added	[redacted]	[redacted]

Distribution:

TTI Testing Ltd (author, file)

MAIB / Shell

Attention:

[redacted]

[redacted] / [redacted]

Contents

1 Introduction and Background to the Study

Following the failure of a HMPE mooring rope on board the LNG vessel Zarga and subsequent investigations into this failure by TTI, it became apparent that this rope had failed due to axial compression fatigue in the load bearing HMPE yarn. Details of the inspection can be found in the specific TTI Report [1].

This type of failure mechanism is a new phenomenon in HMPE ropes as previous studies carried out as part of the FIBRE TETHERS 2000 programme [2] had shown that severe strength loss in HMPE only occurred after 200,000 cycles of axial compression, far more than would have been anticipated to have occurred in the failed mooring line. Indeed, within the industry axial compression fatigue has previously been seen as almost exclusively a concern for Aramid ropes and industry standards even go as far as to state 'Axial compression fatigue is not a concern with polyester and HMPE fibre ropes'.

As part of the ongoing investigations TTI and its partner company TTI Testing have been tasked with modelling the rope design using TTI's Fibre Rope Modeller (FRM) which will be used to assess the axial compression fatigue in this fibre rope. In addition, buckling tests on individual HMPE yarns were carried out to compare with the results obtained from the FIBRE TETHERS 2000 programme [2], and a new section of rope was dissected, yarn tested and two full scale break tests were carried out to assess the rope design.

This document presents the methodology, results, discussion and conclusions of the FRM modelling, yarn buckling tests, visual inspections, yarn and sample break load tests and fibre fracture morphology gained through scanning electron microscope examinations that were carried out by and on behalf of TTI Testing.

2 Report on the Modelling of Axial Compression Fatigue Damage

The rope to be modelled is a nominal 44 mm Bridon Steelite Xtra brand UHMPE fibre rope. It is a Superline circular braided construction comprising a mixed polyester/Supermix abrasion resistant braided jacket over a central 3-strand long lay HMPE fibre load bearing core. The Bridon standard part code is WRG006. The design break load for this rope is 137 tonnes unspliced.

The full report on the specific FRM modelling and buckling calculation's on of the rope design is included in Appendix 1. However, the findings from this report are noted as follows;

- Bending the rope under load over a relatively small D/d ratio as in the fairlead and pedestal roller may have induced incipient damaging yarn compression and subsequent kink band formation,
- The FRM model demonstrated that compressive strains in excess of those needed to initiate kink bands can be caused by a combination of axial load and low twist.
- The buckling model calculated that the critical elastic wavelengths bracketed the 10mm seen in the actual dissected rope failure verifying the model.

- The low twist inner yarns were highly restrained by the jacket and outer layers, and damaging buckles may have developed at loads below 30% of the rope MBL, a relatively common operating load for the ropes.
- The extreme loads of 50 or 60% of MBL experienced by the rope are likely to have accelerated damage and led to the eventual fracture of the buckles.

3 Yarn Buckling Test and Results

Yarn buckling tests were conducted to compare un-restrained and restrained yarn bundle strength loss and to allow comparison with the FRM axial compression model.

Figure 3.1 shows the yarn buckling test machine. A short bundle of textile yarns is held between two clamps, the upper fixed and lower subject to a reciprocating motion. The initial gauge length is 3.74 mm and the reciprocating stroke is set to 1.70 mm. A typical cycle frequency of 6.8 Hz is employed.

The yarn is thus repeatedly buckled and straightened in this test in a form termed 'unrestrained buckling'. Initially, the form of buckling is a smooth curvature, which is determined by yarn bending stiffness. However, as plastic deformation develops or as fibres start to weaken at the region of maximum curvature, a sharp kink forms at the central point. This plastic buckle forms a shape shown in Figure 3.2

Using the standard BS procedure for tensile testing [3] with a gauge length of 500 mm, the residual strength of each textile yarn in each bundle is measured and compared with the original new break strength. These are then plotted on a logarithmic scale.

Yarn buckling was conducted on Dyneema yarns at different cycle levels from 22,000 to 110,000 and in both unrestrained and restrained set ups. 110,000 cycles have been used as an initial benchmark as this is far in excess of the number of wave induced motions possible given the number of port calls and hours of service of the failed ‘Zarga’ rope.

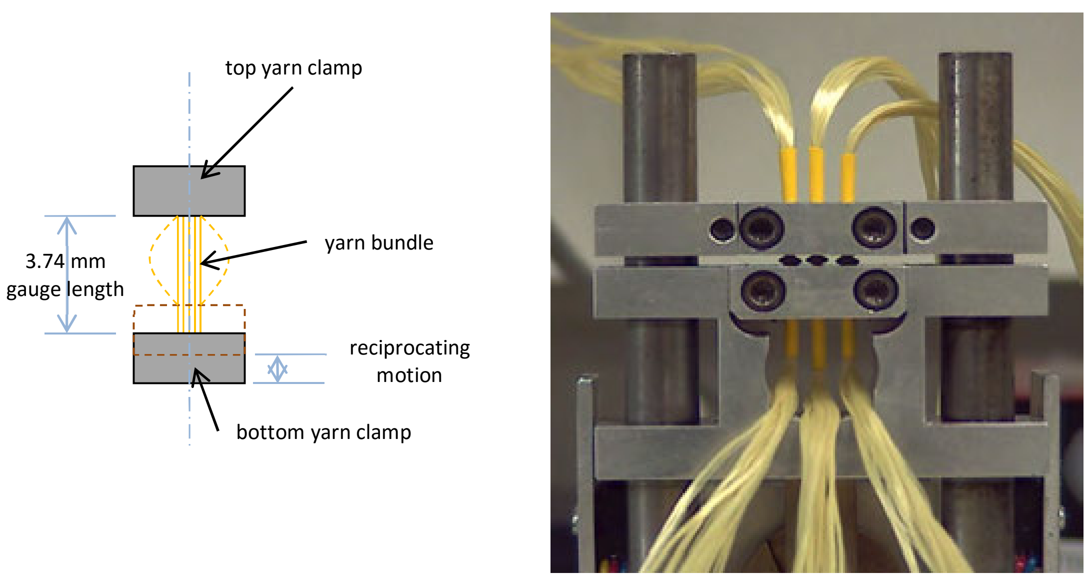


Figure 3.1: Yarn axial compression: schematic arrangement (left) and 3 station test rig (right).

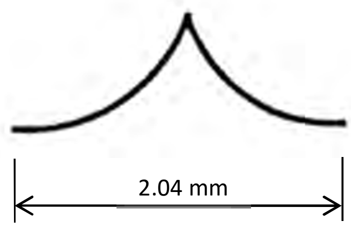


Figure 3.2: Schematic drawing of yarn formed into plastic hinge, mode 1 buckling (from [8]).

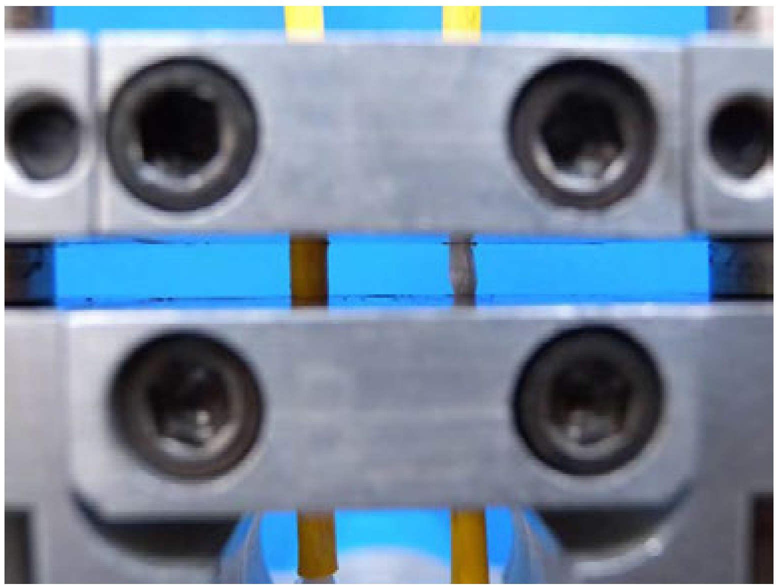


Figure 3.3: Image showing both an unrestrained and restrained yarn bundle sample in the test machine

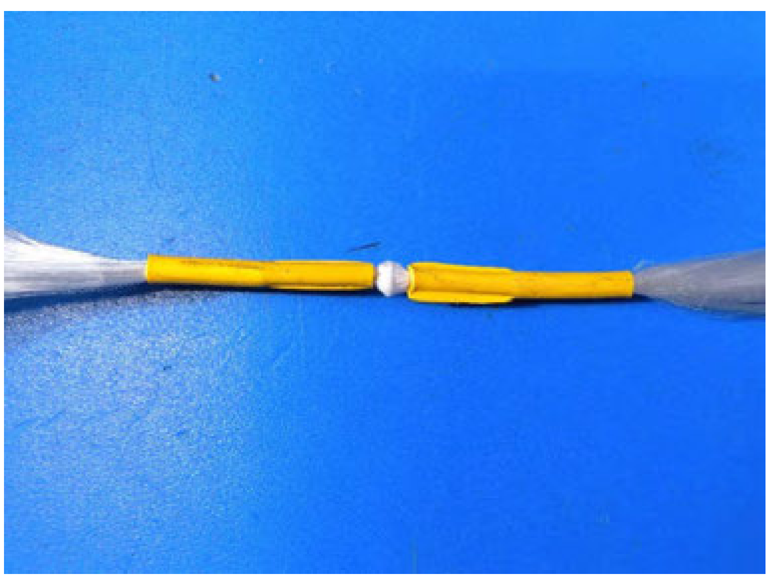


Figure 3.4: Image showing an unrestrained yarn bundle sample prior to break

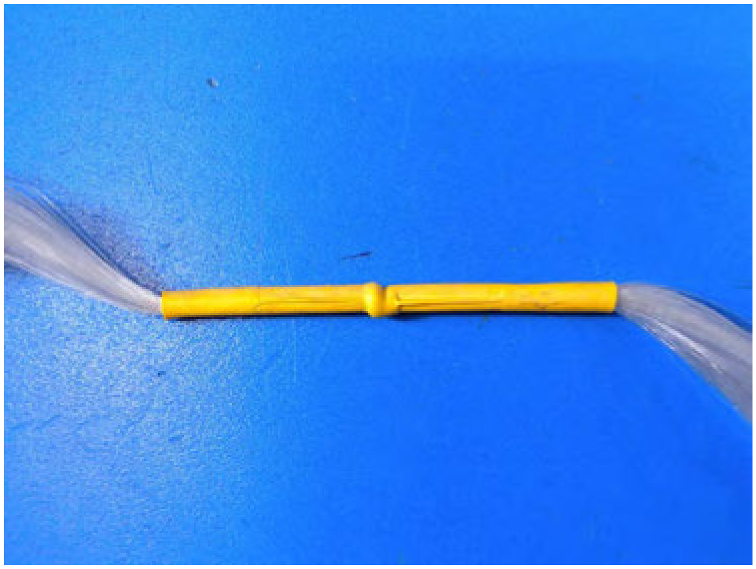


Figure 3.5: Image showing a restrained yarn bundle sample prior to break

3.1 Results

The results obtained for both sets of test data up to 110,000 cycles are shown in the following tables 3.1.1 and 3.1.2.

	Number of Cycles												
	0	21,500			35,853			52,000			110,000		
	New Yarn	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
Yarn Set	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N
1	753.94	703.80	661.10	582.59	575.52	439.48	631.68	414.40	469.03	567.80	319.74	463.89	492.15
2	783.12	679.05	653.46	435.34	614.79	619.49	549.29	450.60	538.70	586.62	421.19	386.49	452.70
3	741.37	641.84	680.38	636.11	639.57	398.00	479.03	612.08	570.20	547.28	483.72	464.12	402.45
4	587.66	671.11	552.13	674.91	525.44	470.97	650.10	543.72	599.58	622.85	396.07	576.32	484.37
Av.	716.52	673.95	636.77	582.24	588.83	481.98	577.53	505.20	544.38	581.14	405.18	472.70	457.92
SD	87.67	25.53	57.55	104.99	49.81	96.42	78.95	89.69	56.05	32.12	67.84	78.15	40.73
CofV	12.24%	3.79%	9.04%	18.03%	8.46%	20.00%	13.67%	17.75%	10.30%	5.53%	16.74%	16.53%	8.89%
Overall Average Strength			**630.98**			**549.45**			**543.57**			**445.27**	
Retained Strength			**88.1%**			**76.7%**			**75.9%**			**62.1%**	

Table 3.1.1: Table of results for unrestrained yarn bundles

	Number of Cycles												
	0	21,500			35,853			52,000			110,000		
	New Yarn	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
Yarn Set	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N	ABL N
1	753.94	653.82	681.63	652.03	589.85	612.53	626.32	321.38	456.80	384.43	433.33	483.63	435.60
2	783.12	648.71	503.88	644.58	533.58	597.40	479.62	514.81	464.96	427.38	274.51	463.96	547.13
3	741.37	732.44	void	711.82	574.71	431.64	609.48	390.54	516.88	498.72	369.06	447.70	397.82
4	587.66	456.71	void	649.13	636.65	500.52	485.34	516.87	505.38	530.12	458.20	529.40	348.57
Av.	716.52	622.92	592.76	664.39	583.70	535.52	550.19	435.90	486.00	460.16	383.78	481.17	432.28
SD	87.67	117.25	125.69	31.77	42.56	85.20	78.52	96.53	29.58	66.31	81.96	35.35	84.45
CofV	12.24%	18.82%	21.20%	4.78%	7.29%	15.91%	14.27%	22.15%	6.09%	14.41%	21.36%	7.35%	19.54%
Overall Average Strength			**626.69**			**556.47**			**460.69**			**432.41**	
Retained Strength			**87.5%**			**77.7%**			**64.3%**			**60.3%**	

Table 3.1.2: Table of results for restrained yarn bundles

From the results note that the overall retained strength is lower for the restrained yarn bundles than for the unrestrained which is consistent with the FRM model results and indicates that the increased radial pressure causes damaging shorter wavelength buckles to be induced into the yarn bundles quicker.

One other point of note which was observed when comparing the results from the FIBRE TETHERS 2000 [2] programme and those of an additional internal TTI study which was carried out in August 1998, is that it would appear that the new SK75 material has less resistance to buckling than the previously tested materials. This may have been caused by the fact that the yarn producers have been continuing development of the yarn properties to increase both its tenacity and resistance to creep deformation which may have altered the crystalline structure of the yarn so that its closer to that of the aramid spectrum. Table 3.1.3, shows results conducted in 1998, compared to the new tests and also the original SK60 data which was conducted in 1994. While we do not have the results at the lower cycle rates of 22,000 and 55,000 cycles for the SK75 tests conducted in 1998, you will note, that at both 110,000 and 250,000 cycles the new data is considerably reduced. The SK60 results are all much higher up to 110,000 which is well within the range of the cycles expected for an LNG mooring line.

The expected mooring line cycles over 5 years to failure for the Zarga rope is shown in the below formula. The Zarga mooring line did 1342 hours and this example is 3000 hours.

TIDE over 5 years' x 20 hrs per mooring x 30 moorings per annum = 5x20/6x30 = **1099 cycles**
WAVE over 5 years, say 20% moorings affected 30% time = 5x20x60x60/10sec period x20%x 30% x30 = **43,200** cycles

Grand total cycles = **44,300** for 3000 hours/year or **22,150** cycles for 1500hrs / year

This data all points to quite low cycles for conditions to create axial compression, so comparison with our buckling data in the region say up to 50,000 cycles for 5 years seems appropriate. It is in this region that the newer grade appears to have much lower buckling performance. Further investigations into this would be recommended.

Test Dates	Yarn Class	Yarn Type	Retained Strength as % of Undamaged Cycles			
			Cycles 22,000	Cycles 55,000	Cycles 110,000	Cycles 250,000
Tethers 2000 (1994)	HMPE	Dyneema SK60	91.1	88.2	81.5	59.5
11/08/1998	HMPE	Dyneema SK75	-	-	76.4	63.6
05/04/2016	HMPE	Dyneema SK75	88.1	75.9	62.1	58.6

Table 3.1.2: Table of results for unrestrained yarn bundles

4 New Rope Inspection and Testing Results

A new 100m section of LNG mooring line to the exact same specification as that supplied to the vessel 'Zarga' was procured from Bridon International to allow further investigation. The rope was supplied with a standard factory spliced soft eye spliced at one end, with the other end being supplied plain. Certificate number BC112014, dated 11/11/2015 refers [4] with a stated design rope break strength of 137 tonnes.

Three 0.5 metre sections were removed for dissection to look at the 'as manufactured' condition of the core. One section was removed for residual strength testing and two further sections were removed to be spliced into full scale test sections for destructive testing.

4.1 New Rope Inspection

Three 0.5 metre sections of rope were removed from the 100 metre length at distances of 20, 40 and 60 metres. The samples then had their outer jackets removed to enable examination of the 3 strand sub-rope core. In particular, this examination was to look for the presence of buckling and to establish the manufactured twist level of the inner yarns which had been noted as being very low to zero in the field failed rope. The examination of the samples is documented in Figures 4.1.1 to 4.1.19 below

It was noted that the outer layer yarns in each strand had very minor buckling whereas the inner layer yarns had severe buckling. The inner layer yarns also had zero twist.

All 3 samples had identical levels of buckling and zero twist in the strand inner layer yarns.

This examination confirmed that the inner yarns had been manufactured with zero twist which is consistent with that observed in the failed rope and therefore confirmed that twist had not been removed from the strands during the rope's service life. The examination also confirmed that buckling had been induced into the inner yarns during the manufacturing process.

The specification of strand pitch was 260mm +/-13mm, so it was confirmed that the rope had been manufactured to the parameters of the specification.

Figure 4.1.1: Sample 1, 3 strand subrope, very minor buckling in outer layer

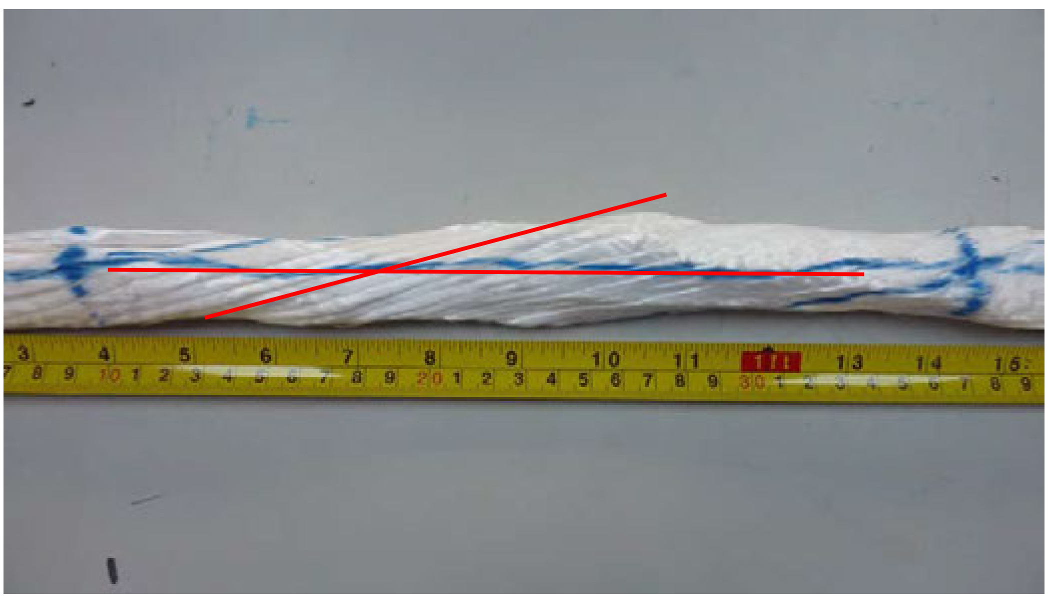


Figure 4.1.2: Sample 1, strand unlaid, and showing only minor buckling to the outer layer yarns (cannot really see from this side of strand, see figure 4.1.5). Lay angle approx. 15 degrees and pitch 260mm.

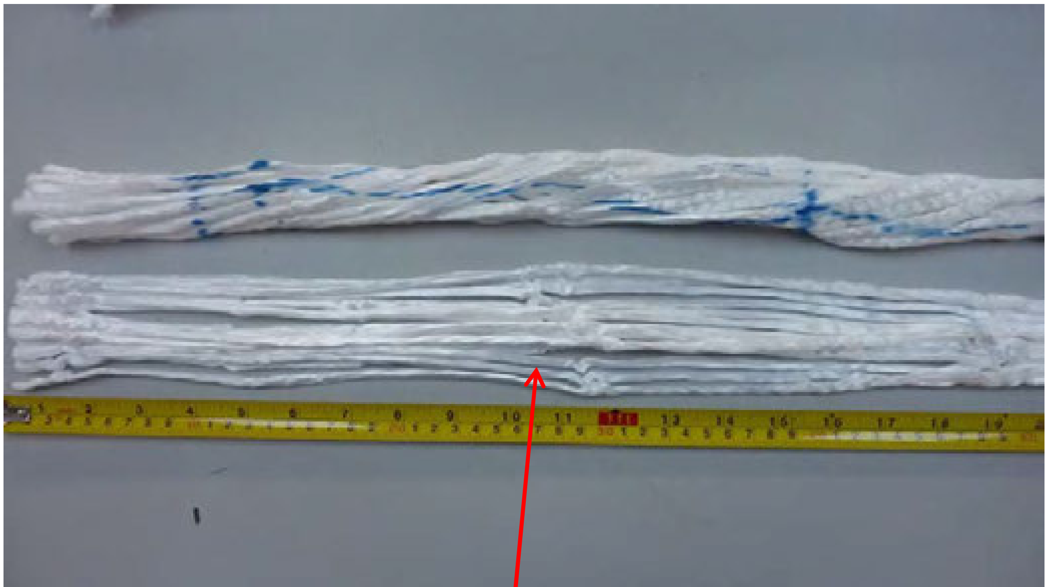


Figure 4.1.3: Sample 1, strand unlaid to rope yarn, inner layers zero twist and severely buckled

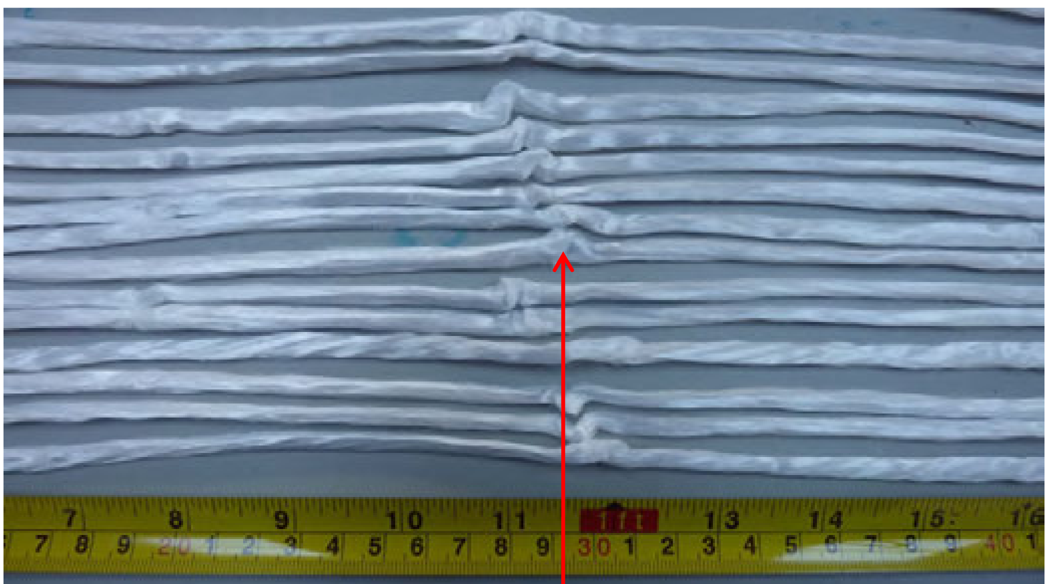


Figure 4.1.4: Sample 1, inner rope yarns, close up of severe buckles shown in figure 4.1.3

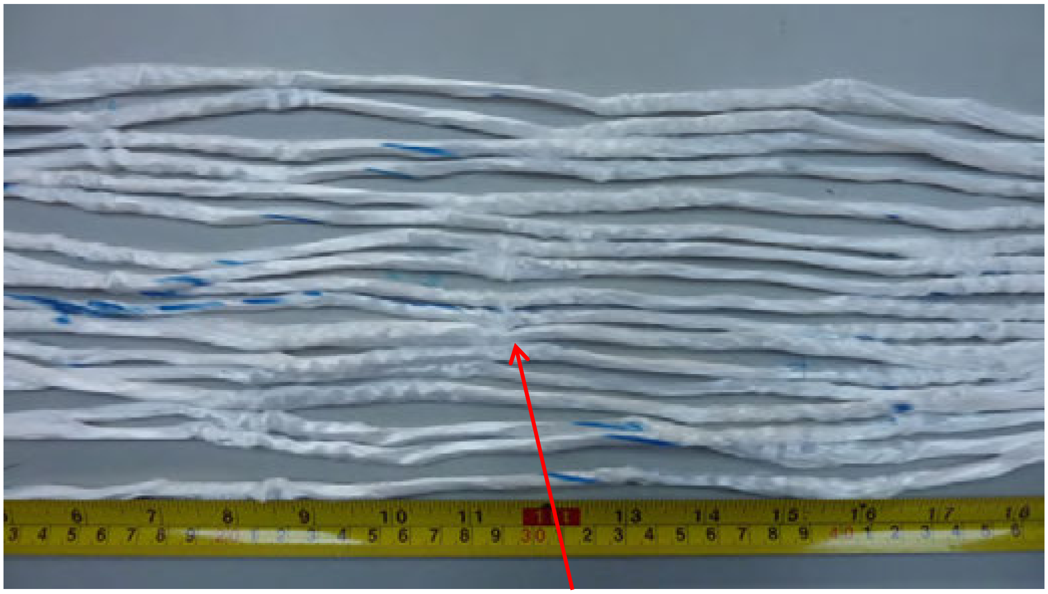


Figure 4.1.5: Sample 1, outer rope yarns, close up of mild buckles shown in figure 4.1.3. Note not all rope yarns buckled

Figure 4.1.6: Sample 2, 3 strand subrope, very minor buckling in outer layer

Figure 4.1.7: Sample 2, 3 strand subrope, close up of very minor buckling in outer layer

Figure 4.1.8: Sample 2, opened outer layer strand to reveal inner rope yarns, close up of severe buckling

Figure 4.1.9: Sample 2, Strand unlaid, very mild buckling in outer layer rope yarns, 15 degrees and pitch 255mm.

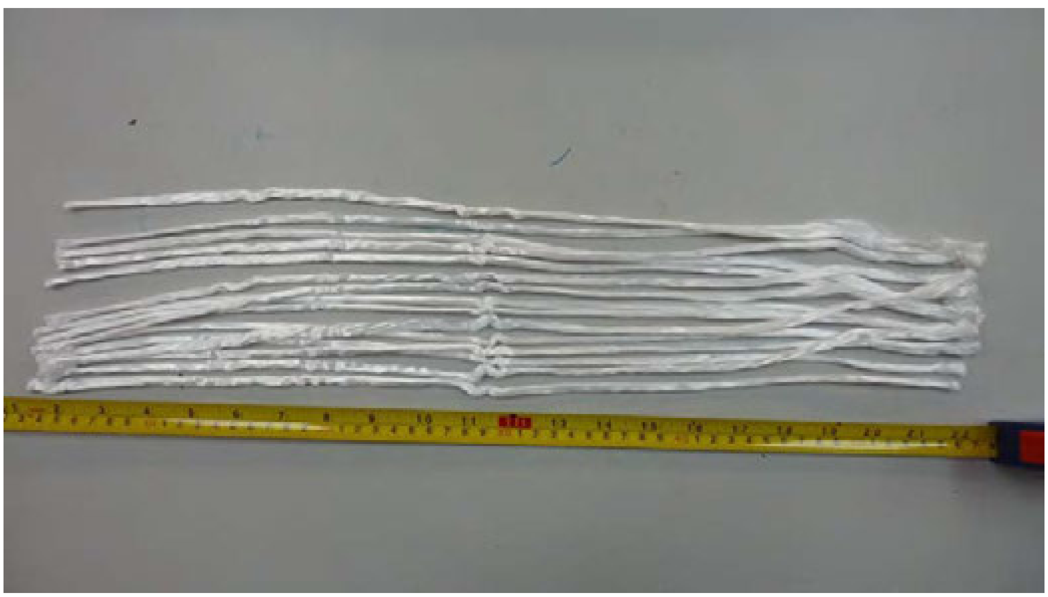


Figure 4.1.10: Sample 2, unlaid strand to reveal inner rope yarns, most severely buckled.

Figure 4.1.11: Sample 2, close up of severe buckling in figure 4.1.10

Figure 4.1.12: Sample 2, outer rope yarns, mild buckles shown in figure 4.1.9, note not all yarns buckled

Figure 4.1.13: Sample 3, 3 strand subrope, very minor buckling in outer layer

Figure 4.1.14: Sample 3, 3 strand subrope, close up of figure 4.1.13, very minor buckling in outer layer

Figure 4.1.15: Sample 3, strand unlayed, very minor buckling outer layer rope yarns (cannot really see from this side of strand, see figure 4.1.19).

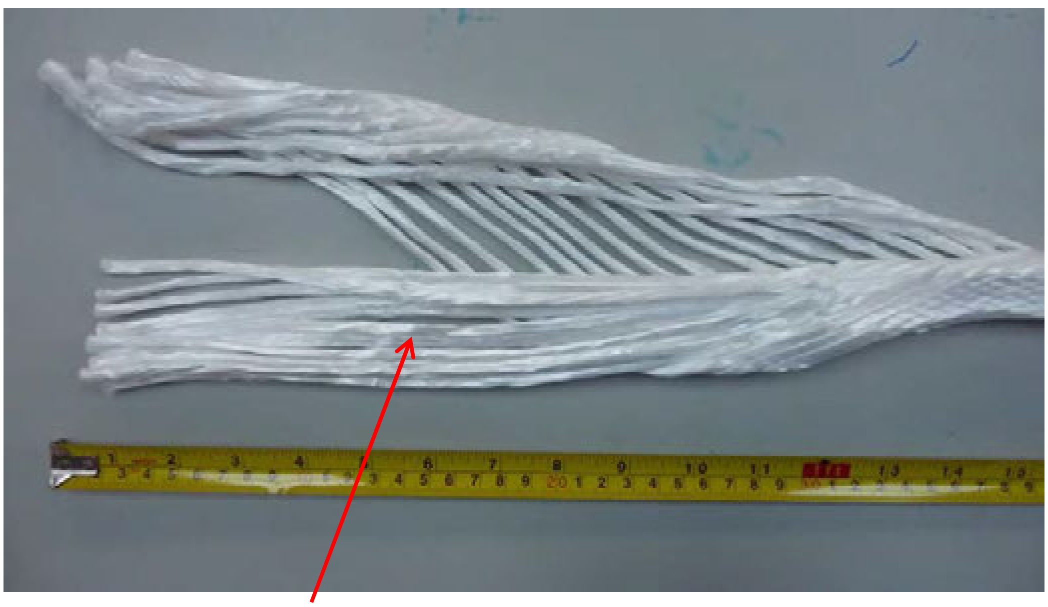


Figure 4.1.16: Sample 3, unlaid strand to reveal inner rope yarns with zero twist

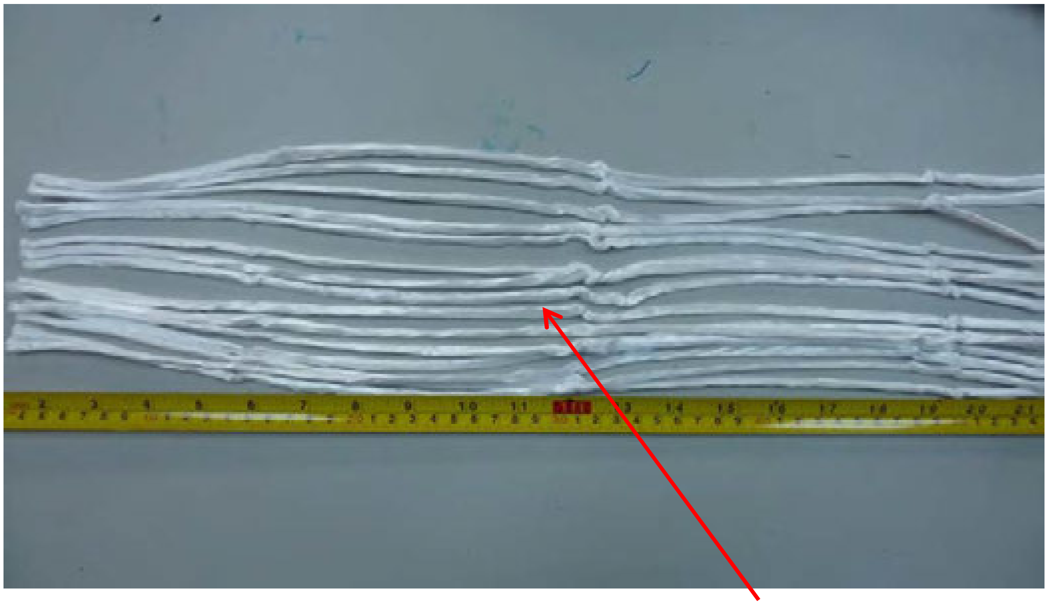


Figure 4.1.17: Sample 3, unlaid strand to reveal inner yarns, most rope yarns severely buckled.

Figure 4.1.18: Sample 3, close up of severe buckling in figure 4.1.17

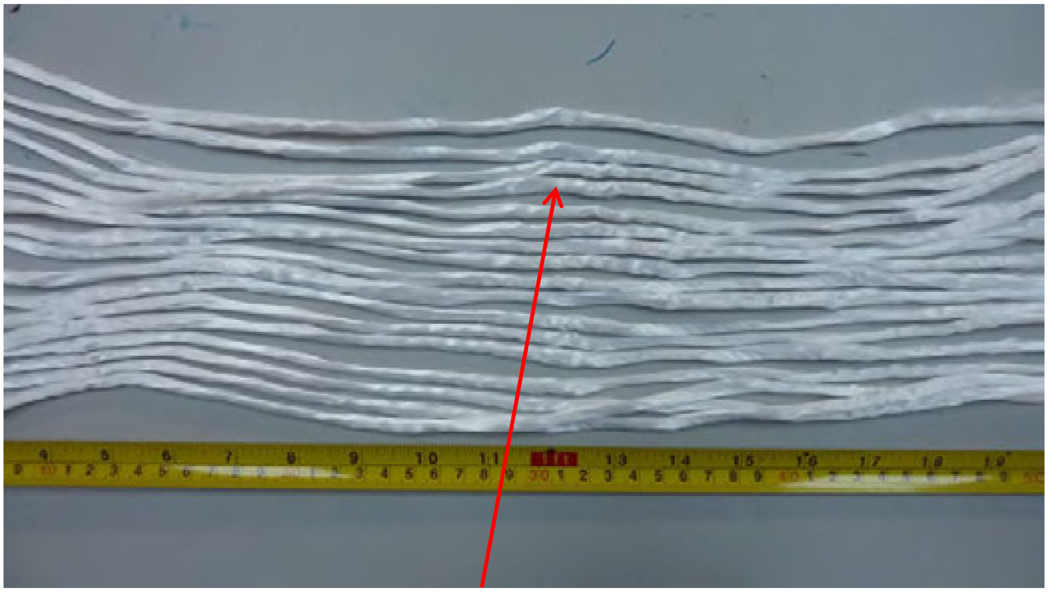


Figure 4.1.19: Sample 3, outer yarns, mild buckles shown in figure 4.1.15, note not all rope yarns buckled

4.2 Yarn Realisation Test

Following dissection of the three 0.5 metre sections, a further single section was removed to allow yarn realisation tests to be completed.

BS EN ISO 2307 [3], gives guidance on the realisation method that can be used to determine rope strength by breaking individual rope yarns and multiplying the average break result by the number of yarns in the rope. This is then multiplied by a realisation factor to give the full rope break strength. This is the standard method employed by Bridon International to test ropes and verify their break load.

The standard calls for a minimum of 15 yarns to be tested for 3 and 4 strand rope of which a minimum of 3 yarns should be taken from the core. However, in order to see if there was any major variance between the inner low twist and outer twisted yarns it was decided to test a complete strand. As noted before there are 32 yarns per strand, configured as 17 outer yarns and 15 inner yarns, giving a total count of 96 yarns per rope.

4.2.1 Yarn Tests

Tests were conducted on TTI's calibrated Instron machine, similar to that shown in Figure 4.2.1.1. Testing was conducted in general accordance with ISO 2307 [3]

Figure 4.2.1.1: Instron test machine

Tables 4.2.1.2 shows the results of the break tests of the yarns, with mean, standard deviation [SD] and coefficient of variation [CV].

	Yarn No.	Break Strength (N)		Break Strength (N)
Outer	1	13897.53	**Inner**	12251.37
	2	14122.00		15164.66
	3	15670.69		13738.37
	4	14430.01		15390.60
	5	12404.02		14460.74
	6	14410.98		14890.25
	7	13842.97		14462.76
	8	13401.31		14038.37
	9	14120.90		14378.43
	10	12961.86		11522.50
	11	14157.02		13883.67
	12	13637.91		14650.46
	13	14720.68		13532.53
	14	12629.73		12237.35
	15	14228.14		15112.06
	16	12477.49		
	17	14416.93		
	Mean	**13854.71**		**13980.94**
	Standard Deviation	**863.53**		**1162.24**
	Coefficent of Variation	**6.23%**		**8.31%**

Table 4.2.1.2: Yarn break test results

Note that while the mean breaking loads of both the outer and inner yarns are close with less than 1% variance, the standard deviation and coefficient of variation in the inner yarn is higher. This is likely to be a direct consequence of the buckling observed in the visual inspection [Section 4.1].

4.2.2 Calculated Rope Strength

Table 4.2.2.1 shows the calculation of residual rope strength for the rope based on Bridon's standard realisation factor of 0.998. This is the factor originally used on the 'Zarga' rope supply. However, as noted in TTI's original investigation report [1], it is believed that this factor is too optimistic and have therefore recalculated the strength using the suggested factor of 0.85. These results are shown in table 4.2.2.2.

Average Outer Yarn Strength	13,854.71	N
Average Inner Yarn Strength	13,980.94	N
Av. Outer Yarn Strength / % overall strength	53%	
Av. Inner Yarn Strength / % overall strength	47%	
Overall Av.	13,913.88	N
SD	999.50	
CV	7%	
Overall yarns / Rope	96	
Realisation Factor	0.998	
Overall Calculated MBL	1,333	kN
Design MBL	1,343	kN
Calculated Actual MBL as % Design MBL	99%	

Table 4.2.2.1: Rope realised break load using original realisation factor

Average Outer Yarn Strength	13,854.71	N
Average Inner Yarn Strength	13,980.94	N
Av. Outer Yarn Strength / % overall strength	53%	
Av. Inner Yarn Strength / % overall strength	47%	
Overall Av.	13,913.88	N
SD	999.50	
CV	7%	
Overall yarns / Rope	96	
Realisation Factor	0.85	
Overall Calculated MBL	1,135	kN
Design MBL	1,343	kN
Calculated Actual MBL as % Design MBL	85%	

Table 4.2.2.2: Rope realised break load using reduced realisation factor

The design minimum break load and these realisation calculations are for unspliced rope and therefore a 10% reduction would be applied to these results before comparing with the actual spliced strengths achieved.

4.3 Spliced Break Load Tests

In addition to the realisation tests, two sections of rope were spliced for full scale break testing. Due to the high anticipated break load, these were tested at Mennens, Dongen in the Netherlands.

Sample 1 had a length of 16.47 metres and included the original factory spliced eye. The other end was spliced with a 0.5 metre soft eye and the jacket was covered in plastic electrical tape for security. Sample 2 was shorter at 12 metres long and was spliced with a 0.5 metre soft eye at each end. Splicing was conducted by a retired Marlow/Bridon splicer who had experience with splicing this type of rope during his service and the rope was spliced in general accordance with Bridon International splicing instructions for Superline Steelite HMPE mooring lines with a 3-strand core [5].

The ropes were installed in the test bed and cycled 20 times to 60 tonnes to ensure that the splices had settled in and then on the 21st cycle the ropes were taken to break load. The ropes were attached to 150 tonne shackles with a pin diameter of 105mm providing a D/d ratio in excess of the manufacturer's minimum requirement of 2:1.

Figure 4.3.1: Rope sample 2 installed in test bed, looking towards active end.

Figure 4.3.2: Rope sample 2 installed in test bed. Looking towards dead end.

Sample 1 was installed with the factory spliced eye on the active end.

The break load results are shown in the Table 4.3.3. The design spliced break load is equivalent to 90% of the unspliced load in accordance with ISO 2307 [3]. (1,343kN x 0.9 = 1208.7kN)

Sample	Length	Max. Elongation	Break Load kN	% Design MBL
1	16.896m	298mm / 1.8%	995kN	82.3%
2	12.038m	221mm / 1.8%	1,036kN	85.7%

Table 4.3.3: Actual spliced break load results

Both samples failed on the active end of the test machine and both appeared to have failed within the splice area itself. Generally, this is considered as not being a good break as we would normally expect the rope to break at the base of the splice at the intersection between the undisturbed rope and the splice. Given this fact, it is likely that the actual full efficiency break load of the rope could have been maybe 5% higher but still below the quoted design MBL. These rope break values were in good agreement with the yarn realisation calculated rope break strength.

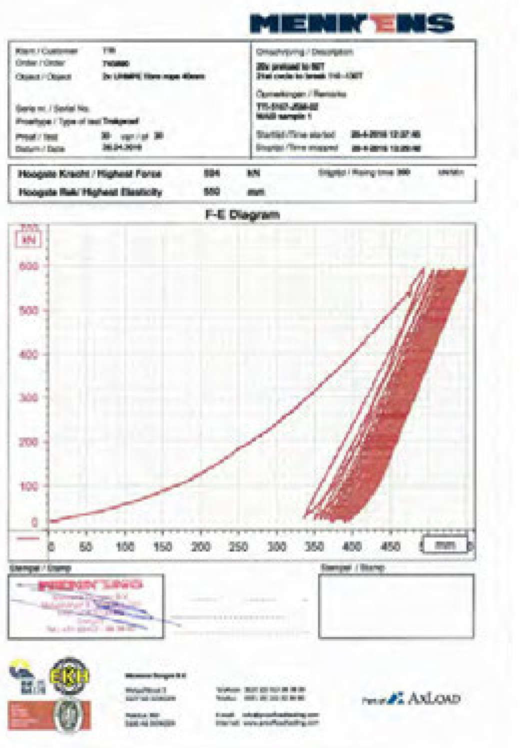


Figure 4.3.4 – Load extension curves for Sample 1 during cycling

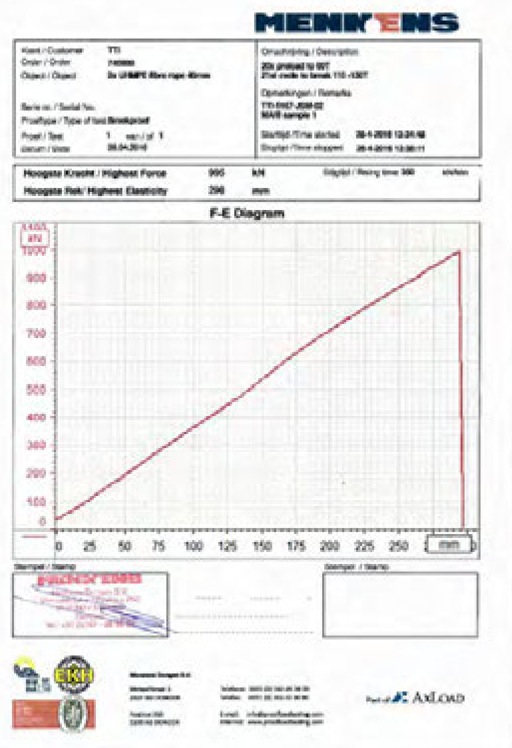


Figure 4.3.5 – Load extension curve for Sample 1 during final cycle to break

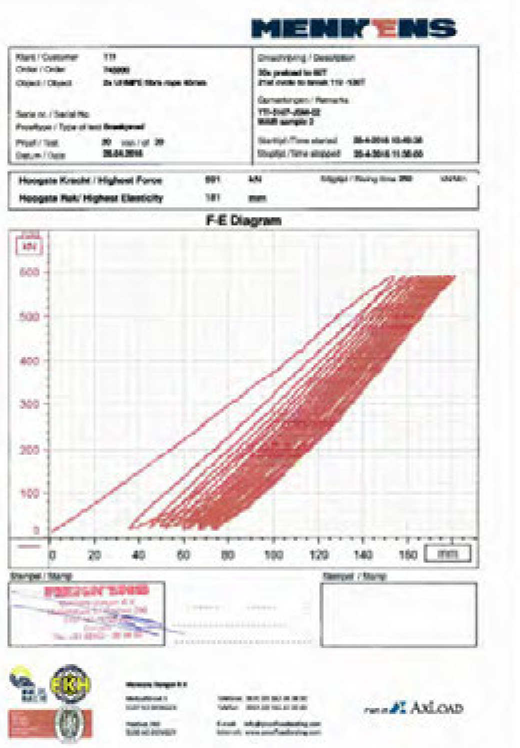


Figure 4.3.6 – Load extension curves for Sample 2 during cycling

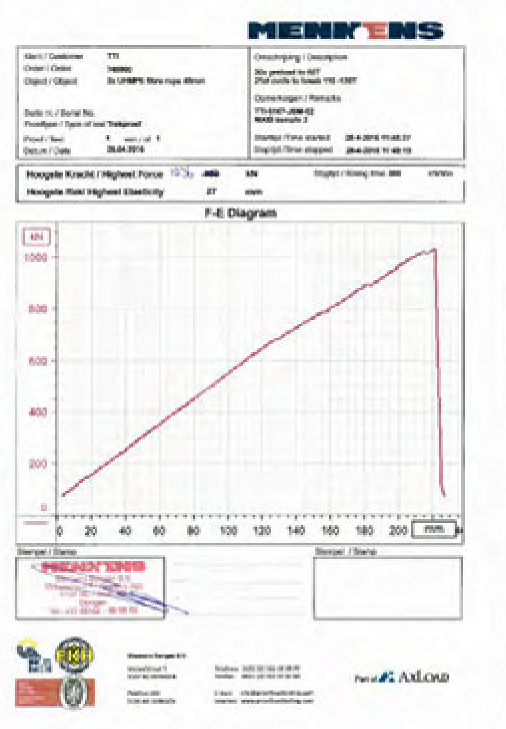


Figure 4.3.7 – Load extension curve for Sample 2 during final cycle to break

4.4 Scanning Electron Microscope [SEM] images and analysis

As noted in section 4.1. yarn buckling had been observed in the new manufactured sections of rope without any loads being applied to the rope and therefore must be induced during the manufacturing process. Images for induced buckles in the new rope are shown in figures 4.4.1 to 4.4.6, below.

In addition to establish if these buckles had any effect on the break points with the two new break test samples images are also provided for sections of yarn removed from one of the samples. These are shown in figures 4.4.7 to 4.4.10.

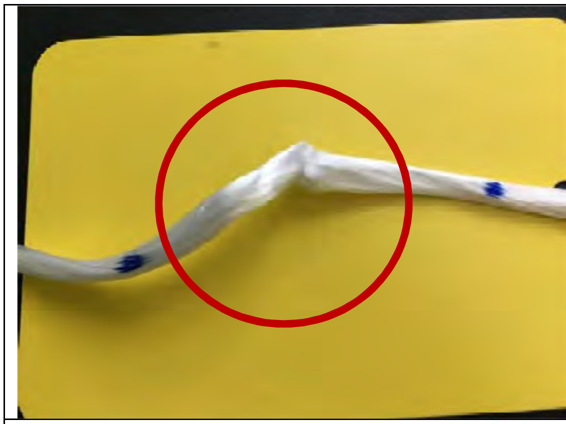


Figure 4.4.1 – New Inner yarn with buckle

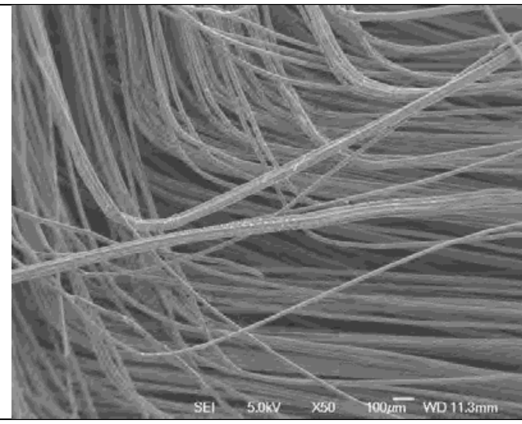


Figure 4.4.2 – Filament bends in kink

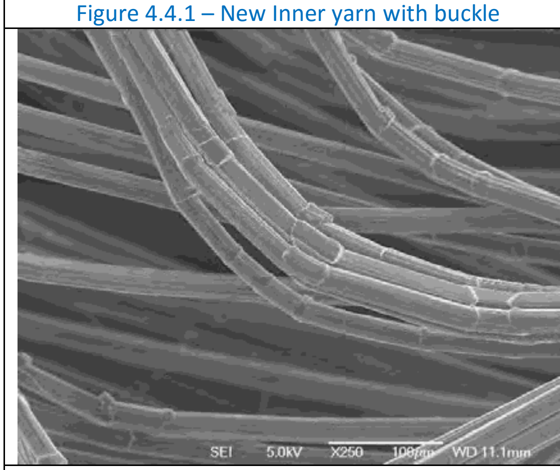


Figure 4.4.3 – Numerous kinks in bend

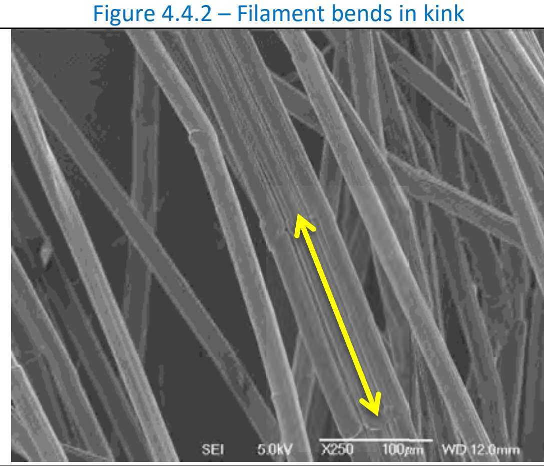


Figure 4.4.4 – Distance between kinks ~213um

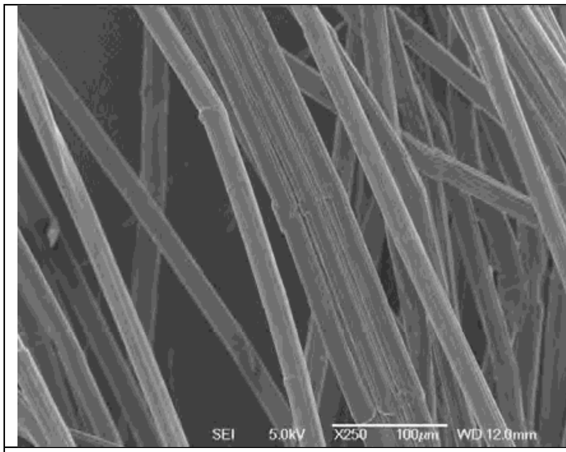


Figure 4.4.5 – Three filaments held together with no bend but kink forming

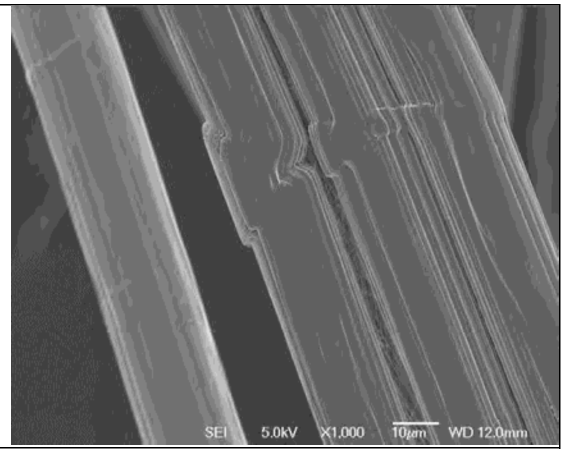


Figure 4.4.6 – Close up of kinks. No bend and is indicative of high radial pressure

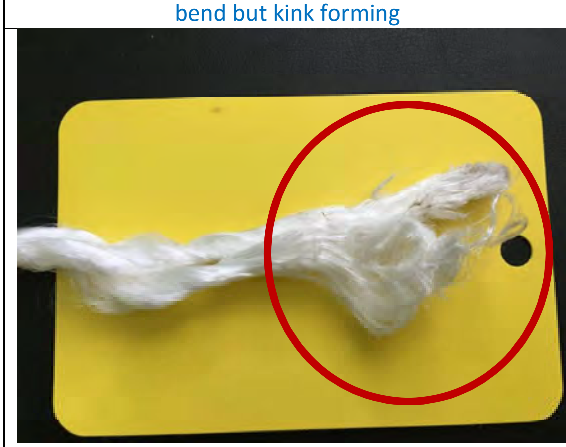


Figure 4.4.7 – Failed end from break test sample

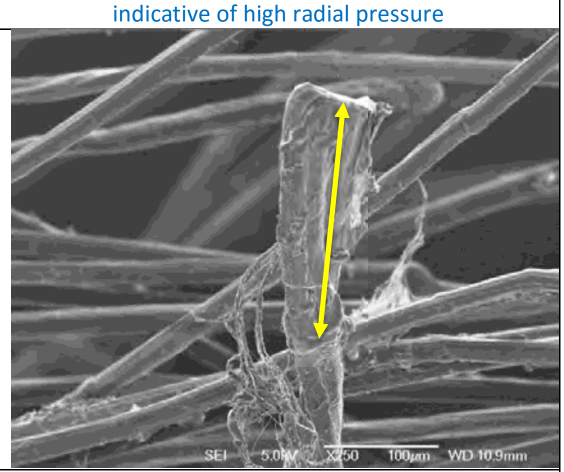


Figure 4.4.8 – Distance between kink and failed tip ~ 220µm

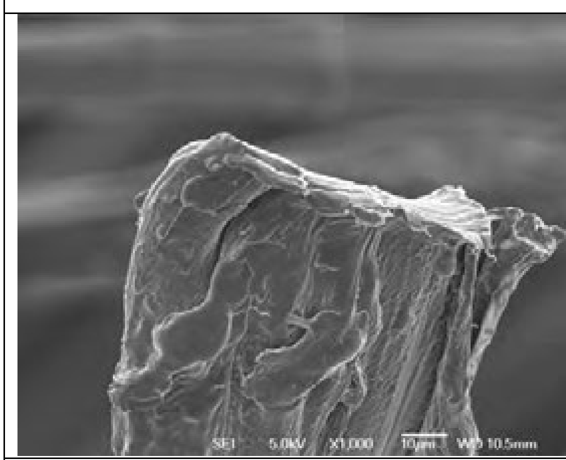


Figure 4.4.9 – Close up failed ends, typical of axial compression

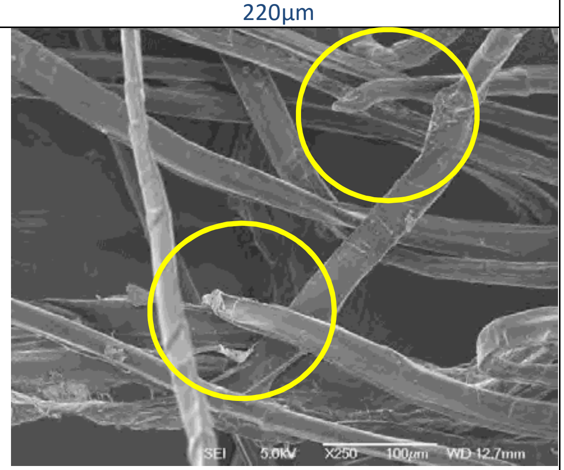


Figure 4.4.10 – Two failed filaments, possible axial compression

The images of the new yarn appear to indicate that there are no kinks away from the bend however in one area shown in images 4.4.5 to 4.4.6, there were three yarns held tightly together that have a clear kink with no bend, indicative of high radial axial pressure. Measurement of the distance between kinks was noted as being approximately 213µm.

Figures 4.4.8, and 4.4.9, taken from the break tests, show three or four filaments that have fused together and failed. The distance between the failure and the closest kink is approximately 220um which is consistent with the measurement between kinks taken from the new section of yarn, and is likely the result of high radial pressure.

Figures 4.4.10 shows two further failed filaments that are consistent with axial compression failure.

5 Discussion and Conclusions

5.1 Discussion

It was clear following the initial investigations into the Zarga incident that the rope parted due to strength loss caused by compression axial fatigue of the load bearing HMPE core. This was the first recorded failure of this type with HMPE ropes and while we have now identified other ropes that have failed in a similar manner, until the clear evidence from the Zarga incident was seen, this failure mechanism was treated as being solely an issue for Aramid ropes.

Indeed, a number of industry standards including the API RP 2SM [6] and ABS Guidance Notes for Fibre Moorings [7] both state that axial compression fatigue is not a concern for HMPE fibre ropes and that analysis and testing are not required.

Previous buckling testing carried out as part of the FIBRE TETHERS 2000 programme [2] indicated that while severe strength loss would occur after only 20,000 cycles in Aramid ropes, for HMPE this figure was 200,000 cycles, far in excess of what could have been seen in the Zarga ropes given their service life. Therefore, some other factors must have contributed to the failure.

Axial compression is most commonly identified in rope yarns and filaments by the presence of kinks or kinkbands that form in the yarns at angle of about 45°. While these can be found in most ropes to some degree they are most prevalent in ropes that have tight fitting jackets or that have been subject to other lateral pressures such as when the rope is used around a sheave or fairlead. The effect of this axial compression force is to cause the yarn and filaments to buckle and in the severest cases the repeated flexing of the fibres in these buckles will lead to failure either due to breakdown along the kinkbands or to axial splitting due to the accompanying stresses. The former breakdown along the kinkbands is what was identified in the Zarga rope.

The Bridon rope design comprises a braided Polyester/Supermix jacket over a single, long-lay 3-strand HMPE load bearing sub-core. The individual rope strands of the 3-strand core have a combination of a twisted outer yarns over very low twist [virtually zero] inner yarns.

Modelling the rope design using the FRM program, it was demonstrated that a combination of low-twist inner core yarns which were highly restrained by the jacket and outer yarns allowed damaging buckles to be developed at rope loads below 30% of design MBL.

Indeed, visual inspection of the new rope actually showed that kinks are most likely formed during the manufacturing process where loads would be in real terms very low but over-length core yarns, and inconsistent yarn and strand tensioning could cause uniform areas of loose fibre to be formed. The combination of the jacket then constrains the fibres which then concentrates the kinks at regular intervals through the rope length which is consistent with what was seen in our investigations.

The FRM model further demonstrated that at relatively low loads, bending the rope around small D/d ratios as in fairleads or rollers can cause compressive strains in excess of those needed to form kink bands. In the actual rope these may have been more severe than anticipated due to the fact that kinkbands were already present.

Break load testing of the new rope indicated that there was a higher variability in yarn strength for the inner yarns which was most likely caused by the preformed kinks.

Full rope break testing and yarn realisation calculated rope strength indicated that the actual break load of the rope is unlikely to meet the specified design break load. Even by taking the highest result of the two spliced break samples and allowing an additional 5% for the fact that the ropes failed within the splice gives a revised spliced break load of 1090.5kN compared to a design strength of 1208.7kN, so at best is achieving only 90% of the design strength.

Using this result, the actual rope realisation factor can now be calculated as being 0.907 against the original factor of 0.998 and our suggested factor of 0.85. Recalculating the original Zarga certificate using this revised factor gives an unspliced rope strength of 137.7 tonnes. Only just on the required design break load.

Given variances in yarn strengths [we have seen averages of 14,909N on the original Zarga supply to 13,913N during this investigation] manufacturers would normally decide on a factor that ensured ropes passed the minimum requirement with at least a 95% confidence level.

Using the results of the yarn tests conducted during this investigation the lower mean level for the yarn can be calculated at 13,567N. For the rope to have met the desired design break load of 137 tonnes, a total of 109.2 rope yarns would be required as opposed to the original 96. As this number does not split equally between the three strands in manufacturing it would be anticipated that an additional 15 yarns [5 yarns per strand] would be required, or conversely using the actual number of yarns that the break load of the rope is equivalent to 120.5 tonnes unspliced.

The extreme loads experienced by the Zarga rope in service particularly in its first 13 mooring operations prior to changing to longer 22 metre tails are likely to have accelerated the axial compression fatigue damage and given the lower actual break load achieved for new rope are likely to represent an even higher proportion than the 50 or 60% of MBL originally thought. This would fit with industry findings so far that axial compression failures are not that common when considering all the moorings such as gas, oil, ferries, cruise ships, bulk, container etc.

The inspection of a section of new rope indicated that kink bands were being formed in the rope inner strand yarns during the manufacturing process. This is most likely caused by variances in the rope yarns being drawn into the stranding machines during the closing procedure. SEM images taken from one of these yarn kink bands show that severe kinks are being induced into the yarn filaments during this process and that resultant filament failure during the rope break testing is in the proximity to these kinks.

Axial compression fatigue in HMPE fibres has not been seen as an issue in rope design and use prior to this rope failure. As an industry rope design has focused on strength efficiency, abrasion and cycle bend resistance. The mooring rope market in particular has focused on strength and manufacturers have reacted to this by designing ropes that have high strength but with minimal material content in an effort to increase their competitive position through a reduction in material and manufacturing costs.

The easiest option for manufacturers is to increase the rope lay length or post draw the yarn both of which will reduce the overall yarn content. However, increasing the yarn/strand lay length and therefore reducing material content for a given design break load can effectively reduce the ropes robustness in certain applications. Rope design is all about reaching a compromise between yarn twist levels, strength and robustness to factors such as abrasion. The relationship between yarn strength and twist is shown in Figure 5.1.1.

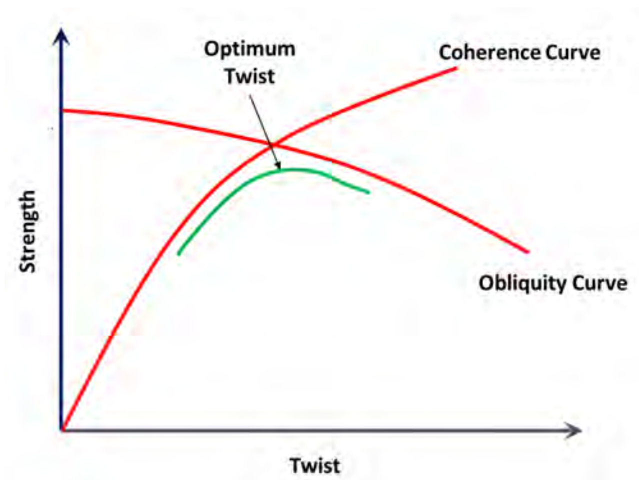


Figure 5.1.1: Relationship between yarn twist and strength

Yarn strength actually increases initially with twist however at the lower twist levels the yarn's resistance to abrasion and other factors such as axial compression fatigue is reduced. Increasing twist up to and beyond the optimum twist sees a reduction in yarn strength but conversely its resistance to abrasion and other factors again such as axial compression also increases.

It is not uncommon for rope manufacturers to reduce yarn twist levels and increase rope lay lengths in jacketed ropes and it is widely accepted in most designs that the jacket forms an abrasive resistant jacket that protects the inner load bearing core.

The results of the FRM modelling and the investigations clearly indicate that the Bridon rope design has been optimised for strength and that due to the low twist level in the inner yarns is has little to no resistance to the effects of axial compression fatigue. However, it should also be noted that this is not limited to the Bridon, jacketed 3-strand long lay core design. Similar kinkbands have also been identified in other jacketed HMPE ropes constructions including 12-strand sub-core ropes with long lay strands and low twist yarn levels.

The limited resistance of Aramid fibres to axial compression fatigue is well documented and as such manufacturers take due diligence in improved rope designs, splices and marine finishes. Apart from temperature and creep resistance, HMPE has generally been seen as a much more resilient and workable material and as such manufacturers may have been somewhat complacent in rope design. However, previous misconceptions that axial compression fatigue was not an issue in HMPE are not totally unfounded. Most of the previous investigation and study programmes have focused on the materials being used as mooring lines for deep water mooring platforms. Here the ropes are produced in relatively long lengths that sit between the anchor on the sea bed and the rig or vessel as shown albeit in polyester in figure 5.1.2

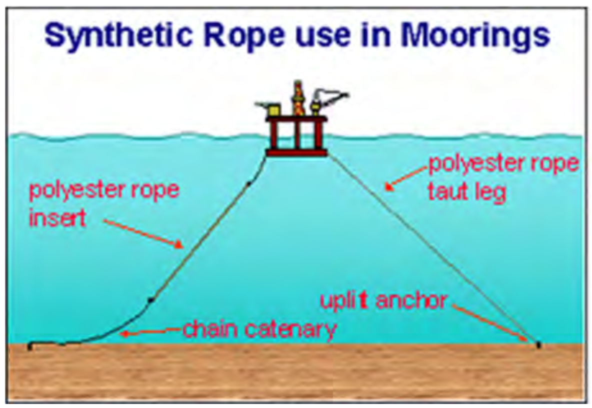


Figure 5.1.2: Synthetic taut leg deep water mooring

Apart from during deployment or recovery and even then at very low loads these ropes never come into contact with fairleads or other external objects that would cause the high compressive stresses to be formed and as such axial compression fatigue may never be an issue. However, given the results of the buckling tests conducted here it is something that now needs to be considered.

In the FIBRES TETHERS 2000 test programme [2] conducted in the mid-90's on SK60 yarn it was concluded that severe strength loss would only occur after 200,000 cycles. Limited tests conducted in 1998, on SK75 verified that data, however, the most recent tests would appear to indicate a more severe strength reduction. This may be as a result of material developments in HMPE over the years that has seen the industry strive to lower creep rates while maintaining or increasing tenacity. These developments may have altered the crystalline structure of the yarn so that it is closer to that of the Aramid spectrum. Given the choice of other fibres particularly from DSM Dyneema in SK75, SK78 and DM20 more work needs to be carried out in understanding their resistance to axial compression fatigue.

5.2 Conclusions

- Due to a combination of long lay rope strands, low-twist inner yarns and tightly braided outer jacket, the rope has little to no resistance to the forming of kinkbands in the inner load bearing yarns.
- The inner low twist yarns suffered severe kinking leading to yarn failure in the Zarga incident while the outer higher twist yarns had only moderate damage. This has also been observed in other ropes.
- High loads [50-60% of MBL] were induced in the rope prior to replacing the 11m tails with 22m tails during the first 13 mooring operations.
- A combination of very high loads, low twist rope construction and compressive axial stresses caused by low D/d ratios on the fairleads and rollers caused severe kinkbands to be formed significantly reducing rope strength and leading to ultimate failure.
- The stated rope design strength is overstated when compared with the actual strengths achieved and should be re-evaluated.

5.3 Recommendations

- Ropes to be used in this application need to designed more robustly and candidate rope constructions and indeed load bearing materials need to be subject to a rigorous test programme and manufacturers should be able to demonstrate this to vessel operators and ports.
- A minimum lay/twist angle should be applied at all levels of rope construction. Tests would need to carried out to verify this twist level but a minimum of 15 degrees would seem to give good strength translation and provide compliance in compression.
- Further investigative work should be carried out to understand the buckling resistance of the newer grades of HMPE available.
- Adopt the yarn buckling test method which is a good test to filter out changes in material performance over time, within the next revision of the OCIMF 'Mooring Equipment Guidelines'
- The use of 22 metre as a minimum and were possible 33 metre nylon tails should be advocated by vessel operators and ports as this has been shown to dramatically reduce damaging peak loads while additional vessel excursions are kept to a minimum.
- While axial compression fatigue has not been an issue for HMPE ropes used to date in Offshore Mooring Applications, and the major classification societies and other industry standards dismiss axial compression fatigue in HMPE, some guidance should be issued to warn potential users of the associated risks, albeit low, following the findings of these investigations.

6 References

[1] Inspection and Test Report on Failed UHMPE LNG Mooring Line, TTI-JSM-2015-5147 dated 3rd September 2015.

[2] Fibre Tethers 2000 phase 1 report, Noble Denton Europe Ltd, National Engineering Laboratory and Tension Technology International Ltd, 10th February 1995

[3] BS EN ISO 2307:2010, Fibre Ropes – Determination of certain physical and mechanical properties, International Standards Organization, Geneva, 2010

[4] Fibre rope certificate document BC112014 dated 29th August 2008.PA, 2004

[5] Superline Steelite 3 Eye Splice Method, AS Issue 4, Bridon International Limited, 2006

[6] API Recommended Practice 2SM, Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring – 2nd Edition – July 2014

[7] ABS Guidance Notes on The Application of Fiber Rope for Offshore Mooring – August 2011 (updated February 2014)

[8] Hearle, J.W.S., Hobbs, R.E., Overington, M.S. and Banfield, S.J., "Modelling axial compression fatigue in fibre ropes" Proceedings of Fifth International Offshore and Polar Engineering Conference Chung, J.S. *et al.* (eds) (ISOPE, Golden, Colorado) 1995 Vol 2, 273-277. (Proc ISOPE-95).

Appendix 1 TTI_SJB_2015_1679/1-R

Report on Yarn Compression Modelling

TTI Testing Ltd

Unit 2, Beadle Trading Estate, Hithercroft Road, Wallingford, Oxfordshire, OX10 9DG, UK

www.tti-testing.com

Yarn compression modelling

Reference number TTI-SJB-2015-1679/1-R

Date	Rev.	Description	Prepared by	Authorised by
05/02/16	0	Draft for client review	[redacted]	[redacted]
27/05/16	1	Final Version	[redacted]	[redacted]

Distribution:

TTI Testing Ltd (author, file)

MAIB

Shell

Attention:

[redacted]

Contents

1 Introduction

As part of a larger programme of work on the Zarga rope failure, TTI Ltd has been asked to carry out numerical studies of the possible causes of yarn buckling in the rope. This work includes identification of possible causes of compression in the inner yarns, and some modelling of possible buckling modes that may occur in response to such compressive forces.

The driver for this study was the identification of compressive kink band buckling failures in samples of the Zarga rope. At first sight, it is difficult to imagine how axial compression may be generated in a rope whose essential purpose is to carry large tension forces. However, it is recognised that compression parallel to the length of the rope may be generated within components (yarns) of a rope which is carrying an overall tension. Causes of such compression may include a combination of twist with the principal tension, bending over too sharp a radius while under modest axial tension, and possibly cyclic loading effects where internal friction (enhanced as it may be by the radial pressures exerted on the core of the rope by a protective jacket) prevents a component carrying its share of the overall tension after a number of loading cycles. The consequences of such axial compression vary from the trivial if a yarn can shed compression by taking up a gentle curve, to the serious if the yarn is constrained by high radial pressures and can only shed load by forming sharp buckles which induce “plastic hinges” or kink bands. Forensic examination of the Zarga rope has revealed a large number of such kink bands in inner layers of the rope, some of which have failed completely.

2 Causes of compression

This section considers bending over a fairlead and the effects of twist combined with axial load.

Bending over a fairlead can cause compression inside the curve. It is easy to put an upper limit on the compressive strain inside the curve. If the fairlead has a radius R, and the distance from the neutral axis of the rope to the fibre in question is y, then the potential strain is simply given by

$$\epsilon = y/R \ldots (1)$$

As y can equal plus or minus the rope radius r, and the ratio of R/r (or equivalently D/d where D is the fairlead diameter and d the rope diameter) is known the maximum strain at any level in the rope can be assessed. Here D/d is rather modest, at about 9, generating potential strain maxima of +/- 1/9 or +/-11%. In practice, of course, these very large values are moderated by co-existing axial tension in the rope, and to a much greater extent by the helical lay of components in the rope. The effect of the helix is that a given yarn in the rope passes from a compression zone inside the curve to a tensile one outside the curve half a lay length later, and if the yarn can slip within the rope the strains even out to a value very much smaller than the potential maximum.

Two factors will interfere with this helpful slipping process: radial pressure and a large lay length. Radial pressures from the fairlead, or from an overtight rope jacket, plus (in layers deeper within the rope) pressure from the outer layers, will generate large friction forces that tend to resist slip and maintain local high strain values in a yarn. Further, the larger the lay length, the greater the slip distance needed to “average out” the strain. Unfortunately, both of these factors (a tight jacket, and a long lay) are present in the Zarga rope.

Comparing the potential value of 11% strain with the known compressive strain limit for a similar HMPE fibre to that used in the rope, of 0.08% (Appendix C), bending over a fairlead could well cause compressive failure by kink banding in parts of the rope.

Turning to the effects of combined twist and axial load, TTI has developed proprietary analytic software (FRM) over a long period, and this has been run for the Zarga rope construction (Appendix A presents detailed results). A summary of the results, Table 1, for some inner yarns demonstrates that modest levels of twist combined with axial loading can generate compressive strains well above the 0.08% limit for the rope fibre. Those strains will be relieved by yarn buckling and kind band formation. On the other hand no compressive strains were found in outer layers, and it is noted that kink banding was only found in inner layers of the rope on examination of the failed rope. Figure 2.1 shows a strand removed from the Zarga rope where the outer layer yarns clearly have some twist with a pitch around 260mm. There was no significant buckling in this outer layer. In contrast the inner two layers had zero net twist as shown in Figures 2.2 and 2.3. (The net twist in the yarn is practically zero because the effects of the original yarn lay can be counteracted by a modest overall twist of the complete rope or maybe due to the original rope design.) A straight yarn has no compliance to absorb axial compressive strains, while an inner yarn is subject to large radial pressures from the jacket and outer yarns. The combination of straightness and high radial pressures ensures any buckling occurs with a short wavelength and a strong tendency to kink band formation

% MBL	kN	% Rope strain	Rope Twist TPM	% Yarn strain
Outer yarn				
18%	275	0	1.5	-0.9287
23%	356	0.35	1.5	-0.5856
28%	431	0.7	1.5	-0.2425
18%	275	0	1	-0.743
23%	356	0.35	1	-0.4006
28%	431	0.7	1	-0.0582
18%	275	0	0.5	-0.4335
23%	356	0.35	0.5	-0.0922
Inner yarn				
18%	275	0	1.5	-0.8425
23%	356	0.35	1.5	-0.497
28%	431	0.7	1.5	-0.1515
18%	275	0	1	-0.6855
23%	356	0.35	1	-0.3406
18%	275	0	0.5	-0.4048
23%	356	0.35	0.5	-0.0609

Table 1: Yarn strains for given rope twist levels

Figure 2.1 Strand removed from subrope to measure pitch

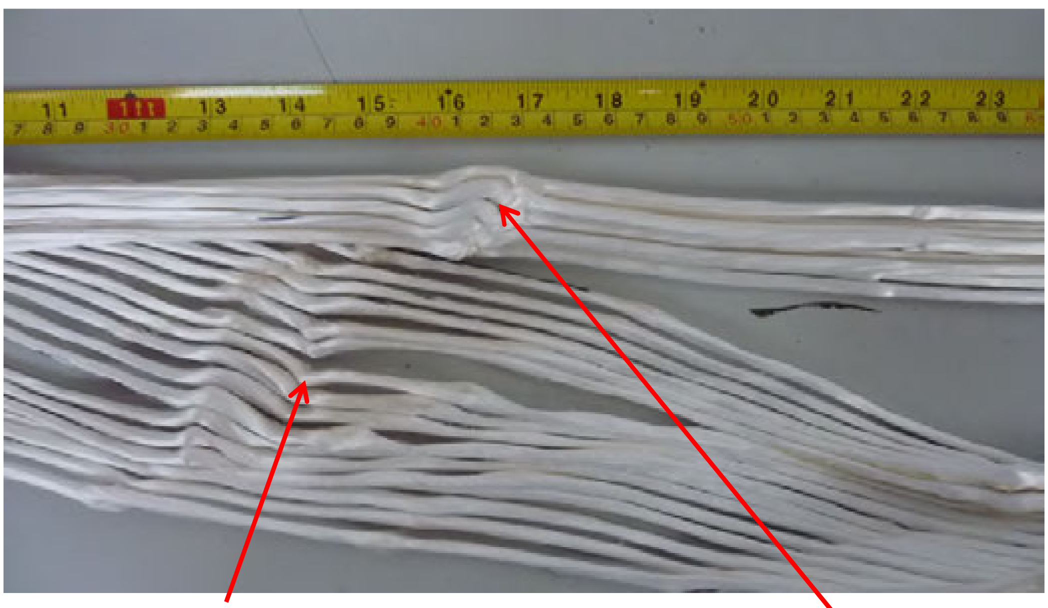


Figure 2.2 Outer layer peeled away, axial compression minor buckles, but inner layer yarns severe compression

Figure 2.3. Close-up of an inner yarn buckle (Mode 4, see below) with a characteristic length of about 10mm

3 Yarn buckling analysis

TTI has developed software to model yarn buckling in the presence of radial restraint and axial load (Appendix B). It can model a number of modes of elastic buckling (Figure 3.1), modes which are regarded as precursors to plastic buckling (Figure 3.2) with the same characteristic length and kink band formation. In general, modes 3 and 4 occur at lower loads than the other modes. Plastic buckling itself has been treated in an approximate way.

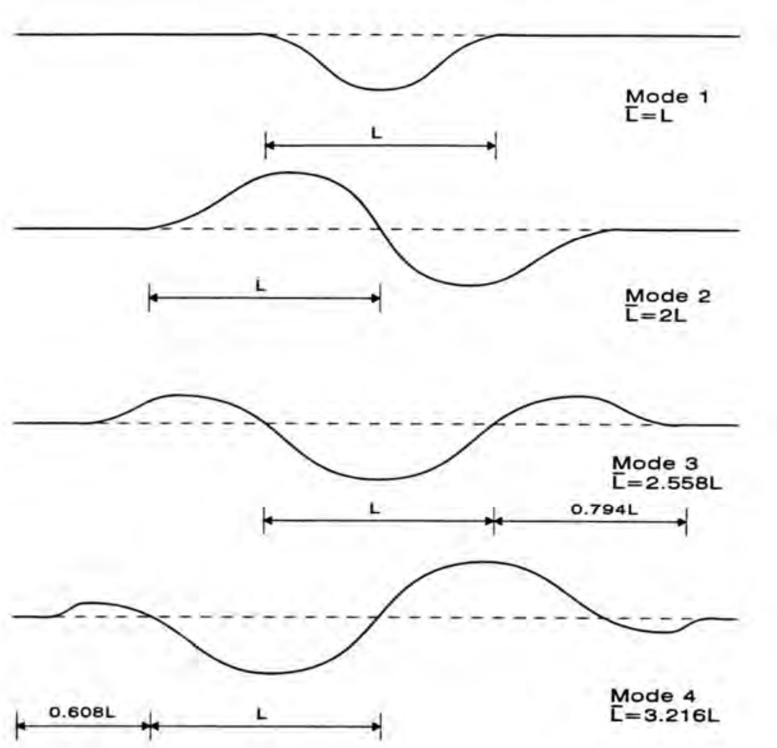


Figure 3.1 Elastic buckling modes

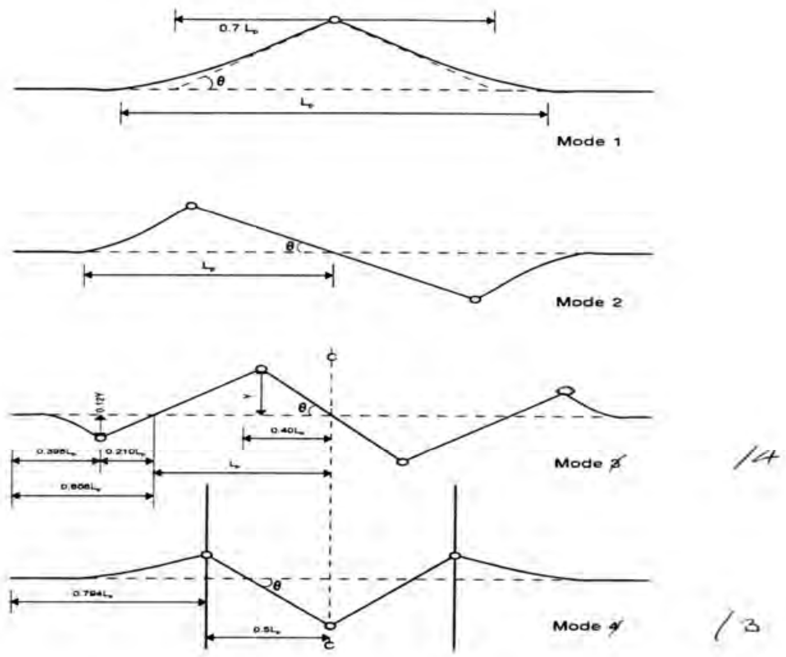


Figure 3.2 Plastic (kinkband) buckling modes (kinks shown as circles)

A key variable is the radial restraint provided by the jacket and outer yarns, and it has been necessary to consider a range of values for this parameter (three examples are included in Appendix B) For a typical inner yarn radial restraint of 50MPa (at around 85% rope MBL as detailed in table 3.1) the minimum elastic buckling load is about 4000N, while at 10MPa (around 10% MBL) the minimum falls to 1400N. At 2.5MPa restraint, the minimum is 566N, rather close to the failure load of a yarn calculated by the failure strain of 0.08% times the EA value for the yarn.

More importantly, the characteristic buckle lengths (ranging from 12mm at 10MPa to 6mm at 80MPa) bracket the 10mm seen in Figure 2.3. This fact suggests that displacements that could be precursors to elastic buckling rapidly turn into the substantial plastic (kinkband) buckles with the wavelength seen in the dissected rope.

Rope strain %	Rope load kN	Ropeyarn load % MBL	Radial pressure N/mm^2
0.35	242.5	15.7%	12.8
0.7	435.1	28.2%	19.7
1.05	613.2	39.7%	26
1.4	777	50.4%	31.8
1.75	927.3	60.1%	37.1
2.1	1065	69.0%	41.9
2.45	1190	77.1%	46.2
2.8	1306	84.6%	50
3.15	1412	91.5%	53.7
3.5	1511	97.9%	56.9

Table 3.1. Calculated yarn radial pressures

4 Conclusions

Rope bending over a relatively small fairlead (D/d = 9) may have induced yarn compression and subsequent kink band formation.

Use of the FRM program has demonstrated that compressive strains significantly greater than those needed to initiate kink band formation can be caused in some inner yarns by a combination of axial load and twist.

The yarn buckling program identified elastic buckling loads rather above those needed to initiate kink band formation for a range of radial restraint values. However, for a radial restraint of 2.5MPa, the minimum buckle force in a mode with three half waves was, at 566N, rather close to the force of 603N calculated from a failure strain of 0.08% times the EA value of a yarn. More to the point, the calculated critical elastic wavelengths bracketed the 10mm seen in the dissected rope. It appears that damaging buckles may have developed at loads below 30% MBL, a relatively common daily operating load, because of the zero net twist in the highly restrained inner layers. By the extreme loads of 50 or 60% MBL that the rope has also experienced, those buckles are likely to have fractured as the overall strain on the rope was applied to a pre-buckled region.

Guide to Purchasing High Modulus Synthetic Fibre Mooring Lines

SIGTTO

OCIMF

Oil Companies International Marine Forum

Guide to Purchasing High Modulus Synthetic Fibre Mooring Lines

First edition February 2014

The purpose of the Society of International Gas Tanker and Terminal Operators is to promote shipping and terminal operations for liquefied gases which are safe, environmentally responsible and reliable.

The OCIMF mission is to be the foremost authority on the safe and environmentally responsible operation of oil tankers, terminals and offshore support vessels, promoting continuous improvement in standards of design and operation.

Issued by the
Oil Companies International Marine Forum
29 Queen Anne's Gate
London
SW1H 9BU
United Kingdom

The Society of International Gas Tanker and Terminal Operators
17 St Helen's Place
London
EC3A 6DG
United Kingdom

First published 2014

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

The Oil Companies International Marine Forum (OCIMF)
is a voluntary association of oil companies having an interest in the shipment and terminalling of crude oil and oil products. OCIMF is organised to represent its membership before, and to consult with, the International Maritime Organization and other governmental bodies on matters relating to the shipment and terminalling of crude oil and oil products, including marine pollution and safety.

Society of International Gas Tanker and Terminal Operators (SIGTTO)
is a non-profit making organisation dedicated to protect and promote the mutual interests of its members in matters related to the safe and reliable operation of gas tankers and terminals within a sound environment. The Society was founded in 1979 and was granted consultative status at IMO in November 1983.

Terms of Use

Contents

Glossary

Within this guide, the terms below have the following meanings:

Abrasion resistance	The ability of a fibre or rope to withstand wear and rupture due to motion against other fibres or rope components (internal abrasion) or a contact surface which can be a portion of the rope itself (external abrasion).
Aramid fibre (also para-aramid)	A manufactured high-modulus fibre made from a long-chain synthetic aromatic polyamide in which at least 85% of the amide linkages join two aromatic rings.
Axial compression fatigue	The tendency of a fibre to fail when it is subjected to cyclic loading which exerts compression along its axis.
Braided rope	Rope formed by braiding (intertwining) or plaiting the strands together as opposed to twisting them.
Breaking strength	For cordage, the nominal force (or load) that would be expected to break or rupture a single specimen in a tensile test conducted under a specified procedure. On a group of like specimens it may be expressed as an average or as a minimum based on statistical analysis.
Creep	A time-dependant increase in length while under a continuing load which is non-recoverable following the removal of the load.
Creep rupture	Creep rupture is failure of a material due to a sustained load that it less than the break strength of the material.
Critical temperature	The temperature at which the properties of a fibre begin to deteriorate.
Cyclic loading	Repeated loading of a rope or other structure in service or on a test machine.
Design factor	A factor that is used to calculate the recommended working load by dividing the minimum breaking strength of the rope by the design factor. The design factor should be selected only after a professional assessment of risk.
Density	The mass per unit volume. See Linear Density.
Diameter nominal	Approximate diameter of cordage used for naming or reference purposes.
Dynamic load	Any rapidly applied force that increases the load on a rope significantly above the normal static load.
Elastic elongation	The temporary change in length of a fibre or yarn under tension which is reversed when the tension is removed.
Elasticity	The elastic (non-permanent) elongation of a unit length of an element caused by a unit load. May refer to a material or a composite structure such as a mooring line.
Elongation	The ratio of the extension of a rope, under an applied load, to the length of the rope prior to the application of the load expressed as a percentage.
End-for-end	The process of rotating a rope or wire on its stowage drum so that the working section is changed. This involves removing the rope or wire from the drum and re-stowing it with the previous outboard end next to the drum.
Extension	The deformation (change in length) of a rope when a load is applied.
Fibre	A long, fine, very flexible structure that may be woven, braided, stranded or twisted into a variety of fabrics, twine, cordage or rope.
Filament, continuous	Manufactured fibres of an indefinite length, which may be converted into filament yarn, staple or tow.

High Modulus Polyethylene (HMPE)	A polyethylene fibre produced by gel spinning of an Ultra High Molecular Weight PolyEthylene (UHMWPE) feedstock. Also called extended chain PE (ECPE) or high performance PE (HPPE).
High Modulus Synthetic Fibre (HMSF)	The generic term given to a range of fibre materials that include Aramid, LCP and HMPE fibres.
Inspection, Tactile	Manipulation of the rope by hand or other means to determine hardness and flexibility.
Inspection, visual	Examination of the exterior or interior of a rope by visual methods, which may include magnification.
Laid ropes	Ropes made by twisting of three or more strands together with the twist direction opposite that of the strands.
Lay length	Length along a rope for a complete revolution of a single strand in laid, twisted or plaited rope or cordage.
Linear density	The mass per unit length of a fibre, yarn or rope.
Liquid Crystal Polymer (LCP)	A class of aromatic polyester polymers.
Minimum Breaking Load (MBL)	The minimum breaking load of a new dry mooring line as declared by the manufacturer. For the purposes of this document, the MBL refers to that of a spliced rope.
Plaited Rope	A rope structure consisting of two pairs of strands twisted to the right and two pairs of strands to the left and braided together such that pairs of strands of opposite twist alternately overlay one-on-another.
Pre-tension	Additional load applied to a mooring line by a powered winch over and above that required to remove sag from the main run of the line.
Size number	A nominal designation of rope size, determined from the approximate circumference measured in inches, calculated as three times the approximate rope diameter.
Splice	The joining of two ends of yarn, strand or cordage by intertwining or inserting these ends into the body of the product.
Strand	The largest individual element used in the final rope-making process and obtained by joining and twisting or braiding together several yarns or groups of yarns.
Stranding	The process of combining a number of roping yarns by twisting to form a strand.
Tail (pennant)	A short length of synthetic rope attached to the end of a mooring line to provide increased elasticity and also ease of handling.
Tension-tension fatigue	Fatigue caused by cyclic axial loading at given mean load, load amplitude and frequency.
Twist	A rotation induced in the rope during service.
Twisting	The process of making rope in which two or more strength members (yarns or strands) are rotated together around a central axis.
Wire-lay rope	Rope made by stranding three or more strength members together in a helical pattern. Also called stranded rope.
Yarn	A generic term for a continuous strand of textile fibres, filaments or material in a form suitable for intertwining to form a textile structure via any one of a number of textile processes.

Yarn-on-yarn abrasion	Wear that occurs when two or more yarns move against each other.

Abbreviations

ECPE	Extended chain PolyEthylene
EUROCORD	European Federation of Rope, Twine and Netting Industries
HMSF	High Modulus Synthetic Fibre
HPPE	High performance PolyEthylene
ISO	International Organization for Standardization
LCP	Liquid Crystal Polymer
MBL	Minimum Breaking Load
OCIMF	Oil Companies International Marine Forum
SIGTTO	Society of International Gas Tanker and Terminal Operators
UHMWPE	Ultra High Molecular Weight PolyEthylene

Bibliography

The following publications and documents are referenced within the text:

Reference 1	Mooring Equipment Guidelines (3rd Edition) (OCIMF)
Reference 2	ISO 2307 (2010) – Fibre ropes – Determination of certain physical and mechanical properties.
Reference 3	CI 1500 (Current version) – Test Methods for Fiber Rope
Reference 4	ISO 9001 (2008) – Quality Management Systems

In addition to the above referenced documents, the following publications are useful sources of additional information:

ISO 1968	Fibre Ropes and Cordage - Vocabulary
ISO 9554	Fibre Ropes – General Specifications
ISO 10325	Fibre Ropes – High Modulus Polyethylene
CI 1202	Terminology for Fiber Rope
CI 1903	Aramid Fiber Rope
CI 1904	HMPE Fiber Rope
CI 1907	HMPE Fiber Rope – Extra High Strength
CI 2001	Fiber Rope Inspection and Retirement Criteria
CI 2003	Fibers for Cable, Cordage, Rope and Twine

Introduction

The purpose of this document is to provide guidance to those involved in the procurement of High Modulus Synthetic Fibre (HMSF) mooring lines. HMSF lines include those manufactured from Aramid, Liquid Crystal Polymer (LCP) and High Modulus Polyethylene (HMPE) fibres.

The guidance is provided with the aim of increasing the understanding of the particular properties of the HMSF mooring lines and to encourage the adoption of improved specifications and quality assurance processes. It should be noted that international standards exist for the construction of HMPE but the standards for Aramid and LCP fibres are very limited. The guidance contained in this document should assist when considering procurement options.

HMSF mooring lines may be considered as an alternative to traditional steel wire ropes owing to their higher strength to weight properties and advantages associated with their relative ease of handling. Over the years, the marine industry has gained considerable experience using moorings constructed from HMPE, but the use of Aramid and LCP fibres for large ship moorings has not been extensive.

With regard to HMPE mooring lines, after many years of relatively incident-free use, the industry has experienced a number of failures recently, particularly on large liquefied gas carriers. Although analysis of the failures has not identified any specific cause, a number of contributory factors have been highlighted as being of potential importance including rope design, manufacturing quality, ambiguity in the specification of minimum breaking load (MBL), impact and frequency of dynamic loads, consideration of creep and high ambient temperatures.

As a result, the lack of a clear detailed industry specification for use in the procurement of HMPE mooring lines was considered significant. It was found that purchasers often specified an MBL based, for example, on a shipyard specification, but did not appreciate how to define this number and did not always specify other requirements such as line construction, minimum HMPE content, grade of HMPE and requirements for testing the finished product.

This Guide contains recommendations relating to the scope of procurement specifications and provides brief information on the relevance of the various specified requirements to the mooring line's in-service performance. The guidance has been developed by a working group comprised of representatives from OCIMF and SIGTTO member companies. In addition, rope manufacturers and suppliers, represented by the industry associations Cordage Institute and the European Federation of Rope, Twine and Netting Industries (EUROCORD), have provided valuable technical contributions.

1 Properties of High Modulus Synthetic Fibre mooring lines

1.1 General

When considering the procurement of High Modulus Synthetic Fibre (HMSF) mooring lines, it is useful for the purchaser to have an understanding of the basic properties of the different materials used in construction. These properties are briefly described in the following section and are summarised in table 1.1.

1.1.1 High Modulus Polyethylene fibres

High Modulus Polyethylene (HMPE) is a fibre that has a high strength to weight ratio and low stretch characteristics but limited resistance to high temperatures. The fibres have good abrasion resistance and tension-tension fatigue life.

HMPE is resistant to axial compression and has a low coefficient of friction. It is susceptible to creep that under certain conditions can lead to creep rupture. However, this can be mitigated through design and/or choice of HMPE fibre. For further information on creep see section 1.2.5.

Mooring lines constructed from 100% HMPE fibres float. If jacketed, HMPE ropes can have a higher density and may sink. However, this will depend on the rope's diameter and the material that the jacket is made from.

1.1.2 Aramid fibres

Aramid fibre typically has high strength and low stretch. It does not creep significantly and does not melt, but chars at high temperatures. Aramid is susceptible to axial compression fatigue that occurs when tightly constrained fibres are forced into axial compression. Aramid is resistant to tension-tension fatigue.

Aramid ropes do not float. They are typically jacketed with some other synthetic fibre, such as polyester, to increase abrasion resistance and protect against UV degradation.

1.1.3 Liquid Crystal Polymer fibres

Liquid Crystal Polymer (LCP) fibres have high strength and low stretch and good resistance to creep and tension-tension fatigue. The fibre has a temperature resistance between that of HMPE and Aramid.

LCP fibres are known for their long-term durability to fatigue, cutting and abrasion.

Table 1.1 provides details of some of the typical properties of HMSF ropes when compared with steel wire ropes.

Material	Specific Gravity	Specific Modulus N/tex	Specific Strength N/tex	Dynamic Coefficient of Friction against Metal	Melt Point Deg. C	Other Characteristics
HMPE	0.97	110	3.5	0.07	147	Low melt point. Lighter than water Potential creep and creep rupture problems Long tension- tension fatigue life
Aramid	1.44	49	2.03	0.15	Chars @ 500	Potential axial compression fatigue problems, but these can be overcome Long tension-tension fatigue life
LCP	1.40	60	2.4	0.13	300	High strength and low stretch Long tension-tension fatigue life
Steel wire	7.85	26	0.18	0.23*	1,600	Corrodes Heavy Moderate tension-tension fatigue life
Notes: Table indicates approximate values, actual properties may vary. The unit 'tex' is the weight in grammes of 1,000 metres of material. Newtons/tex = MN/(kg/m) where kg/m is rope linear density. Multiply Newtons/tex by 102.3 x SG to obtain kg/mm^2. Multiply Newtons/tex by 145,400 x SG to obtain lb/in^2. * Steel wire is 0.23, but when lubricant/finishing is used the coefficient may vary.						

Table 1.1: Typical properties of High Modulus Synthetic fibres and steel wire ropes

1.2 Factors that may impact the service life of high modulus synthetic fibre mooring lines

Table 1.2 summarises factors that may affect the service life of HMSF mooring lines. The purchaser and supplier should discuss individual requirements in order to develop the optimal purchasing specification, taking into account intended use and operating environment.

All mooring lines will be exposed to wear and tear in service and it is important that they are subjected to routine inspection. A record should be maintained on board documenting the number of mooring hours and any significant events (see section1.3.5).

On board handling and care procedures should include instructions for in-service repair and, if required, end-for-ending. In addition, retirement criteria should be established taking into account manufacturer's recommendations.

In a dynamic environment, the use of tails of a suitable material and length could reduce peak loads in the mooring and mitigate wear.

Factor	Description	Occurrence	Preventive Measures
Abrasion – External	Rope contacting rough surfaces	**Normal Usage**	• Maintain smooth surfaces • Use of jacketed rope • External chafe protection • Proper use of tails to mitigate wear
Abrasion – Internal	Yarn-on-yarn abrasion Ingress of foreign material	**Normal Usage**	• Use of coatings • Construction of the rope • Storage arrangements • Use of jacketed rope • Handling procedures
Cut	Exposure to sharp object under tension	**Normal Usage**	• Inspect mooring fittings and deck for sharp objects, grind smooth where needed • Avoid contact from crossing of mooring lines • External chafe protection
Twist	Introduction of twist in line which decreases strength	**Normal Usage**	• Proper installation on the drum • Proper line handling • Conduct periodic visual rope inspections • Avoid combining dissimilar rope constructions (braided versus twisted) in series • Include a tracing marker on the exterior of the rope
Tension - Tension Fatigue	Cyclic loading of rope	**Applicable to open water berths and STS operations**	• Maintain balanced tension on all lines • Proper type and length of tails
Creep and Heat Exposure	Irreversible elongation caused by loading over extended periods of time. Impacted by temperature	**Applicable to high loads and/or temperatures (HMPE only)**	• Keep ropes within manufacturer's stated operating range • Adequate rope design and/or HMPE fibre for creep performance
UV Degradation	Prolonged exposure to UV radiation	**Aramid and LCP fibres more susceptible**	• Adequate rope design • Proper storage when not in use

Axial Compression	Compression induced in line	**Applicable to Aramid fibres only**	• Adequate rope design • Proper tail connection
The factors listed above may combine, resulting in heightened effect			

Table 1.2: Factors that may Impact the service life of HMSF ropes

The factors identified in table 1.2 are further described in the following sections

1.2.1 Abrasion

Different synthetic fibres have different coefficients of friction, as well as general strength against abrasion. Abrasion can come from external influences, such as a chock, but may also occur inside the rope between strands and fibres. There are a number of ways to protect against abrasion and these are discussed in the following sections.

1.2.1.1 External abrasion

All HMSF mooring lines are susceptible to chafing damage from contact surfaces. It is important that deck fittings are regularly inspected and are kept smooth and free from chafe points. Ideally, steel fairleads should be clean, smooth and rust-free but this may be difficult to achieve in practice. As an alternative, consideration may be given to fitting sleeves or liners in way of contact surfaces. Roller fairleads should be well maintained and kept free to rotate.

The ability of a rope to resist external abrasion damage may be improved by the addition of an abrasion resistant overall jacket or individual strand jackets. Alternatively, additional external chafe protection may be considered (see Section 1.3.6).

Relative to other HMSFs, Aramid fibres have lower abrasion resistance. However, like all HMSFs, certain coatings used on Aramids can increase the lifetime of the fibre.

1.2.1.2 Internal abrasion

Internal abrasion, such as yarn-on-yarn abrasion, occurs when a rope is subjected to cyclic loading or cyclic bending. The impact may be mitigated by the use of tails of the correct material and length attached to the mooring line (see section 1.3.4). Internal abrasion can be alleviated with particular rope constructions and/or the application of coatings.

Internal abrasion will increase should the rope be exposed to contaminants such as grit or sand and it is therefore important that ropes are protected by covers when stowed.

1.2.2 Cut

Deck arrangements, including outboard fittings such as fairlead foundations, should be assessed to determine whether there is a risk of deployed moorings contacting sharp edges which could cut the rope and rapidly result in mooring failure. Where necessary, localised chafe protection should be used to prevent damage.

Ropes under tension may be damaged by contact with other mooring lines. Mooring arrangements should be carefully planned to minimise the risk of such contact.

1.2.3 Twist

Induced twist may reduce a mooring line's strength and, where possible, measures should be taken to minimise the introduction of twist into a deployed rope. Such measures include the proper stowage of ropes on their drums and the avoidance of connecting ropes with tails of dissimilar constructions in series.

Ropes should be inspected under tension to assess the degree of twist that may be present. Depending on the rope's construction, the use of an external tracing marker may assist in determining the extent of induced twist.

1.2.4 Tension-tension fatigue

Tension-tension fatigue occurs under conditions of cyclic loading, such as those experienced in open water or exposed berths. The impact of cyclic loading may be reduced by the use of tails of the correct material and length attached to the mooring line (see section 1.3.4).

1.2.5 Creep and heat exposure

Creep is the tendency of a solid material to slowly move or deform permanently under the influence of load. Creep always increases with temperature and is more severe in materials that are subjected to heat for long periods. The rate of deformation is a function of the material properties, exposure time, exposure temperature and the applied load. Depending on the magnitude of the applied load and its duration, the deformation may become so large that a component can no longer perform its function, resulting in failure.

There are two key properties of creep, namely creep strain and creep rupture. Creep strain is the non-recoverable increase in length and creep rupture is the failure that occurs after a period of time with an applied load.

Rope creep is of particular concern when evaluating ropes that operate under high loads and/or high temperatures.

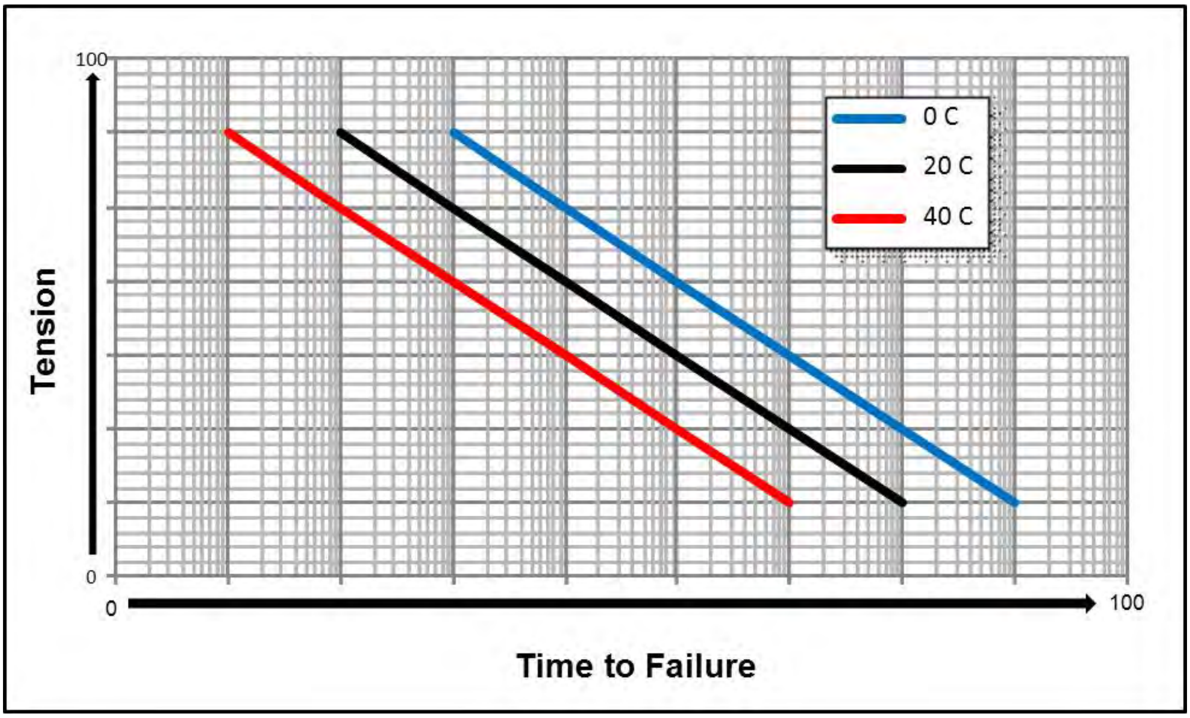


Figure 1.1: The impact of heat and load on creep for high modulus polyethylene fibre

The creep rate depends on the type of fibre used. For Aramid and LCP ropes creep rate and creep life are negligible in most likely operating conditions. For HMPE mooring lines, elevated temperature and load accelerate the creep rate. For HMPE mooring lines, elevated temperature and load accelerate the creep rate. This should be considered as being of relevance when the ambient temperature is 40°C or greater. Figure 1.1 illustrates the impact of heat and load on creep for HMPE. Manufacturers or suppliers should be consulted as the effect of creep can be mitigated by rope design, fibre or increased size.

1.2.6 Ultra violet degradation

Aramid and LCP fibres may be susceptible to the effects of ultra violet (UV) degradation. It is important that the exposure of the fibres is minimised and that ropes are properly stowed and covered when not in use. A jacket constructed from polyester or other suitable synthetic fibre, while primarily providing chafe protection, will also serve to protect the HMSF from UV exposure.

1.2.7 Axial compression

Some Aramids are susceptible to repetitive axial compression causing local fatigue, which can occur when a rope is at a low tension and fibres are actually pushed into compression.

Three primary causes of axial compression are rope non-uniformity, induced twist and bending.

Rope non-uniformity: if the rope's components are not the same length, when tension is relieved the longer components will be in compression and the shorter ones will be in tension. This is especially important in spliced terminations.

Induced twist: when the rope is twisted in service the outer fibres in the longer path are under tension and the inner fibres will be forced into compression.

Bending: when a rope is bent and cycled, the strands and yarns on the inside of the bend can be forced into compression.

Yarn coatings and specific rope constructions may impact axial compression and guidance should be sought from manufacturers.

Aramid ropes should not be attached to tails by a cow hitch as this leads to axial compression.

Figure 1.2: High modulus synthetic fibre mooring line on split drum winch

1.3 Considerations associated with the use of high modulus synthetic fibre mooring lines

Although this document is primarily intended to address issues relating to the procurement of HMSF mooring lines, it may be beneficial for purchasers to be aware of some of the operational aspects that impact on line performance and service life. These are briefly described in the following sections.

1.3.1 Considerations when using high modulus synthetic fibre mooring lines

The vessel's expected trading route and the environmental conditions it will likely be subjected to in the ports of call, need to be taken into account when selecting the type of HMSF mooring lines that are to be installed on a vessel. Factors to consider, when determining the type of HMSF to be installed on a vessel, should include the primary strength material and the amount used, rope construction and if necessary chafe protection, such as a jacket or specialised coating.

The location of the berths, exposed or sheltered, will indicate the potential for the lines to be exposed to dynamic loads.

Mooring arrangements at exposed berths can be subject to first-order wave motions that will induce tension-tension loads. Wave forces are of two types, the first order forces at wave period and the second order wave drift forces which vary much more slowly. The periods of first order ship motions are normally much shorter than the periods of natural response of the ship-mooring system, so the wave induced motion analysis can be decoupled from the properties of the mooring system. First order wave motion will not have much effect on vessel movement, although this is very dependent on wave period and direction. Long period waves quartering or beam on will create large vessel motions Larger ships experience proportionally higher tension loads from the wave induced motions as compared to smaller ships. In addition, the tension induced by wave motion can be more pronounced in aft breast lines than forward breast lines due to the considerable increase in weight aft versus forward on ships with accommodation blocks aft.

The expected environmental conditions will indicate if the lines will be subjected to extreme temperatures or exposure to abrasive particles.

The rope supplier should also be consulted on the proper installation of their rope for the type of winch it will be used on.

1.3.2 Bedding-in of mooring lines

When a new mooring line is first placed into service, the construction elements will compact as the fibre components of the line adjust under load. It may take several operations for the line to stabilise. The associated elongation and reduced restraint capability may adversely impact load sharing when a new line is deployed in conjunction with existing lines. Care needs to be taken during this new line bedding-in period to ensure that the integrity of the overall mooring pattern is not compromised.

1.3.3 Load sharing

When two or more lines are performing the same function, for example, as breast lines, they should be of the same material and construction, have the same MBL and be of similar length. It is important that the lines are properly tended to ensure that the load is shared equally between them. Incorrect tending could result in more stress being put on the higher-loaded line.

1.3.4 Use of tails

Tails may be used on mooring lines to improve the overall elasticity in the mooring system and therefore lower peak loads. Tails may be constructed from various materials including polyester, polyester/polyolefin, or nylon (polyamide).

Tails should be properly matched to the mooring line to which they are attached. Experience indicates that tails of different lengths should be used depending on the location of the berth. For further information, reference should be made to Mooring Equipment Guidelines (reference 1).

The rope manufacturer's recommendations regarding the proper method of connecting tails to the mooring lines, such as by use of a cow hitch or shackle, should be followed to improve the service life of both the mooring lines and tails. Some HMSF line types can be damaged should tails not be connected using the recommended method.

1.3.5 Records of mooring line service

A record should be maintained on board of the use of HMSF mooring lines detailing the number of mooring hours. Any significant events, for example, brake rendering and the effect of surge such as from passing ships, should also be recorded. Individual lines should be clearly identified and the record should state when the lines were placed on board and the date when placed in service.

Any use of lines in non-traditional service, such as to secure a tug, being turned up on bitts or to warp the vessel along the berth, should be recorded.

The log of mooring hours should only record the time when the vessel is moored and lines are deployed, namely from all-fast, to all-let-go.

1.3.6 Ship's fairleads

HMSF mooring lines may suffer from abrasion if fairleads, chocks and other contact surfaces are not maintained clean, smooth and rust-free. Consideration should be given to fitting chafe protection to the section of rope passing through the fairlead (see figure 1.3: An example of a low-friction, low-abrasion fairlead insert). At exposed terminals, chafe protection may assist in reducing the effect, but may not completely prevent the rope being abraded. Care should be taken to maintain the effectiveness of the chafe protection during the port stay.

For Panama leads, chafe protection in the form of retrofitted low friction inserts may be considered. The insert reduces the coefficient of friction between the line and the fitting. Inserts should not be fitted in a manner that adversely affects the strength of the Panama lead.

Figure 1.3: An example of a low-friction, low-abrasion fairlead insert

HMPE lines may also experience damage from frictional heat generated by high loads at leads. Chafe protection or jacketing may reduce this effect.

HMPE lines may also suffer heat damage from prolonged exposure to hot mooring surfaces, such as chocks and fairleads, which could occur during daylight hours in high ambient temperature ports.

Figure 1.4: Examples of Chafe protection

2 Guidance for specifying high modulus synthetic fibre mooring lines

2.1 General

Mooring rope manufacturers will produce an advertised range of ropes designed to meet the requirements of a diverse customer base. Unlike some specialist applications, such as single point mooring (SPM) hawsers, High Modulus Synthetic Fibre (HMSF) mooring lines will be batch manufactured against standard designs and be offered in a range of constructions, sizes and strengths. The onus is therefore on the purchaser, in discussion with potential suppliers, to ensure that the specified rope will meet the required performance criteria.

This section provides guidance on the various factors that should be considered when procuring HMSF mooring lines. Particular attention should be given to the specifications of the initial outfit of mooring lines procured for new buildings.

Rope characteristics should be measured using an international standard such as ISO 2307 (Reference 2) or Cordage Institute (CI) 1500 (Reference 3).

A mooring analysis should be conducted to determine the performance parameters of the mooring lines necessary for maintaining mooring system integrity (refer 'Mooring Equipment Guidelines' – Reference 1).

2.2 Rope application

General information should be provided by the purchaser to the supplier regarding the proposed application and intended service of the rope, such as:

- Vessel type/size.
- Winch design and arrangements.
- Information on fairleads (type and condition).

Purchasers should also consider the following and exchange relevant information with suppliers:

- Vessel's likely trading area/pattern.
- Potential berth arrangements – exposed/sheltered.
- Environmental conditions (e.g. temperature, wind, swell, current, etc.).

When replacing a line or lines from an existing mooring outfit, it is recommended that the replacement lines are compatible with the existing lines. For example, they should have similar strength and elasticity characteristics.

2.3 Minimum breaking load

The minimum breaking load (MBL) is a critical performance criteria when procuring rope. The required MBL of individual lines will be established at the vessel's design stage following mooring force calculations and an analysis of mooring restraint requirements against standard environmental criteria, as described in Mooring Equipment Guidelines (reference 1). Where necessary, site-specific studies may be undertaken to assess factors that may include the impact of dynamic loads on the mooring arrangement.

The specified MBL should be for spliced ropes, based on break tests undertaken in accordance with ISO 2307 or CI 1500 (References 2 and 3). The manufacturer should have type approval for the rope being supplied, issued by an approved third party, such as an IACS member.

2.4 Diameter

For naming and reference purposes, ropes are specified by Nominal Diameter. The rope's actual diameter may vary. Some standards and specifications require that for a specific rope size the measured diameter or circumference be within a stated tolerance. In some cases the variance of the actual diameter can be up to ± 10% from the nominal diameter, depending on the rope's material and construction, and whether it has been bedded-in or not.

The nominal diameter of a jacketed rope includes the additional thickness of the jacket. For storage purposes the actual diameter should be used.

Should there be any physical constraints, where the rope dimensions are critical, the purchaser should specify the maximum physical diameter of the rope, including jacket if applicable.

2.5 Length

The purchaser should specify the length of mooring line required for the rope application, taking into account end termination arrangements as necessary, and any additional length required to cater for residual strength testing.

2.6 Rope construction

2.6.1 Construction options

HMSF mooring lines are commonly available having the following constructions:

- 3, 4, 6 or 7 strand wire lay.
- 8 or 12 strand braided.
- Double braided.
- Parallel lay.

These constructions may or not be jacketed, and may or may not use multiple cores.

Depending on the rope's construction, consideration should be given to having a means to easily determine the presence of induced twist in the rope.

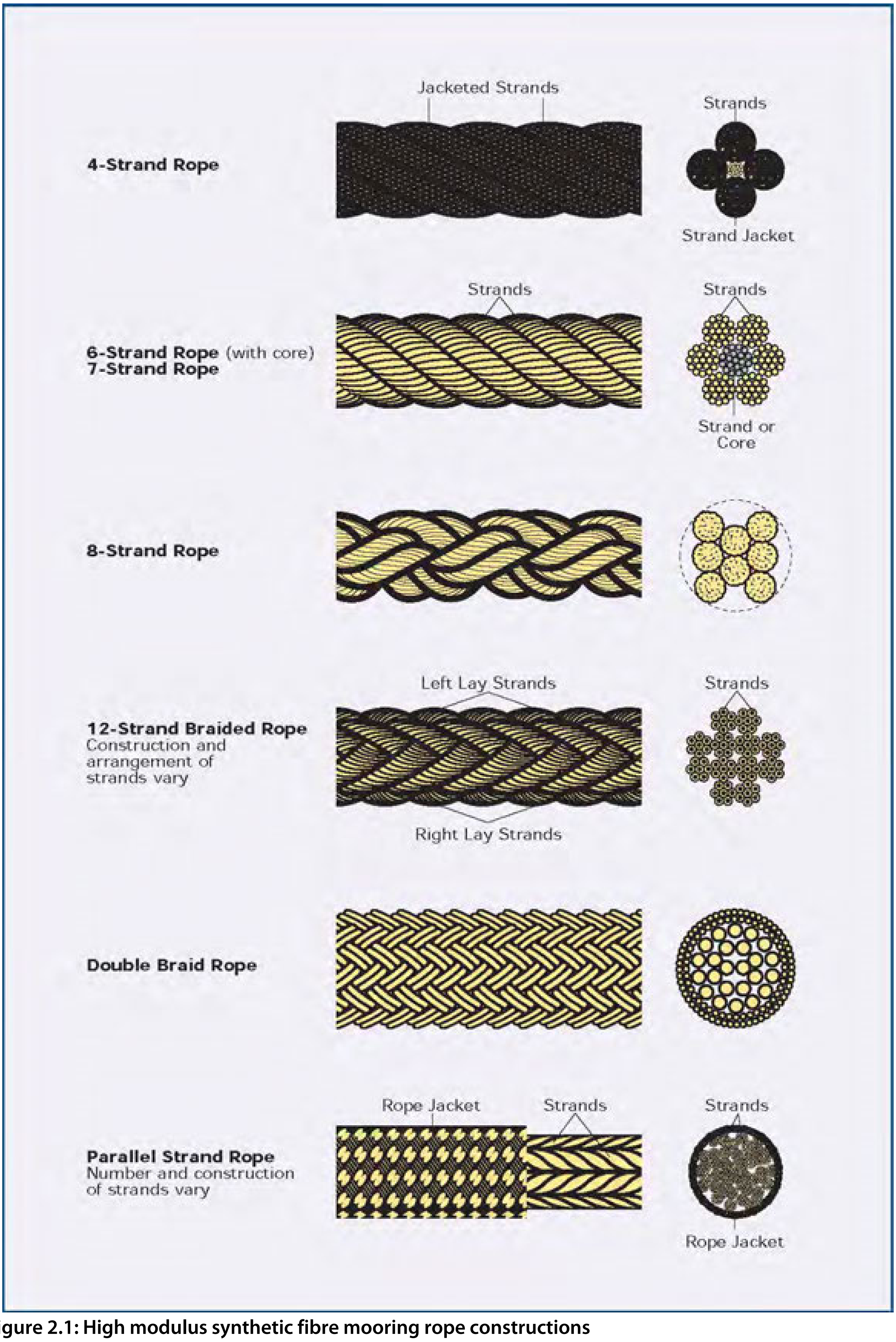


Figure 2.1: High modulus synthetic fibre mooring rope constructions

2.6.2 Linear density

Linear density is the weight of the rope per unit length, typically expressed in kg/100 m and tested in accordance with ISO 2307 or CI 1500 (references 2 and 3). The manufacturer should supply this information.

It should be noted that some rope manufacturers allow up to ± 10% tolerance in the linear density of supplied ropes from the prototype design.

2.6.3 Rope protection

2.6.3.1 Jacket

Purchasers should specify whether or not the rope should be jacketed to provide additional chafe protection. Ropes can be provided with overall jackets and/or individual strand jackets.

The jacket, while serving to protect the load bearing core, will make it difficult to monitor the condition of the core, should that be necessary. With some constructions, the jacket and core may move separately, risking possible abrasion between the two components.

While unjacketed ropes are more vulnerable to external damage and particle ingress, the absence of a jacket facilitates inspection, repair and splicing.

The jacketed rope may have a larger diameter than a non-jacketed rope having the same MBL and this may be an issue if storage space on winch reels is limited.

2.6.3.2 Coating

Suppliers may offer the option of coated ropes or ropes constructed from coated yarns. The specialist coatings may serve to enhance the rope's performance and potential service life in a number of areas.

Purchasers should request information from suppliers regarding the coatings used and their potential benefits.

2.6.3.3 Independent chafe protection

Rope manufacturers may be able to supply independent chafe protection, such as that fitted to the rope during construction (fixed or sliding), or retro-fitted to the rope in service. When determining the need for chafe protection and its specification, purchasers should discuss their requirements with suppliers.

Considerations should include material type, construction, length(s) and placement.

2.6.4 End terminations

The purchaser should specify the requirements for spliced eyes at one or both ends of the mooring line. The length of eye should be specified by the purchaser. Typical eye lengths will be from 1.8 to 2.5 metres.

The purchaser should indicate whether chafe protection for the eye, such as a protective sleeve, is required.

The provision of eyes on both ends of the rope will facilitate end-for-end rotation, potentially increasing the rope's service life.

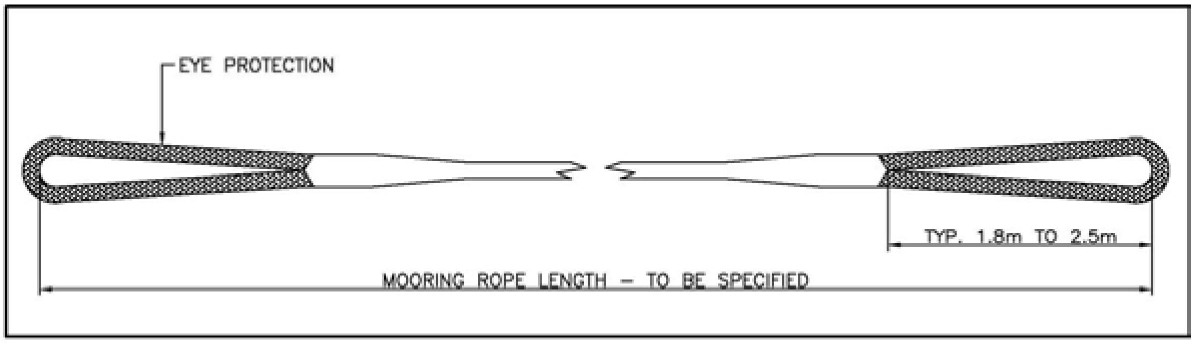


Figure 2.2: End terminations

2.7 Material specification and certification

The purchaser should indicate the fibres from which the rope is to be made and should request a certificate from the manufacturer.

2.8 Marking and certification

2.8.1 Marking

The purchaser should specify the requirements for the rope to be uniquely identified by product labels firmly attached to each end of the rope. The label should include information to link back to the rope's certificate such as the following:

- Rope manufacturer.
- Serial number.
- Product name.
- Minimum breaking load.

2.8.2 Certification

Certification may be in the form of the following:

Rope certificate

The manufacturer should provide a certificate to accompany each supplied rope demonstrating compliance with the requirements of the purchase order. Certificates may be issued by the manufacturer and/ or a third party, such as a classification society.

The certificates should identify either a specific line or a batch or run of line that is made into multiple mooring lines. Details on the certificates should include:

- Product name.
- Product type.
- Detailed description - size, length, diameter.
- Detailed description of yarn, including yarn producer and yarn grade or type.
- Details of coatings, jackets and eyes, as appropriate.
- Weight per unit measure.
- MBL and test method.
- Identification number.

Type certificate

A type certificate is a certificate confirming that the rope is manufactured in accordance with the particular design. The certificate may be issued following third party inspection. The Type Certificate will not typically be provided to the purchaser unless specifically requested.

Additional test results such as those from cyclic bend or abrasive tests may also be available for specific rope applications.

2.9 Purchaser's test requirements

The manufacturer will typically undertake a break load test, on a prototype and batch basis, for a rope of similar size and construction in accordance with ISO 2307 or CI 1500 (references 2 and 3). The purchaser should ask for and understand the test methods employed by the manufacturer.

The purchaser may require a full scale break load test of a sample rope taken from the ordered batch. The purchaser may also specify requirements for independent observation and verification of the test.

Depending on the rope's application, the purchaser may specify their own additional test requirements.

2.10 Packing and delivery

The purchaser and the supplier should discuss, and mutually agree, on the requirements for packing and delivery of the mooring line(s).

2.11 After sales service

2.11.1 User manual

The purchaser should identify the documentation they require from the supplier. This may include guidance on issues such as:

- Pre-installation preparation of contact surfaces.
- Mooring line installation.
- Safe handling.

- Chafe protection and repair procedures.
- Connection of tails.
- Stopper materials and use.
- End-for-ending.
- Storing.
- Cropping and splicing.
- Mooring log recommended practices.
- In-service inspection procedures and recommended intervals.

2.11.2 *Training*

The purchaser should identify any instructional resources required from the rope supplier to support crew training. Training may be in the form of documentation, computer based resource or hands-on with a representative from the supplier.

2.11.3 *In-service testing*

The purchaser may wish to consider having a sample of the supplied mooring lines tested to determine residual strength following a period of time in service. The supplier's procedures for such testing should be requested as part of the procurement process. When tests are intended, allowance for them should be made when specifying the length of the line. Tests should be undertaken in accordance with ISO 2307 or CI 1500 (references 2 and 3).

2.12 Purchaser's requisition form

The purchaser's requisition form should contain as much detail as possible, particularly with regard to the intended rope application (see section 2.2). A detailed requisition form will enable the supplier to provide the best match possible to the purchaser's requirements.

2.13 Quality control

HMSF mooring lines should be manufactured and supplied under quality assurance processes that are independently verified, such as those required under ISO 9001 (reference 4) or equivalent.

Effective control of raw materials and finished products is of critical importance and the manufacturer's quality assurance and control procedures should address material certification, traceability, and testing requirements.

The design of individual rope types should be based on fully documented and independently-verified prototype tests. Ropes should be constructed in accordance with the agreed design specification. The manufacturer should have documented procedures that address the frequency of batch break tests to confirm that stated MBL criteria is being met, in accordance with ISO 2307 or CI 1500 (references 2 and 3).

The manufacturer should have an inspection and test plan that includes the following, as a minimum:

- Manufacturing and test plan.
- Identification and control of materials, parts and components.

- Inspection process for verification of materials and manufacturing process.
- Designated inspection and test points.

A copy of the plan should be made available to the purchaser on request.

2.14 Summary of considerations

Table 2.1 below provides a summary of items that purchasers should consider when procuring HMSF mooring lines:

Mooring Information	Rope Characteristics
Mooring analysis results	MBL (Spliced)
Vessel type/size	Construction
Winch rating, design and arrangements, including drum storage capacity	Material
Mooring arrangement	Diameter
Information on fairleads (type and condition)	Length
Berth arrangements – exposed/sheltered	Termination (type and required protection)
Trading area/pattern	Rope protection (jacket, coatings, chafe protection)
Environmental conditions	Colour
	Quantity required (including spares)
Additional requirements	
Tails if required (type, quantity, length, diameter, and termination)	
Marking and certification	Delivery terms and timing
Packaging and shipping	Training requirements
After sales support	Quality control procedures

Table 2.1: Summary of considerations

OCIMF Guidelines for the purchasing and testing of SPM hawsers compliance certificate – Form A

FORM A OCIMF GUIDELINES FOR THE PURCHASING AND TESTING OF SPM HAWSERS COMPLIANCE CERTIFICATE

Date ____________

Rope Manufacturer ____________
Address ____________
Rope Design Designation ____________
Material Type (nylon, polyester, etc.) ____________
Material Description (or mfg's code) ____________
Rope Structure (8-strand, double braid, etc.) ____________
Maximum Rope Size to be Made ____________ Weight / unit Length ____________

Prototype Rope Production

Plant Location ____________ Quantity Produced ____________ Date ____________
Quality Control Supervisor ____________
Name of Independent Inspector ____________
Inspection Company ____________
Address ____________

Certified by Independent Inspector (indicate Yes or No if listed requirements have been reviewed)

Rope Design Specification?	________	Material Specification?	________
Manufacturing Specification?	________	Splicing Instructions?	________
Quality Assurance Manual?	________	Quality Control Report?	________
Yarn Quality Testing?	________	Rope/Yarn Strength Ratio Determination?	________

Prototype Rope Testing

Test Facility ____________ Location ____________ Date ____________
Test Engineer ____________
Name of Independent Inspector ____________
Inspection Company ____________
Address ____________

Certified by Independent Inspector (enter average test result)

	NDBS	DExt20%	DExt50%	NWBS	WExt20%	WExt50%
Size 6	______	______	______	______	______	______
Size 15	______	______	______	______	______	______

Largest Size Tested (if maximum rope greater than size 20) (enter size and average test result)

Size __	______	______	______	______	______	______

Size 6 TCLL (enter test result) ________ Size 6 Standard Deviation (enter test result) ________

Certified by Independent Inspector (indicate Yes or No if listed calculations have been reviewed)
Extension at 20% (Ext20%) and 50% (Ext50%) Determination? ________
Thousand Cycle Load Level (TCLL) Determination? ________
Rope Size/Strength Power Determination? ________ Rope/Yarn Strength Ratio Determination? ________

Signature/Seal of Independent Inspector ____________

Certification indicates that documents have been reviewed for full compliance and that tests have been witnessed by Independent Inspector.

Compliance and/or certification do not indicate approval and/or certification by OCIMF.

Material Chemical Composition ______________________________

Rope Producer's Material Description ______________________________

Fibre Producer ______________________________

Plant Address ______________________________

Fibre Producer's Material Description / Designation ______________________________

Type ______________________________ Finish ______________________________

Merge Number ______________________________ Grade ______________________________

Size of Basic Yarn ______________________________ Twist ______________________________

Melting Point ______________________________ Finish Content ______________________________

STRENGTH AND ELONGATION

	Min.	*Max.*	*Dry S.D.**	*Min.*	*Max.*	*Wet S.D.**
Yarn Breaking Load, YBL	______	______	______	______	______	______
Load at 5% elongation, LASE5	______	______	______	______	______	______
Load at 10% elongation, LASE10	______	______	______	______	______	______
Elongation to Break, YETB	______	______	______	______	______	______

* Standard Deviation

SHRINKAGE AND CREEP	*Min.*	*Max.*
Boil-off shrinkage	______	______
Heat Shrinkage	______	______
Creep	______	______

WET YARN-ON-YARN ABRASION (see CI 1503 for definitions and calculation methods)

Prototype Yarn Abrasion Tests

Applied Tension	______	______	______	______	______
Mean Cycles to Failure (CTF) (calculated on log-cycles basis)	______	______	______	______	______
CTF Standard Deviation (anti-log of value calculated on log-cycles basis)	______	______	______	______	______

Production Yarn Abrasion Tests

Applied Tension ______

Mean Cycles to Failure (CTF) ______ (calculated on log-cycles basis)

CTF Standard Deviation ______ (anti-log of value calculated on log-cycles basis)

YARN AND STRAND MAKING

	*Nominal Value**	*Unit*	*Allowable Deviation***	*Production Value*	*Unit*
Size of basic yarn, (denier or tex)	______	______	+/- 5%	______	______
Twist of basic yarn	______	______	+/- 5%	______	______
Ply count of intermediate yarn (number of basic yarns)	______		+/- 5%	______	
Ply count of rope yarn (number of intermediate yarns)	______		+/- 5%	______	
Twist of rope yarn	______	______	+/- 5%	______	______
Number of rope yarns per strand	______		+/- 2%	______	
Gearing of stranding machine	______	______	0	______	______
Speed of stranding machine	______	______	+/- 10%	______	______
Strand closing die bore diameter	______	______	+/- 3%	______	______
Yarn lay length in strand (measured on stranding machine)	______	______	+/- 5%	______	______

Arrangement of rope yarns per layer in stranding machine register plate

Layer	*Centre*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Nominal Number*	______	______	______	______	______	______	______	______
Production Number	______	______	______	______	______	______	______	______

* Given in Manufacturing Specification

** The Manufacturer may set more stringent allowable deviation limits.

DETERMINATION OF ROPE STRENGTH (See Appendix III for calculation example)

Yarn Position	*Number of Samples*	*Average Strength*		*Number of Yarns in this Position in a Strand*		*Number of Strands in Rope*		*Total Position Strength*
______	______	______	x	______	x	______	=	______
______	______	______	x	______	x	______	=	______
______	______	______	x	______	x	______	=	______
______	______	______	x	______	x	______	=	______
______	______	______	x	______	x	______	=	______
______	______	______	x	______	x	______	=	______

Total Yarn Strength ______

Rope / Yarn Strength Ratio (from Manufacturing Specification) x ______

Calculated Strength (total yarn strength times RYSR) ______

Nominal Rope Strength ______

Product Rope Strength shall not be less than 95% of the nominal strength

MATERIAL IDENTIFICATION TESTS

Material in rope should be ______________________________

At least two and sufficient of the following tests shall be conducted to identify material
(See Appendix II for description of tests)

Melting point of fibre expected value ________ test value ________

Specific gravity of fibre expected value ________ test value ________

Material dissolves in ________________ But not in ________________

Burning characteristics were as follows ______________________________

Stain characteristics were as follows ______________________________

Material is determined to be ______________________________

Remarks ______________________________

INSPECTION AT REFERENCE LOAD

Reference Load ______________________

	Nominal or Specified Value	*Product Value*	*Tolerance*
Overall hawser assembly length	______	______	
	Individual assembly		+/- 1%
	Between matched hawsers		+/- 1/2 %
Strand pitch	______	______	+/- 5%
Yarn lay angle	______	______	+/- 10%
Maximum rope width (if specified)	______	______	+0

ROPE QUALITY

	Observed Value	*Allowable*
Eight-Strand and Laid Rope:		
Maximum number of separated rope yarns in any 1 m length	______	2
Total number of hockled strands	______	0
Number of areas of stain or discolouration	______	
Did any area extend over 50% of the rope yarns on any strand surface?	______	*
Did any area extend beyond surface yarns?	______	*
Single- and Double-Braid:		
Total number of separated strands	______	0
Number of areas of stain or discolouration	______	
Did any area extend over 10% of the strands in either core or cover?	______	*

* If any area extended beyond stated tolerance, describe nature and extent of stain or discolouration and tests or other methods used to determine nature of and effect of damage

____

Is nature of damage of a type which causes degradation of rope material? ______________________

OIPEEC Conference paper: Appraisal of ropes for LNG moorings

[redacted], [redacted] and [redacted] **ODN 0918**
Tension Technology International Ltd, Bridon International, [3]Teijin Aramid

Appraisal of ropes for LNG moorings

Summary

The movement of the Liquified Natural Gas (LNG) market to larger vessels has meant that larger and, more exposed offshore terminals are now employed. This presents challenges for the ropes which are used as mooring lines for these vessels. A programme to appraise the suitability of ropes for the mooring application is reported. It included assessment of: strength; operation over ship's fairleads; tensile fatigue performance and creep rupture behaviour (the latter is of particular relevance in hot climates). The programme was defined so as to model as closely as possible the service conditions which will be encountered.

The paper describes the assessment criteria and reports a substantial body of work undertaken on ropes made using different fibres with a view to assessing their suitability for service in the challenging application of LNG moorings. The results of the study show that whilst HMPE ropes will perform very satisfactorily in cooler ambient conditions, at raised temperatures creep becomes an issue. In these situations aramid fibre ropes offer a better overall performance.

1 Introduction

Large ocean-going vessels are moored to piers or jetties typically by an array of up to 18 mooring lines. These lines are stored on and tensioned by deck mounted winches, leave the vessel via fairleads, and are secured to bollards on the quayside (Figure 1).

A given vessel will moor at different ports or terminals, with either port or starboard toward the quayside. As deck space on the vessel is limited, some mooring winches may need to be available for use to both sides of the vessel. This means that some mooring lines will cross the deck between winch and fairlead (in some cases for as much as 25 m) before passing through the fairleads and outboard to the quayside. See, for example, Figure 1 which shows a schematic view of a deck layout, indicating typical positions of the winches and a few of the lines that may be used in a complete mooring, which may comprise 18-20 lines each 275 m long. The largest LNG vessels currently in operation, 'Q-max', are themselves 345 m long and 55 m wide.

The traditionally used steel wire ropes have recently been partially displaced by synthetic fibre ropes. Whilst more expensive, synthetic ropes have many attractive properties:

- they are lighter and generally last longer than steel ropes, and thus promise cost effectiveness;
- their light weight means that they are easier to handle which leads to savings on crewing costs;
- they cause fewer injuries, are intrinsically non-sparking and,
- cause less damage to the fairleader surface over which they operate.

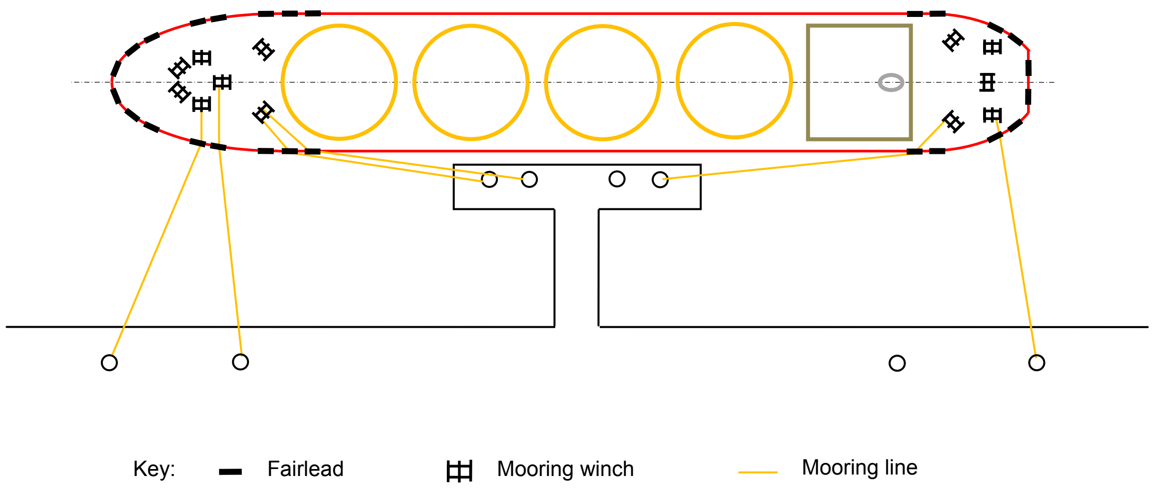


Figure 1: Schematic diagram showing how the mooring ropes may run from the mooring winches across the deck before going through the fairleads (only a few lines have been shown).

However, the adoption of synthetic fibre ropes has presented some of its own challenges. As the moored vessel moves in response to the movement of the sea (and particularly the surge motions), the tension in the mooring line changes, it stretches between the winch and the fairlead, and it moves over the fairlead. This movement over the fairleads causes wear and eventual rope degradation.

The movement of the rope over the fairlead is a function of:

- the tension range in the rope;
- the length of rope between the winch and fairlead;
- the rope axial stiffness, EA (where E is the Young's Modulus and A the cross sectional area of the rope);
- the interaction between rope and fairlead (angle of wrap and coefficient of friction); and,
- the number of turns on the tension drum of the winch and the coefficient of friction between the rope and drum (which determines the effective length of the rope between fairlead and winch).

Sponsored by vessel operators and rope manufacturers, TTI Testing has previously undertaken an extensive programme of testing; modelling the wear mechanisms in ropes as they pass over the fairlead. Through this work, equipment has been developed that allows an understanding and realistic modelling of the fairlead abrasion damage mechanism and assessment of rope performance [**1**, **2**].

Figure 2 shows an example of Panama fairleads. These are typically cast steel structures (Figure 2 left) without moving parts which are welded to the deck of the vessel. The two fairleads in the centre of Figure 2 have been fitted with nylon ‘liners’ manufactured by Nylacast, which are designed to provide a robust yet smooth surface for the rope to operate over.

Figure 2: Fixed steel Panama fairleads, right, with ropes and nylon liners.

More recently, and coinciding with the advent of offshore terminals (rather than more sheltered traditional harbours) a new spate of failures has occurred, many of which may not be attributed to fairlead abrasion damage, with the lines failing clear of the fairlead. Possible causes include:

- Simple overload;
- Creep-rupture (this might be particularly relevant at terminals in hot climates); or,
- User induced failures such as twist; lines being incorrectly tended (leading to overload); local damage (crushing or cutting); or, e.g. exposure to chemicals.

This paper presents the results of an extensive testing programme to appraise aramid fibre rope for overall suitability as a vessel mooring line. Testing has covered three main areas seen as critical in this application:

- Operation over a fixed fairlead (with nylon liner);
- Tension-Tension performance; and,
- Creep Rupture, especially at elevated temperatures.

The programme has made comparative tests between a three-strand HMPE rope used in this application and alternative aramid fibre ropes made with fibre material supplied by Teijin Aramid.

2 Rope samples

In addition to the three-strand HMPE rope, three different aramid fibre products were selected for testing in this programme of work. Materials were as follows:

- Technora, T200W, (Technora with 12% by weight marine finish);
- Technora T200WL (Technora with 3% by weight marine finish); and,
- Twaron, TW2304, (Twaron with 3% by weight marine finish)

All rope samples had a braided polyester jacket and were nominal 32 mm diameter. Although at the lower end of the range normally used for mooring lines, this diameter was still large enough to provide results relevant to the application.

3 Test programme

3.1 Operation over a fixed fairlead

The assessment of ropes operating over a fairlead has been previously described in detail by Ridge *et al.* [**1**, **2**]. With reference to Figure 3 below, two 'idler' sheaves wrap a rope sample over the fixed test fairlead (in this instance) through an angle of 40°. The test fairlead was a (black) nylon liner material such as shown in Figure 2. Additionally a chafe sleeve was used on the rope, as these were becoming the industry standard. The relatively short test sample was connected in series with a nylon grommet (this can just be seen in Figure 3), with the purpose of allowing a larger cyclic movement over the fairlead, representative of the full mooring line in service.

Figure 3: Photograph showing the setup for the abrasion tests.

For the tests reported here, two types of loading sequence were employed:

- A block loading sequence comprising shorter blocks of relatively high loads interspersed with a larger number of low load cycles (Figure 4). The load levels were expressed as a percentage of the rope breaking load.
- A 'mixed sea state' loading sequence designed to provide a more realistic assessment of the performance of the ropes over a fairlead, and particularly the heat build up for random loading sequences. A generic load-time series, 45 minutes long, was used as the building block to develop a 30 hour test. The series (Figure 5) was arbitrarily scaled so as to model light, medium and severe wave loading sequences (as a % rope MBL). The different load levels were then combined randomly in appropriate ratios to produce the 30 hour test.

As with previous investigations [**1**, **2**] a series of K-type thermocouples were inserted along the rope to monitor any heat build up due to friction whether internal friction from the rope flexing or from the rope jacket rubbing over the fairlead itself.

During the set up stage of the test the rope was loaded to its maximum and minimum loads, and the extreme positions of the rope on the fairlead marked. Thermocouples were then inserted along this length and just past. In the case of the block load testing five thermocouples about 150mm apart were employed (see for example Figure 6), whilst for the mixed sea state, seven thermocouples, typically 125 mm apart were used (Figure 7). Finally a thermocouple was inserted in the rope near the actuator to monitor any change in temperature due to the cyclic tensile loading.

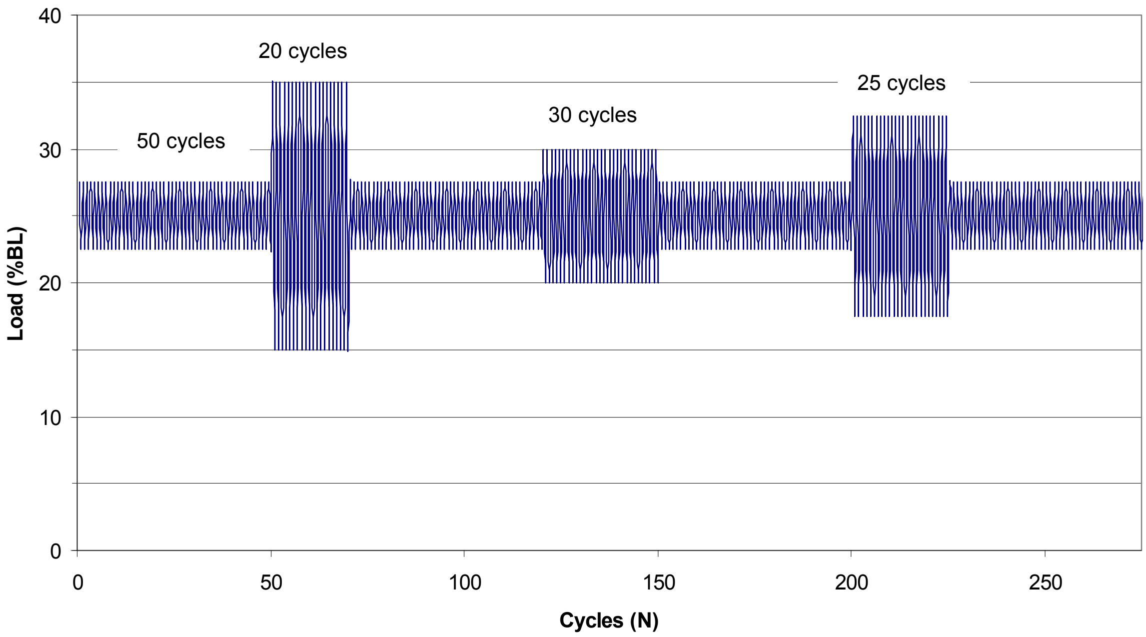


Figure 4: The seven loading blocks, which were repeated six times to give the 1650 cycles as per the earlier work.

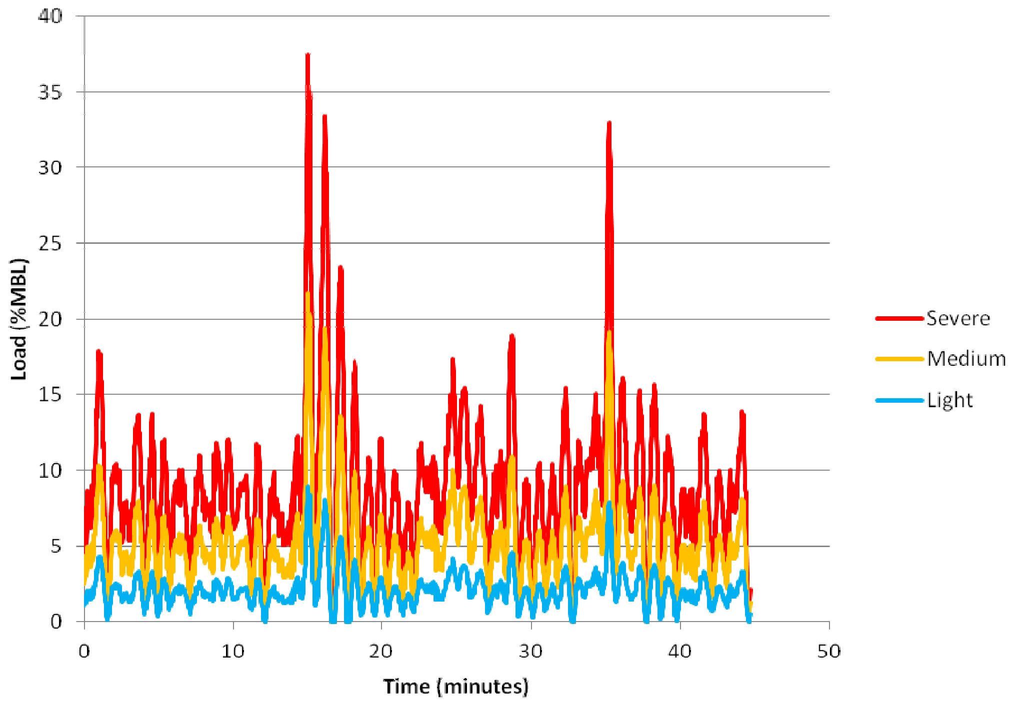


Figure 5: The 45 minute load-time series used to develop a 30 hour test.

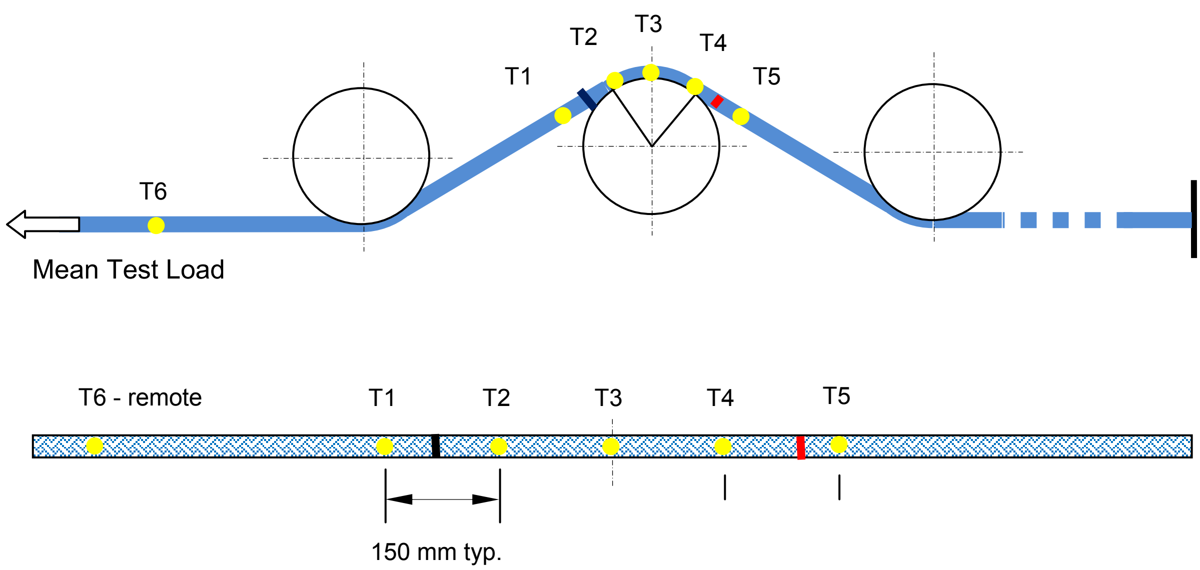
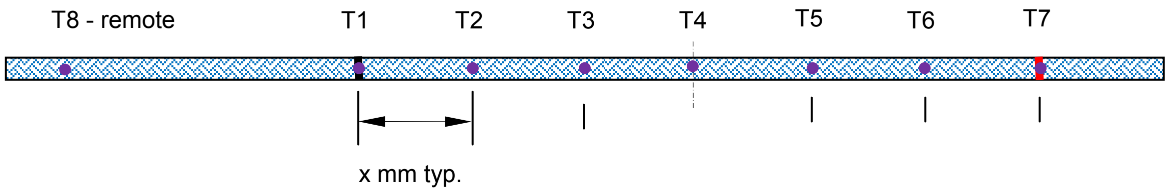


Figure 6: Positioning of the thermocouples in the rope during block loading testing. (Note the red and black marks are the extremes of motion of the rope over the fairlead.)



Material	Distance x (mm)
T200W	120
T200WL	130
Twaron 2304	125
HMPE	120

Figure 7: Distribution and numbering of the thermocouples along the different rope materials for the mixed sea state samples.

3.2 Tension-Tension fatigue performance

In addition to the performance over the fairlead, the other main requirement for a mooring line is that it has sufficient tensile fatigue performance. In order to assess the tensile fatigue performance of these ropes, the method outlined in the OCIMF thousand cycle load level (TCLL) test was adopted [**3**]. The TCLL test has become an industry standard for the qualification of SPM hawsers.

The basic idea behind the TCLL test is to determine the peak load level at which failure will occur in 1000 cycles. The rope is initially cycled 1000 times from a small reference load (in the work described here from 2%) to 50% rope new wet breaking strength (NWBS). If it survives these cycles, it is then cycled 1000 times to 60%BS, then 70%BS, and finally if it survives to this stage for 2000 cycles at 80%BS.

If the rope is still intact after the 2000 cycles at 80%BS the sample is then loaded to break to determine its residual strength.

Using these results, the OCIMF guidelines set out a calculation method to determine the single load level equivalent to the 1000 cycles to failure [**3**, Appendix III-9]. Obviously if the rope survives the 2000 cycles at 80%, the TCLL will be in excess of 80% (81.95%) which is a very good result.

As stated above, the TCLL test was originally intended for the qualification of SPM hawsers. Although similar, there are differences between the two applications which mean that the OCIMF TCLL test does not perfectly model the mooring application considered here:

- The OCIMF specification proposes tests should be run at periods of 20 s to 60 s (and the period of each load range increased to maintain the same strain rate). It was felt prudent to check the sensitivity of the rope to shorter (typical wave) period loading (e.g. starting at 10 s).

- The OCIMF specifies a wet test. The vessel mooring application will tend to be dry, and so it was felt that an equivalent test should be run with the rope in the dry condition.
- Finally, the OCIMF test stipulates a water temperature between 10 and 25°C, again, if the rope is operating in a warm climate (e.g. 40 °C) the test temperature should be elevated to reflect the real working temperature.

Thus two variants of TCLL tests were run:

- Following the OCIMF guidelines; and,
- Modelling more closely the LNG mooring application; dry, at 40°C and shorter loading periods.

As with the fairlead assessment work, the rope core and surface temperatures were measured during these tests.

3.3 Creep Rupture

The challenge with the assessment of creep performance is to generate a measurable effect (if any) within a economically sensible timeframe. Work undertaken with a very harsh loading regime is open to the criticism that the loading is unrealistic when compared to that which might normally be experienced in service.

Thus a twofold test was employed:

1. An initial 'severe' test, at 70% rope MBL and 50°C to be sustained for 100 hours. If the rope ‘passed’ that test, that is, it did not fail, it could be taken that its creep service performance would be sufficient and no further testing would be required.
2. If the rope failed under test 1, then a longer duration, lower load test would be conducted at 50% MBL and 40°C for up to 400 hours.

During the tests the equipment monitored temperature and elongation.

4 Results

4.1 Breaking load test results

A series of wet and dry breaking load tests was undertaken on samples with spliced eye loops. These tests were conducted according to the OCIMF guidelines [**3**, section F]. From this data, the minimum breaking loads (MBL) presented in Table 1 were determined. The values presented in Table 1 were used to define the loading for each of the ropes throughout the series of tests.

Rope material	MBL (tonnes)	MBL (kN)
Technora T200W	82	804.4
Technora T200WL	82	804.4
Twaron	75	735.8
HMPE	70	686.7

Table 1: Rope MBLs used to define the loads for the abrasion, creep and TCLL tests.

4.2 Operation over a fixed fairlead

4.2.1 Block loading results

All of the rope samples successfully completed the six repeats of the seven blocks of loading (total 1650 cycles). Figure 8 presents a plot of the temperatures measured in the fairlead section of rope throughout the test. In this case the results are for the Twaron 2304 fibre rope sample, but all sets of results were broadly similar. The thermocouple (T3) in the centre of the test zone which would have experienced most contact with the fairlead generally recorded the highest temperatures, then those closest on either side (T4 and T2) and so on. T4 readings were generally higher than T2 as they were associated with the rope travelling onto the fairlead under higher tension. It is also noted that during the course of the test elongation of the nylon grommet allowed the thermocouple in position T4 to move towards the centre of the test zone.

A consideration of the peak temperatures (Table 2) shows that the highest temperatures attained were all fairly similar over the set of tests. The two Technora samples attained the highest temperature increases (ΔT3). The reason for this is probably because the cyclic test loads were the highest being defined as a percentage of rope MBL - and so the rope would move more over the test fairlead (the same nylon grommet was used for all tests). It is however noted that the Twaron sample which had the next highest MBL had the lowest temperature increases of the four samples.

The Technora sample with the higher level of lubricant on the fibres (T200W) showed a slightly bigger temperature increase than the otherwise similar sample (T200WL). Given that the work put into the rope would be the same it is possible that the added lubricant level promoted inter fibre slip and heat build up. It is equally possible that the thermocouples were in slightly different positions in the rope with respect to the fairlead and the observed difference is not a real effect.

Finally, the results for the HMPE rope (Figure 9) showed temperature rises which were just above the Twaron fibre sample, but below the two Technora samples. It is interesting to note, comparing the results for the aramid and the HMPE samples (Figures 8 and 9), that the HMPE heats and cools more quickly. Each of the seven different loading blocks in the six repeats is readily discernible.

The thermocouple inserted away from the fairlead, near the actuator end showed that for the size of rope and cyclic frequency employed in the tests, there was no appreciable heating caused by the tensile fluctuations for any of the materials.

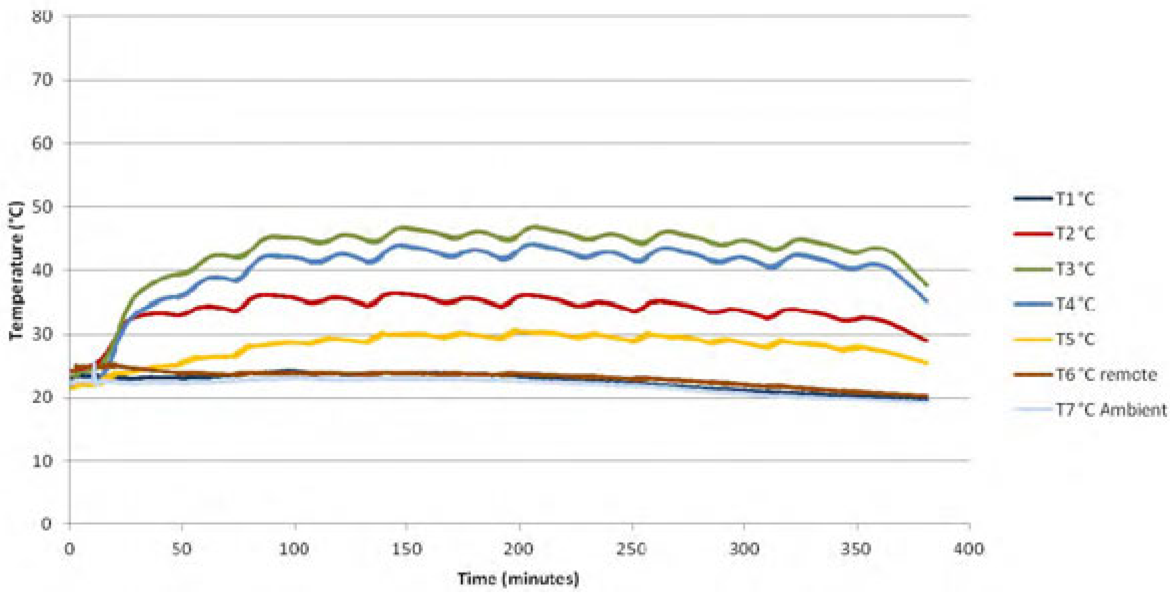


Figure 8: Temperature of the thermocouples at various positions along the sample Twaron 2304 throughout the block loading fairlead test.

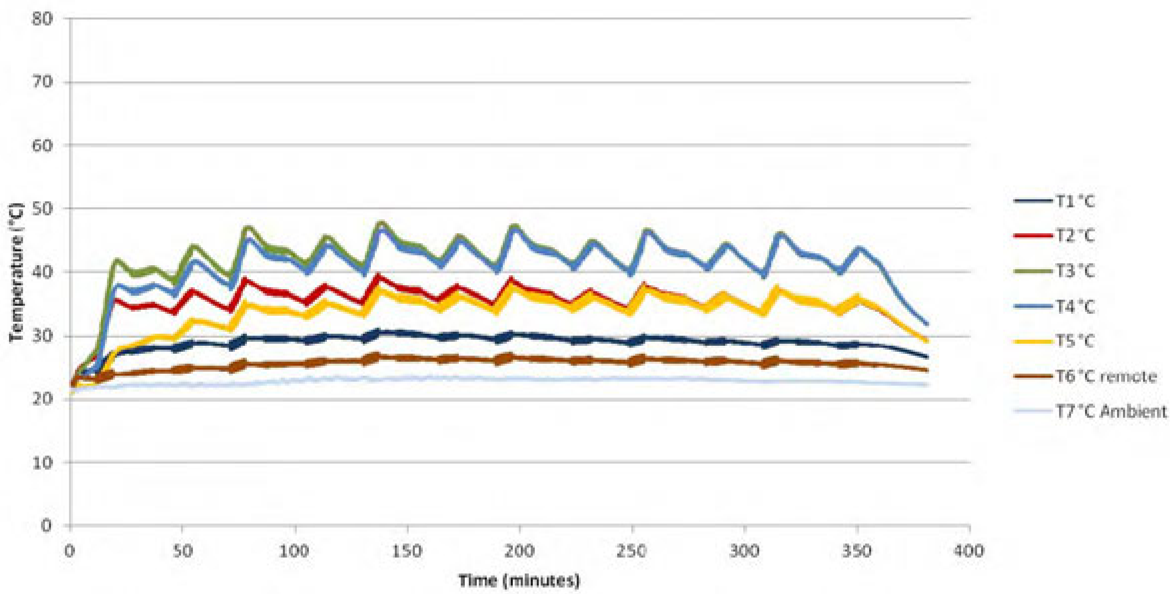


Figure 9: Temperature of the thermocouples at various positions along the sample HMPE throughout the block loading fairlead test.

Material	T3 °C	T4 °C	Ambient °C	ΔT3 °C	ΔT4 °C
T200W	51.1	48.7	22.0	29.1	26.7
T200WL	47.0	43.3	20.0	27.0	23.3
Twaron 2304	46.8	44.1	22.4	24.4	21.7
HMPE	48.0	46.7	23.0	25.0	23.7

Table 2: Summary of peak temperatures (and those temperatures above ambient) during the block loading fairlead tests.

Following completion of the block loading fairlead tests, the four samples were examined for degradation. All ropes exhibited minimal damage to the jackets on the outside of the rope. The jackets were removed to allow examination of the load bearing core. In all samples there were dimples/imprints on the surface of the strands where the jacket had contacted.

The samples were then examined for inter-strand abrasion. Figure 10 shows the condition of each in the region of the T3 position. Both of the T200 samples had similar levels of inter-strand abrasion. The inter-strand abrasion on the Twaron 2304 sample seemed slightly lower. The condition of the HMPE rope was very good, with little abrasion and only a few broken filaments noted (Figure 10d).

(a) T200W

(b) T200WL

(c) Twaron 2304

(d) HMPE

Figure 10: Internal condition of the ropes on completion of the block loading fairlead tests.

4.2.2 Mixed sea state results

As with the block loading tests, all samples successfully completed the mixed sea state fairlead test. An example of the results for a mixed sea state test is shown in Figure 11. With reference to this Figure, along the bottom of the graph is an indication of the sea state level at that time during the test, in increasing height: low, medium or severe.

Table 3 summarises the peak temperatures relative to ambient for each of the samples for the three central thermocouples. Generally the ropes were hottest on the completion of two consecutive severe sea states (repeats 7 and 8 at about 300 minutes), although the HMPE sample did reach a higher peak further on in the test. However, this was only because the ambient temperature had increased too.

The increase in temperatures experienced by the ropes was lower than that in the block loading tests, showing that the ropes will readily cool under less severe load cycling. A peak temperature of 50.5 °C was recorded on T5 during the Twaron 2034 test. It is not obvious why this should be so, but may be as a result of the positioning of the thermocouple which is difficult to do very accurately.

As with the block loading tests, on completion of the load cycling the samples were dismantled for inspection. The damage was similar in nature to that found in the block loading test samples, but more distributed over the rope, which was to be expected given the 'random' nature of the loading. The level of damage was also slightly increased, but again this was to be expected as the test duration was about 5 times as long. The HMPE rope had experienced some creep. It felt hard to touch, and the lay length had increased locally in the area which had been operating over the fairlead.

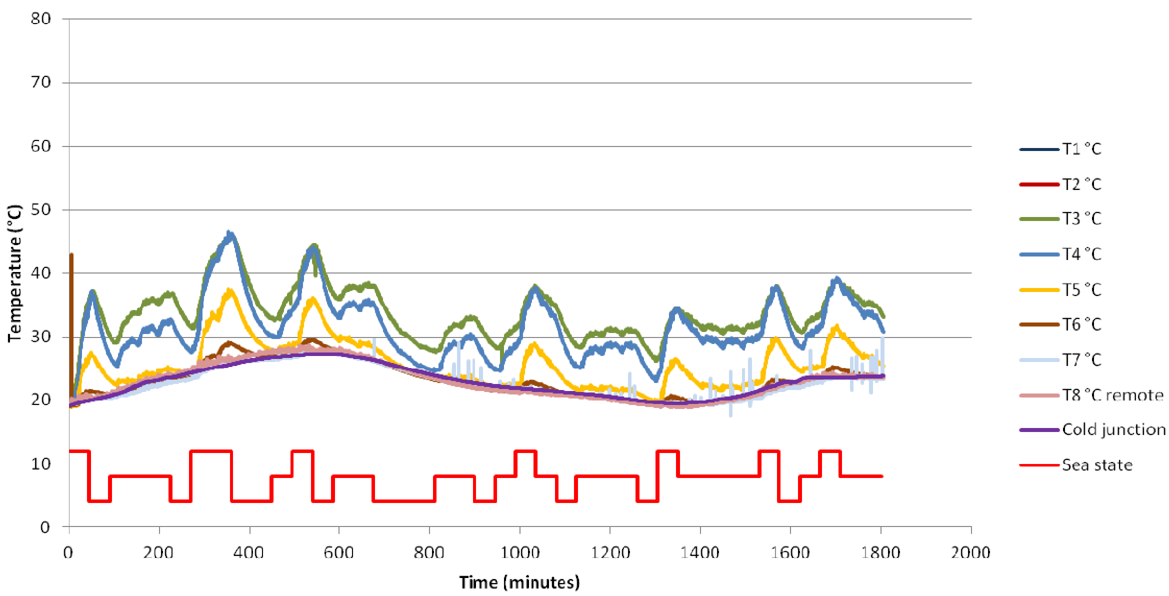


Figure 11: Temperature of the thermocouples at various positions along the T200WL sample throughout the mixed sea state loading fairlead test.

Material	T3 °C	T4 °C	T5 °C	Ambient °C	ΔT3 °C	ΔT4 °C	ΔT5 °C
T200W	35.3	42.7	43.1	23.3	12.0	19.4	19.8
T200WL	46.6	46.6	37.5	25.5	21.1	21.1	12.0
Twaron 2304	36.5	45.8	50.5	19.9	16.6	25.9	30.6
HMPE	36.6	-	32.3	18.5	18.1	-	13.8

Table 3: Summary of peak temperatures relative to ambient during the mixed sea state fairlead tests.

4.3 Tension-Tension fatigue performance

The results of the two sets of four TCLL tests are presented in Tables 4 and 5. Table 4 presents the results of the test conducted to the OCIMF specification, whilst Table 5 presents the results for the tests conducted with parameters more representative of service conditions.

Figure 12 compares these two sets of results. It can be seen that the pairs of results for each of the aramid ropes are broadly in line with each other at about 70%. The T200W and T200WL samples both had very consistent results, with the TCLL under service conditions giving results just higher than for the equivalent standard OCIMF test. The difference in absolute values is probably a feature of the different weight of marine finish on the fibres of these two samples, with the heavier finish leading to marginally better results. There is a greater difference in the results for the Twaron 2304 tests. The 'service' TCLL life is in line with the other aramid samples, but the result for the OCIMF is down. A review of the post test inspection suggests that this test failed prematurely at the termination, and is therefore not a true measure of the rope's performance.

In sharp contrast to the consistent performance of the aramid samples, the HMPE material showed a significant drop in performance when comparing the OCIMF and 'service' results. The HMPE OCIMF TCLL test was the best of all four materials at just under 75%. The 'service' TCLL on HMPE was just over 12%, showing the much higher sensitivity to elevated temperatures.

Material	Block in which rope failed (%)	No. of cycles in that block	Equivalent from previous blocks	Total	TCLL%
T200W	70	539	215	754	68.7
T200WL	70	96	215	311	63.9
Twaron 2304	60	82	251	333	52.4
HMPE	80	108	113	221	74.4

Table 4: TCLL to OCIMF, wet, room temperature, longer cycling period.

Material	Block in which rope failed (%)	No. of cycles in that block	Equivalent from previous blocks	Total	TCLL%
T200W	80	20	113	133	71.7
T200WL	70	416	215	631	67.8
Twaron 2304	70	786	215	1001	70.0
HMPE	50	51	0	51	12.1

Table 5: Modified TCLL: dry, 40°C, 0.1 Hz.

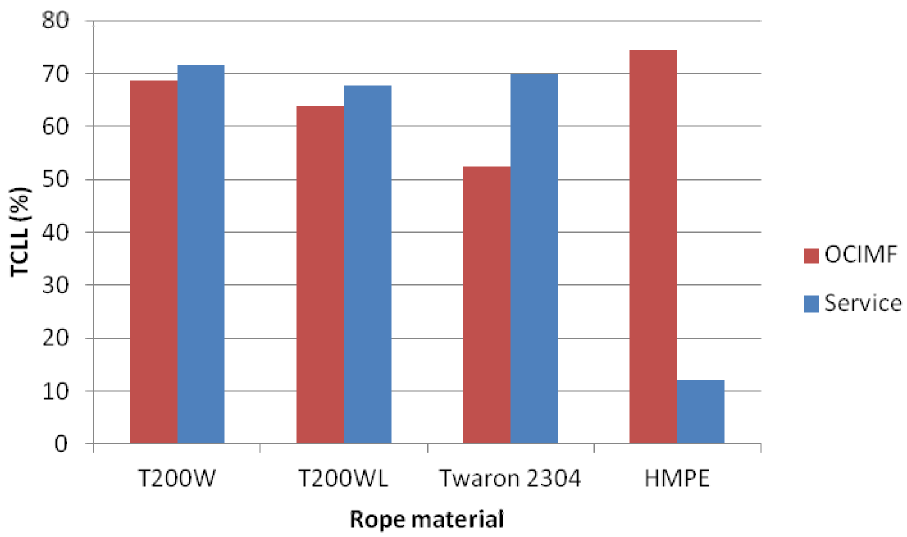


Figure 12: Comparison of TCLL results for tests run to OCIMF specification and to more representative service conditions.

4.4 Creep

Creep tests were initially conducted on all four rope materials under a load of 70% MBL in a thermostatically controlled chamber at 50°C. These tests were scheduled to run for 100 hours.

The rope and chamber temperatures were checked by means of thermocouples to ensure that the rope temperature was as required.

Thermocouples were placed:

- axially along the rope in the middle of the chamber in the centre (core) of the rope;
- in the same axial position on the outer jacket of the rope; and,
- in the chamber opposite the thermostat.

The rope was placed in the test machine and the heating chamber turned on. The rope was allowed to reach a stable temperature before any load was applied. Once the rope was at temperature the data logger was started and the sample was loaded to the test load.

Figure 13 shows the results of the '100 hr' creep tests. It can be seen that the three aramid samples completed the full 100 hours with very low creep. Note that the results are based on machine cross head movement and include termination effects and approximately 1.5 m of rope which would have been outside of the heated chamber.

In contrast to the aramid ropes, the HMPE sample failed after about 10 minutes under load. Figure 14 shows the section of the graph shown in Figure 13 with an expanded x-axis.

As defined in the test programme, any material which did not complete the 100 hour test was then tested under less severe conditions in a '400 hour' test.

Figure 15 presents the results of the 400 hour creep test undertaken on the HMPE rope. In this test the temperature was 40°C and the test load 50% MBL (for ease of reference the 100 hour test result is also shown in Figure 14). It can be seen that the HMPE sample failed after about 60 hours into the 400 hour test.

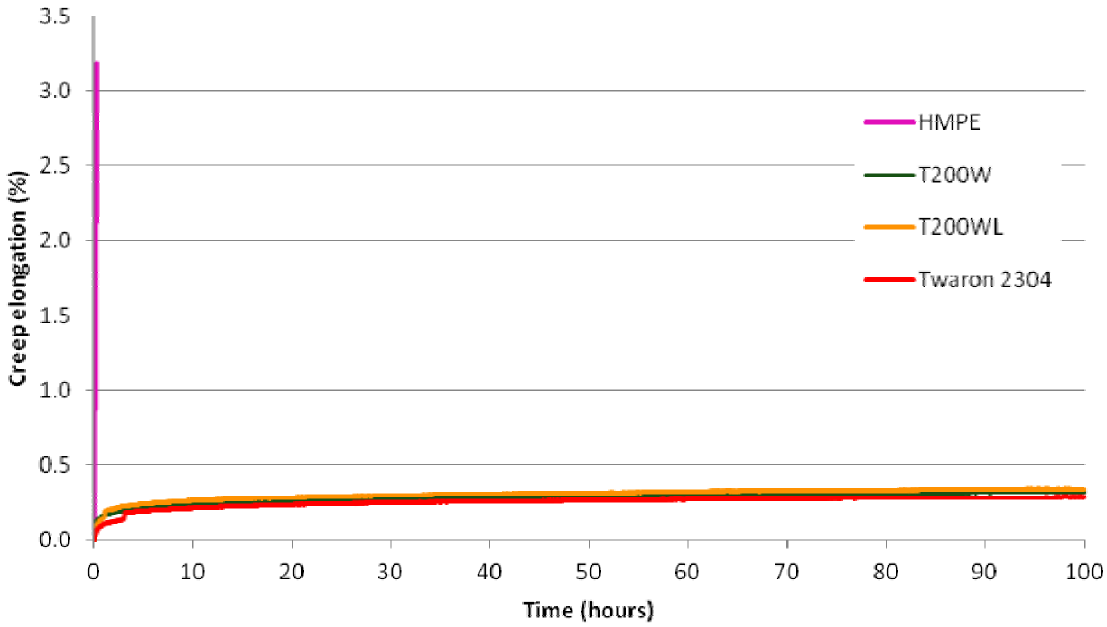


Figure 13: Comparison of 100 hr creep test results for samples at 70% rope MBL and 50°C.

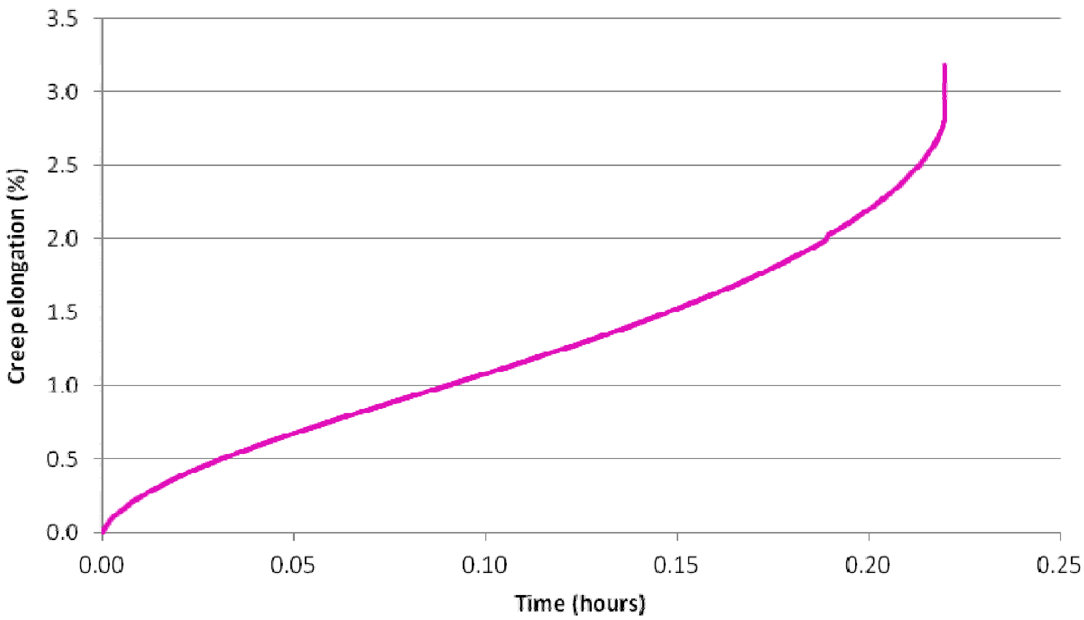


Figure 14: 100 hr creep test result for HMPE sample at 70% rope MBL and 50°C.

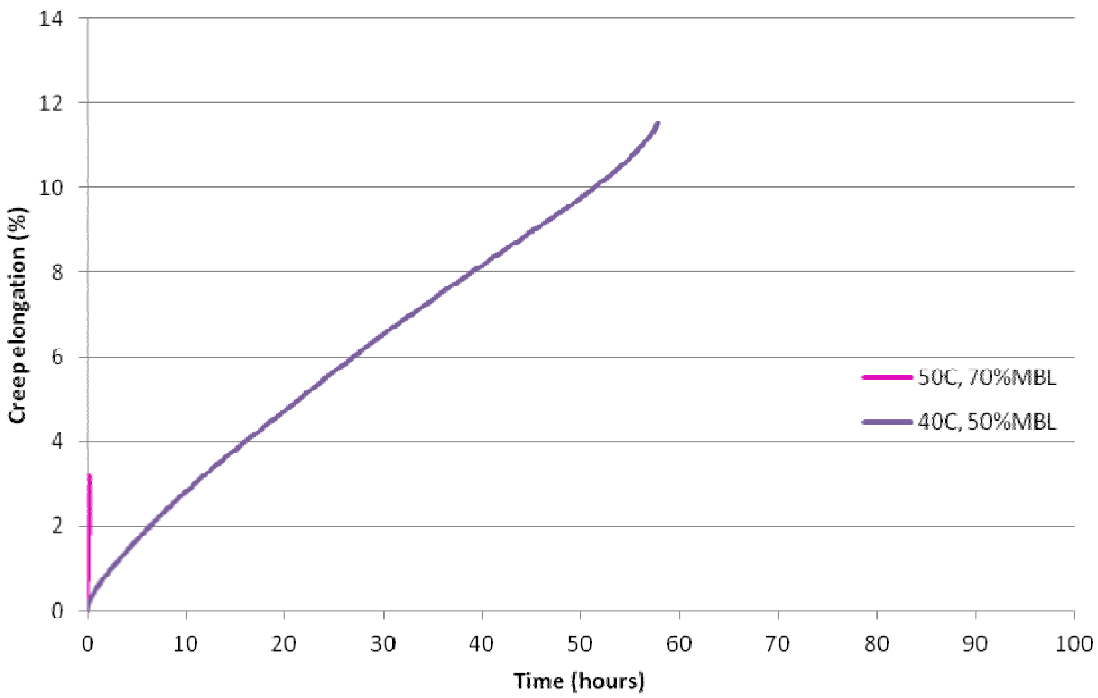


Figure 15: 400 hr creep test result for HMPE sample at 50% rope MBL and 40°C.

5 Discussion and Conclusions

The programme of work reported here was designed to examine the key performance requirements for ropes for LNG moorings. These tests have included:

- Tensile break loads;
- Operation over fixed fairleads;
- Tensile fatigue performance (TCLL); and,
- Creep performance

Tests have been undertaken on a range of aramid samples:

- Technora, T200W, (Technora with 12% by weight marine finish);
- Technora T200WL (Technora with 3% by weight marine finish); and,
- Twaron, TW2304, (Twaron with 3% by weight marine finish)

Comparative tests have also been performed on a three-strand HMPE rope, one of the products currently in use in the market.

Tests have shown that it is possible to produce aramid ropes of similar diameters to the HMPE ropes which meet and exceed its strength. It is, however, noted that the HMPE rope which was used as a comparison in these tests was a three strand construction with a lower packing efficiency than that seen in the aramid ropes.

The block loading and mixed sea-state fairlead tests showed that all ropes performed well. All ropes completed both test scenarios without failure. A comparison of the ropes following testing showed that the aramid samples exhibited more severe inter-strand abrasion than the HMPE sample.

In the tensile fatigue tests (TCLL), the three aramid samples showed very consistent behaviour both for the OCIMF tests (wet and low cycling frequency) and for the tests designed to be more representative of service in hot climates: 40°C, dry and shorter period with a TCLL level of about 70%. The HMPE sample performed well in the standard OCIMF TCLL test (a TCLL level of about 75%), but performed poorly in the tests at elevated temperature (TCLL level of about 12%).

The poor performance of the HMPE rope in the service TCLL tests was echoed in the creep tests. The HMPE rope failed very quickly in the 100 hour test (after about 10 minutes at 50°C and 70% MBL), whilst the aramid samples completed the 100 hours with only minimal creep. At a lower temperature (40°C combined with 50%MBL) the HMPE rope lasted longer, but still showed a vulnerability to creep rupture.

The results of this work show that in mooring applications at elevated temperature a rope with aramid load bearing structure will provide a better overall performance than the currently offered HMPE rope.

6 References

[**1**] **Ridge, I.M.L., Hobbs, R.E. and Banfield, S.J.** Wear of ropes in mooring fairleads, Proceedings of the OIPEEC Conference 'Safe use of ropes' March 2011, 61-83, ISBN: 978-0-9552500-3-3.

[**2**] **Black, K., Flory, J.F., Banfield, S.J. and Ridge, I.M.L.** Low-Friction, Low-Abrasion Fairlead Liners, *MTS/IEEE Oceans 2012 Hampton Roads Conference*, IEEE, Piscataway, NJ and MTS, Washington, DC, 2012.

[**3**] **OCIMF** Guidelines for the purchasing and testing of SPM hawsers, first edition 2000, pub. Witherby Seamanship International Ltd., Scotland, 2009.

MAIB Safety Bulletin SB1/2016

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

SAFETY BULLETIN

SB1/2016

February 2016

Extracts from The United Kingdom Merchant Shipping (Accident Reporting and Investigation) Regulations 2012

Regulation 5:
"The sole objective of a safety investigation into an accident under these Regulations shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of such an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

Regulation 16(1):
"The Chief Inspector may at any time make recommendations as to how future accidents may be prevented."

Press Enquiries:
020 7944 3021

Out of hours:
020 7944 4292

Public Enquiries:
0300 330 3000

NOTE

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall be inadmissible in any judicial proceedings whose purpose, or one of whose purposes is to attribute or apportion liability or blame.

All bulletins can be found on our website:
https://www.gov.uk/maib

For all enquiries:

Email: maib@dft.gsi.gov.uk
Tel: 023 8039 5500
Fax: 023 8023 2459

Mooring line failure resulting in serious injury to a deck officer on board *Zarga* alongside South Hook LNG terminal, Milford Haven on 2 March 2015

Photograph courtesy of Fotoflite.com

Zarga

MAIB SAFETY BULLETIN 1/2016

This document, containing safety lessons, has been produced for marine safety purposes only, on the basis of information available to date.

The *Merchant Shipping (Accident Reporting and Investigation) Regulations 2012* provide for the Chief Inspector of Marine Accidents to make recommendations at any time during the course of an investigation if, in his opinion, it is necessary or desirable to do so.

In co-operation with the Republic of the Marshall Islands, the Marine Accident Investigation Branch (MAIB) is carrying out an investigation into a mooring line failure resulting in the serious injury to a crewman on board the Marshall Islands flagged Liquefied Natural Gas (LNG) carrier *Zarga* at the South Hook LNG terminal, Milford Haven on 2 March 2015.

The MAIB will publish a full report on completion of the investigation.

Steve Clinch
Chief Inspector of Marine Accidents

<u>NOTE</u>

This bulletin is not written with litigation in mind and, pursuant to Regulation 14(14) of the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012, shall not be admissible in any judicial proceedings whose purpose, or one of whose purposes, is to apportion liability or blame.

This bulletin is also available on our website: www.gov.uk/maib

Press Enquiries: 020 7944 3021; Out of hours: 020 7944 4292

Public Enquiries: 0300 330 3000

BACKGROUND

On 2 March 2015, a deck officer on board the LNG carrier, *Zarga*, suffered severe head injuries when he was struck by a mooring rope that had parted while repositioning the vessel at the South Hook LNG terminal, Milford Haven. The officer, who was in charge of the vessel's forward mooring party, was airlifted to a specialist head injuries trauma unit for emergency surgery.

In July 2015, MAIB issued Safety Bulletin SB1/2015 in relation to the same incident. The Safety Bulletin highlighted the dangers of snapback when a high-modulus, low elongation, mooring rope fails when it is connected to a high elongation tail that is intended to reduce excessive dynamic loads on the mooring line during normal or severe operating conditions. This Safety Bulletin should be read in conjunction with SB1/2015.

MOORING ROPE

The mooring lines fitted to *Zarga* were high-modulus polyethylene (HMPE) jacketed synthetic fibre ropes. They had a 44mm diameter and were 275m long with a minimum breaking load (MBL) when new of 137 tonnes. A close-fitting braided abrasion-resistant jacket encased the rope's HMPE load-bearing core, which comprised three, low twist construction strands. Each strand consisted of 32 rope yarns. The core was wrapped in a self-amalgamating tape that assisted in bonding the jacket to the core.

The failed mooring rope had completed 1342 operating hours; it was 5 years old and had been expected to last for at least 8 years. The rope had a documented history and its previous on board visual and tactile inspection assessed it to be in good condition. Through life information recorded for each of the vessel's 20 mooring lines included the port of use, and the prevailing ambient air temperatures and local weather conditions during use.

INITIAL FINDINGS

The rope failed at an indicative load of 24 tonnes. Subsequent non-destructive assessment of the rope by an industry expert did not identify any defects that would indicate that it had been used or operated incorrectly **(Figure 1)**.

When the close-fitting jacket was removed from the rope at each side of the failure point, the rope yarns in all three strands exhibited moderate to severe kinking. The Z-shaped kinks were visually apparent and were found at close intervals with, for example, 22 occurring over a length of 2.78m **(Figure 2)**.

During the rope's dissection, 12 of the 96 rope yarns were found to have separated. The rope yarns were found to have failed at kink points and had separated as if they had been cut with a sharp knife at 45 degrees **(Figures 3** and **4)**.

Following the identification of the kinking and failed rope yarns, a number of additional sections of the rope were inspected. Further rope yarn failures and damage to the rope yarns at filament level were seen **(Figure 5)**. The damage identified was consistent with axial compression fatigue.

Operating ropes around tight bend radii can exacerbate axial compression fatigue and also cause internal abrasion damage. In this case, the failed mooring rope had been run from its winch drum to the LNG terminal hook via a deck roller bollard and a ship's side roller fairlead. The diameters of the rollers for both the deck bollard and deck fairlead were less than the minimum recommended by the rope manufacturer for its 44mm HMPE jacketed ropes.

Figure 1
Failed end of rope

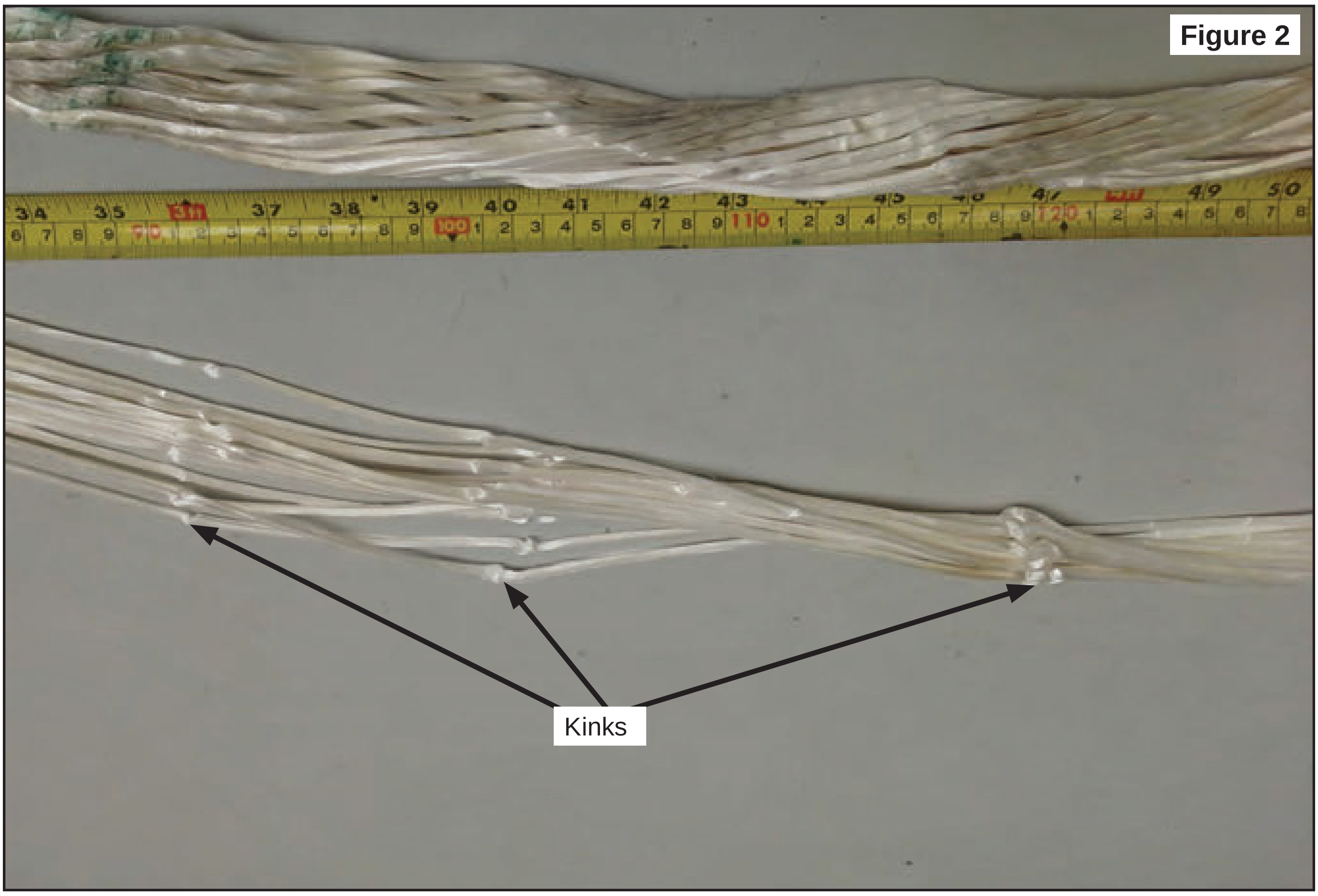


Figure 2
Kinks

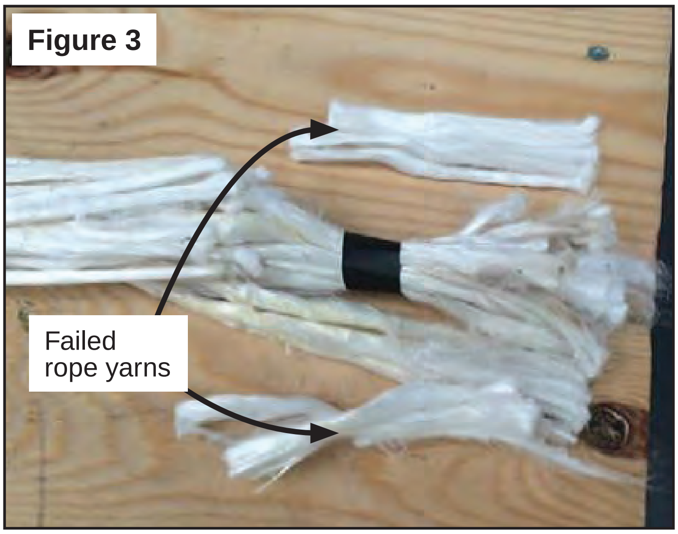


Figure 3

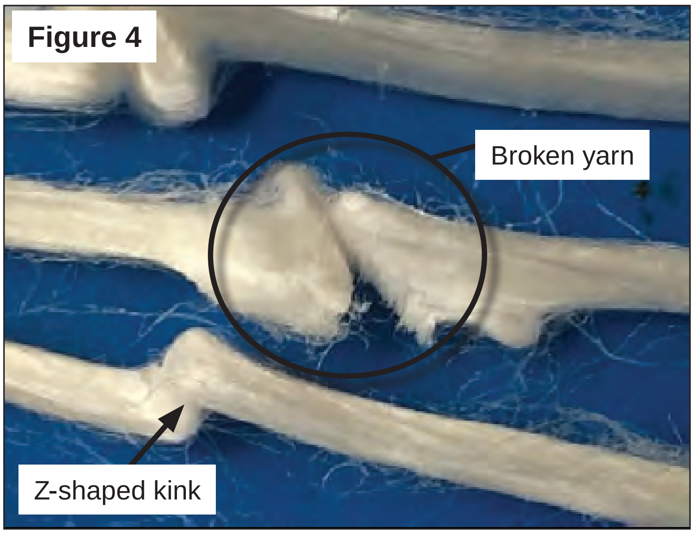


Figure 4

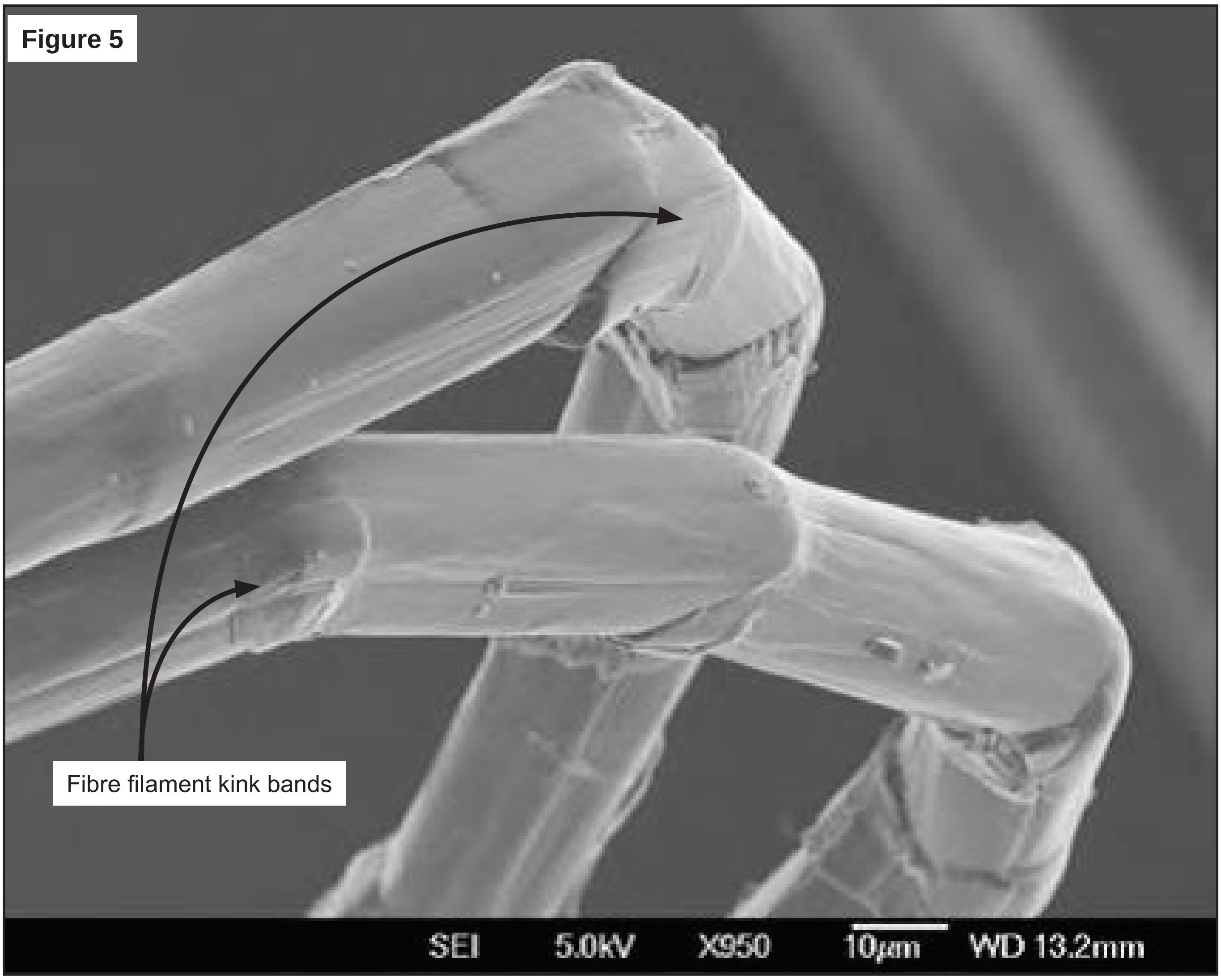


Figure 5

Close-fitting jackets prevent operators from visually inspecting these types of rope for core and yarn fatigue damage, and there are currently no non-destructive tests available to assess the level of fatigue degradation in fibre filaments in ropes. If it had been possible to visually inspect the load-bearing core of *Zarga*'s rope, the rope yarn kinks and the broken rope yarns would have been identified.

The HMPE rope failed at well below its certificated minimum breaking load and well before its anticipated lifetime prediction. This was the latest in a series of mooring line failures that had occurred on board large LNG carriers at, mainly, exposed berths over several years. The investigation into the causes and circumstances of the rope failure is ongoing and will be discussed in the full investigation report, along with other safety issues identified during the investigation.

SAFETY LESSONS

Close-fitting jacketed synthetic fibre ropes with low twist constructions are more prone to failure under normal operating conditions than other mooring rope constructions. This is especially the case where the diameter to diameter (D:d) ratio between a ship's deck fittings and its mooring ropes, is less than that recommended by the rope's manufacturer. The nature of the close-fitting jacket precludes visual inspection of the rope's core for signs of degradation. Operators of vessels using close-fitting jacketed synthetic fibre mooring ropes are strongly advised to contact the rope's manufacturer/supplier to:

- Confirm or otherwise that the rope is suitable for its intended use and envisaged operating conditions including, specifically, that it is compatible with the vessel's deck fittings, and,
- Ensure that an appropriate regime exists to monitor the condition of the ropes in use so as to maintain a high level of confidence that they can be replaced before they become materially weakened or degraded.

Issued February 2016

OCIMF information paper on *Zarga*'s rope failure

The Hazards of Snap-back

Initial learnings from a serious incident of mooring line failure

September 2015

Issued by the

Oil Companies International Marine Forum
29 Queen Anne's Gate
London SW1H 9BU
England
Telephone: +44 (0)20 7654 1200
Fax: +44 (0)20 7654 1205

Email enquiries@ocimf.com

www.ocimf.com

The Oil Companies International Marine Forum (OCIMF)
is a voluntary association of oil companies with an interest in the shipment and terminalling of crude oil, oil products, petrochemicals and gas.

Our mission is to be the foremost authority on the safe and environmentally responsible operation of oil tankers, terminals and offshore support vessels, promoting continuous improvement in standards of design and operation.

Contents

Introduction

A deck officer in charge of the forward mooring party on board a very large liquid natural gas (LNG) carrier was seriously injured when a tensioned mooring line parted. At the time of the incident, the deck officer was standing in a location that was not identified on board the vessel as being within a snap-back danger zone. This incident has highlighted the behaviour of High Modulus Synthetic Fibre (HMSF) mooring lines fitted with synthetic tails when they fail under load.

Snap-back is the sudden release of the energy stored in a tensioned mooring line when it parts as the mooring line reverts to its original length. The two ends of the line recoil or snap-back towards or past their secured ends. When a synthetic mooring line breaks, the snap-back effect can be extremely powerful and the rope ends may reach a high velocity as they recoil. Anyone standing within the snap-back zone at either end of the line risks serious injury or death.

This information paper provides a brief description of the incident and considers if additional guidance, including that contained in OCIMF publications such as *Mooring Equipment Guidelines* (MEG3) and *Effective Mooring*, is required. Reference is also made to the incident investigation being conducted by the UK's Marine Accident Investigation Branch (MAIB) and the recommendations contained in the interim Safety Bulletin issued in July 2015 (SB1/2015).

Background

At the time of the incident, the vessel was being warped into position by tensioning the forward back springs. The deck officer was in charge of the forward mooring party standing aft of the fairlead through which the spring lines passed. He was directing operations by signalling to a seaman who was located well forward, and who was in a position to relay the signals to the winch operator.

The mooring line parted inboard from a pedestal fairlead. The section of the line between the break and the port shoulder roller fairlead struck the deck officer on the head as it whipped back before going overboard through the fairlead. The deck officer was found lying unconscious forward of the roller fairlead. He had sustained multiple skull fractures.

The mooring line that failed was a 44-millimetre diameter sheathed ultra-high modulus polyethylene (UHMPE) line. The line was fitted with a 22-metre long polyester/polyethylene tail. The section of UHMPE line in use between the winch and the connection with the tail was approximately 68 metres long.

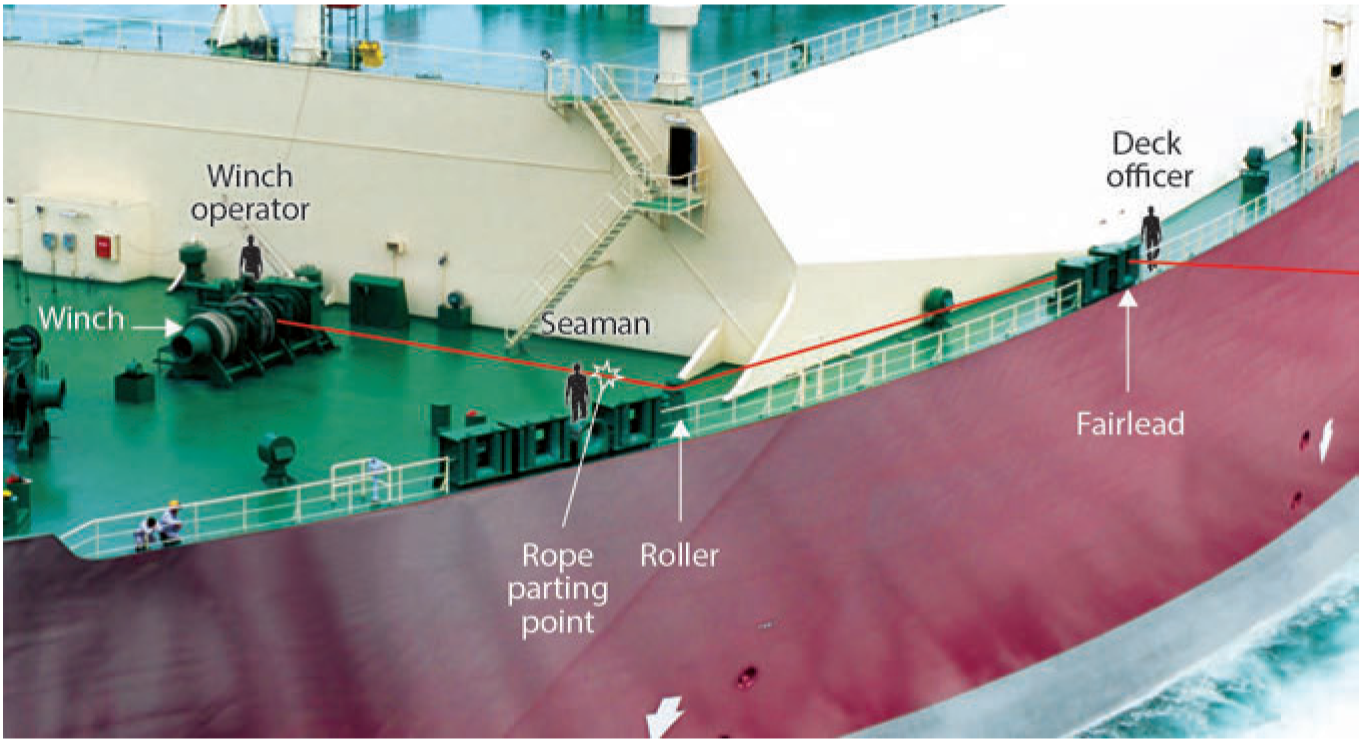


Figure 1: *Location of injured deck officer relative to rope parting point*

Following the incident, computer modelling was used to assess the dynamic trajectory of the entire length of the UHMPE rope from its point of failure. The modelling indicated that it was highly probable that the rope would go aft of the roller fairlead and wrap around it before finally going outboard. The results support the theory that the deck officer was struck while standing aft of the roller fairlead, and that he was knocked forward to the position where he was found.

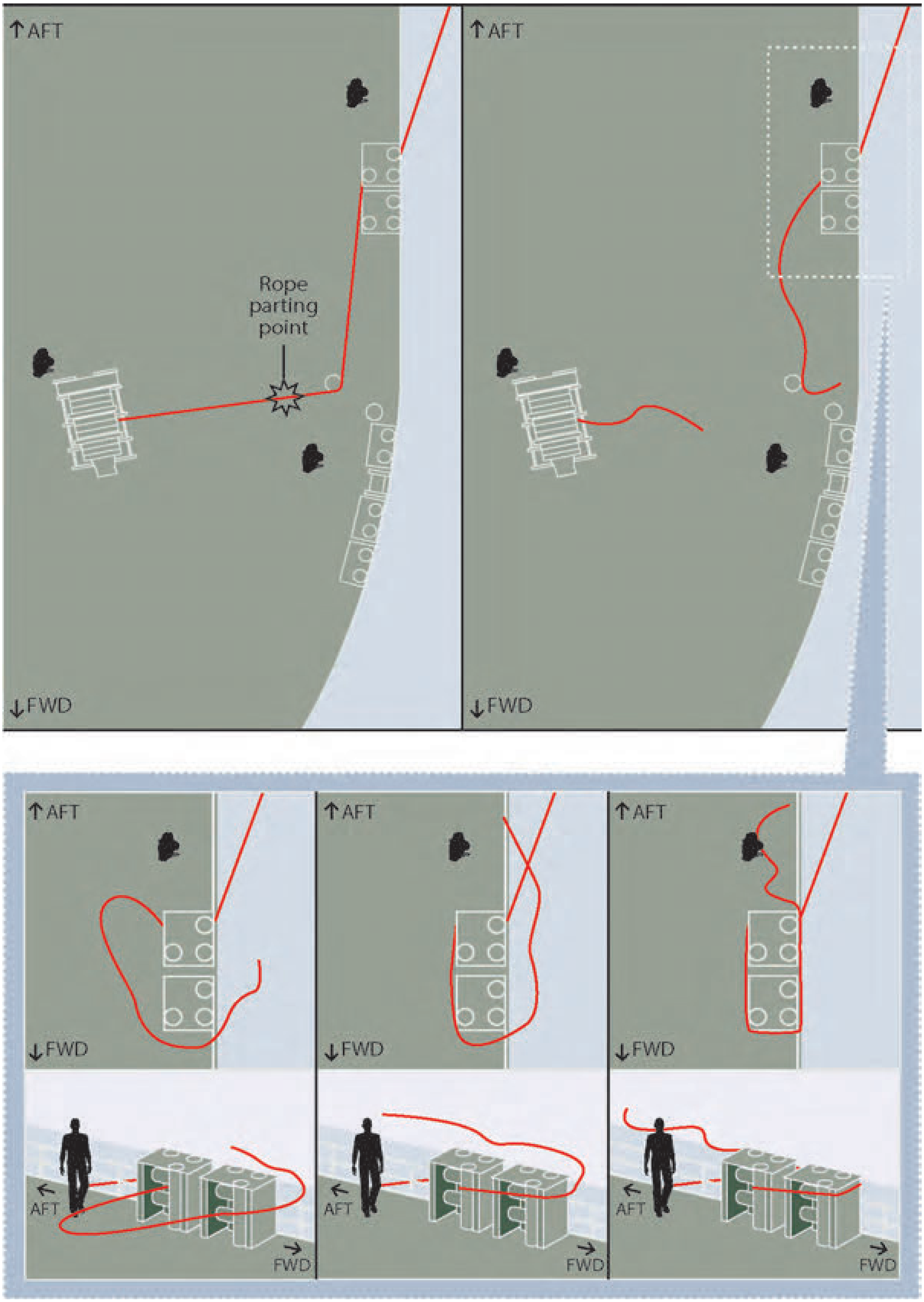


Figure 2: *Example trajectory of failed line between 0.19 and 0.29 seconds after parting*

General considerations

The safety hazards associated with mooring lines under tension are described in various industry publications, such as OCIMF's *MEG3* and *Effective Mooring* and those published by other bodies, such as the UK Maritime and Coastguard Agency's *Code of Safe Working Practices for Merchant Seamen*. Snap-back is recognised as posing a significant danger, and the publications provide examples of potential danger zones.

The existing guidance is designed to be simple so that it can be adapted to suit various mooring scenarios and arrangements and, as the publications acknowledge, it is not possible to predict all the potential danger zones. However, the various guidance documents do not highlight the complex nature of snap-back and the many factors that may influence the trajectory of a parted line.

Actual mooring arrangements on board require specific analysis to determine the most likely snap-back zones. The simplistic diagrams in *MEG3* may be used to guide this analysis, but they should not be considered as representing all mooring configurations.

With regard to HMSF mooring lines, *MEG3* states that their low elasticity when compared with conventional fibre lines results in them having very little snap-back when they fail. *MEG3* indicates that the snap-back characteristics of the lines are considered to be similar to wire ropes, excepting that the snap-back "will generally be along the length of the line and not in a snaking manner, as found with wire ropes". In the recent incident, the shorter length of line between the break and the winch dropped to the deck and did not snap back.

However, the existing guidance does not highlight what the impact on snap-back will be when a synthetic tail is added to an HMSF mooring line. Synthetic tails provide additional elasticity in the mooring system and serve to reduce peak dynamic loads. As a result of the tail's elasticity, the elongation of the total mooring line under tension is increased; this introduces significant stored energy that will be released if the mooring line fails. The snap-back characteristics of the HMSF mooring line, initially considered to be relatively benign, will be heavily influenced by the addition of the synthetic tail.

The length of tail fitted to the HMSF mooring line will influence the amount of stored energy in the system. The longer the tail, the greater the elasticity and stored energy, and the greater the likelihood of recoil and snap-back should the mooring line fail.

Recommendations and lessons learnt

The following recommendations and lessons learnt include those contained in the MAIB's interim Safety Alert relating to snap-back; these should be widely promoted and shared:

- When connecting synthetic tails to HMSF and wire mooring lines, the energy introduced because of the elasticity of the tails can significantly increase the snap-back hazard.
- Elongation is proportional to the length of the tail. The fitting of longer synthetic tails, e.g. 22m tails, proportionally increases the stored energy and the amount of snap-back that can be expected.
- Elongation of the tail will increase the amount of stored energy in the tail when it is under load. Should a mooring line fitted with a synthetic tail fail, it should be expected that the snap-back will affect the entire length of the mooring line, irrespective of the type of mooring line used. It is important that ship's personnel are aware of the increased snap-back hazard introduced by the fitting of synthetic tails.
- Ship owners/operators should ensure that the type of mooring lines and tails used for mooring are suitable for the task and that the dangers of snap-back are fully analysed, taking account the mooring configuration employed. Mooring plans should depict the identified snap-back hazardous zones.
- Mooring lines led around roller pedestals and fairleads have the potential to create complex snap-back zones. Ship operators and masters should conduct their own risk assessments to ensure potential snap-back zones are identified and reviewed for every mooring configuration.
- Prior to any mooring operation, a pre-mooring tool box talk should be held to ensure that mooring teams are aware of the potential for snap-back in the proposed mooring configuration, and the probable areas of the mooring deck that are not safe when mooring lines are under load.
- For new-build ships, full consideration should be given to this revised understanding of snap-back and the ergonomics involved with positioning of both mooring equipment and mooring team to minimise the dangers to personnel. Issues such as the provision of clear line of sight between the winch operator, personnel signalling and personnel in supervisory oversight of the mooring operations should be considered.

Future activity

In light of this serious incident, OCIMF will undertake a review of the existing guidance on snap-back contained in *MEG3* and *Effective Mooring* to clarify the use of the example snap-back diagrams and to include other learnings from this incident. The aim will be to better understand the many factors that influence snap-back, and to recommend procedures aimed at minimising the exposure of mooring personnel to the potential hazards.

Further work will be undertaken to gain a better understanding of the technology of ropes manufactured from HMSF materials and the issues that may affect their performance. Such issues may include the impact of temperature, time in service, cyclic loads, rope memory, inspection procedures and their susceptibility to damage, such as kink banding and axial compression.

A voice for safety

Oil Companies
International Marine Forum
29 Queen Anne's Gate
London SW1H 9BU
United Kingdom

T +44 (0)20 7654 1200
F +44 (0)20 7654 1205
E enquiries@ocimf.com

ocimf.com