ACCIDENT REPORT

Report on the investigation of

the failure of a mooring line

on board the LNG carrier

Zarga

while alongside the South Hook Liquefied

Natural Gas terminal, Milford Haven

resulting in serious injury to an officer

on 2 March 2015

SERIOUS MARINE CASUALTY REPORT NO 13/2017 JUNE 2017

MAIB
MARINE ACCIDENT INVESTIGATION BRANCH

Extract from

The United Kingdom Merchant Shipping

(Accident Reporting and Investigation)

Regulations 2012 – Regulation 5:

"The sole objective of the investigation of an accident under the Merchant Shipping (Accident Reporting and Investigation) Regulations 2012 shall be the prevention of future accidents through the ascertainment of its causes and circumstances. It shall not be the purpose of an investigation to determine liability nor, except so far as is necessary to achieve its objective, to apportion blame."

NOTE

This report 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.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ABS	-	American Bureau of Shipping
Bridon	-	Bridon International Ltd
°C	-	Degree Celsius
CCR	-	Cargo control room
CCTV	-	Closed circuit television
cm	-	centimetre
C/O	-	Chief officer
COSWP	-	Code of Safe Working Practices for Merchant Seamen
DDRS	-	Deepwater deployment and recovery system
DNV-GL	-	Det Norske Veritas – Germanisher Lloyd
DSC	-	Differential Scanning Calorimetry
DSM	-	DSM Dyneema® BV
EUROCORD	-	European Federation of Rope and Twine Manufacturers
Fo’c’s’le	-	Forecastle
For’d	-	Forward
Fps	-	Feet per second
FRM	-	Fibre Rope Modelling
GPa	-	gigapascal
HMPE	-	High Modulus Polyethylene (or Ultra-High Molecular Weight Polyethylene, UHMWPE)
HMSF	-	High Modulus Synthetic Fibre
IACS	-	International Association of Classification Societies
ICS	-	International Chamber of Shipping
IMO	-	International Maritime Organization
INTERTANKO	-	International Association of Independent Tanker Owners
ISO	-	International Organization for Standardization
JIP	-	Joint Industry Project
kN	-	kilo-Newton

kts	-	knots
LCAP	-	Liquid crystal aromatic polyester
LNG	-	Liquefied Natural Gas
LR	-	Lloyd’s Register
m	-	metre
m^3	-	cubic metre
Marlow	-	Marlow Ropes
mm	-	millimetre
MBL	-	Minimum Breaking Load
MBS	-	Minimum Breaking Strength
MCA	-	Maritime and Coastguard Agency
MEG	-	Mooring Equipment Guidelines
MEG-2	-	Mooring Equipment Guidelines, second edition, 1997
MEG-3	-	Mooring Equipment Guidelines, third edition, 2008
MGN	-	Marine Guidance Note
MPa	-	mega pascal (1 MPa = 10 bar = 101,971Kgf/m^2)
mph	-	miles per hour
m/s	-	metres per second
MSC	-	Maritime Safety Committee
Nakilat	-	Qatar Gas Transport Company Ltd
NDT	-	Non-Destructive Testing
NWBS	-	New Wet Breaking Strength
OCIMF	-	Oil Companies International Marine Forum
OiC	-	Officer-in-charge
OOW	-	Officer of the watch
PA	-	Polyamide
PE	-	Polyethylene
PET	-	Polyester

PMS	-	Planned Maintenance System
PP	-	Polypropylene
PVC	-	Polyvinyl chloride
Q-Flex	-	Qatar-flexible
Q-Max	-	Qatar-maximum
RF	-	Rejection factor
SDC	-	Ship Design and Construction
SEM	-	Scanning electron microscope
SHI	-	Samsung Heavy Industries Limited
SIGTTO	-	Society of International Gas Tanker and Terminal Operators
SMM	-	Safety Management Manual
SOLAS	-	Safety of Life at Sea Convention 1974, as amended
SPM	-	Single Point Mooring
STASCo	-	Shell International Trading and Shipping Company Ltd
STCW	-	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 1978, as amended (STCW Convention)
SWL	-	Safe Working Load
t	-	tonne
TCLL	-	Thousand Cycle Load Level
tf	-	Tonnes-force
TTI	-	Tension Technology International Ltd
UTC	-	Universal Co-ordinated Time
UV	-	ultra-violet
VHF	-	Very High Frequency
WLL	-	Working Load Limit

GLOSSARY OF TERMS

Actual break load	The actual force required to rupture a specific rope specimen. Also called 'break force' or 'break tension'.
Angle of lay	The angle at which the strands lie in relation to the axis of the rope. Also called helix angle, particularly for fibres in yarns and yarns in strands.
Axial compression fatigue	Axial compression fatigue occurs when a rope component goes into compression, and causes buckling of fibres into sharp kinks. On the inside of the bends in the fibres, filament level kink bands develop, and after repeated cycling these lead to rupture.
Construction	The geometric arrangement of strands that defines the type of rope.
Dynamic loading	A rapid application of load that causes the force applied to the rope to significantly exceed the static or slowly applied load.
Elasticity	The property of a material by virtue of which it tends to recover its original size and shape immediately after removal of the force causing deformation.
Elastic Modulus	Also known as Young's Modulus. Stress divided by (fractional) strain. The resultant number measures a materials resistance to being deformed elastically. A stiffer material will have a higher elastic modulus.
Elongation	The axial deformation caused by a tensile force measured in units of length but sometimes as a percentage of the original length. Elastic elongation is immediately recovered upon removal of the load. Permanent elongation is not recovered.
Extensibility	The property by virtue of which a material can undergo extension or elongation following the application of sufficient force.
Fatigue	Progressive damage by any mechanism caused by cyclic loading or long-term static loading.
High modulus	Applies to rope constructed from fibres with a tenacity[1] of not less than 1.3N/tex (15gms/denier) that yield rope breaking elongation in the order of 3% to 8%. e.g. aramid, HMPE etc.
Kink	A sharp bend in a rope or in a fibre or yarn within a rope.
Kink band	A sharp buckling of the internal structure of the fibre in overall axial compression or on the inside of a bend in the fibre. The terms 'kink' and 'kink band' have often been used inconsistently to describe two different phenomena when discussing the effects of axial compression in HMSF ropes; this was evident during the literature review conducted as part of this investigation and in the

[1] Tenacity: Also known as specific strength (N/Tex): the break load divided by the linear mass density

	correspondence received by MAIB. Other than direct quotes attributed to external sources, the definitions above will apply throughout this report.
Lay length	The length along the axis of a rope or strand in which a strand makes one complete spiral around the axis. Also ‘cycle length’.
Low modulus	Applies to rope constructed from fibres with a tenacity of no more than 1.0N/tex (11gms/denier) that yield rope breaking elongation in the range of 10% to 30%. E.g. nylon, polyesters, polyolefins and natural fibres.
Minimum Breaking Load	The specified minimum breaking load (MBL) of a new rope is that declared by the rope manufacturer based on its break load test results. The terms minimum breaking force (MBF) and minimum breaking strength (MBS) are often used by manufacturers instead of MBL. The term MBL will be used throughout this report.
Rope yarn	A first stage ply by twisting that creates a building block for successive plies to make strands.
Shock loading	A sudden application of force at such a rate of speed that the rope can be seen to react violently and the normal response characteristics of the rope are changed.
Steelite Superline Xtra	Brand name used for the mooring lines fitted on board *Zarga*. The rope manufacturer used the terms Steelite and Superline to describe a wide range of products. Steelite referred to rope material (HMPE) and Superline to rope construction i.e. jacketed ropes with a low twist core of either a single 3 strand or multiple 3, 6 or 12-strand parallel sub-ropes. The term Xtra was used for ropes manufactured using UHMWPE fibre rather than HMPE fibre.
Stiffness, bending	The property by virtue of which a rope resists bending.
Strain, tensile	Extension under load divided by change in length.
Strand	The largest individual element in the final rope making process.
Strength, residual	The strength remaining after use. It may be estimated or determined by a destructive test.
Stress, breaking	Break load divided by fibre area.
Stretch	The ability to elongate. A general term applied to extensibility or elongation.
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.

Textile yarn	The yarn as supplied by yarn manufacturers to rope makers. A number of textile yarns are twisted together to make rope yarns.
Working Load Limit	The working load that must not be exceeded for a particular application.

TIMES: All times used in this report are UTC unless otherwise stated.

SYNOPSIS

At 1908 on 2 March 2015, the officer-in-charge of the forward mooring party on board the LNG tanker *Zarga* suffered severe head injuries when he was struck by a mooring rope that parted during a berthing operation at the South Hook LNG terminal, Milford Haven. The high modulus polyethylene mooring rope had been deployed as a spring line and was being used to warp the vessel along the berth against strong gusting winds.

The officer-in-charge of the forward mooring party was injured because he was standing in the snap-back zone of the spring line when it parted. The area where he was standing was designated as a safe area; this was because a thorough snap back assessment had not been carried out by the vessel operator and there was a perception that high modulus polyethylene ropes did not recoil on failure.

The spring line parted due to tensile overload even though the load being applied to the line at the time was less than a quarter of its specified minimum breaking load. The predominant cause of the rope's loss of strength was found to be axial compression fatigue. Factors that contributed to this included high cyclic loading at exposed ports, repeated and prolonged bending around deck fairleads and radial compression exerted on the load bearing core by the rope's tightly bound jacket.

Zarga's mooring lines had been subjected to regular visual inspections by the ship's crew and the rope manufacturer's representatives, but their condition had always been assessed to be good. The ropes' jacketed design prevented the identification of key discard criteria such as broken yarns and fused fibres. In addition, other high modulus synthetic fibre rope condition degradation phenomena, such as creep, cannot readily be assessed without physically dissecting the rope.

The investigation has concluded that: the arrangement of *Zarga*'s mooring decks contributed significantly to the rope's loss of strength and the officer being injured; the mooring lines used on board *Zarga* and similar vessels in the same fleet were not suitable for the application; and the primary influences on rope degradation and failure modes were not fully understood by the user, or appreciated by the shipping industry.

As a result of its initial findings, the Marine Accident Investigation Branch issued two Safety Bulletins: the first relating to the snap-back injury and the second to the difficulties of inspecting jacketed ropes. The vessel operator, Flag State, rope manufacturer and industry bodies have all taken action to improve awareness of the issues identified in this report. The Oil Companies International Marine Forum has undertaken to carefully consider the findings of this report during the revision of its Mooring Equipment Guidelines.

Recommendations have been made to Shell International Trading and Shipping Company Ltd, The Oil Companies International Marine Forum, Bridon International Ltd and Eurocord aimed at improving the levels of knowledge among the ship owners, managers, builders and crew regarding the complex properties of high modulus synthetic fibre ropes, and the advantages and limitations they present when used on board ships for mooring line and towing line applications.

SECTION 1 - FACTUAL INFORMATION

1.1 PARTICULARS OF *ZARGA* AND ACCIDENT

SHIP PARTICULARS	
Vessel's name	*Zarga*
Flag	Marshall Islands
Classification society	American Bureau of Shipping
IMO number	9431214
Type	Liquefied natural gas carrier Q-Max
Registered owner	Nakilat S.H.I. 1752 Inc.
Manager	Shell International Trading and Shipping Company Ltd
Construction	Steel-welded
Year of build	2010
Length overall	345.30m
Registered length	333.73m
Gross tonnage	163922
Minimum safe manning	30
Authorised cargo	Liquefied natural gas
VOYAGE PARTICULARS	
Port of departure	Ras Laffan, Qatar
Port of arrival	Milford Haven
Type of voyage	International
Cargo information	266000m^3 liquefied natural gas
Manning	31
MARINE CASUALTY INFORMATION	
Date and time	2 March 2015, 1908
Type of marine casualty or incident	Serious Marine Casualty
Location of incident	South Hook LNG terminal
Place on board	Port forward mooring station
Injuries/fatalities	One crewman seriously injured
Damage/environmental impact	One mooring rope failure
Ship operation	Alongside discharge berth
Voyage segment	Arrival
External environment	30kts westerly, gusting 38kts High water 1636 Current north-westerly 1.5m waves, ebbing
Persons on board	32

1.2 BACKGROUND

Zarga was one of 14 Qatar-maximum (Q-Max)[2] liquefied natural gas (LNG) carriers specifically built to transport LNG from Ras Laffan, Qatar, to major LNG terminals such as South Hook, Milford Haven, UK. The Q-Max vessels had a cargo carrying capacity of 266,000m^3.

Figure 1: *Zarga* at berth 1, South Hook LNG terminal

The jetty at South Hook LNG terminal **(Figure 1)** had two berths specifically designed to accommodate Q-Max and Qatar-flexible (Q-Flex)[3] vessels. Each berth had 12 mooring dolphins; each dolphin was equipped with either two or three quick release mooring line hooks. *Zarga*'s standard mooring plan for the South Hook terminal required three head lines, five breast lines and two spring lines to be connected forward, and three stern lines, five breast lines and two spring lines to be connected aft, each in a 3-2-3-2 configuration **(Figure 2)**.

1.3 NARRATIVE

1.3.1 Events leading up to the accident

On 13 February 2015, *Zarga* sailed fully loaded from the Ras Laffan LNG export terminal bound for South Hook, Milford Haven. On 28 February, the master held a planning meeting for the vessel's intended arrival at Milford Haven on 2 March, which was attended by the chief officer (C/O), the officers in charge of the fore and aft mooring parties and the bosun. During the meeting, the mooring plan was discussed and it was agreed that, in accordance with the standard procedure for South Hook, 10 mooring lines would be attached fore and aft.

[2] Q-Max – the maximum size of ship able to dock at the LNG terminals in Ras Laffan port, Qatar.

[3] Q-Flex – prior to the entry into service of the Q-Max fleet, the Q-Flex vessel was the world's largest LNG carrier, with a capacity of 210,000-216,000m^3.

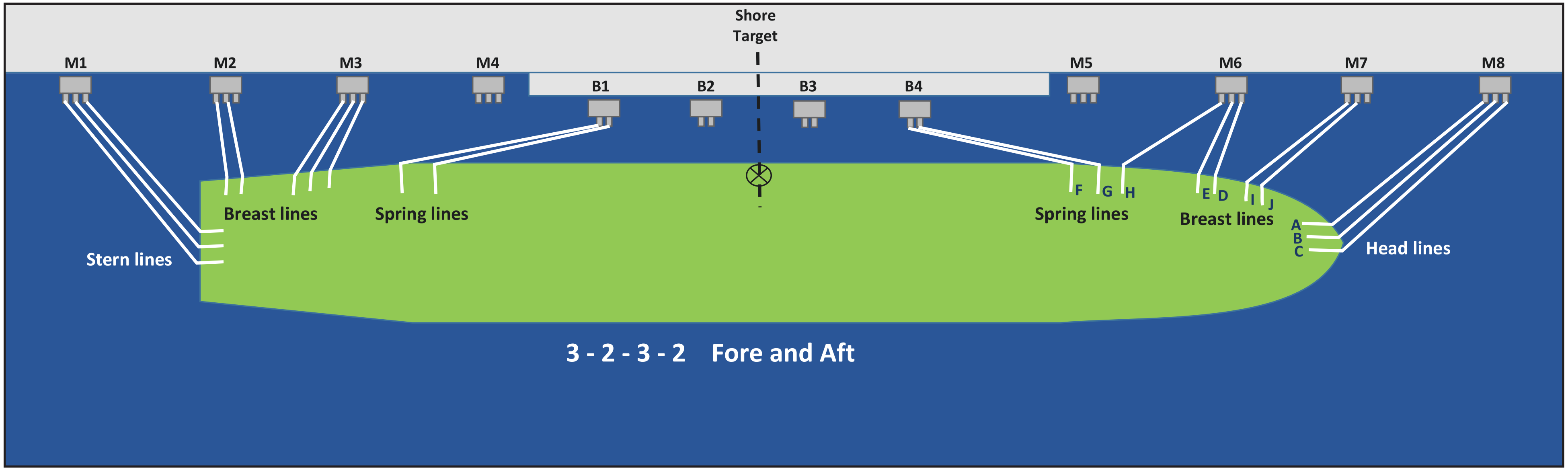

Figure 2: Mooring plan at berth 1, South Hook LNG terminal

On 1 March 2015, *Zarga*'s master, senior officers and bosun discussed the daily work plan for the vessel's arrival the following day at Milford Haven. The work plan, which included details of the mooring arrangements, was later posted on the crew noticeboards. The instructions contained in the work plan directed the deck crew to prepare nine mooring lines in a 3-4-2 configuration fore and aft. The instructions also required the bosun to deliver a toolbox talk to the mooring parties.

On the morning of arrival (2 March), the deck crew prepared nine mooring lines fore and aft in accordance with the published daily work plan. At 1330, *Zarga* arrived at the entrance to the port of Milford Haven. When the officer-in-charge (OiC) of the aft mooring party arrived at his mooring station he recognised that the mooring lines had not been laid out as agreed at the pre-arrival planning meeting. The OiC got his team to prepare a tenth mooring line and then, at 1500, he reported to the bridge that he had briefed his team and he was ready for arrival. At 1510, two Milford Haven pilots boarded *Zarga* and, 8 minutes later, the first of four harbour tugs was made fast aft.

Following the initial master/pilot information exchange, the lead pilot recorded in the vessel's information exchange form that high winds might affect the vessel when alongside. He also noted that the weather was improving and the mooring configuration would be 10 lines fore and aft.

During this time, the third officer (3/O), who was OiC of the forward (for'd) mooring party briefed his six-man team, which included the vessel's bosun. During the brief, the number of mooring lines that had previously been laid out by the deck crew was not challenged and no alterations were made. Between 1540 and 1555, the other three harbour tugs were made fast to *Zarga*.

Assisted by the tugs, *Zarga* was manoeuvred port side alongside the South Hook jetty's number 1 berth and, at 1625, the first forward spring line was connected. By 1650, all four spring lines had been connected and the mooring parties had begun to pass the fore and aft breast lines ashore.

At about 1723, with three breast lines attached fore and aft, the lead pilot released one of the tugs. At 1741, the master informed the OiC of the for'd mooring party that he was going to send the 6-12 watch 3/O to relieve him. When the new 3/O arrived on the fo'c's'le, the OiC told him that he would stay and complete the mooring operation.

At 1753, the OiC of the for'd mooring party informed the bridge that two forward head lines had been made fast. The master asked for confirmation and then told the OiC that there should be three head lines. The OiC then advised the master that one of the head lines had been rigged as a breast line and, in order to rectify the problem, all the breast lines needed to be repositioned. Frustrated with the apparent failure of the mooring plan, the master sent the C/O forward to help resolve the problem.

During the following 15 minutes, discussions were held between the master, C/O, pilots and the shore mooring team on the most appropriate and quickest method of realigning the forward mooring arrangements. During this time, the terminal's cargo engineer informed the master that *Zarga* was 30-40cm forward of its target position on the berth. This was within the vessel's normal tolerance and was accepted by the master.

The C/O, confident that the OiC was managing the re-arrangement of the mooring lines, returned to the cargo control room. At the aft mooring station, the aft spring lines had been slackened off to allow rope chafing guards to be fitted.

The lead pilot disembarked *Zarga* at 1824, and 4 minutes later the OiC of the for'd mooring party reported that the forward lines were in position. The second pilot then told the tugs to stop pushing *Zarga* onto the berth and to let go. The master declared *Zarga* all fast, and then began to discuss his concerns about the prevailing wind and sea conditions with the second pilot. The pilot reassured the master and explained that if he needed further tug assistance he should contact Milford Haven port control.

With the forward lines correctly arranged, the for'd mooring party began to fit chafing guards to the ropes where they passed through the deck fairleads and panamas **(Figure 3)**. This required each line to be slackened in turn. Once the chafing guards had been fitted, the OiC released his for'd mooring party.

At 1854, the terminal staff informed the C/O that *Zarga* had moved further forward and was out of position by 1.5m. The C/O told the terminal staff that members of the vessel's deck crew would be sent to the mooring stations to reposition the ship.

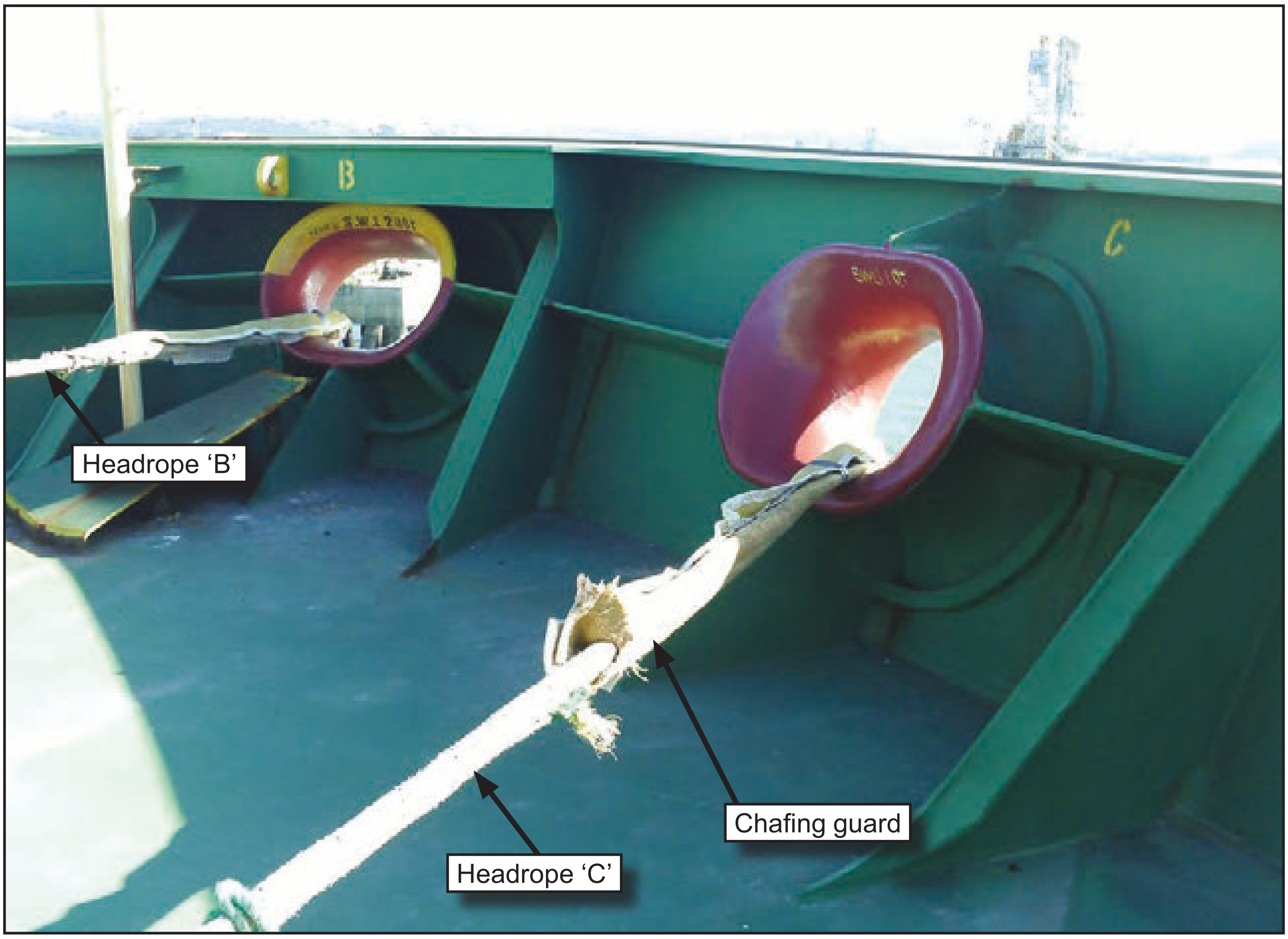

Figure 3: *Zarga* forward mooring lines and chafing guards

1.3.2 The accident

The master, in consultation with the pilot, decided to use the forward spring lines to reposition the vessel. As the OiC, bosun and 6-12 3/O had not left the forward mooring station, the OiC directed the bosun to take control of the mooring winch **(Figure 4)** and the 3/O to act as his signaller. The OiC stood outboard of the cargo tank casing aft of the spring lines' universal roller fairleads **(Figure 5)**. The signaller stood on the port side of the fo'c's'le in line of sight with the OiC and the bosun.

At 1859, with the C/O monitoring the vessel's position from the cargo control room, the bosun set the mooring winch to heave in one of the spring lines. Within a couple of minutes, the C/O informed the master that the vessel, having been heaved 0.5m astern, had stopped moving aft. In response, the master told the aft mooring party to slacken the aft spring lines, and the for'd party to keep heaving up on the spring lines.

The bosun, following the signals relayed to him by the 3/O, repeatedly set the winch to heave until it stalled under load. Each time the winch stopped, the bosun released its control lever, and then operated it again. On several occasions, the winch rendered slightly as he released the lever.

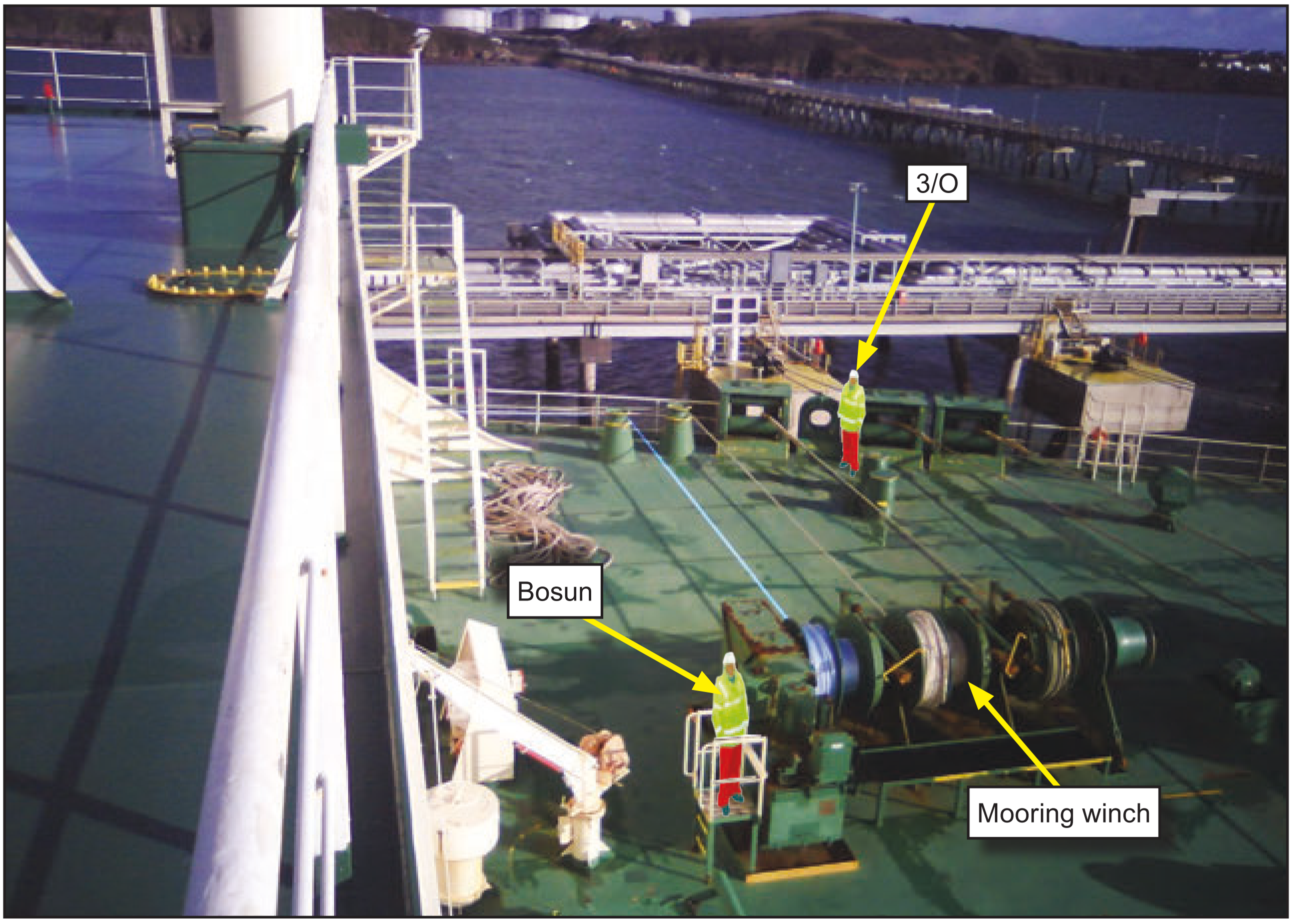

Figure 4: *Zarga* for'd mooring deck: winch and crew positions

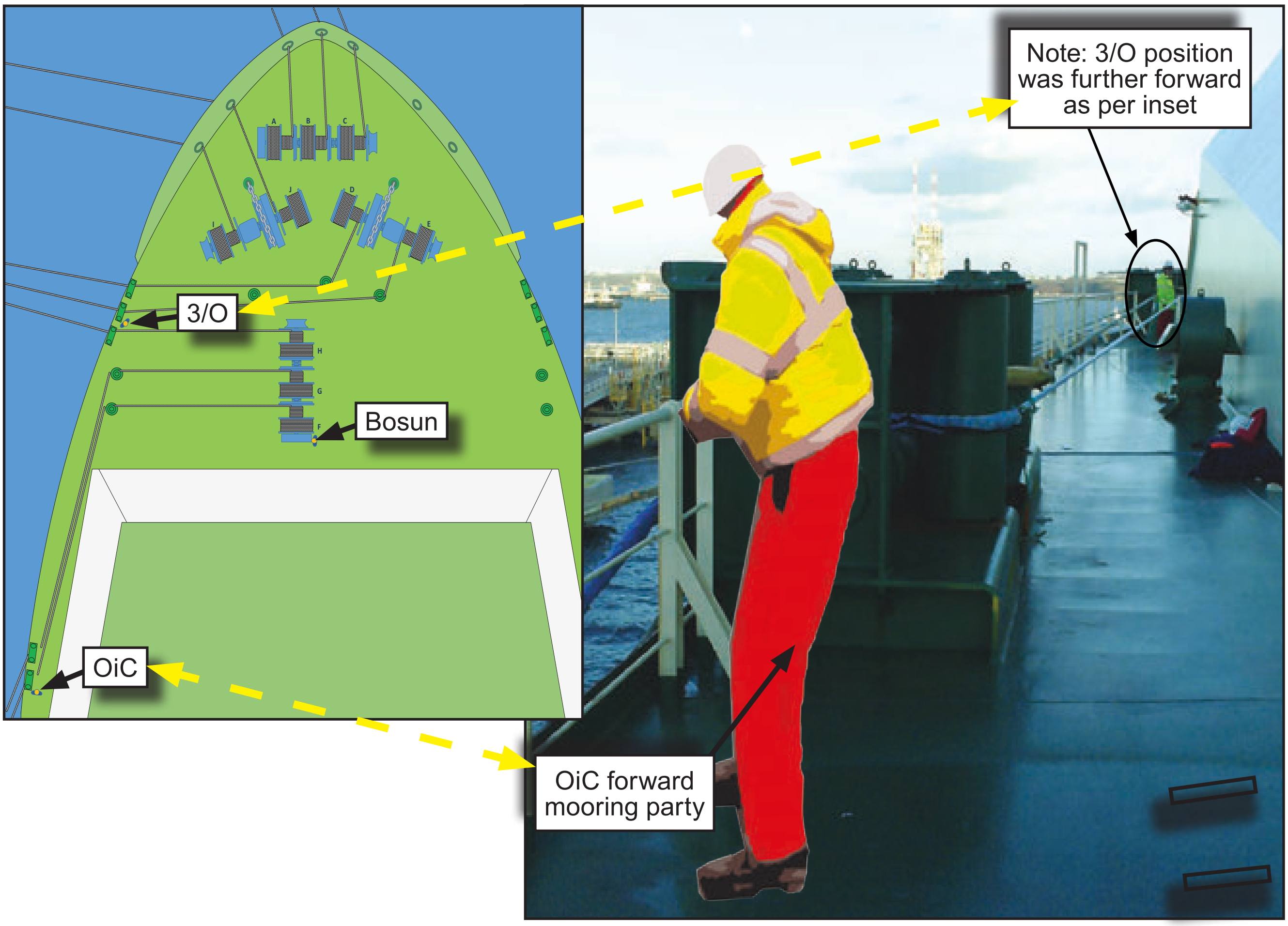

Figure 5: Approximate OiC position outboard of cargo tank port side (**inset:** deck plan)

By about 1905, the misalignment of the vessel had reduced to 75cm. The master told the for'd mooring party's OiC to ensure the two forward spring lines were equally tight; the instruction was acknowledged by the OiC. *Zarga*'s slow movement astern stopped again with the vessel still 70cm out of position. Again, the master told the aft mooring party to ensure the aft spring lines were slack. The aft OiC confirmed that they were.

At 1908, the 3/O on the fo'c's'le heard the forward inboard spring line rattle and ducked down as it suddenly parted. The bosun saw the spring line go slack and stopped hauling in on the winch. When the 3/O looked up he saw the OiC lying on the deck, forward of the spring line roller fairleads **(Figure 6)**. The 3/O and the bosun ran to the aid of the OiC, who was unconscious and bleeding from the head.

1.3.3 Post-accident events

On discovering the extent of the injuries suffered by the OiC, the bosun called the bridge on his hand-held very high frequency (VHF) radio and attempted to raise the alarm. The bosun's transmission coincided with other VHF communications and his rapid speaking became garbled and was not understood. At 1910, the master was made aware of the spring line failure by the vessel's cargo engineer. Shortly after, the 3/O made contact with the bridge and informed the master that there had been an accident and that the OiC had been injured.

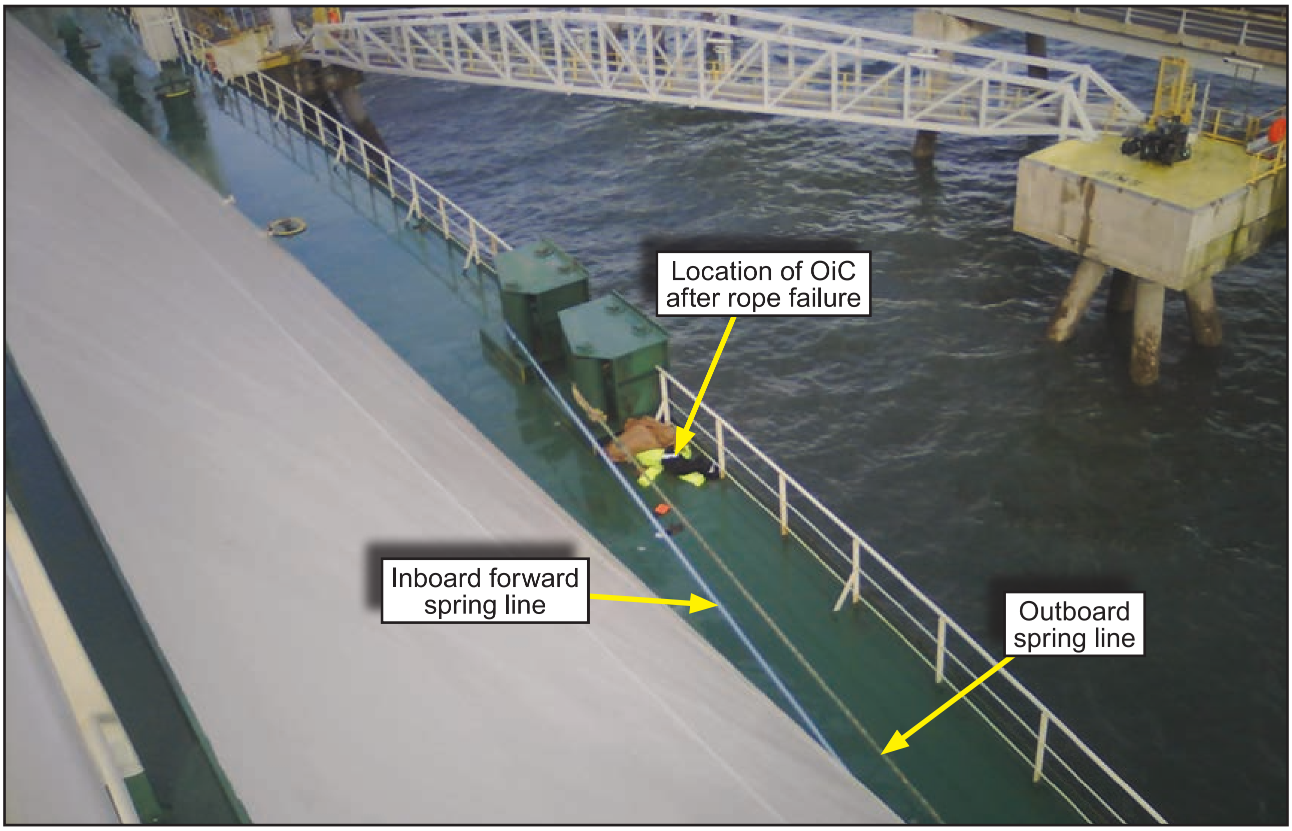

Figure 6: Location of OiC found after rope failure

The master advised Milford Haven port control of the accident and requested the attendance of a medical team. He also requested two tugs to help keep the vessel alongside. The vessel's onboard emergency team were mustered and then sent forward with a stretcher and resuscitation pack.

Shortly after, the C/O, who had gone to the fo'c's'le, informed the master that the OiC was unconscious and had suffered a serious head injury. The master then requested that the terminal gangway be lowered to provide access for an ambulance crew.

By 1919, two tugs were back alongside and first-aid medical support was being provided by the LNG jetty operations crew, who had arranged for a defibrillator to be brought on board.

The C/O decided that the casualty should not be moved, and in order to make the area safer for the first-aiders he asked the master for approval to slacken the second spring line. In response, the pilot instructed one of the tugs to pull the vessel aft to reduce the load on the remaining forward spring line. At 1940, two more tugs were called to provide additional support.

By 1946, an ambulance crew were on board and 12 minutes later the casualty was taken off the vessel by stretcher and airlifted to hospital in a police helicopter. At 2203, *Zarga* was declared all fast and the tugs were stood down.

Following major surgery and several weeks in hospital, the injured deck officer was repatriated to his home in India, where he received further medical care.

1.4 ENVIRONMENTAL CONDITIONS

1.4.1 The day of the accident

When *Zarga* arrived at the Milford Haven pilot station the sea was rough with a moderate to long swell and the winds were westerly Beaufort Force 6 to 7[4].

When the line parted the wind was westerly at about 32kts and the tidal stream was ebbing to the west at 0.6kt (the tidal range was 4m and high water occurred at 1636). The air temperature was about 6°C, it was raining and it was dark. These conditions were similar to those predicted in the local inshore weather forecasts.

1.4.2 Operating limits for Milford Haven and South Hook terminal

Due to the geographical location of Milford Haven, the prevailing winds are often strong and predominantly west-south-westerly. Average annual wind speeds are 10.6kts, with February and March averaging 12.1kts and 11.5kts respectively. Spring tides in Milford Haven have a mean range of 6.3m and an extreme range of nearly 8m. In the lower reaches of Milford Haven, including South Hook LNG terminal, tidal streams are strongest 3½ hours after high water on the spring tide. Easterly tidal streams of up to about 1.5kts can be experienced.

Milford Haven port authority's pilotage procedures included guidance on weather limits for vessels entering and transiting the Haven. The entry and transit limit for LNG carriers bound for South Hook was 25kts, gusting to 30kts.

The South Hook LNG terminal standard operating procedure for jetty operations on berth did not set any berthing limits for weather. For extreme wind and sea conditions, the decision whether to berth would be made following consultation between the ship's master, harbour pilot, and the terminal's process supervisor and shipping operations supervisor. Limits were set for cargo operations **(Table 1)**.

Action	Operational limit
Stop cargo transfer	35 knots (18m/sec)
Manoeuvring gangway (off or on)	40 knots (20m/sec)
Disconnect cargo transfer equipment	40 knots (20m/sec)
Review need for further action	40 knots (20m/sec)
Loading arm operating limit	43 knots (22.5m/sec)
Take further action (e.g. tugs to push up)	45 knots (23m/sec)

Table 1: Cargo weather operational limits at South Hook LNG terminal

The actual wind conditions at the entrance to Milford Haven were recorded on the mid-channel rock[5]. Between 1400 on 2 March and 1400 the next day the recordings **(Figure 7)** showed westerly winds of about 27kts, gusting to 32kts that had persisted throughout the day. At 1845 the wind conditions worsened, with speeds increasing to about 36kts and gusting to about 41kts.

[4] Beaufort Force 6: (strong breeze) wind strength 22-27kts. Beaufort Force 7: (near gale) wind strength 28-33kts.

[5] The mid-channel rock is 3.93 nautical miles from the South Hook jetty.

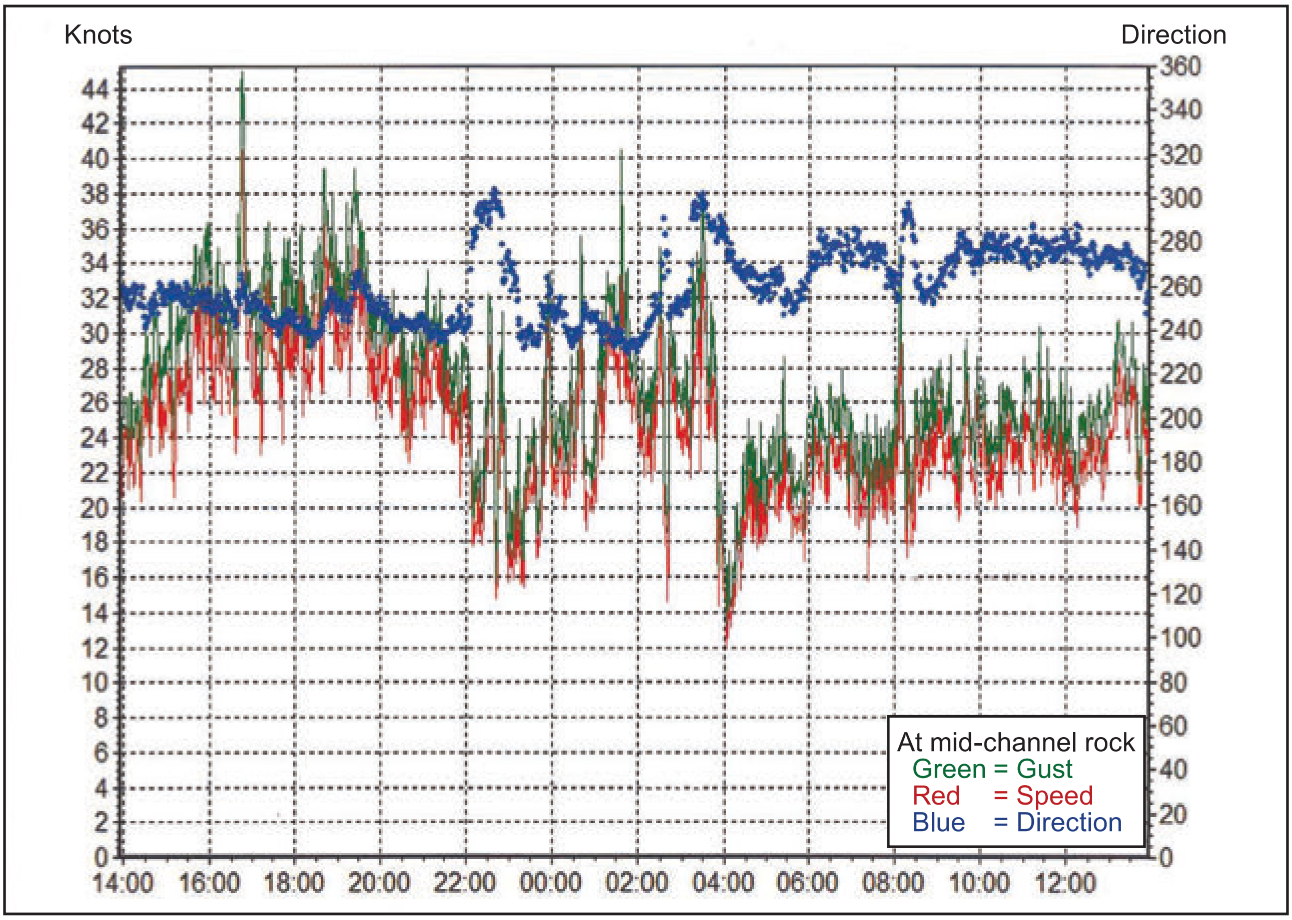

Figure 7: Actual wind conditions recorded 2-3 March 2015

1.4.3 Ras Laffan

Ras Laffan was the world's biggest LNG export complex; it was capable of despatching 1000 LNG cargoes per year and was the largest artificial harbour in the world **(Figure 8)**. Ras Laffan was classed as a desert climate, with annual average temperatures of 26.5°C and maximum temperatures in the peak summer months of about 40°C.

1.5 THE CREW

Zarga's crew of 31 comprised six different nationalities and there were seven crew members in each mooring party. The for'd mooring party comprised a 3/O, who was the OiC, the bosun, two able seamen, an ordinary seaman, a machinist and an engine room oiler.

The master was a 52-year-old Croatian national. He joined Shell in 1995, served as a chief officer on board oil tankers until 2008 and then moved on to LNG carriers. He first became the master of an LNG carrier in 2009.

The C/O was a 39-year-old Croatian national. He began his maritime career in the mid-1990's, and between 1998 and 2004 he rose from fourth officer to C/O on crude oil tankers. In 2008 he joined the Shell International Trading and Shipping Company Ltd (STASCo). He had previously sailed on board *Zarga* and had been involved in 15 of its cargo deliveries. This included several to South Hook.

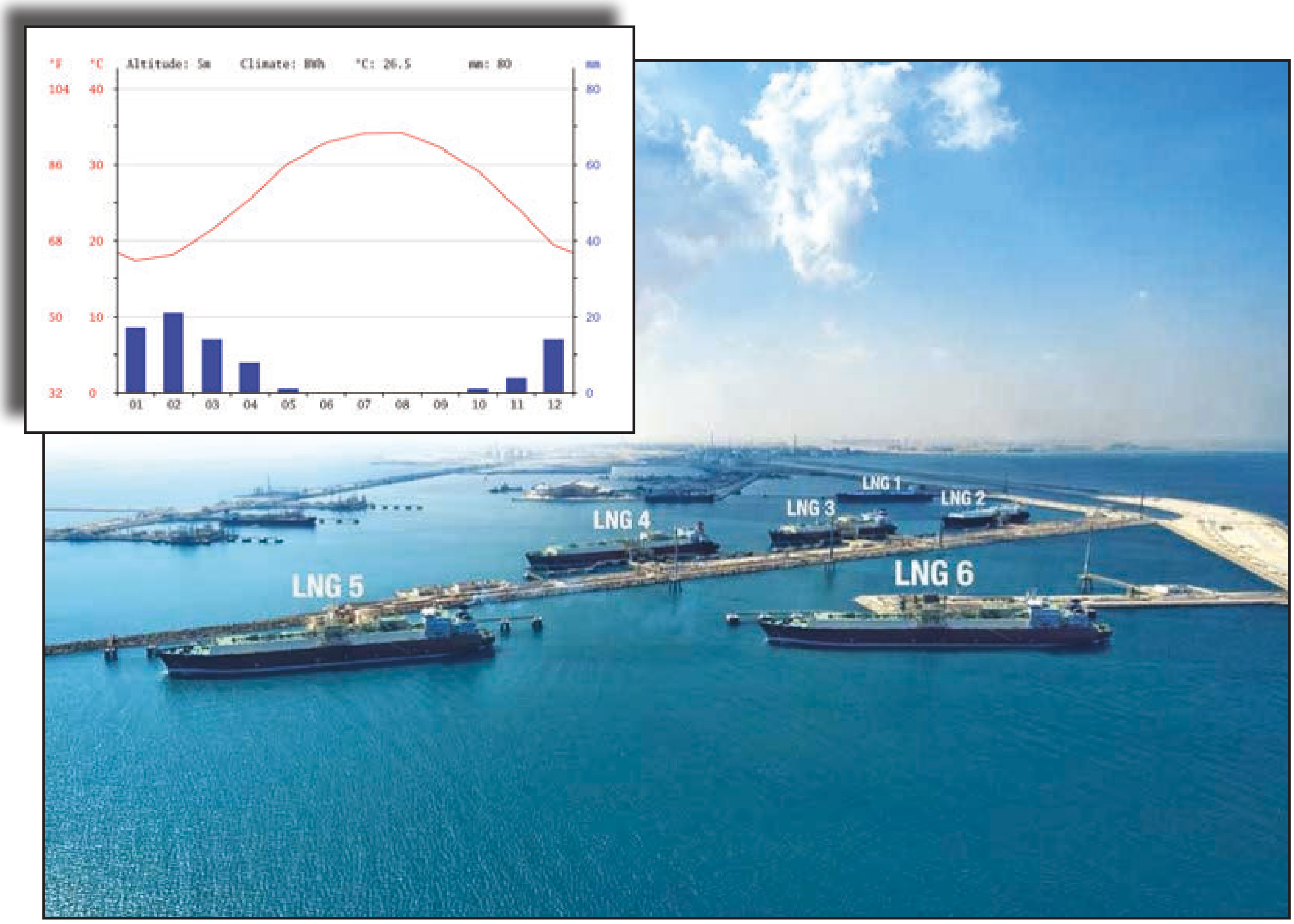

Figure 8: Ras Laffan port

The OiC of the for'd mooring party was a 26-year-old Indian national. He started his cadetship with MOL in 2010 and obtained his officer of the watch (OOW) STCW Class II/1 certificate of competency in September 2011. He joined STASCo in 2012 as a 3/O. He joined *Zarga* on 10 November 2014; it was his fourth contract on board a STASCo-managed LNG vessel. Prior to the accident he kept the 12-4 watch on the bridge.

During his employment with STASCo, the OiC of the for'd mooring party had undertaken a wide range of operational and emergency training activities. This included computer-based training for personal safety (November 2012), ship general safety (December 2012), and mooring operations (July 2013). The arrival at Milford Haven on 2 March 2015 was his 6th cargo delivery on board *Zarga* but his first visit to South Hook LNG terminal. The OiC was considered to be a very enthusiastic and competent member of the ship's crew and had been assessed as being capable of carrying out the duties of a second officer. His personal hours of rest log for February indicated that he had regularly received at least 13 hours of rest per day.

The bosun was a 42-year-old Filipino national. He had been a bosun for 7 years and had worked on board STASCo vessels since 2000. This was his first visit to the South Hook LNG terminal.

The 3/O sent to assist the OiC of the for'd mooring party was an Indian national.

1.6 THE VESSEL

1.6.1 General

Zarga was built at the Samsung Shipbuilding and Heavy Industries Company Limited (SHI) shipyard at Goeje Island, South Korea. The vessel was launched on 2 May 2009 and delivered on 5 March 2010. It was classed by the American Bureau of Shipping (ABS) but was built to Lloyd's Register (LR) classification rules.

Two other major shipyards were involved in the construction of the Q-Max and Q-Flex vessels. By July 2010, the fleet of 14 Q-Max and 31 Q-Flex vessels accounted for 18% of the total number of LNG ships worldwide and 25% of the world's LNG shipping capacity.

Zarga was owned by the Qatar Gas Transport Co Ltd (Nakilat), chartered to Qatargas and managed by STASCo. Nakilat owned and operated the world's largest fleet of LNG carriers; of the 45 Q-Max and Q-Flex vessels, 25 were wholly owned by Nakilat and 20 were part-owned. Qatargas had been an LNG producer since 1996 and had chartered all 14 of the Q-Max vessels. STASCo was responsible for *Zarga*'s operational, maintenance and crewing requirements.

1.6.2 Mooring lines

Zarga was equipped with 22, 275m long, 44mm diameter *Steelite Superline Xtra* high modulus polyethylene (HMPE)[6] rope mooring lines. The *Steelite Superline Xtra* ropes were manufactured by Bridon International Ltd (Bridon) and had a specified minimum breaking load (MBL) of 137t.

The *Steelite Superline Xtra* rope had a single 3-strand, long-lay[7] HMPE load bearing core, which was encased in a tightly fitted braided jacket. Each of the strands within the central core contained 32 yarns (17 outer yarns and 15 inner yarns) **(Figure 9)**.

The use of HMPE mooring lines was stipulated by SHI for the Qatargas LNG vessels' build specification, which asked for:

> *Twenty-two (22) sets, each 275m long and not more than 44mm diameter Ultra High Molecular Weight Polyethylene (UHMWP) rope with each 11m long nylon tail rope (M.B.L: 137 metric tonnes). One (1) side of each mooring rope shall be fitted with eyesplice. [sic]*

Bridon won the tender process and provided SHI with copies of its high modulus synthetic fibre (HMSF) rope manual and the LR rope **(Annex A)** and tail inspection reports for each mooring line. The ropes were manufactured to the BS EN919:1995 standard: *Fibre ropes for general service*. Determination of certain physical and mechanical properties[8].

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[6] For the purpose of simplification, HMPE will be used in this report as an abbreviation for both *ultra-high molecular weight polyethylene* and *high modulus polyethylene*.

[7] Also known as low twist construction.

[8] BS EN919:1995 was withdrawn on 24 March 2005 and replaced with BS EN ISO2307:2005.

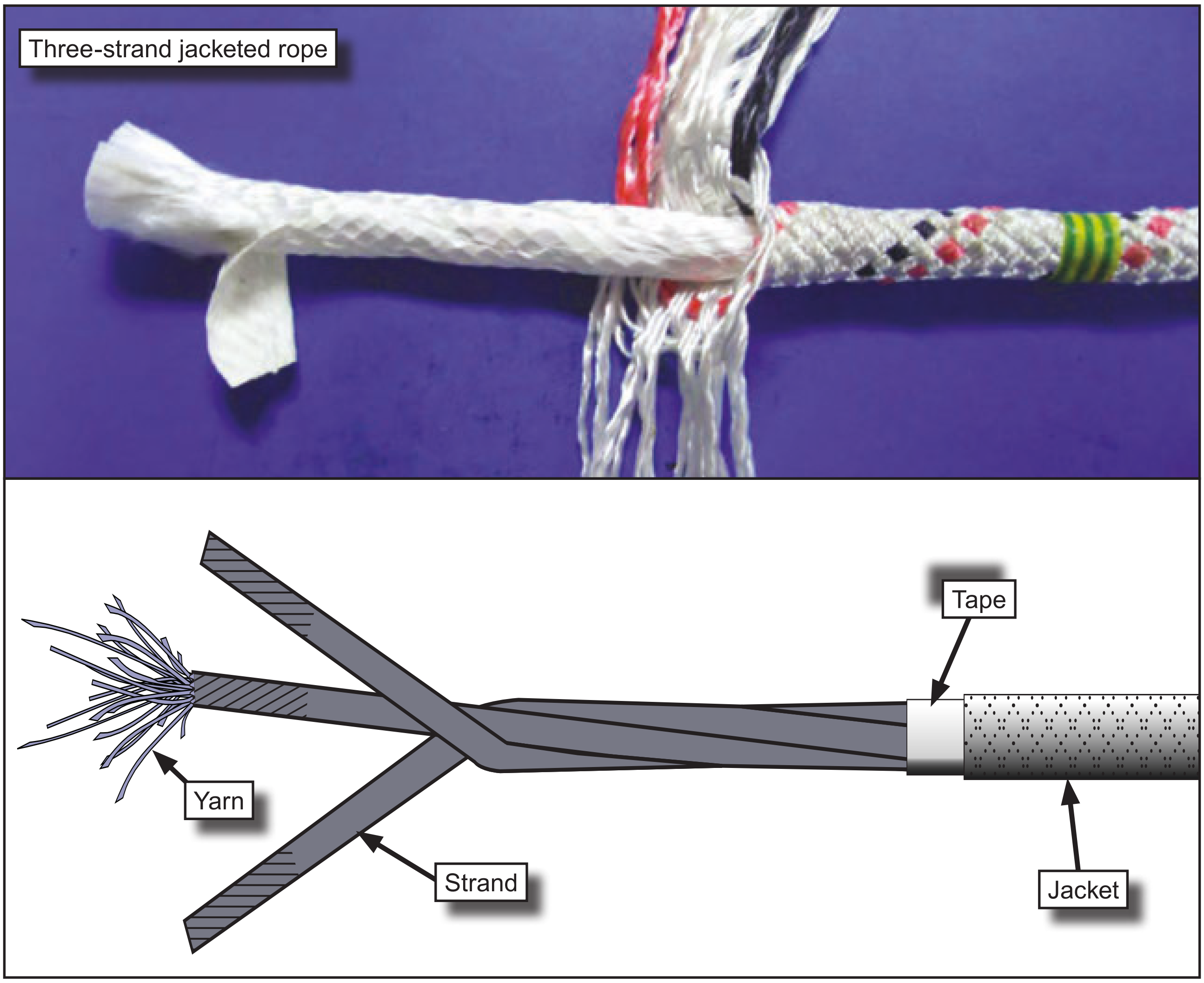

Figure 9: Structural illustration of *Steelite Superline Xtra* rope

1.6.3 Mooring line tails

As steel wire and HMPE ropes both have low elongation characteristics (approximately 1% and 3% elongation at break respectively), dynamic loading due to vessel movement can introduce shock loads and cause overloads. To provide additional elasticity, tails or pennants are fitted to the shore end of the lines. Common tail materials include polyester, polyester/polypropylene composites and polyamide[9]. Each has different elastic properties and the material chosen will affect the fatigue life of the mooring line/tail combination.

The materials used to manufacture a mooring line tail and the length of the tail are critical factors that affect a mooring line's ability to absorb dynamic loads; the higher the elasticity, the greater the dynamic load absorption. At the time of failure, the spring line was attached to a 22m long, 88mm diameter *Euroflex®* tail[10].

[9] Polyamide – also known by its brand name, Nylon.

[10] The Euroflex® tails were manufactured by Lankhorst Ropes and constructed using polyester and polypropylene composite yarns.

1.6.4 Mooring winches

Zarga was equipped with seven TTS Kocks GmBH, electro-hydraulic mooring winches, two on the fo'c's'le and five aft. It also had two dual purpose TTS Kocks GmBH, electro-hydraulic anchor and mooring winches fitted on the fo'c's'le **(Figure 10)**. Each winch was fitted with clutched split-type rope drums.

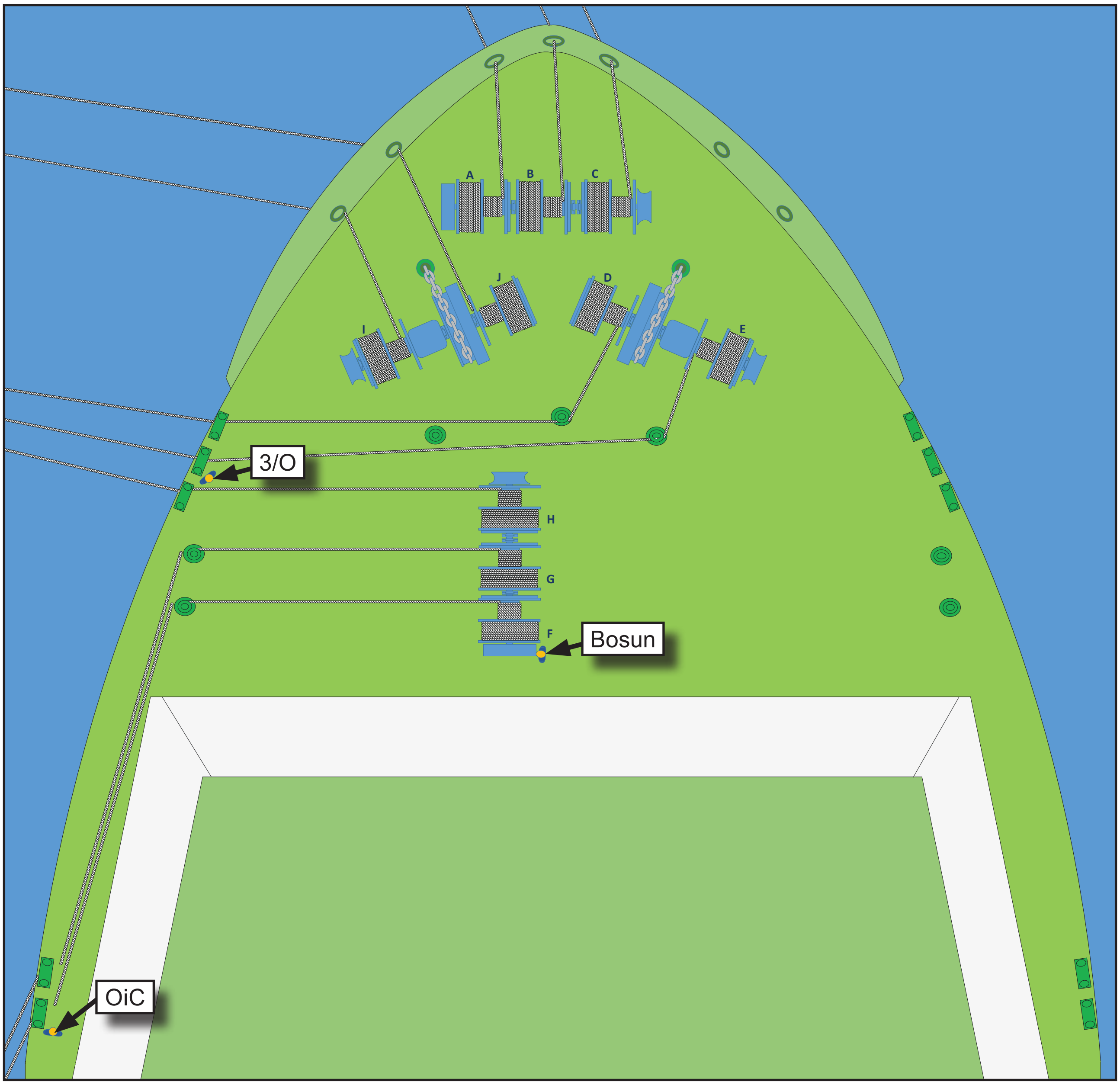

Figure 10: *Zarga* for'd mooring deck arrangement

The forward winch in use at the time of the accident was positioned at the aft end of the fo'c's'le, slightly to port of the vessel's centreline, with the axis of the drums aligned forward to aft. It had three drums: the after two drums were used for the spring lines and the forward one for a breast line. When *Zarga* was connected port side to the berth, mooring lines were led from the bottom of the drums **(Figure 11)**.

Each split-type drum comprised a tension section that held one layer of mooring line and a storage section that the remainder of the rope was wound onto. The drum diameter was 710mm and the tension section held about 9 turns of rope. The mooring winch performance parameters are set out in **Table 2**.

Winch Parameters			**Winch power as a percentage of line MBL (137t)**
1	Winch pull	300kN (31t)	22%
2	Winch rendering	333kN (34t)	24.8%
3	Brake Holding Load	806kN (82t)	60%
4	Brake Design Load	1075kN (110t)	80%
5	Winding speed	15m/minute	
6	Line stowage capacity	44mm x 275m + 75mm x 11m	

Table 2: Mooring winch performance parameters

During operation, the winch would render slightly unless the winch brake was applied while the winch control lever was held in the heave position.

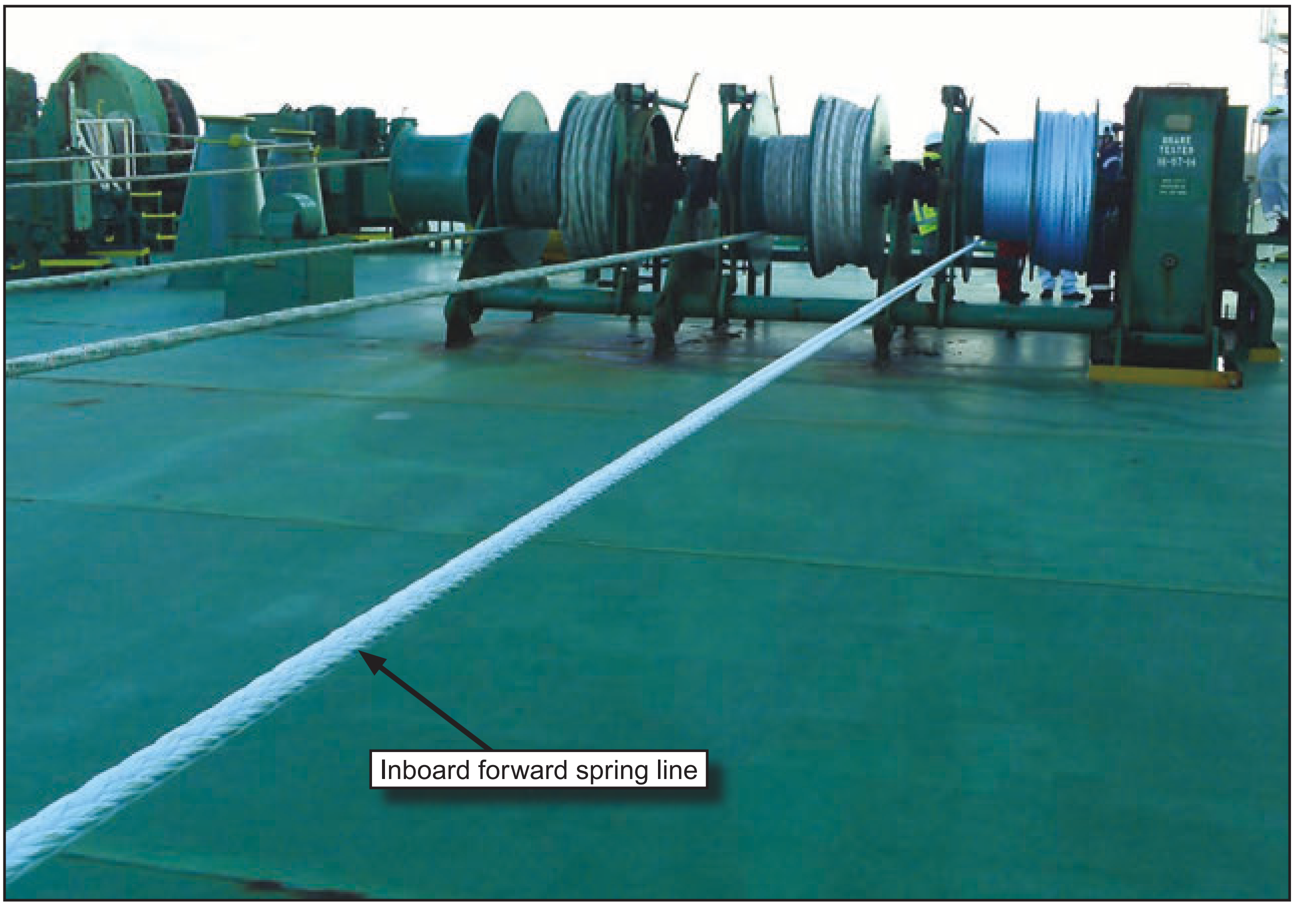

Figure 11: *Zarga* forward spring winch
(Note: Inboard forward spring line shown was a replacement to the failed rope and was of a different manufacture and construct)

1.6.5 Deck fittings

The size and strength of the mooring lines, and the associated deck fittings used on *Zarga* had been determined using guidance and calculations provided by the Oil Companies International Marine Forum (OCIMF)[11] publication, *Mooring Equipment Guidelines, Second Edition, 1997* (MEG-2).

Each of the forward spring lines was led around a horizontally mounted pedestal roller fairlead and passed overboard through a universal (multi-angle) roller fairlead. The diameters of the pedestal and universal fairlead rollers were 450mm and 400mm respectively. The specified safe working load (SWL) of the roller fairleads was 74t.

Prior to the order being placed, Bridon was not directly consulted on the suitability of its ropes for their intended application or their compatibility with the vessel's deck fittings. Its technical information document for synthetic fibre ropes warned that:

> *The ratio between rope diameter and sheave diameter is critical to the safe usage of a rope.*

Its Fibre Rope Catalogue guidance also stated that, as a general guide, a minimum ratio of 12:1 should be used for *Superline* ropes.

1.7 BRIDON INTERNATIONAL LTD

1.7.1 Background

Bridon designed and manufactured ropes for use in a wide range of applications for both land-based and offshore industries worldwide. Prior to 2006, Bridon specialised in the manufacture of steel wire ropes for use in the fishing, crane lifting and offshore industries. In January 2006, Bridon acquired the offshore and commercial marine-related assets of Marlow Ropes (Marlow)[12] and began to produce synthetic fibre ropes. The purchase included Marlow's fibre rope manufacturing facility at Coatbridge, Scotland, and the design and manufacturing rights for the *Steelite Superline Xtra* ropes.

Marlow developed and marketed its first jacketed HMSF ropes in the 1980s and its 3-strand *Steelite Superline Xtra* rope was first manufactured, tested and placed on the market in 2003. By this time, Marlow's HMSF ropes were commonly used by the offshore industry and the company was recognised as a world leader in the design and manufacture of HMSF deep water tethers and single point mooring hawsers.

The HMPE fibres used by Bridon and Marlow (pre-2006) in the construction of its *Steelite* ropes were manufactured and supplied by DSM Dyneema® BV (DSM). Most of the HMPE mooring ropes fitted to the Q-Max and Q-Flex LNG carriers were supplied by Bridon. Up until 2012, approximately 50% of the mooring lines used on board all LNG vessels were manufactured using DSM's Dyneema® fibres.

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[11] OCIMF is a voluntary organisation of oil companies having an interest in the shipment and terminalling of crude oil and oil products. It utilises the accumulated knowledge of its members, including the International Association of Independent Tanker Owners, the International Chamber of Shipping and the International Association of Classification Societies to produce best practice guidance.

[12] Marlow Ropes Ltd since 2006

1.7.2 Rope manufacturing process

Bridon followed a six-step process to construct its *Steelite Superline Xtra* 3-strand ropes. These were:

Step 1 - The Dyneema® HMPE textile yarn was twisted into rope yarns on a twister machine.

Step 2 - Seventeen outer rope yarns were twisted around the 15 inner yarns on a planetary strander machine to form a single strand.

Step 3 - Three strands were brought together on a planetary closing machine.

Step 4 - The end or ends of the rope were spliced.

Step 5 - A self-amalgamating tape was wrapped tightly around the 3- strand rope.

Step 6 - The tightly bound external braided jacket was applied; this process was done in conjunction with the Step 5 taping process.

The components of the rope were maintained under some nominal tension during each step of the manufacturing process.

The tape was used to bind the strands and jacket to prevent relative movement between the two. Bridon was unable to provide specific information on the radial pressure induced by the jacket on the rope's load bearing core.

1.7.3 Rope break load testing

The specified MBL of a new rope is that declared by the rope manufacturer and is based on break tests conducted in accordance with prescribed test procedures. While in use, ropes will be exposed to many different types of forces and factors that will cause them to lose strength and fail at much lower loads. Therefore, the working load limit (WLL) of a rope is generally much lower than its MBL.

Internationally recognised break test methodologies for HMSF ropes were set out by the International Standards Organization (ISO) in ISO 2307:2010[13] *Fibre Ropes – Determination of certain physical and mechanical properties* and the Cordage Institute in CI1500-2015 – *Test methods for fiber rope*. The tests involve pulling the rope or components of the rope at a slow steady state in a straight line until they break.

The actual MBL of a rope is established by break testing the whole rope. For larger diameter, high strength ropes a calculated, or realised MBL can be established by break testing a selection of rope yarns and applying the following formulas found in ISO 2307:2010:

Un-spliced rope $\boldsymbol{F_r = F_y \times n \times R_f}$

Spliced rope[14] $\boldsymbol{F_r = F_y \times n \times R_f \times 0.9}$

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[13] ISO 2307:2010 superseded ISO 2307:2005, which had superseded BS EN919:1995.

[14] A factory spliced new rope is subject to a 10% strength reduction.

Where:

$\boldsymbol{F_r}$ is the realised break load of the rope,

$\boldsymbol{F_y}$ is the mean yarn break load,

n is the total number of yarns in the rope, and

$\boldsymbol{R_f}$ is the rope realisation factor.

Realisation factors can be established by dividing the actual break load of a whole rope by the aggregated yarn break loads, i.e.:

$$R_f = \text{Whole rope break load} / F_y \times n$$

Generic realisation factors for various types of synthetic fibres and rope constructions were tabulated in the ISO standard. The standard did not include realisation factors for HMPE ropes.

Marlow's realisation test methodology for its 40 and 44mm diameter 3-strand *Steelite Superline Xtra* rope, developed in 2003, required at least eight yarns to be tested and stipulated a realisation factor of 0.998. The test methodology allowed yarns to be taken from either the sample rope or the yarn spools. For its 44mm diameter rope, the quality assurance test sheet **(Annex B)** gave a specified MBL of 127t for an un-spliced rope.

Bridon's product brochures and technical guidance sheet quoted an MBL of 134t for its 44mm diameter *Steelite Superline Xtra* rope. The MBLs quoted by Bridon in its brochures and guidance documents were for un-spliced ropes.

Zarga's failed rope was manufactured in 2008 and was examined, as part of a batch of 44 mooring lines prepared for SHI, by an LR surveyor on 29 August 2008. The LR surveyor witnessed yarn realisation break testing carried out by Bridon on a selected rope sample. Based on the results of the tests and using Marlow's realisation factor of 0.998, Bridon calculated a realised break load of 151.47t for the un-spliced core of the rope and declared a specified MBL of 137t for the spliced ropes. During testing for a later batch of 22 mooring lines for the Q-Class LNG carriers in October 2009, Bridon calculated an un-spliced realisation break load of 145.66t and again, declared an MBL of 137t for the spliced rope.

Bridon did not subject its *Steelite Superline Xtra* ropes to whole rope break testing. Bridon and Marlow Ropes Ltd were unable to provide records to demonstrate how the realisation factor of 0.998 had been derived.

1.7.4 Technical guidance and information

Bridon provided information and guidance for rope purchasers on its website and in its HMSF rope manual **(Annex C)**. The rope manufacturer's guidance stated that its *Steelite* ropes provided the ideal synthetic substitute for steel wire and explained that:

> *Size for size it displays the same strength as wire and has the advantage of floating in water. Steelite exhibits lower lash back energy than other synthetic fibres and unlike wire will not unravel dangerously. Mooring times can be cut*

resulting in quicker turnaround periods in port and vessels can be moored securely with only a small number of personnel. The lightweight properties of Steelite make handling easy and reduce the risk of personal injury.

For factors that affect rope life, the HMSF rope manual included the following technical information:

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...

Working loads

Working loads are the loads that the rope will see in normal use. These loads are expressed as a percentage of break strength of the rope when new. The factor by which the rope 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 ropes' 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.

1.8 DSM DYNEEMA® BV

DSM, based in the Netherlands, is a global company that is active in the fields of health, nutrition and materials sciences. Originally a state-owned coal mining company, DSM diversified into materials technology and biotech science areas in the 1960's. The company's scientists invented the gel-spinning process to spin ultra-high molecular weight polyethylene (UHMWPE) in to a fibre and branded that fibre as Dyneema®. Dyneema® fibres had been commercially available since 1990 and were used for a wide variety of applications, including the manufacturing of rope.

DSM produced different grades of Dyneema® fibre and Bridon used its SK75 multi-purpose fibre to manufacture the *Steelite* ropes. The SK75 fibre was the most commonly used grade of Dyneema® in the construction of both jacketed and unjacketed HMPE mooring rope.

1.9 HIGH MODULUS POLYETHYLENE ROPE

1.9.1 Synthetic polymer fibres

Polymer fibres are traditionally classified as natural, artificial or synthetic. Synthetic fibres are formed from synthetic polymers such as:

- Polyamide (PA)[15]
- Polyester (PET)
- Polyvinyl chloride (PVC)
- Polyacrylonitril (acrylic fibre)
- Aromatic polyamides (aramids)
- Polyolefins:
  - Polypropylene (PP)
  - Polyethylene (PE)
    - HMPE or UHMWPE
- Carbon Fibre (CF).

HMPE fibre is produced from ultra-high molecular weight polyethylene using a gel spinning process. In this process the molecules of synthetic polymer are dispersed in a dispersing agent and the resulting gel-like fluid is spun through small holes, stretched and then solidified by rapid cooling. This process produces a fibre with a chemical structure composed of a very high level (over 95%) of macromolecular chains orientated along the axis, compared with the relatively low tensile strength non-orientated polyethylene structure **(Figure 12)**. The long molecular chain length structure gives the fibre a high tensile strength and low elastic elongation (high modulus) compared to more traditional synthetic fibres.

[15] Nylon is often used as the generic name when referring to all kinds of polyamides

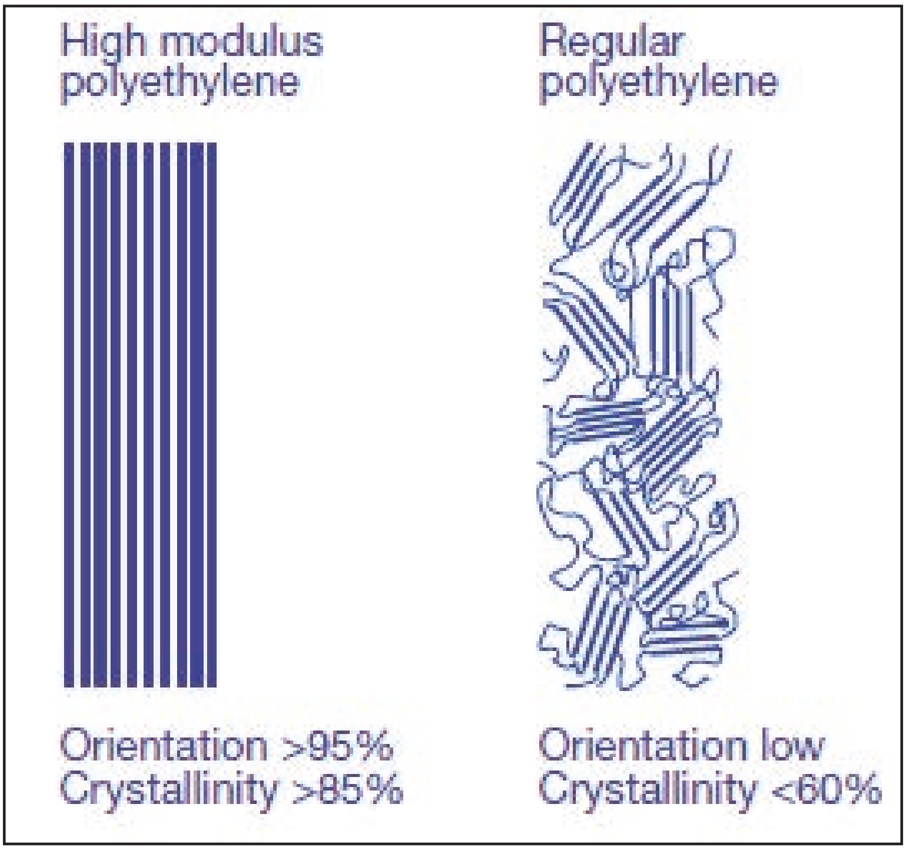

Figure 12: HMPE and polyethylene fibre macromolecular chain orientation and structure

HMPE fibre has a typical elongation at break of about 3.5% **(Figure 13)**, high yield strengths[16] (>2.4GPa) and high strength to weight ratios. The fibres have a high resistance to abrasion, water, most chemicals, UV radiation and micro-organisms. Its melting point can vary between about 144°C and 152°C. Of all the main HMSF materials, HMPE has the lowest maximum continuous operational working temperature (70ºC)[17].

HMPE is a visco-elastic[18] material and its stiffness characteristics will vary dependent on load intensity, duration of loading and number of loading cycles. Visco-elastic behaviour is also influenced by load amplitudes versus mean load and environmental conditions. During early loading cycles, the bedding-in of the rope will result in some initial constructional elongation.

1.9.2 Rope design

The most common type of ship's mooring rope is of a multiplait polypropylene construction. However, HMSF ropes have become more widely available, leading to an increased usage on board ship.

When HMSF ropes are used for ships' moorings, their construction generally falls into one of two types: braided unjacketed high twist (short-lay) or braided jacketed low twist (long-lay).

[16] Yield strength - the maximum stress that a material can withstand before plastic deformation occurs.

[17] Resistance against temperature is dependent on the duration of exposure to that temperature.

[18] Molecular slip, or plastic deformation, does not occur instantaneously but is time dependent since it is related to viscosity. The combined elastic and plastic deformation is said to be visco-elastic.

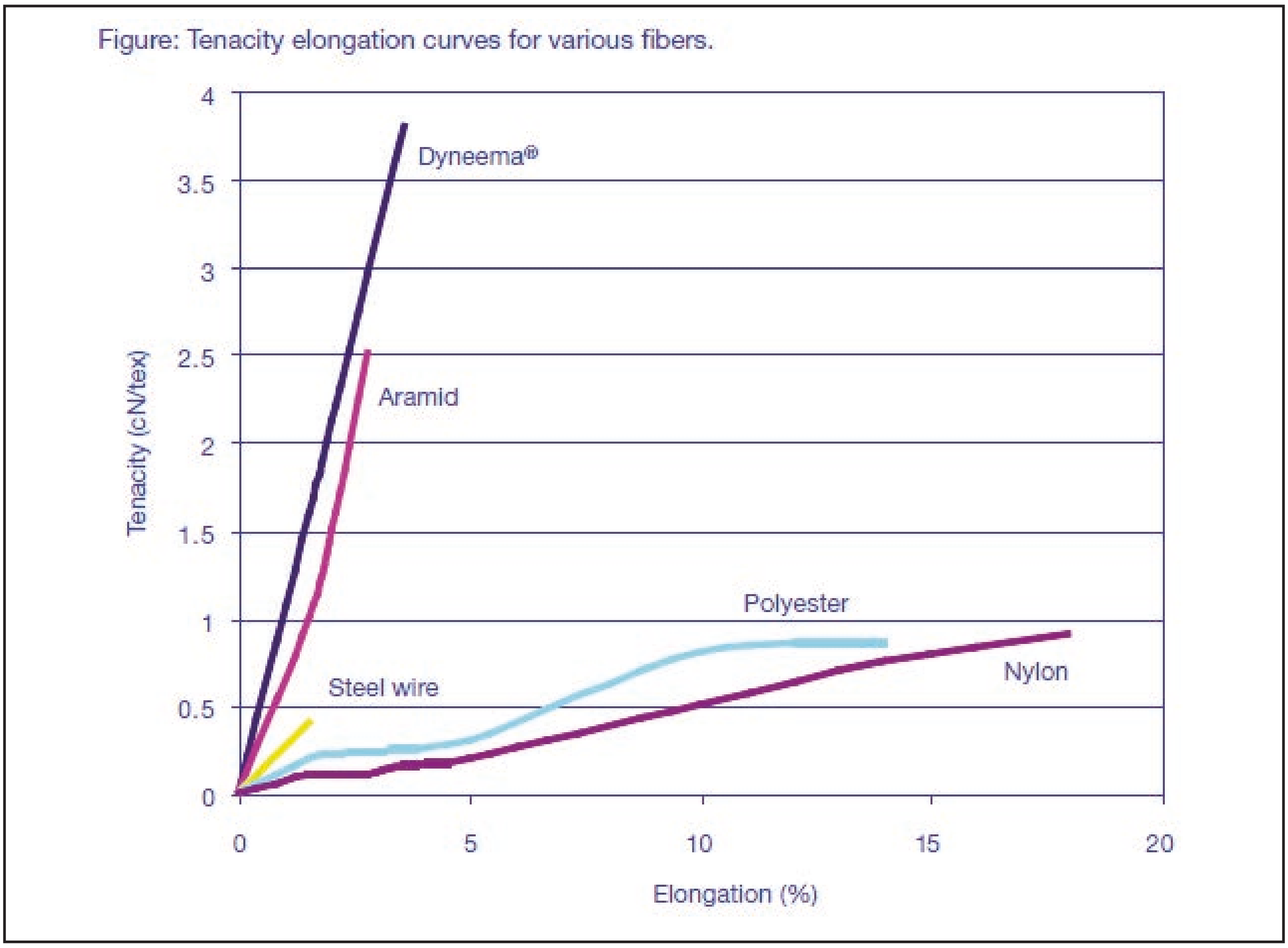

Figure 13: HMPE elongation comparison

Unjacketed HMSF ropes have been used because they are very flexible and easy to inspect. Long-lay jacketed HMSF ropes have often been used for specialist applications; for example, the tethering of offshore oil and gas platforms. The rope construction relies entirely on the jacket for its structural integrity as, without it, the low twist load bearing core would easily separate. The use of jacketed HMSF rope for ship/shore mooring has become increasingly popular as it has several perceived advantages over unjacketed rope; these include:

- High strength and low weight.
- Protection of the load bearing core by the outer jacket.
- Cover has the potential for greater heat resistance.
- Usually less expensive.

However, the disadvantages of jacketed rope include:

- Inability to inspect the load bearing core.
- Lower long-term residual strength due to lower volume of fibre core for given diameter.
- Harder to repair or splice.

- Less cut and abrasion resistance.
- Might not float.
- Less flexibility.
- Potential for jacket rupture.
- Higher susceptibility to kink damage when bent around tight bends.

1.9.3 Failure modes

In virtually all operational rope failures, tensile overload is the ultimate failure mode. In instances of dynamic and cyclic loading, damage (in various forms) will accumulate in individual components over time. Depending on the type(s) of damage accumulated, the effect may be to reduce the load bearing cross-section of material at a specific location, or reduce the load bearing capacity of the material at the location. The effect of both these scenarios is to increase the relative stress at a specific location for a given tension until tensile failure occurs.

The most common forms of external damage that might lead to the failure of an HMSF rope include abrasion, cutting, heat, twisting and overloading. Types of internal damage include tension-tension fatigue, axial compression fatigue, creep rupture, flex fatigue and hysteresis[19] heating.

Tension-tension fatigue occurs under conditions of cyclic loading. Cyclic loading is likely to occur in mooring lines at all berths, but the magnitude of the cycling will be greater at an exposed berth. Under relatively high tensions and frequent cycling of the load, rope will increase in temperature due to hysteresis.

As the tension in a rope varies, its helix angles change; this can cause the rope fibres to slip and rub against each other and abrade the filaments and induce frictional heating effects. The rate of tensile fatigue and the related internal abrasion will depend on the material and the operating conditions i.e. load, wet or dry, temperature, and whether the rope is bent around a deck fitting. The impact of cyclic loading may be reduced by attaching suitable length elastic tails to the mooring line.

Axial compression fatigue is the tendency of a fibre to fail when it is subjected to cyclic loading, which exerts compression along its axis. In a rope where the fibre filaments are unrestrained, the filaments will gently flex without suffering any physical damage **(Figure 14)**. Where the rope's load-bearing yarns and filaments are restrained, and subject to axial compression, individual filaments are prevented from slipping axially to equalize the load. Unable to gently flex, the yarns form sharp buckles, which induce "plastic hinges" or z-shaped kinks **(Figure 14)** and kink bands at filament level **(Figure 15)**. The most dominant mechanism likely to induce axial compression and axial compression fatigue in a rope under tension is low mean load cycling; axial compression can also be caused when a rope is twisted or bent around a fairlead. Frequent flexing can introduce fatigue at the kink hinge point and cause fibres to fail at the kinks. This can lead to a rope yarn failure that has the appearance of a cleanly severed cut **(Figure 16)**.

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[19] Heating of ropes in cyclic loading comes from the energy lost per cycle. Generated heat is distributed throughout the rope and wet ropes will conduct heat away better than dry ones.

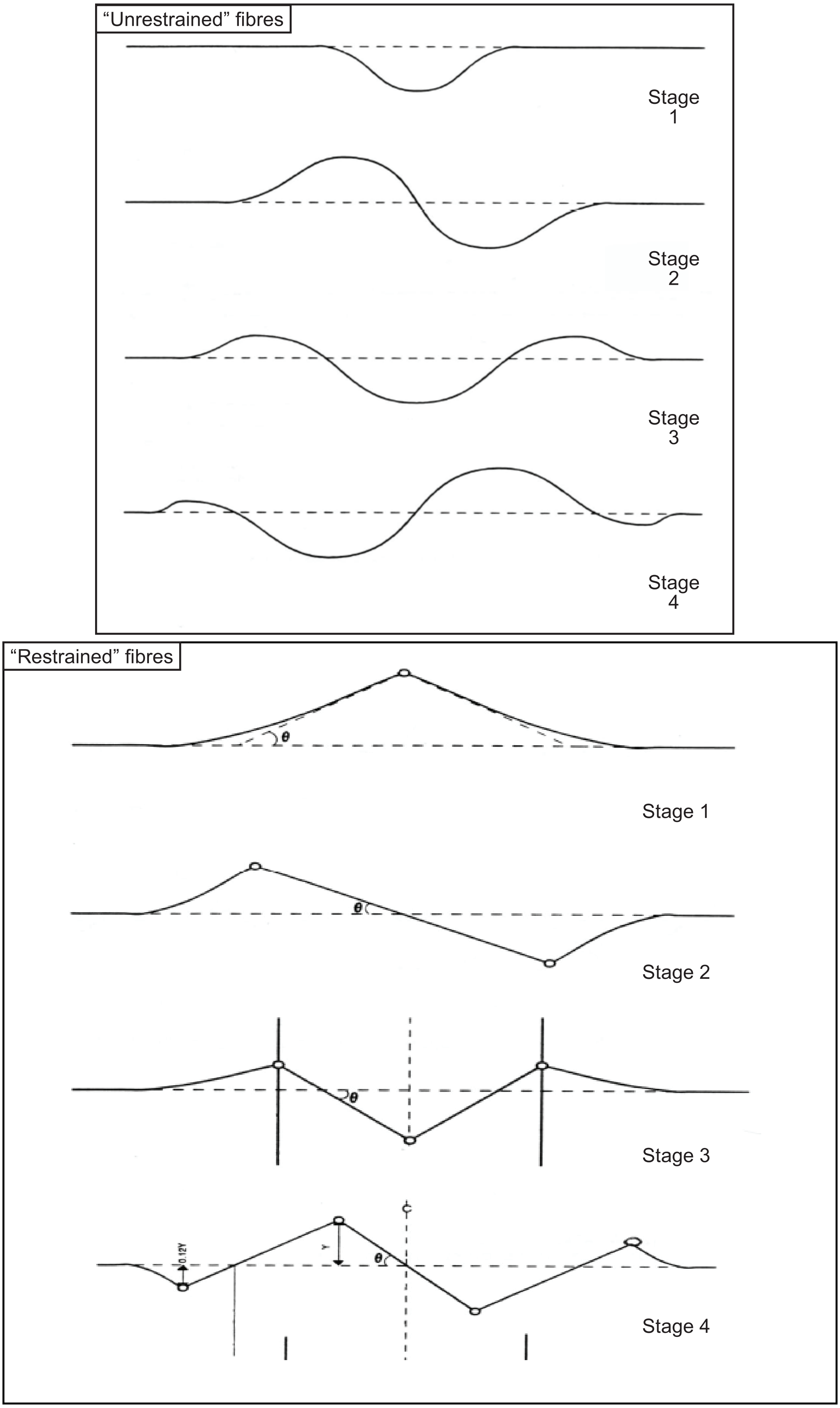


Figure 14: Development of elastic to plastic fibre buckling

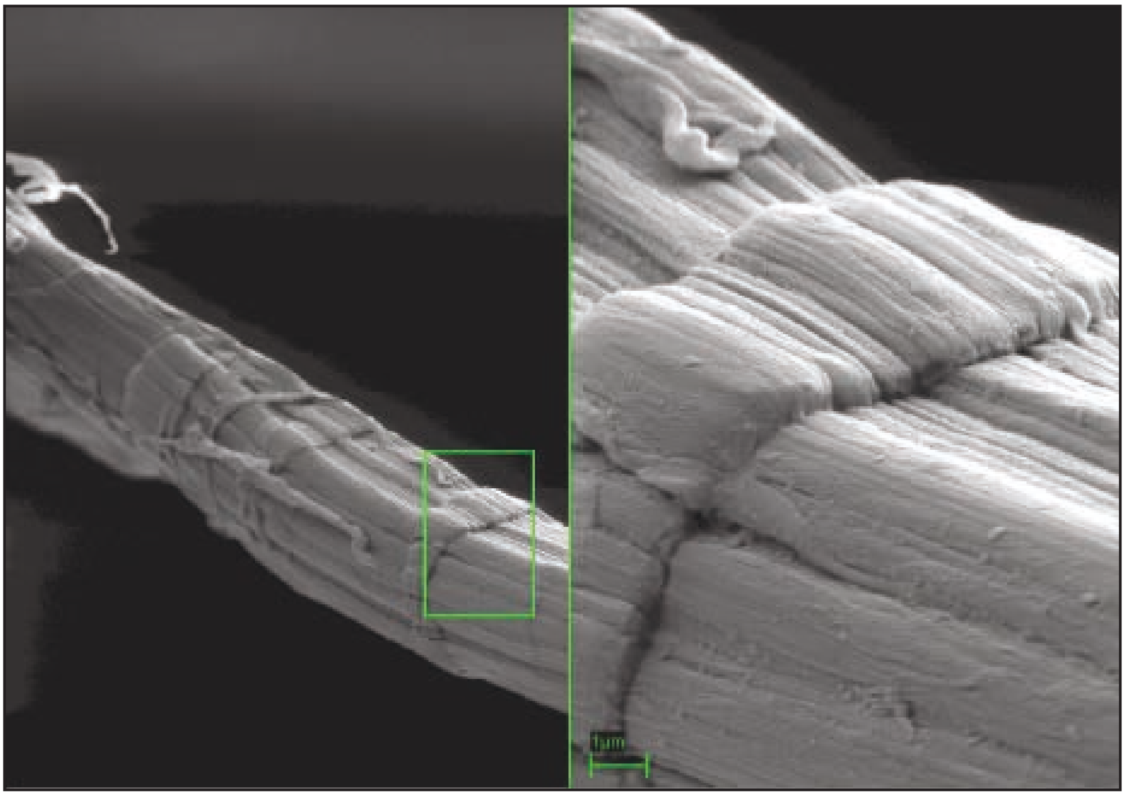


Figure 15: Kink bands at filament level

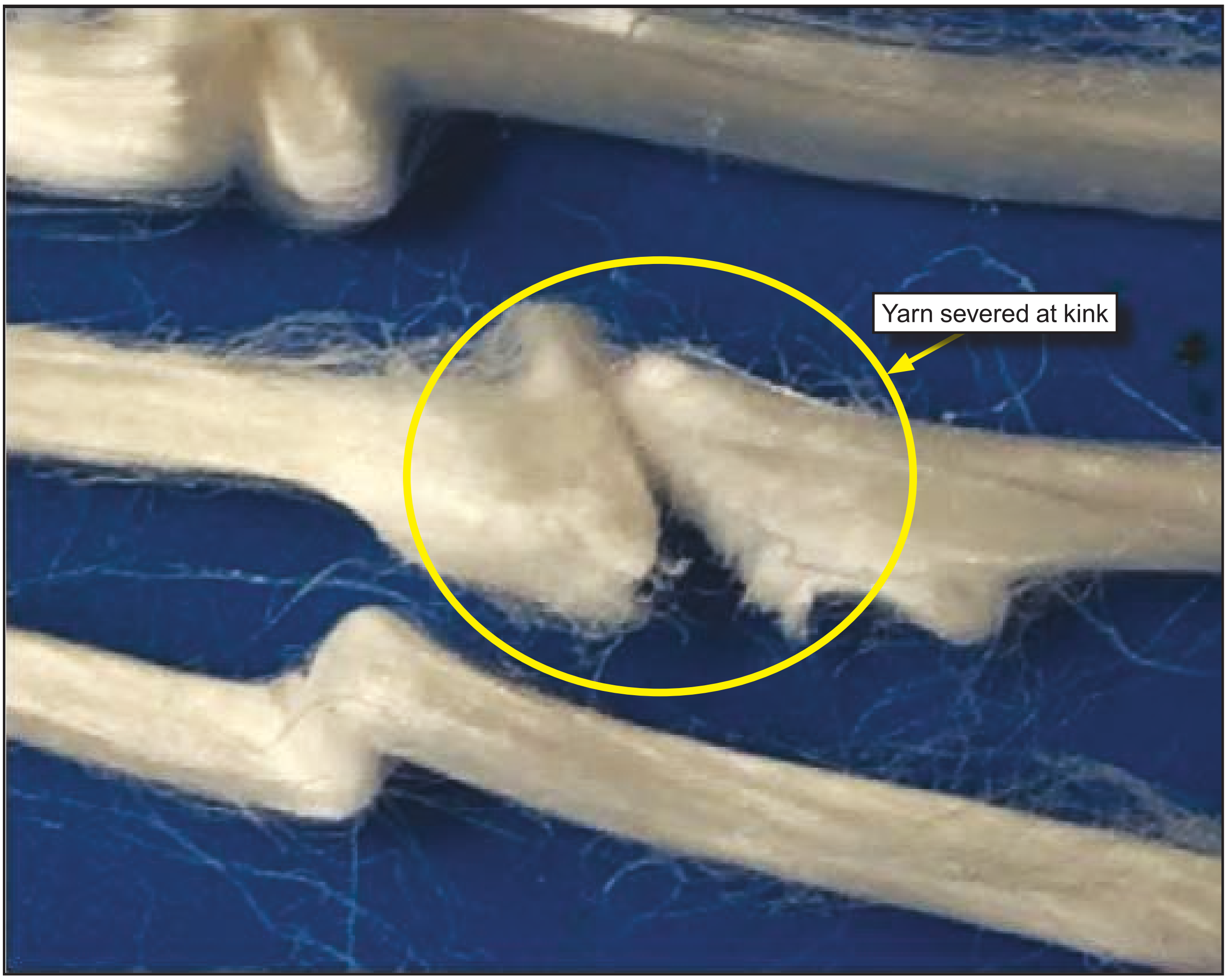


Figure 16: Z-kinks in HMPE rope yarn

Creep is the tendency of a solid material to slowly move or deform permanently under the influence of load. Creep is a process that occurs in all materials as a result of long-term exposure to levels of stress that are below the yield strength of the material. HMPE has three distinct phases in the creep process: primary, secondary and tertiary **(Figure 17)**. Primary creep occurs relatively quickly, with the material's elongation rate decreasing over time. Secondary creep occurs at a constant rate and is predictable; at low loads it can occur over a long period of time. The tertiary creep phase occurs beyond the linear creep rate region; the creep rate increases rapidly as a result of breakage of individual filaments. The consequence is a rapid cumulative loss of strength in the final stages before total rupture.

The creep rates of HMPE fibres can be high and are influenced by the fibre grade, the load, the time and the ambient temperatures to which they are exposed. Very high loads (i.e. low factors of safety) and/or high temperatures will significantly accelerate the creep process **(Figure 18)**. DSM had published generic creep graphs of the three main variables - time, load and temperature - for the primary and secondary creep phases **(Figure 19)** of HMPE fibres.

1.10 THE SOUTH HOOK LNG TERMINAL

1.10.1 General

Milford Haven was home to two LNG terminals: South Hook **(Figure 20)** and Dragon. Construction of the South Hook terminal began in 2006 as part of the *QatarGas 2*[20] supply chain project. The first delivery by a Q-Flex class vessel was on 20 March 2009.

When fully commissioned in 2010, South Hook LNG was the largest LNG re-gasification terminal in Europe with the capacity to process 15,600,000t of LNG annually, representing around 20% of the UK's LNG gas needs.

1.10.2 Mooring arrangements

The dolphins and their respective hooks on the South Hook jetty berths were labelled for identification; *Zarga*'s failed spring line was connected to B1B4-2, which was berth 1, dolphin B4, hook number 2 **(Figure 21)**. Each hook was fitted with an *Exaquantum* load tension sensor that enabled the load in each mooring line to be continuously monitored and recorded ashore. The hook loads were recorded to a database at 5-second intervals, and the high and low hook load alarms were set at 80t and 0t respectively. The hook load cells were tested and calibrated yearly and had previously been inspected on 24 June 2014. Line tension monitoring equipment is commonly only installed at LNG terminals.

Once a vessel was declared all fast, a fibre optic umbilical cable was passed to the vessel's crew to enable them to monitor the line loads on board and adjust the line tensions as required. *Zarga*'s crew were unable to view the loads on the forward spring lines during the repositioning attempt because the fibre optic cable had not been passed to the vessel prior to the accident.

[20] One of four LNG supply projects which serves markets in the UK, USA, Asia and Europe.

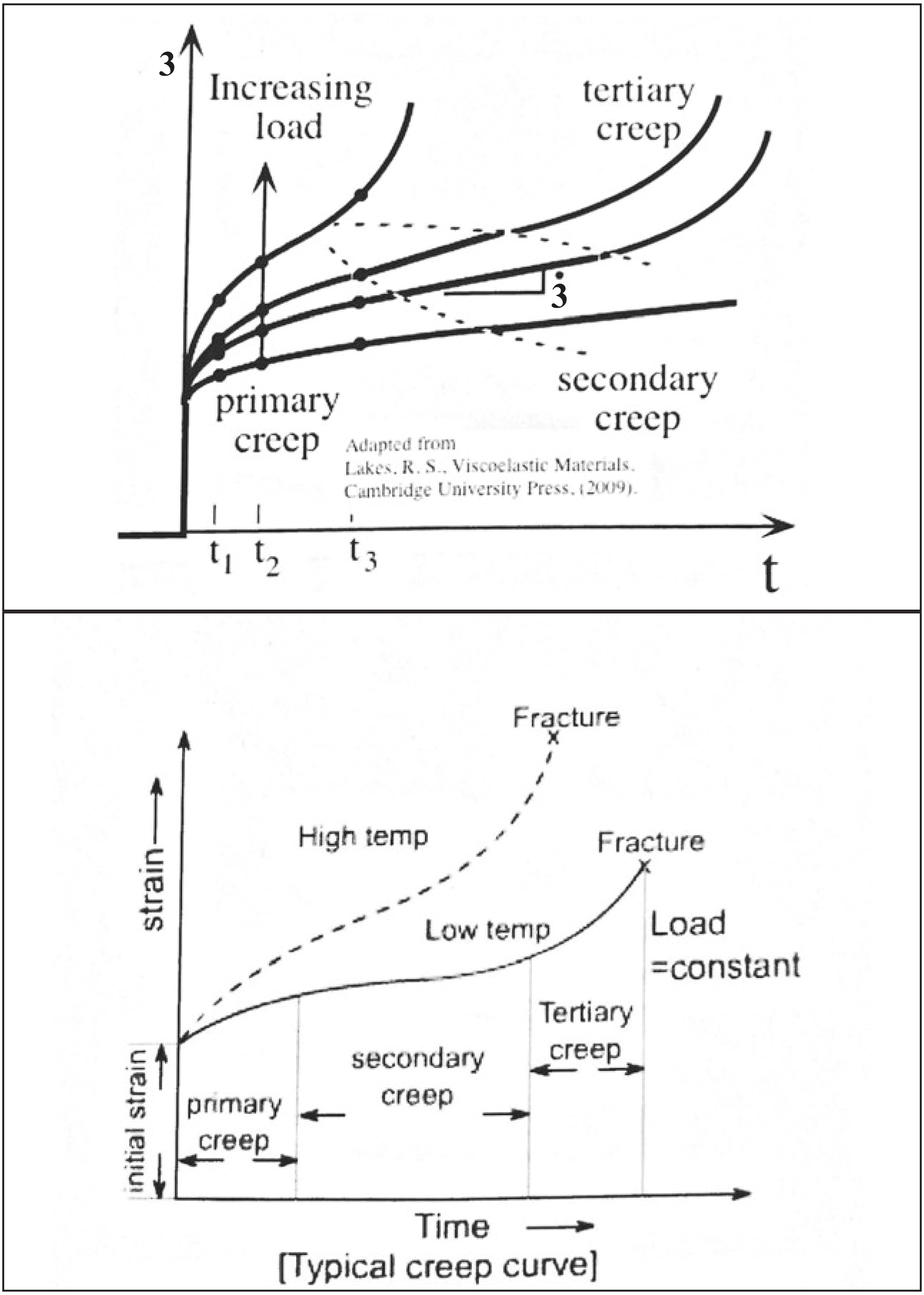


Figure 17: HMPE fibre creep curve

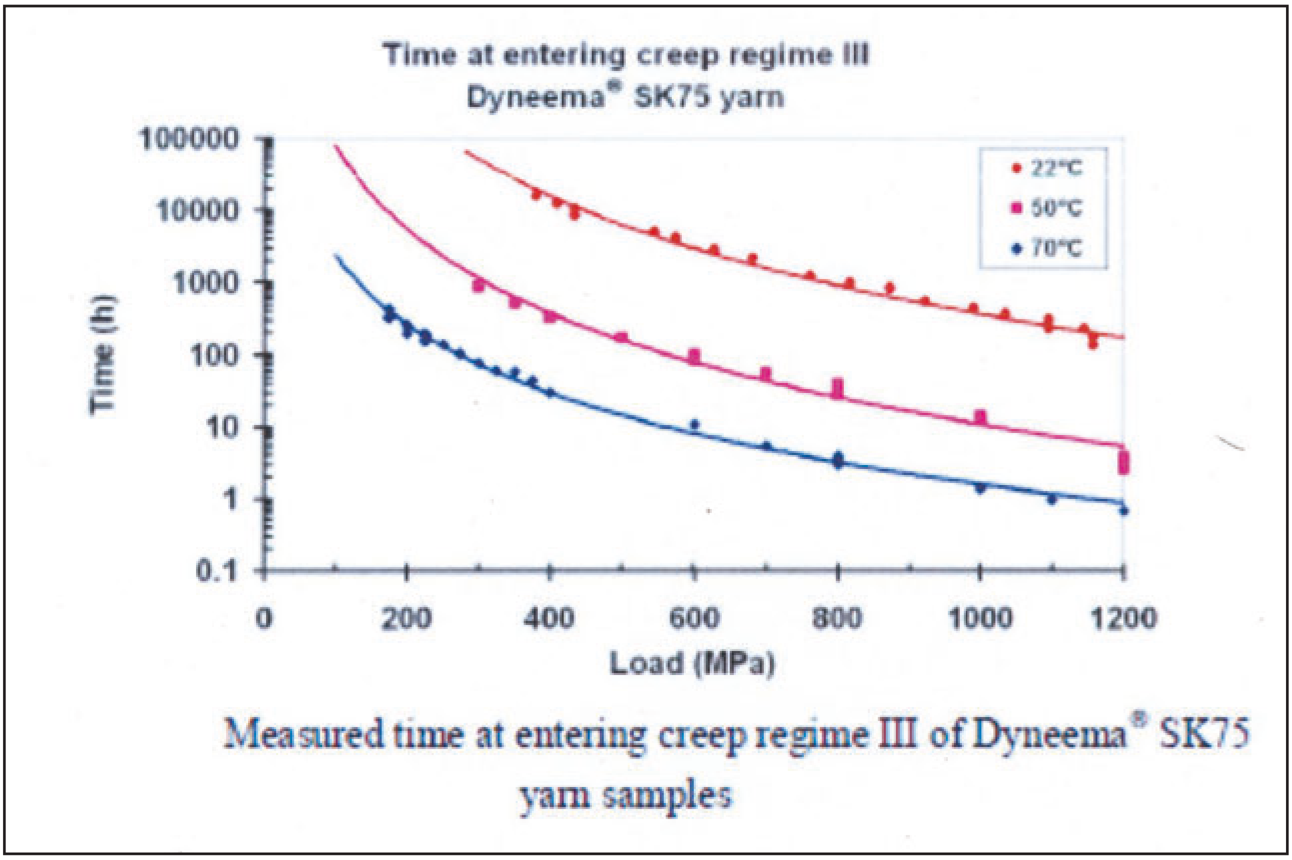


Figure 18: Dyneema SK75 tertiary creep phase load-time curve

ELONGATION AS A FUNCTION OF LOAD, TEMPERATURE AND TIME AS USED IN THE CREEP MODEL

	Regime I Delayed elastic	Regime II Flow	Regime III Failure
Time	Log time	Proportional	Not modeled
Load	Proportional	Non-linear	
Temperature	Weak	Exponential	

Figure 19: HMPE fibre elongation as a function of load, temperature and time

Figure 20: South Hook LNG terminal

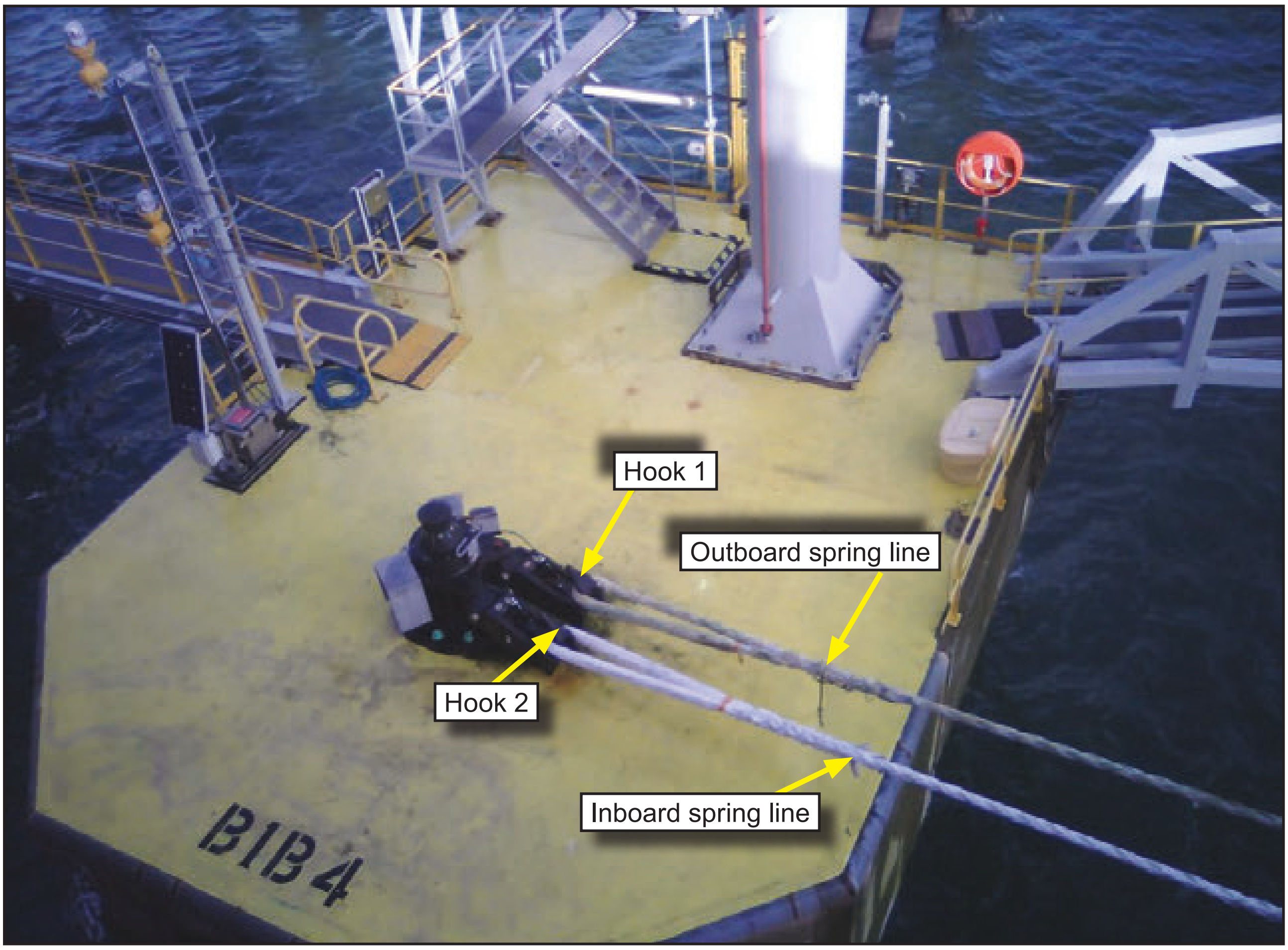


Figure 21: South Hook jetty berth 1 dolphin hook B1B4-2

1.10.3 Loading arms

Each berth had five counterweighted loading arms. The operating limits for the loading arms allowed a moored LNG vessel to drift up to a maximum of 4.6m fore or aft of the in-alignment spotting line; this took into account the highest and lowest astronomical tides. Two sequential emergency shutdown alarms initiated ‘cargo transfer stop’ and ‘auto disconnect’ of the loading arms if the vessel drifted outside of the specified drift envelope.

1.11 BERTHING PRACTICES AND PROCEDURES

1.11.1 Port entry and berthing plan

The Q-Max vessels’ typical inward transit passage plan to the South Hook LNG terminal was timed to allow the vessels to be swung off the berth and manoeuvred on to the jetty during the last hour of the flood tide. The intention was to make the vessels fast alongside before high water, and use the remains of the flood tide to help increase the tension in the mooring lines.

Once secure, the standard procedure was for the deck crew to monitor the lines during the ensuing ebb tide and tension the ropes as necessary to prevent the vessels moving out of position. The deck crew were required to maintain a minimum tension of 15t on each line. The individual hook load low tension alarms on board the vessels were set at 10t as this was considered the minimum aggregate tension required to keep them alongside.

1.11.2 Mooring procedures

Zarga’s risk assessment for *mooring/unmooring and tug operations*, which was last reviewed in December 2014, identified poor communications, inexperience and failure of mooring line as hazards that might result in personal injury or damage to equipment. The control measures listed in the risk assessment included:

- The provision of training and operating procedures.
- Use of correct people for the job.
- OiCs to fully understand the mooring plan and to attend the pre-mooring meeting.
- The delivery of safety briefs and toolbox talks.
- Identification and avoidance of snap-back zones.
- The provision of at least two VHF radios with fully charged batteries; radios to be checked before operations begin.

The risk assessment warned that special care should be taken while handling the forward spring lines and stated that a person should be used to transmit signals from the OiC to the winch operator.

Guidance on the conduct of mooring operations was provided by STASCo in *Zarga*'s safety management manual (SMM). Section 3.7.1 of the SMM, *Mooring*, provided the following safety guidance:

> *The following key aspects **must** be considered:*
>
> - *The mooring party leader [OOW or Bosun] in charge of the mooring operation **should** always maintain a helicopter view of the physical mooring operation…. Distractions **should** be avoided, detached supervision of the process with visible control using prescribed hand signals to control the operation is required.*
>
> - *If OOW or Bosun is distracted at any time the operation **should** be temporarily suspended. The principle danger comes from progressively tensioning mooring lines that go undetected until it becomes* overloaded. [sic]

Section 3.7.2, *Review of Mooring Practices*, required a quarterly review of mooring practices. The scope of the review included the assessment of:

- The proximity of ship-side observation platforms to snap-back zones.
- The optimum position of OiC with respect to maintaining a helicopter view over the entire operation.
- Onboard communications during mooring operations, in particular, ways in which the OiC communicates with remotely located winch operators who are not in direct line of site. The SMM stated that: *The use of additional portable radios might be considered*.
- The use of a relay signaller if the winch operator is not in line of sight of the OiC.
- The procedure for tending mooring lines that are already under tension.

Section 3.7.3, *Extra Moorings and/or Tug Assistance*, stated that:

> *Masters must not hesitate to use extra moorings when the strength of wind, tide or currents indicates it prudent to do so. Tugs should be ordered in ample time when tug assistance is necessary to maintain the vessel safely alongside.*

The maximum number of mooring lines that could be used on board *Zarga* was 20 (10 fore and aft), all of which were required in the standard berthing plan for South Hook.

As a result of concerns raised following previous line failures at the South Hook terminal, and problems maintaining sufficient line tensions, STASCo provided additional guidance to masters for mooring at South Hook. This included an instruction to the winch operators to heave in the mooring lines until the winch stalls, and hold the winch lever in the heave position while a second crewman applies the drum brake. The guidance also advised that:

- *The mooring winches have a heaving power of 30 tonnes which is less than 25% of the MBL of the ropes. So it should be impossible to break a mooring* *line by only heaving on it with the mooring winch and it is noted that no lines have broken whilst they are being tensioned by the mooring winches only.*

- *High-modulus ropes are designed to have very little stretch when tension is put on them. The elasticity required in the system is provided by the mooring tail. So as long as persons are not standing between the mooring winch and the fairlead at the ships side they are not in danger of being caught by whiplash.* [sic]

1.11.3 Mooring line snap-back danger zones

All mooring lines under tension will stretch, particularly those made from low modulus conventional synthetic fibres. Should the line part, the energy stored within the elongated rope will be released and the two ends of the line will recoil or snap back towards their anchor points. This snap-back effect can be extremely powerful and the rope ends may reach velocities in excess of 200 metres per second (m/s) (500mph). Anyone standing within the snap-back zone at either end of the line risks serious injury or death.

Where a mooring line is led around a deck fitting such as a fairlead roller, the rope will whip around the fitting in a wide arc towards its anchor point; this will significantly increase the area of the snap-back danger zone.

The Code of Safe Working Practices for Merchant Seamen (COSWP) consolidated edition 2010 – Chapter 25: *Anchoring, Mooring and Towing Operations* provided guidance on mooring operations and included illustrations of typical snap-back zones on both simple and complex mooring decks **(Figure 22)**. *Zarga*'s snap-back zones for its mooring and towing lines were identified at build, in accordance with the guidance provided in COSWP and MEG-2, and marked on the vessel's deck plans **(Figure 23)**.

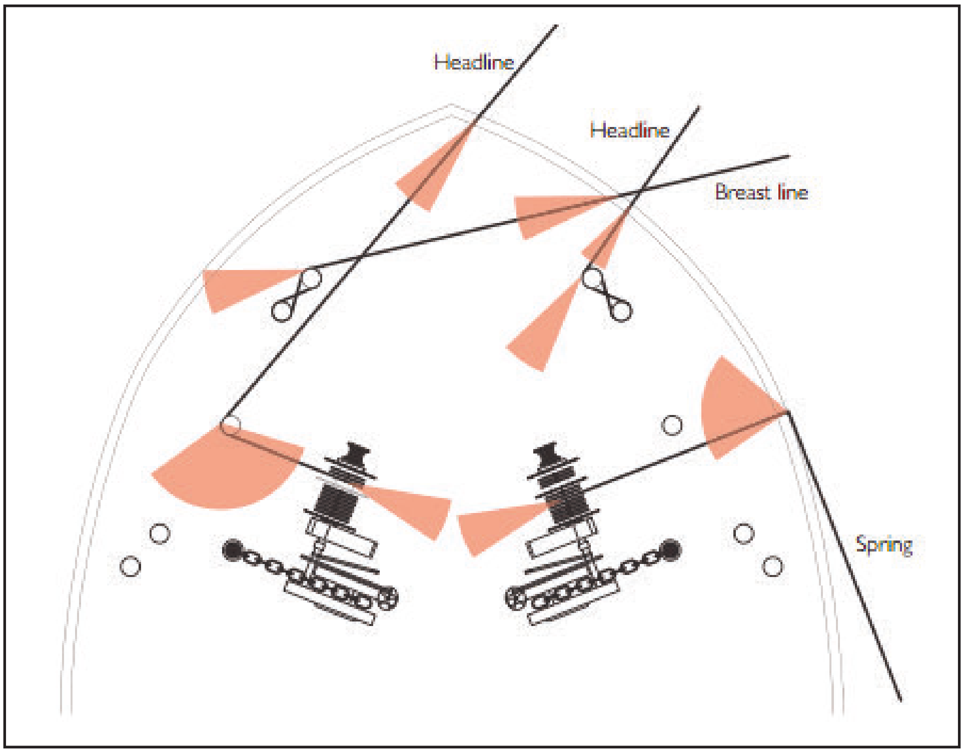


Figure 22: COSWP 2010 edition: snap-back zones
Note: shaded areas are snap-back zones on the for'd mooring deck

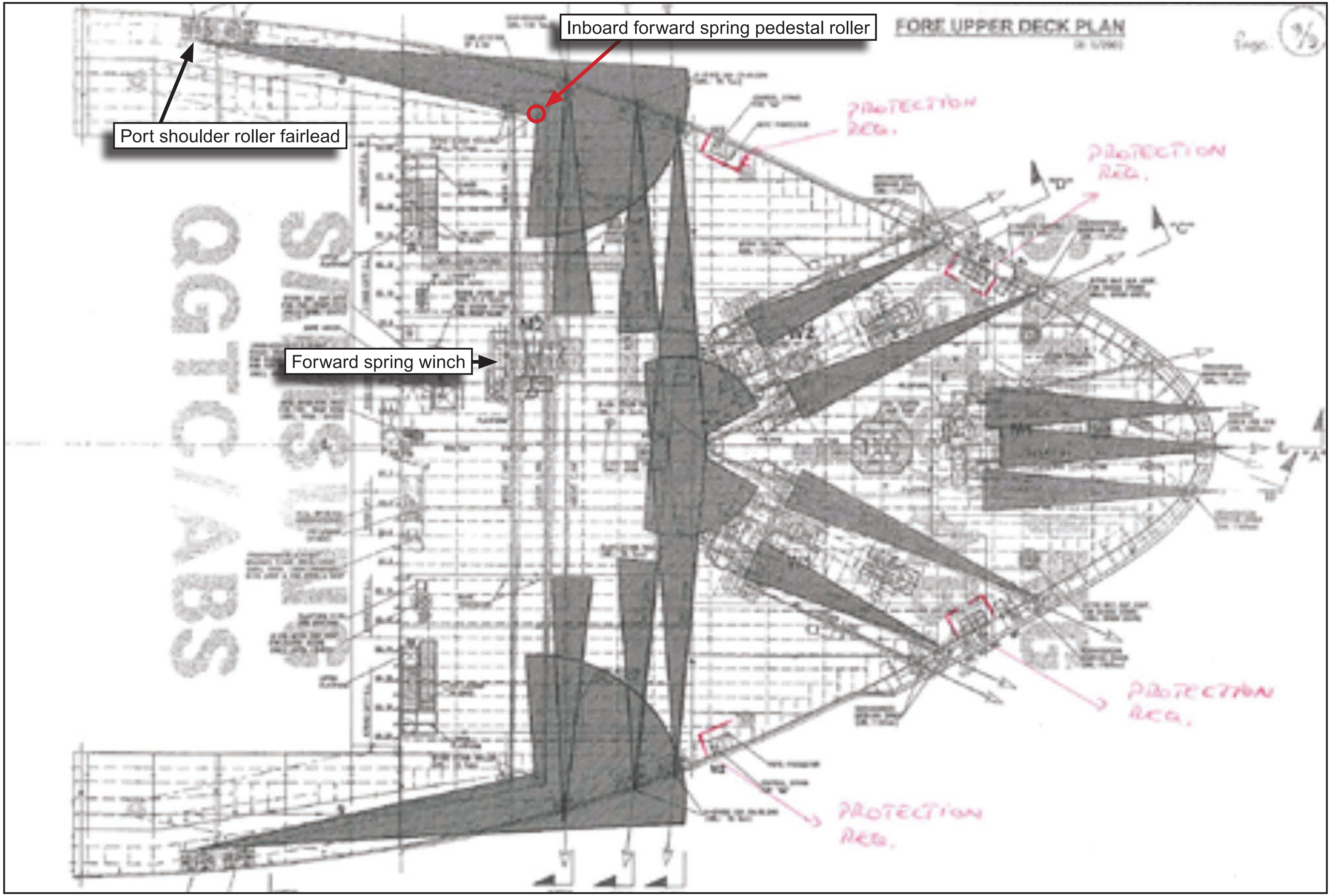


Figure 23: Q-Max forward upper mooring deck plan and snap-back zones (shaded areas)

In September 2015, a revised COSWP[21] introduced additional guidance on snap-back zones and advised that the entire area of a mooring deck should be considered a potential snap-back danger zone. The revised guidance also warned against the painting of snap-back zones on mooring decks as this can introduce a false sense of security. Using similar reasoning, STASCo had decided not to paint snap-back zones on the mooring decks of its Q-Max and Q-Flex vessels.

The International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS) regulation II-1/3-8 (Towing and Mooring Equipment) set out the requirements for the provision and approval of appropriate arrangements, fittings and equipment for safe mooring and towing operations. On 6 March 2015, a proposal was made to the IMO's Maritime Safety Committee (MSC) to revise the SOLAS regulation and its supplementing guidelines to encourage innovative design. The aim of the proposal was to prevent unsafe and unhealthy work situations during mooring operations on new ships.

The paper supporting the proposal provided data for the recorded number of injuries and fatalities that had occurred during mooring and towing operations on board Danish registered ships. Between 1997 and 2013, 402 accidents had been registered on Danish ships, leading to 4 fatalities and 43 injuries.

In June 2015, the MSC added the following new output to the 2016-17 agenda of its Sub-Committee on Ship Design and Construction (SDC):

> *Revised SOLAS regulation II-1/3-8 and associated guidelines (MSC.1/Circ.1175) and new guidelines for safe mooring operations for all ships.*

The associated agenda item (SDC 3/15/1) included a proposed draft amendment to the regulation to include guidelines on the maintenance of mooring lines.

The SDC fourth session was held from 13-17 February 2017. The Committee's Correspondence Group took into account industry views on the draft guidelines. Subsequently, the Committee took a range of actions including that the Correspondence Group should be re-established to finalise the draft guidelines on the design of safe mooring operations and to develop guidelines on the selection, identification and use of mooring lines as well as generic guidelines on inspection and/or maintenance of mooring lines.

1.11.4 Mooring arrangement plan

STASCo used the OPTIMOOR[22]computer software program, developed by Tension Technology International Ltd (TTI), to estimate the forces the Q-Max vessels' mooring lines were likely to experience at the LNG terminals. The OPTIMOOR software applied the standard environmental criteria set out in OCIMF's MEG and the standards required by US legislation[23] to estimate the mooring loadings. The standard environmental criteria stated that the mooring restraint available on board the ship should be sufficient to satisfy the following conditions:

> *60 knots wind from any direction simultaneously with either:*

---

[21] The revised version of COSWP was renamed *The Code of Safe Working Practices for Merchant Seafarers*.

[22] OPTIMOOR is an electronic tool for assessing the mooring forces on a vessel and determining the most suitable mooring arrangement to remain within specified line load criteria.

[23] US Oil Pollution Act 1990.

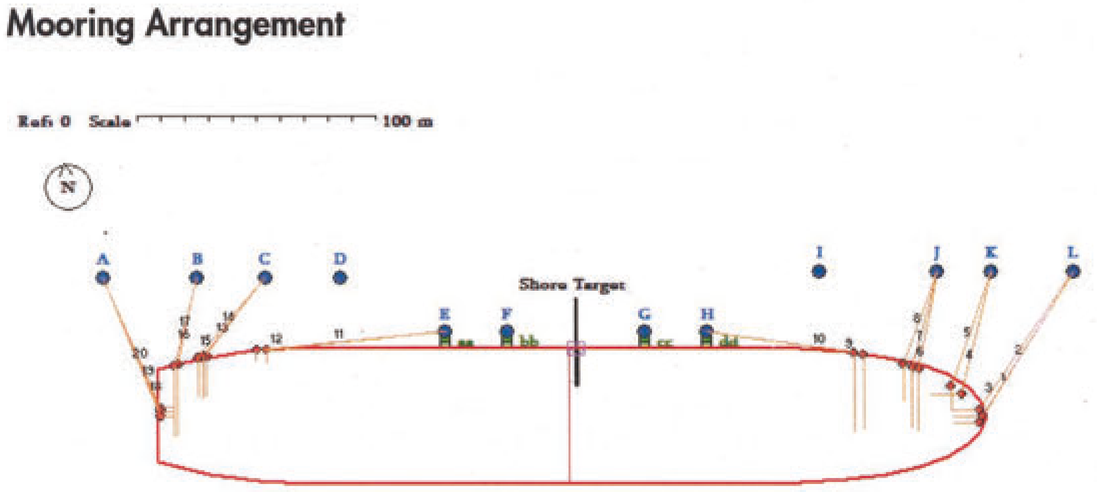
3 knots current at 0º or 180º; or

2 knots current at 10º or 170º; or

0.75 knots current from the direction of maximum beam current loading.

MEG-2 explained that the standard criteria did not cater for the most extreme combination of environmental conditions at every terminal worldwide, particularly exposed terminals. The guide recommended that for those terminals where for some reason the criteria are likely to be exceeded, the vessel's mooring restraint should be supplemented with appropriate shore-based equipment.

The initial OPTIMOOR assessment for the Q-Max vessel mooring arrangements at South Hook, conducted in July 2008, determined that 18 lines (nine forward and nine aft, in a 3-4-2 configuration) would be sufficient. In December 2010, a further OPTIMOOR study concluded that the 20-line mooring arrangement would be more appropriate for South Hook **(Figure 24)**.



VESSEL BERTHED: PORT SIDE ALONGSIDE

FWD: 3, 2, 3, 2. AFT: 3, 2, 3, 2.

Optimoor Hook Reference	A	B	C	D	E	F	G	H	I	J	K	L
Shore Dolphin ID	M1	M2	M3	M4	B1	B2	B3	B5	M1	M2	M3	M4
Hooks Available	3	3	3	3	2	2	2	2	3	3	3	3
No. Lines to each Dolphin	3	2	3	-	2	-	-	2	-	3	2	3

Figure 24: OPTIMOOR mooring plan for South Hook LNG terminal

1.12 ROPE INSPECTION AND MAINTENANCE PROCEDURES

1.12.1 Maintenance management

Zarga's mooring lines were regularly inspected and maintained by the vessel's deck crew. STASCo had provided rope inspection and maintenance training, and guidance was given by the rope manufacturers' representatives. The inspection regime was managed within the vessel's planned maintenance system (PMS) by the C/O.

The PMS required 4-monthly inspections of each rope. To do this, the ropes were removed from the winch drums and visually inspected over their entire length. The PMS provided information on types of damage to look for and guidance on rope rejection or discard criteria. In order to prolong the life of the mooring ropes, the PMS recommended that:

- *Ropes normally used as 'Springs' should be rotated with other ropes every 2 years; and,*

- *All ropes should be end-for-ended every 4 years.*

The maintenance undertaken and observations made during the rope inspections were recorded in the vessel's electronic PMS database. In addition, records were maintained of the air temperatures and wind speeds at the terminals while the vessel was moored.

To avoid chafing damage, the contact surfaces of the deck fittings were inspected regularly and chafing guards were fitted around the mooring lines **(Figure 3)**.

1.12.2 Rope rejection/discard criteria

Section 3.7.4.6 of *Zarga*'s SMM, *Inspection of Mooring Ropes*, included the following guidance:

> *A frequent and thorough inspection program is required to ensure that a rope is removed from service before its strength is substantially reduced. The inspection procedure is based on a system of points (rejection factors – RF) which are allocated for each inspection of the rope.*

The SMM provided the following eight areas of inspection and guidance for rejection, inter alia:

1. *Broken strands*

    a. *>10% of fibres cut, fused or badly abraded in a single cross section*

2. *Splices*

    a. *>3 splices on full length of rope*

3. *Length*

    a. *<80% length of rope remaining*

4. *External abrasion damage*

    a. *Heavy surface fuzz – progressive*

    b. *Oil and grease (wash in mild detergent)*

    c. *Abrasion on inside radius of eye, with bulk of surface yarns or strands reduced by 50% or more*

    d. *Hockles*[24] *that cannot be removed*

    e. *Exposure to chemicals*

5. *UV degradation*

    a. *Splinters on yarn surface*

6. *Thermal damage*

    a. *Melting or fusing affecting 10% or more of rope yarns in a cross section*

    b. *The rope shows hard, melted, flattened areas*

    c. *Exposure to excessive temperature as specified for type of fibre*

7. *Internal degradation*

    a. *Powdering between adjacent strand contact surfaces*

8. *For braided jacketed ropes*

    a. *Cover jacket is damaged. Determine core coverage and assess criticality of coverage for particular application (core is undamaged)*

    b. *Core damage: pulled, cut, abraded, powdered, or melted strands*

    c. *Herniation: core pokes through cover (sheath) which cannot be massaged back into original structure*

The guidance also emphasised that localised areas of stiffness along a rope indicated that the rope had been subjected to shock loading, and that a rope suspected of being shock loaded in excess of its WLL or when the winch brake had rendered (+82t), should be condemned.

Zarga's crew, and those of other STASCo vessels, often identified localised areas of stiffness in ropes during inspections. In line with the training provided, their standard practice was to attempt to relax the ropes by flexing them around the deck pedestal rollers. Some of the crew had also used wooden mallets to help massage the ropes back to a flexible state.

[24] Hockle - A loop of cordage caused by twisting against the lay.

1.12.3 External inspections and testing

Bridon had advised its customers that the retirement point of a rope could be estimated by comparing the test results of used ropes with the operational history of in-service ropes. The operational history data required included: load history, ambient temperatures, operational geometries and maintenance inspection records.

STASCo had returned several failed or rejected mooring lines to Bridon for examination and testing. Bridon had typically carried out rope break tests to determine residual strength and assess whether the ropes should be returned to service or discarded. Vessel operators, including STASCo, did not routinely provide the operational data required by Bridon for its external assessment of in-service rope condition.

1.13 HISTORY OF THE FAILED SPRING LINE

1.13.1 Rope application

In accordance with the design specification, *Zarga*'s mooring lines were originally supplied with 11m long, 84mm diameter polyamide tails.

The failed spring line was initially used as a head line and was installed on the starboard side of the head line winch (position C) **(Figure 10)**. Maintenance records **(Annex D)** showed that it operated in this configuration for 520.6 working hours before the 22m long *Euroflex* tail was fitted in June 2011. During this period, *Zarga* visited South Hook on five occasions and the recorded wind conditions at the berth varied between Force 2 and Force 5. The highest temperatures recorded were 35°C and 33°C at Ras Laffan in October 2010 and May 2011 respectively.

The line remained as a head line for a further 655 hours (total hours 1175.7). The terminals visited during this period were South Hook, Ras Laffan, Jiangsu, Chita and Isle of Grain, and the recorded wind conditions varied between Force 2 and 8.

On 25 July 2012, the HMPE rope was end-for-ended[25] and continued to be used as a head line. On 25 October 2014, the line was inspected by the crew; it was then end-for-ended a second time and moved to the inboard line on the forward spring winch (position F). The following observations were recorded in the PMS database:

> *'C' rope in good condition, flexed 10m from eye in use, no signs of high stress, jacket damage or any chemical and thermal deterioration. Rope suitable to turn 'end for end'. Last 'end for end' done at 25/7/2012. Rope transferred to spring line 'F' with original eye end in service.*

The line was used as the inboard spring line for 167.1 hours (total hours 1342.8) until it failed. During this time the recorded wind conditions varied between Force 4 and 7 while alongside.

[25] This was done after a Bridon representative had inspected the rope on board and spliced the original drum end of the rope.

1.13.2 Hook load data for the South Hook jetty

A review of *Zarga*'s hook load records between 2010 and 2012 for South Hook LNG terminal **(Annex E)** showed that the line loads fluctuated sinusoidally with the tidal cycle. They also showed smaller, more regular, current and wind-related fluctuations that occurred within the tidal changes.

Line loads varied considerably, particularly in the earlier years when the 11m tails were in use. For example, on 27 April 2010 the recorded loads on one spring line indicated a range from 2t at 1137 to 121t at 1827[26]. Following the fitting of the 22m tails, the hook load records showed that the lines were exposed to generally lower loads.

The hook load records on the day of failure **(Figure 25)** showed that the load on the failed mooring line fluctuated between 0 and 40t. At about 1843, the average load increased from about 17t to about 30t; it remained there for about 5 minutes, with a peak load of 40t being recorded at 1845. At about 1848, the average load dropped to about 5t, and at 1857 it dropped to zero, where it remained for about 7 minutes. The load then increased rapidly to 25t. At 1908, when the line parted, the recorded load was 24t.

1.14 HISTORY OF MOORING LINE FAILURES ACROSS STASCO'S Q-MAX AND Q-FLEX FLEETS

Between 2009 and December 2015 a total of 45 mooring line failures was recorded across STASCo's fleet of Q-Max and Q-Flex vessels, the vast majority of which were Bridon's *Steelite Superline Xtra* rope. Prior to *Zarga*'s forward spring line failure on 2 March 2015, none of the failures had caused any injuries to crew or shore workers.

Bridon had attended STASCo's Q-Max and Q-Flex vessels, equipped with *Steelite Superline Xtra* mooring lines, on a number of occasions due to failed ropes. The inspection report undertaken after a visit to the Q-Flex carrier *Lijmilia*, dated 8 October 2009, stated:

> *While on board an inspection of the remaining available ropes and fairleads was carried out. Leads were in good condition with no concerns.*

and,

> *Some ropes had some hard spots that were discussed with our engineer. The rope will during normal application become hard and compressed as it is loaded or worked over a lead. This has no detrimental effect and can be eliminated by flexing the rope in this point. If however this cannot be removed then this can indicate that the core has suffered a high overload and as such a full inspection of the line will be required.*

On 15 December 2009, an aft breast line used to moor the Q-Max vessel *Al Ghuwairiya* to the South Hook LNG terminal parted. Bridon, as the rope manufacturer, conducted an investigation and identified that the load on *Al*

[26] Although the winch brakes were set to render at 80t, peak loads registered at the dolphin hooks would be lower at the winch due to frictional losses through the deck mooring equipment. Hence, brief brake rendering might have occurred, which would have reduced the overall tension in the line.

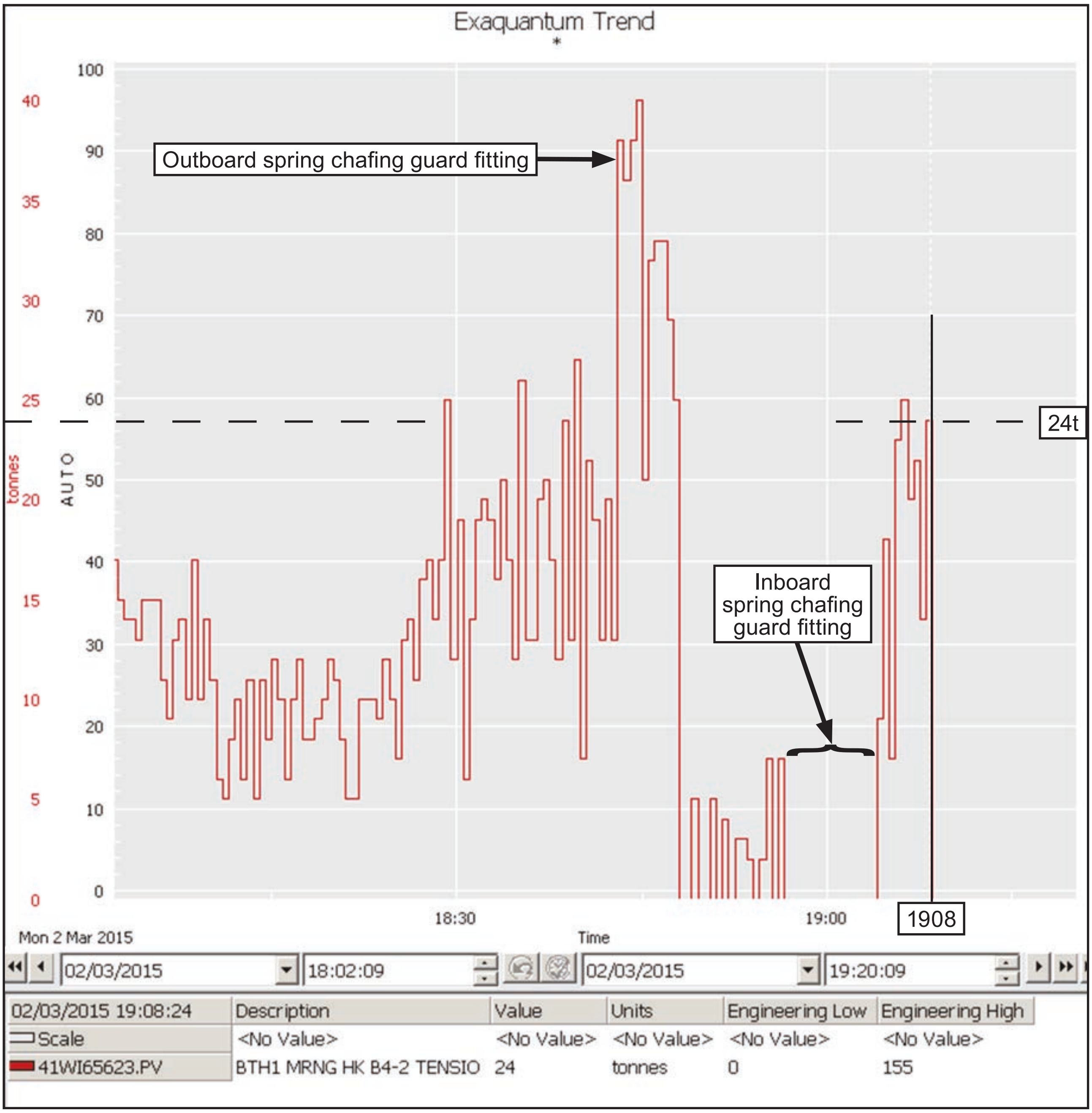


Figure 25: Inboard spring line hook electronic load readings for 2 March 2015

Ghuwairiya's lines was higher than expected and, on occasion, had exceeded the maximum recommended by OCIMF. Bridon found similar trends with other LNG vessel mooring lines and concluded that the continued exposure to such high loads would have a detrimental effect on rope life. Bridon's investigation report **(Annex F)** recommended that the working load of its *Steelite Superline Xtra* ropes should not be allowed to exceed 20% of the rope's specified MBL. Separately, Bridon also suggested that 48mm[27] diameter HMPE mooring lines would be more appropriate for the larger vessels. As the LNG carriers' mooring winches were designed to accommodate a maximum rope diameter of 44mm, no further action was taken.

[27] The MBL specified in Bridon's Fibre Rope Catalogue for its 48mm *Steelite Superline Xtra* rope was 164t.

During 2010, mooring line failures became more frequent, with 11 being recorded **(Annex G)**. All of the recorded failures occurred at the South Hook LNG terminal; at least eight of these were Bridon's *Steelite Superline Xtra* ropes. Two of the lines were forward springs that had failed on the same vessel on the same day, but the majority were breast lines. On two other occasions, multiple failures occurred on the same day on different vessels. In May 2010, STASCo decided to replace the mooring lines' 11m polyamide tails with the 22m *Euroflex* tails.

Thirteen mooring line failures were recorded in 2011. Of these, 6 occurred at South Hook and at least 11 were *Steelite Superline Xtra* ropes; 1 was a forward spring line but, again, the majority were breast lines. In May 2011, STASCo decided to replace the 22m *Euroflex* tails with 22m polyamide tails on all mooring lines, except spring lines.

During 2012, the failure of eight mooring lines was recorded, all of which were *Steelite Superline Xtra* ropes. Two of the lines parted at the South Hook terminal on the same vessel on the same day. Of the eight, one line was a forward spring, four were breast lines and three were stern lines. By November 2012 the mooring lines on all STASCo-managed Q-Max and Q-Flex vessels had been fitted with 22m tails.

During 2013, five line failures occurred, all of which were *Steelite Superline Xtra* ropes. Two of these occurred at the Isle of Grain, with one recorded as having a line load of 40 tonnes, and two at Ras Laffan where, on one occasion, wind speeds were recorded as being gale-force.

During 2014, three mooring lines failed, all of which were *Steelite Superline Xtra* ropes. One of these, an aft spring line, failed during the berthing operation at Ras Laffan while the vessel was being positioned using the aft springs. The other two lines - a forward spring and a forward breast - failed at South Hook.

In response to the identified high incidence of rope failures, Bridon ceased the manufacture and sale of its 3-strand *Steelite Superline Xtra* ropes.

Following *Zarga*'s mooring line failure on 2 March 2015, three more lines failed during 2015. Two were Bridon ropes and one was a Samson rope; all three were jacketed.

1.15 HMPE USERS' GROUP REPORT

In February 2011, an HMPE Users Group was formed by a range of interested parties that included owners and operators of LNG vessels, rope and fibre manufacturers, port operators and industry bodies. The aim of the group was to pool their knowledge and resources to investigate the industry's high HMPE mooring line failure rate.

The HMPE Users Group commissioned TTI to analyse the data recorded for 90 rope failures between 2007 and 2011. TTI's objective was to identify associations between the failure rate and rope construction, vessel type and terminal location. In addition, TTI visually examined several of the failed ropes considered in the study.

In respect of incidence rate, TTI stated in its *HMPE Users Group LNG Mooring Line Failures Final Report*[28] **(Annex H)** that:

> *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 experience of at least one HMPE line failure in this market sector*[29].

Four HMPE rope types featured in the study: three of long-lay jacketed construction and one 12-strand single braid unjacketed. The initial data analysis identified that:

- Bridon/Marlow had supplied 1360 HMPE jacketed mooring ropes to LNG vessels, while Samson Ropes had supplied 1429 jacketed ropes and 706 12-strand unjacketed ropes.

- The Bridon/Marlow rope contained the lowest amount of HMPE fibres per metre.

- The average mooring hours of a failed rope was 1011, with a minimum of 62 and a maximum of 1940 hours.

- Of the failed ropes:

    - 99% (89) were of a long-lay jacketed construction.

    - 92% (82) were manufactured by Bridon/Marlow, 5% (5) by Samson Ropes and 3% (3) by Koronakis.

    - 63.3% (57) occurred on Q-Max or Q-Flex vessels, and

    - 23.3% (21) occurred at the South Hook LNG terminal and 20% (18) at the Isle of Grain terminal in England.

- 50% (45) of the lines failed at 20 tonnes-force or below (16% or less of the ropes' MBL).

- 13.3% (12) of failures occurred at loads in the region of 80 tonnes-force.

The HMPE Users Group report highlighted the importance of reducing levels of peak loading to the HMPE ropes and explained that:

> *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 11m nylon tails at sheltered berths and 22m nylon tails at exposed berths to reduce peak line loads in any situation and extend line life.*

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[28] TTI's *HMPE Users Group LNG Mooring Line Failures Final Report* was completed on 19 October 2011.

[29] An estimate based on information received from non-user group operators suggests that the number of total rope failures was twice the number considered in the study.

TTI considered a range of possible failure modes. These included those introduced by rope design and construction, such as internal abrasion and axial compression; and those that might have been induced by the users, such as overload, dynamic loading and structural damage caused by rope handling and interaction with deck fittings.

The investigation identified a wide range of failure mechanisms but found no significant evidence of internal strand-on-strand or yarn-on-yarn abrasion damage. On axial compression, TTI's report stated that:

> *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.*

Some evidence of structural damage, such as length difference, hockles, and strand distortion, was found in the failed rope samples. TTI explained that the extent of the damage would have contributed to a reduction in the strength of the ropes examined, but found that:

> *The most dominant type of failure was well clear of fairleads 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[30].*

The report concluded that the dominant factors that had contributed to the increased failure rate of HMPE mooring ropes was rope construction and exposure to harsh environmental conditions. The report stated that:

> *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.*

The report recommendations covered a range of subject areas. With respect to rope procurement the report stated:

> *Currently the specification focusses 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 per rope construction type, further work needs to be considered.*

For comparison, at a nominal rope diameter of 44mm, Bridon's *Steelite Superline Xtra* rope had approximately 24% less HMPE content than its *Steelite Xtra* 12-strand (unjacketed) rope. The specified MBL for the 44mm diameter *Steelite Xtra* 12-strand rope was 146t.

The HMPE Users Group placed a 5-year moratorium on the wider release of TTI's report.

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[30] The workgroup had no consensus over the failure modes. A subsequent test conducted by DSM concluded that creep was not one of the failure modes.

1.16 INITIAL POST-ACCIDENT INSPECTIONS, LABORATORY EXAMINATIONS AND ROPE BREAK TESTING

1.16.1 Accident site inspection

The accident site was inspected on 3 March 2015 by MAIB inspectors and a Marshall Islands Flag State inspector. *Zarga*'s master had taken measures to preserve the accident site and provided photographic evidence taken by the ship's crew.

It was apparent that the mooring line had parted on the fo'c's'le, part way between the winch and the inboard pedestal roller fairlead **(Figure 26)**. Measurement of the outboard section of the failed rope established that the break point was 57m from the eye of the rope. It was also noted that the inboard section of the rope was stiff at the break point and the exposed yarns appeared to be fused.

Both parts of the failed mooring rope, and its tail, were coiled onto pallets **(Figure 27)** and taken ashore for further examination.

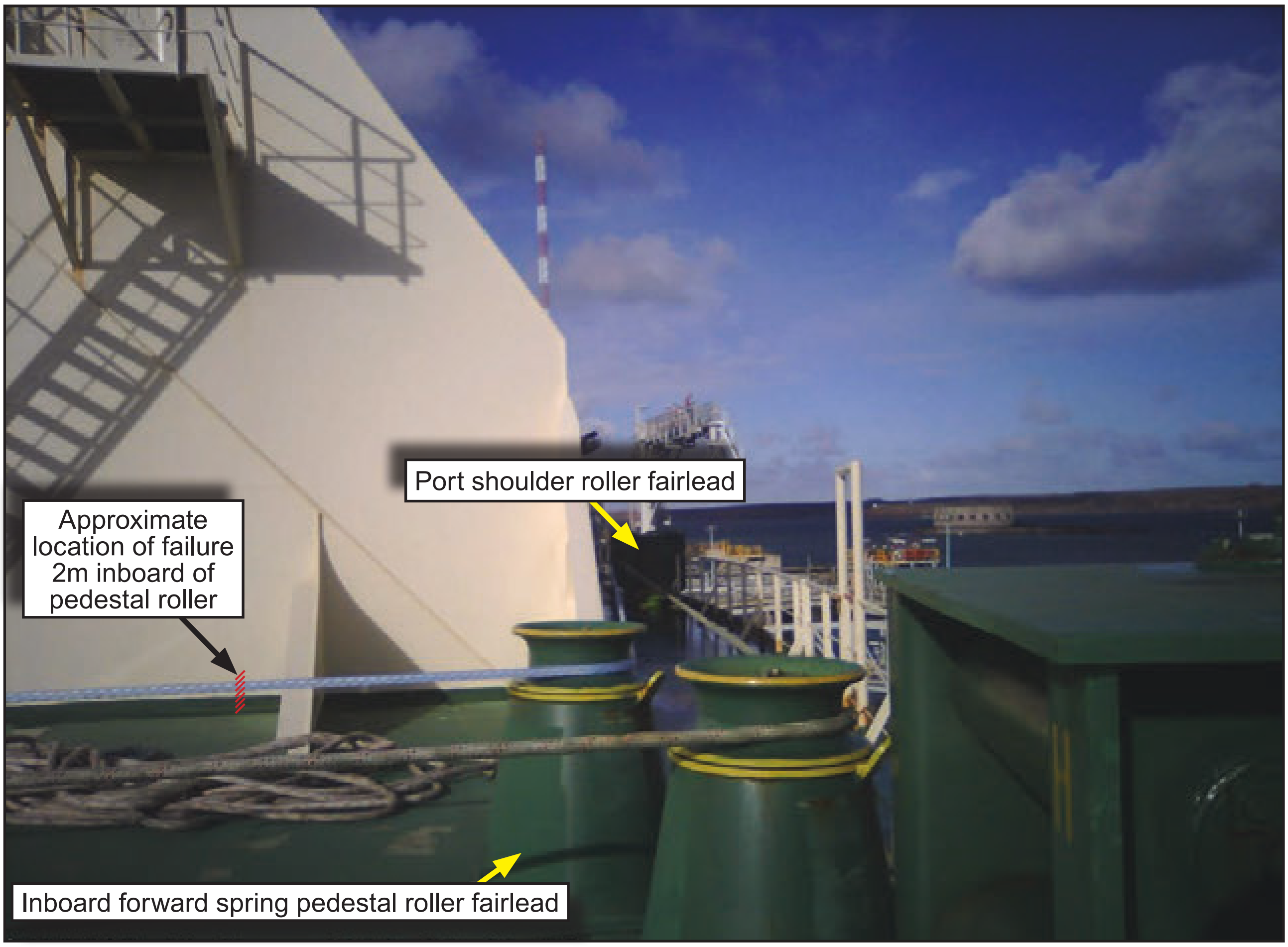

Figure 26: Location of rope failure

Figure 27: Failed rope on pallet for delivery to MAIB

1.16.2 Initial laboratory examination and yarn break testing of the failed rope

TTI was contracted **(Annex I)** to conduct a laboratory examination of the rope and break testing of its yarns. Close visual examination of the break site identified that the yarn fibres had suffered localised fusing and hardening, and that the failure had been caused by tensile overload. Away from the break site, the rope **(Figure 28)** appeared to be in generally good condition.

Figure 28: Initial visual examination of failed rope

Following the initial external examination, the rope was cut into sections and prepared for internal inspection and yarn break load testing. The braided outer jacket was removed from selected sections of the rope to expose its HMPE load bearing core **(Figure 29)**. Once the jacket was removed, kinks in the rope yarns were visually evident at intervals of 100 to 150mm in all three strands over the entire length of the samples **(Figure 30)**. When the strands were opened up for internal examination, it was noted that the extent of the kinking was more severe in the inner yarns **(Figure 31)**.

During the jacket removal process, TTI discovered 12 sheared yarns remote from the break site. These had sheared at locations where kinks had occurred **(Figure 32)**.

TTI then selected three rope samples (two from the vessel side of the break point and one from the shore end) and took 36 yarns from each for break testing; 12 from each strand, of which 3 were taken from the inner core. TTI then used the realisation test methodology described in ISO 2307:2010 to determine the average break strength of the yarns and, by application of a realisation factor, to calculate the residual strength of the rope samples. The residual strengths of the three rope samples were calculated to be 57%, 79% and 88% of the rope's specified MBL using Bridon's realisation factor of 0.998.

Having recognised that the yarns were failing at kink locations, and that the kinks in the inner yarns were significantly more severe than those in the outer yarns, a further 32 yarns from the shore end rope sample were tested. This time six inner and six outer yarns were used from each strand. The calculated residual strength of the sample dropped from 79% to 61% of the specified MBL.

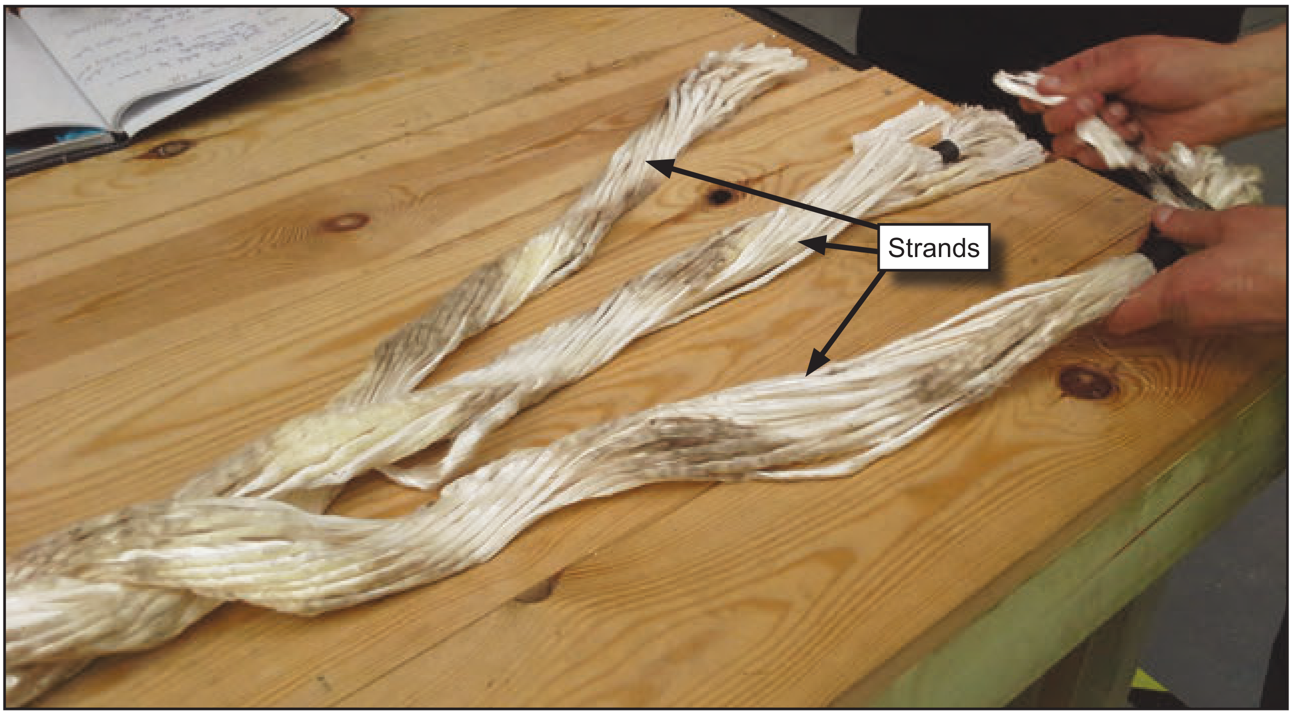

Figure 29: HMPE load bearing 3-strand core of failed rope

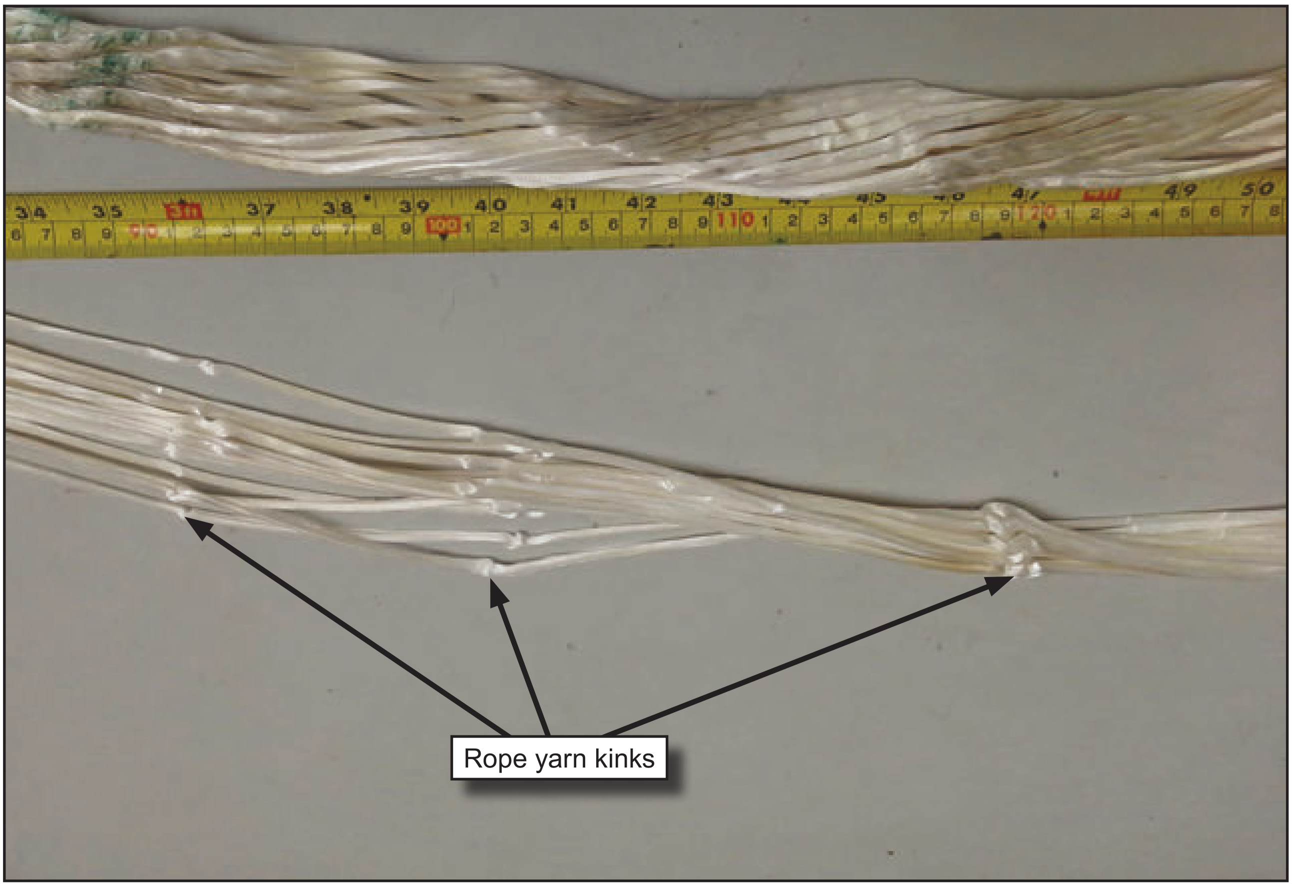

Figure 30: Rope yarn kinks in the strands

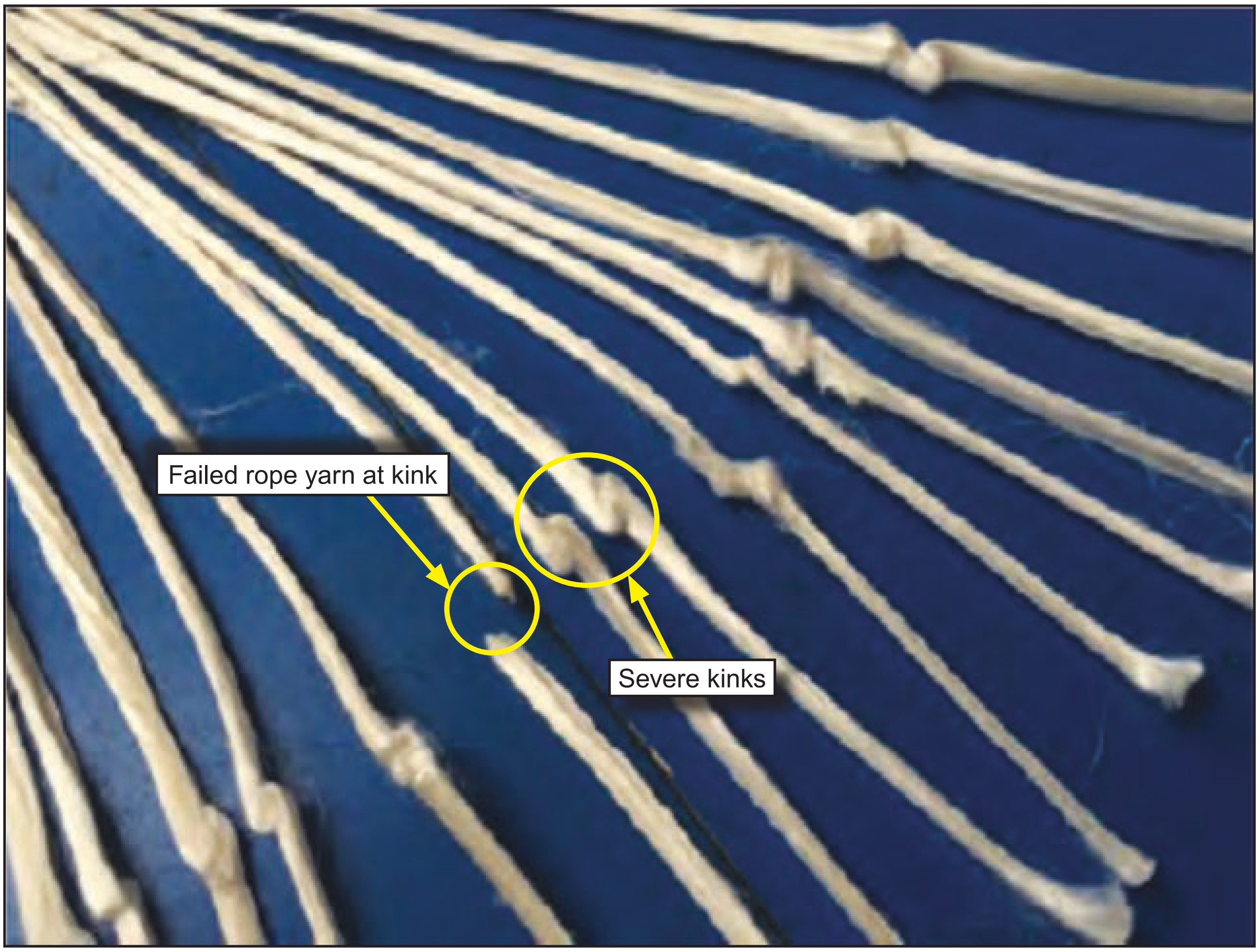

Figure 31: Severe kinking within the inner rope yarns

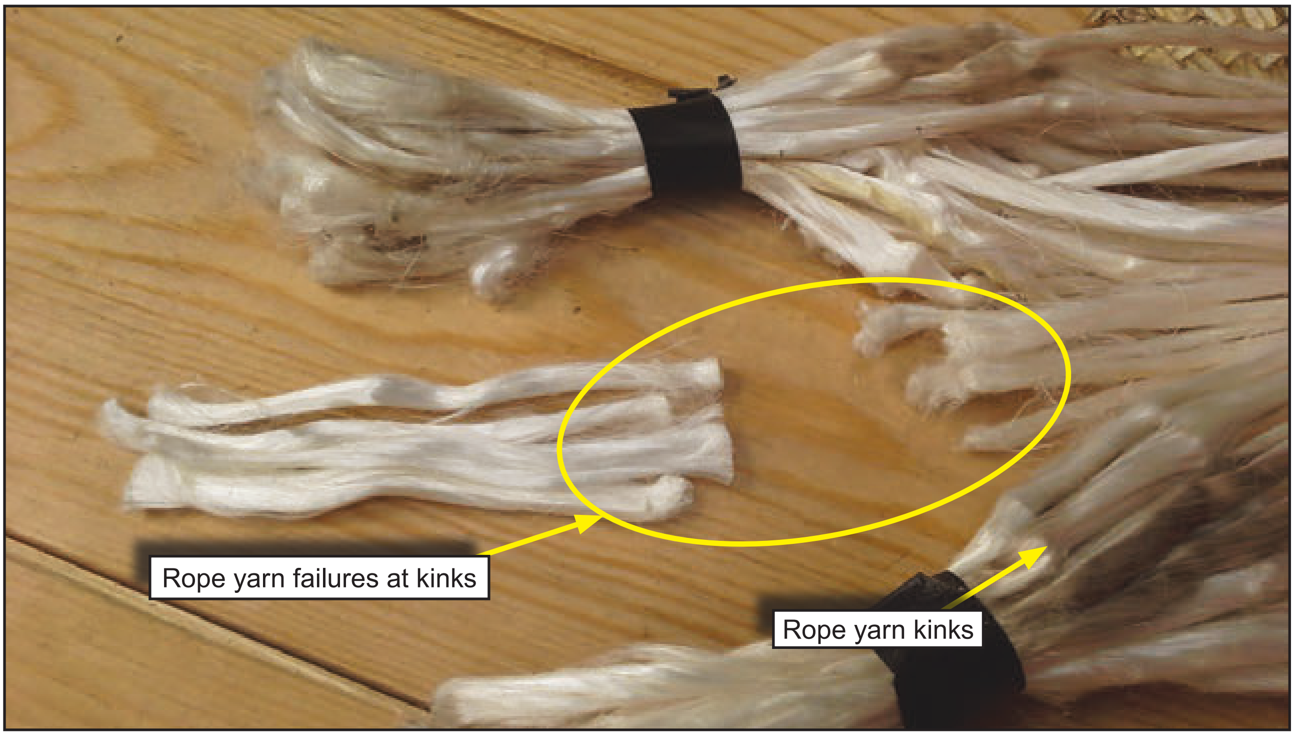

Figure 32: Sheared rope yarns at kinks

Based on the results of its realised break load tests, and taking the number of failed yarns discovered in *Zarga*'s rope into account, and using a revised realisation factor of 0.85, TTI estimated that the residual strength of the rope samples tested could have been as low as 61.6t. This was about 45% of its specified MBL.

1.16.3 Scanning electron microscope examinations

TTI sent a selection of the sheared yarns to an Oxford University laboratory for scanning electron microscope (SEM) examination of the fibres at the break points and the kink sites. The SEM examination **(Annex I)** identified the formation of kink bands[31] at filament level along the length of the fibre filaments, and failures at kink bands where the yarns had sheared **(Figure 33)**.

1.16.4 Whole rope break testing and snap-back assessment

Four sections of the rope (three from the vessel side of the break point and one from the shore side) were spliced into 10m test samples. The test samples were despatched with a shortened (15m) *Euroflex* tail to Mennens, Dongen B.V. Netherlands for tensile break load testing.

[31] The terms 'kink' and 'kink band' have often been used inconsistently to describe two different phenomena when discussing the effects of axial compression in HMSF ropes; this was evident during the literature review conducted as part of this investigation and in the correspondence received by MAIB. Other than direct quotes attributed to external sources, the term 'kink' will be used in this report to describe the regular Z-shaped buckles found in a rope at fibre, yarn or strand level, whereas 'kink band' will be used to describe Z-shaped kinks found at the filament level within the fibres.

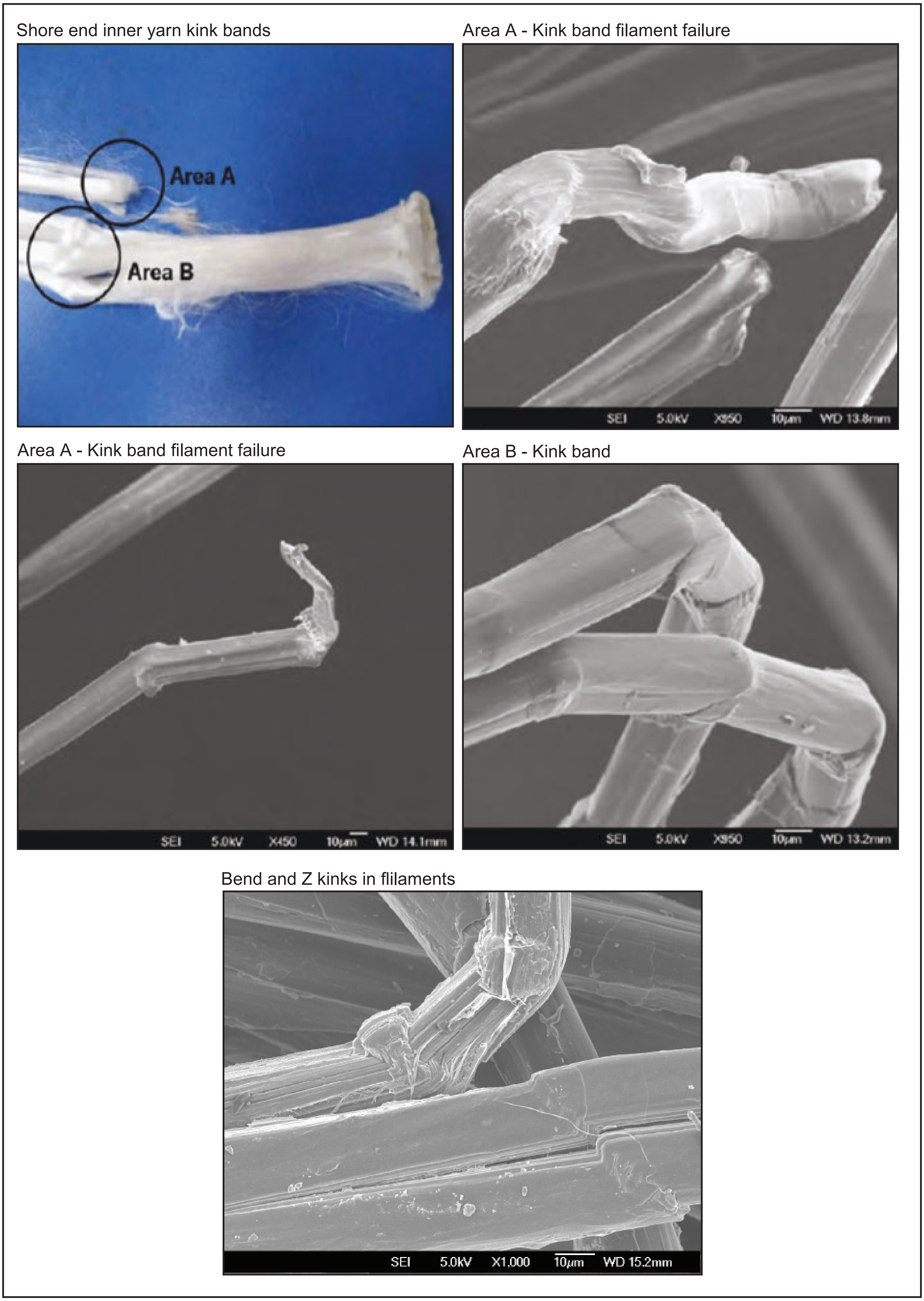

Figure 33: SEM examination of yarn kinks and fibre kink bands

Three rope samples were connected directly to the test bed and subjected to full load break tests; the fourth was tested with the tail connected. The tests were recorded using high speed cameras[32] operating at 5000 and 10000 frames per second, and the footage was used to study the mechanics of the rope failure and its snap-back trajectory **(Figure 34)**.

Figure 34: *Zarga* rope break and snap-back testing

[32] Sections of the recorded video were used in support of the MAIB Safety Bulletin (SB1/2015) **(Annex J)** and are available at: https://www.gov.uk/government/news/zarga-safety-bulletin-published

Table 3 shows the recorded loads and residual unspliced strength, as a percentage of the specified MBL (137t), at failure:

Test	Rope Section	Load at failure kN tonnes-force (tf)	Residual Strength: % of original MBL
1	Shore end – 10m from failure point	671kN 67.34tf	50.2
2	Vessel end – adjacent to failure point	465kN 46.66tf	34.8
3	Vessel end – opposite end of rope to failure	847kN 85tf	63.37
4	Vessel end - middle of rope + 15m tail	645kN 64.73tf	48.26

Table 3

The effect of the *Euroflex* tail on rope snap-back was visually evident during the break load tests. The tail end of the rope recoiled violently as the stored energy was released; whereas the other end of the rope, which had stiffened under the strain, fell to the floor. It was apparent from witness evidence that the inboard section of *Zarga*'s failed rope also suffered minimal recoil before falling to the deck.

TTI utilized the results of the snap-back testing to carry out a computer modelled trajectory analysis of the failed rope. The trajectory analysis indicated that the parted end of the outboard section of rope whipped around the pedestal roller fairlead and then looped outboard and aft of the spring line's universal roller fairlead. It then whipped inboard and forward before being pulled through the fairlead into the water **(Figure 35)**. The computer modelling analysis also estimated that the outboard section of rope recoiled overboard at approximately 150m/s (335mph).

1.16.5 Rope examination and break test report discussion and conclusions

TTI's report **(Annex I)** explained that the type of kinks and damage found in the rope yarns was typically associated with axial compression fatigue. The report went on to say:

> *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.*

and

> *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 the rope strength. While the design uses a*

Image courtesy of OCIMF

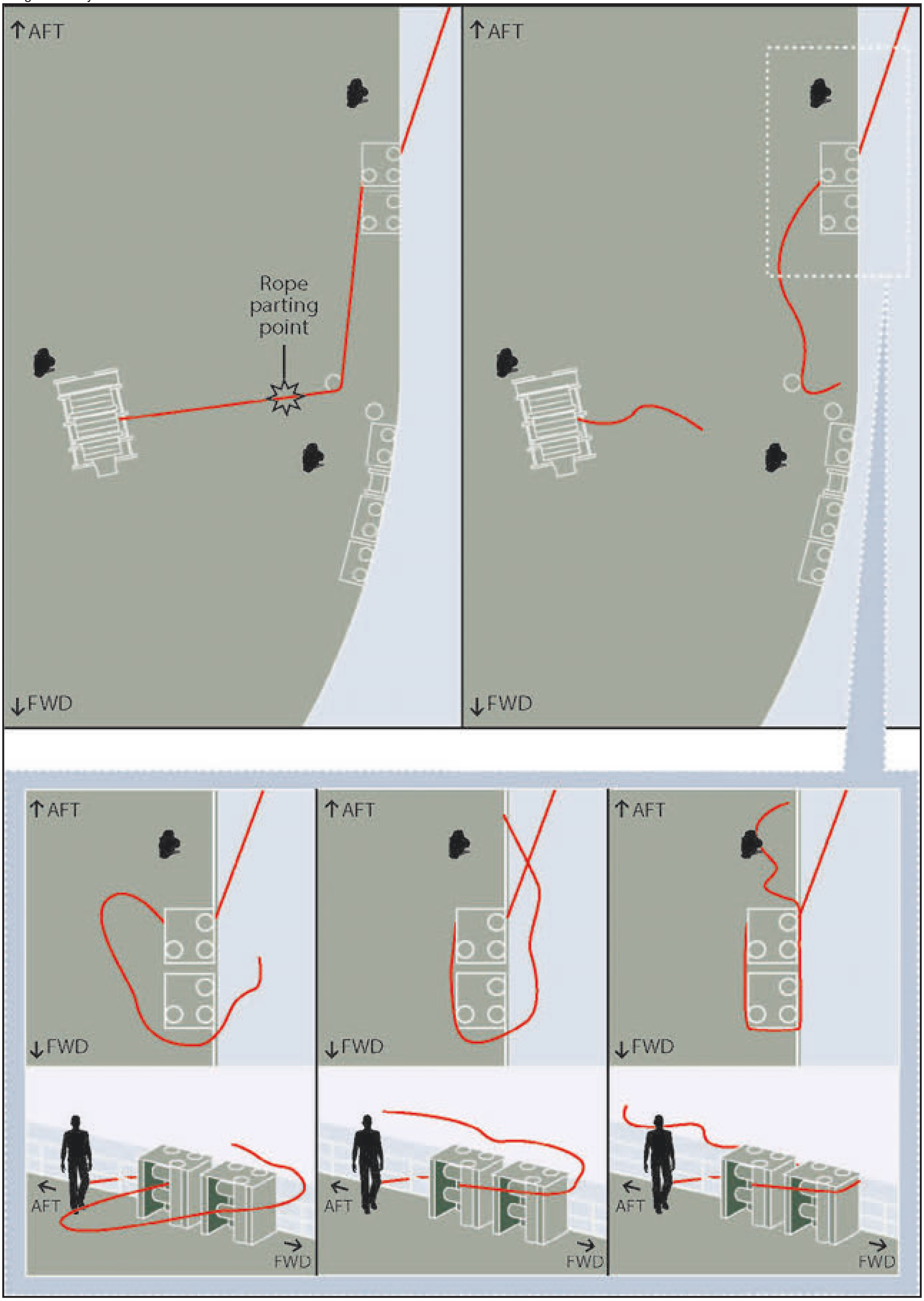

Figure 35: Trajectory analysis of failed rope

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. [sic]

The report conclusions included:

- *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.*

- *Kink bands were observed throughout the rope length and were severest in the inner yarns around the 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 this 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 Users Group report 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.*

1.16.6 Rope manufacturer's technical investigation

Following the testing and analysis carried out by TTI, the remaining segments of *Zarga*'s failed rope were sent to Bridon for further investigation. This work included a visual examination of the as-received rope, tensile testing of its yarns and analysis of the failure and degradation modes. Bridon's report, produced in November 2015, acknowledged TTI's conclusion that the fibre rope industry had not previously recognised the failure mode in HMPE rope i.e. parted yarns at kinks caused by axial compression fatigue. The Bridon report went on to explain that the classification societies, Det Norske Veritas - Germanischer Lloyd (DNV-GL)[33] and ABS[34], did not require offshore stationkeeping ropes to be tested for axial compression fatigue.

The initial visual inspection of the rope found no evidence of significant mechanical damage to the jacket. However, some areas of the jacket had suffered minor scuffing damage and paint transfer; probably from contact with the deck rollers and fairleads. Some sections of the rope were found to be notably *stiffer* than others in *manual bending*, and the rope appeared to have undergone a degree of twist in the vicinity of its factory spliced eye.

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[33] Det Norske Veritas – Germanischer Lloyd (DNVGL) RP E305 (2015) *Recommended Practice. Design Testing and Analysis of Fibre Ropes.*

[34] ABS Guidance Notes on the Application of Fiber Rope for Offshore Mooring.

A closer visual inspection identified that the rope yarns were generally clean and free from visible soil or dirt ingress. There was no visible evidence of fusion within the load bearing material but in some locations, corresponding to the paint transfer on the jacket, the amalgamating tape was heavily fused to the jacket and/or rope core.

Kinks were observed in all rope yarns. The outer yarn kinks tended to occur at the same location as inner yarn kinks along the length of the rope, but the inner yarns exhibited more severe kinks than outer yarns. A number of samples were noted to have a distorted strand structure (lay) with inner yarns protruding through the outer layer, and one rope yarn appeared to have failed at a kink. The report noted that:

Yarns removed from different samples had different levels of pliability (i.e. they felt 'stiffer' when manually bent). This is a subjective and qualitative physical analysis but suggests some segments of line were more heavily worked than others….

The tensile testing of the rope yarns identified that all yarns had lost tensile break force[35] compared with the new yarn mean value, with the largest percentage of loss, which was 30%, found in the inner yarns. There was no clear trend in loss of break force along the length of the rope.

The report's discussion of failure and degradation modes explained that the failure mode(s) and accumulation of damage leading to the rope failure was not clear. It identified significant variation in tensile break force between samples and compared these with areas of high paint transfer. These were considered likely to have been operating in bending and tension with a consequent increase in the rate of damage and corresponding reduction in residual strength compared with sections operating purely in tension.

In respect of the causes of the axial compression fatigue, the report provided three possible explanations:

1. *The complex dynamics of tension-tension loading introduced by use of a lower stiffness mooring tail.*

2. *Rope operation in a slack condition, particularly in extreme weather.*

3. *Distortion of the core structure by artificially untwisting the rope when in use.*

In order to explain why the rope yarns might have failed at kinks, Bridon offered the following hypothesis:

…once formed, the kink bands formed hinge points which allowed a flex fatigue mechanism to either gradually weaken the material until it parted (as a direct result of the flex mechanism) or, sufficiently weakened the material to part under strains consistent with normal rope working loads.

The report conclusions included:

- *The failure of this rope in service suggests both that the requirements of the application were not fully covered by the initial specification and that the*

[35] Rope sample tensile testing gave break force tensions of between 65.3 tonnes-force (tf) and 89.9tf.

discard criteria did not encompass all possible failure modes. Whilst activity to address both of these issues should be a key outcome of this investigation, priority should be given to the development of appropriate discard criteria as well as more robust testing procedures, which can be implemented using the existing rope history records for this type of application of HMPE rope.

- *It is recognised that the HMPE Users Group Report marked a new period in the use of HMPE ropes in LNGC mooring applications. Whilst some of the report's recommendations met with industry wide acceptance, many have not been progressed within the industry and consequently should be re-visited. An important element of this work is for the industry to review and fully understand the testing, assumptions, analysis and data review summarised in the final HMPE Users Group Report.*

1.16.7 Fibre manufacturer's technical investigation

The MAIB also provided samples of *Zarga*'s failed rope yarns to DSM for its analysis and testing. DSM conducted tensile testing of the rope yarns and fibre filaments, and used a SEM and differential scanning calorimetry (DSC) equipment to examine the rope's fibre filaments.

During its investigation, DSM highlighted several similarities between *Zarga*'s rope failure and the majority of previous Q-Max and Q-Flex mooring rope failures. These similarities included:

- The rope failed at South Hook terminal.
- The rope was of a long-lay, low twist, 3-strand jacketed construction.
- The rope was manufactured by Bridon.

Similar to TTI and Bridon, DSM identified yarn kinking and kink bands at the fibre filament level in the rope samples it examined. The SEM and DSC examinations found no evidence of creep ruptures or heat damage within the rope fibres. DSM concluded that the kinks had been caused by axial compression during use as a result of cyclic loading, and made a direct link between this and the rope's construction and HMPE fibre content. DSM explained that strand kinking, or buckling, was often associated with long-lay, tightly jacketed ropes, and was also considered to occur during the rope manufacturing process. The fibre manufacturer considered the resultant effect to be increased rope damage due to tension-tension fatigue, inter-fibre abrasion and eventually overload.

Previous synthetic fibre filament tests conducted by DSM had concluded that:

- Kink bands occur on all types of fibres.
- Kink bands occur due to axial compression of fibres.
- Kink bands can only be seen by SEM.
- Strength of HMPE is not affected by filament level kink banding since the filaments can realign themselves when tension is re-applied.

- Kink bands had only a marginal influence on filament tensile strength.

Based on the tensile break testing of the samples, DSM calculated the residual strengths of the yarns to be between 37% and 65% of their original calculated strength. The yarns tested did not break at kinks or buckles.

1.17 FOLLOW-UP LABORATORY ANALYSIS AND BREAK TESTING OF A NEW ROPE

1.17.1 Overview

As a result of TTI's initial report findings MAIB and STASCo commissioned further studies into the failure mode of the rope. The aim of the new work was to:

- Identify the causes of the axial compression fatigue and yarn buckling found within the failed rope.
- Identify if the design and manufacturing process for the *Steelite Superline Xtra* rope contributed in any way to the development of the yarn kinks (or buckles) and the failure of *Zarga*'s rope.
- Assess the validity of the realisation break test calculations for the *Steelite Superline Xtra* rope.

In order to achieve this, Bridon manufactured a new 100m length of its 44mm diameter, three strand, *Steelite Superline Xtra* rope. To further support the analysis and test process, DSM provided samples of its Dyneema® SK75 fibre.

1.17.2 Axial compression and the formation of kinks and kink bands

TTI used its fibre rope modelling (FRM) and yarn buckling software tools to identify possible causes of compression in the rope's inner yarns and subsequent buckling modes. To achieve this, the effects of rope twist and bending over a fairlead were considered.

TTI's FRM and yarn buckling calculations concluded:

- *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*[36] *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.*

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[36] All rope yarns within the strand had the same individual twist level, but the twist imparted by the stranding process was lower in the inner yarns.

- *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.*

The yarn compression modelling study confirmed that both a rope's construction and operational conditions can lead to the creation of the types of damaging kinks, or buckles, found in *Zarga*'s failed rope. As this failure mechanism was a previously unrecognised phenomenon in HMPE ropes, practical buckling tests were undertaken using yarns taken from the failed rope. The yarn buckling tests compared bundles of restrained and un-restrained yarns to measure strength loss and to enable comparison with the theoretical modelling results. The restrained yarns represented a jacketed rope construction.

The selected yarns were placed in the yarn buckling test machine **(Figure 36)** and exposed to between 22,000 and 110,000 cycles. The subsequent residual strength of the yarns was found to vary between 87.5% and 60.3% across the cycle range for the restrained yarns and 88.1% and 62.1% for the unrestrained yarns. This data indicated that 21,500 cycles was needed to create axial compression fatigue.

The practical tests results were consistent with the theoretical modelling calculations, and indicated that the increased radial pressure of a jacket causes damaging buckles to be induced in the yarns more quickly. In addition, specially marked test samples were examined after cycling and found that the break points occurred at buckle points.

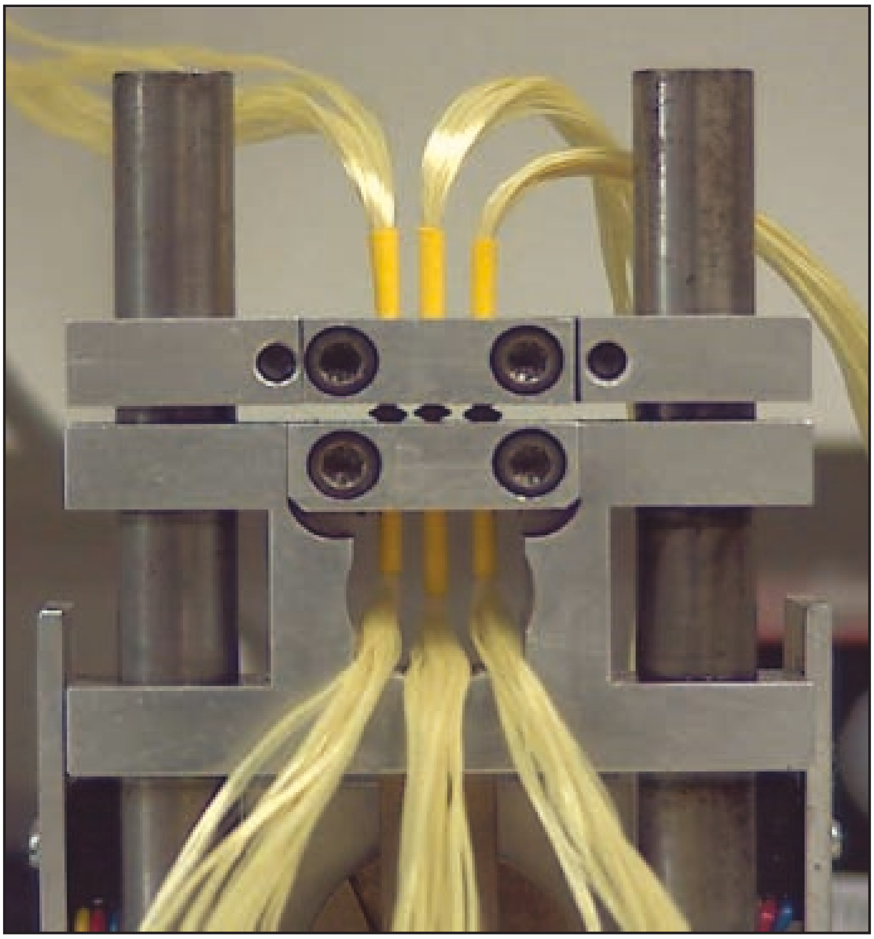

Figure 36: Practical yarn buckling test

1.17.3 New rope examination

The new *Steelite Superline Xtra* rope manufactured by Bridon was constructed to the same specification as those supplied to *Zarga* at build, and had a specified MBL of 137t. Three 0.5m long sections of the rope were removed and dissected to allow internal examination of the rope core. The main aim of the examination was to establish the manufactured pitch of the rope's strands and its outer and inner yarns, and to look for the presence of kinks and kink bands.

When the jacket was removed the strand pitch was measured and found to be within the rope design specification of 260mm (+/-13mm); which was equivalent to a helix angle of approximately 15°. Minor kinks were visually apparent in the outer layer rope yarns of each strand **(Figure 37)**. When the inner rope yarn layers were exposed they were found to have zero twist **(Figure 38)** and more severe kinks **(Figure 39)**. SEM examination of the new rope yarns identified the formation of kink bands in the yarn filaments. Examination of the break tested rope yarns identified failures at the kink bands.

The observations made during the examination of the new rope led TTI to conclude that:

> *…kinks are most likely formed during the manufacturing stranding 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 fibres 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.*

1.17.4 New rope realised break test calculations

A section of the new rope was dissected and prepared for yarn break testing. In order to calculate the realised rope strength, TTI tested all the rope yarns from a single strand i.e. 32 yarns (17 outer and 15 inner layer yarns). The calculated MBL for the new un-spliced rope, using Marlow's and Bridon's realisation factor of 0.998, was 1333kN (135.9t). This equated to 99% of the specified MBL for *Zarga*'s spliced ropes.

TTI considered that the realisation factor used by Marlow and Bridon was too high, so it re-calculated the realised strength using a realisation factor of 0.85. This gave a calculated unspliced MBL of 1135kN (115t).

1.17.5 Full rope break load tests

Two sections of the new rope were removed and spliced in preparation for full rope break testing in the Netherlands. One of the test samples included the original factory spliced eye.

The ropes were rigged in the test bed and cycled 20 times to 60t to settle the splices[37]; on the 21st cycle the ropes were taken to break load. Sample one failed at 995kN (101.46t), which was 74% of the ropes' specified MBL; sample two failed at 1036kN (105.64t), 77% of specified MBL. Both samples failed on the active end of the test machine and both appeared to have failed within the splice area.

[37] Note: ISO 2307 and the Cordage Institute break test methods dictate cycle counts of 3x and 10x respectively.

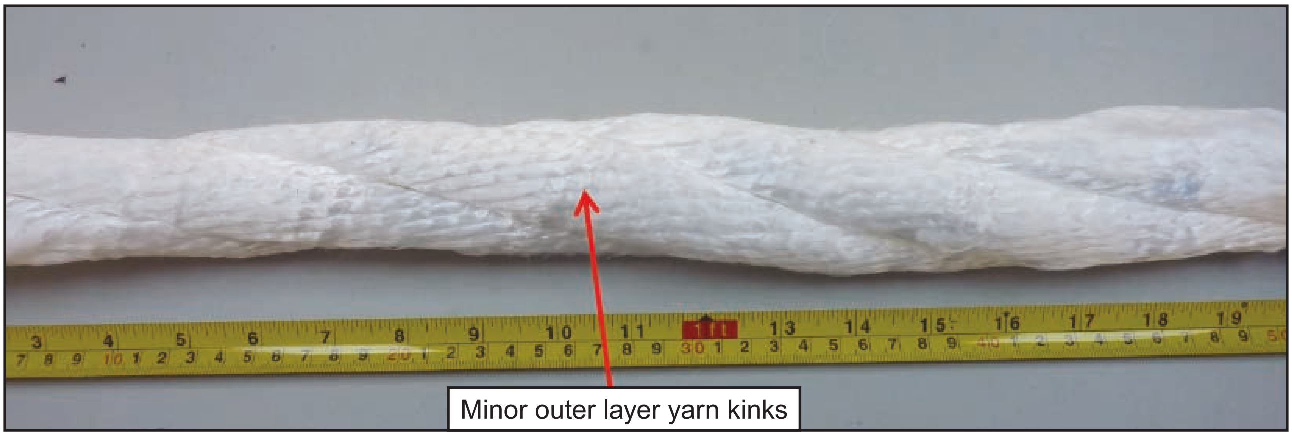

Figure 37: New rope minor kinks in outer yarns

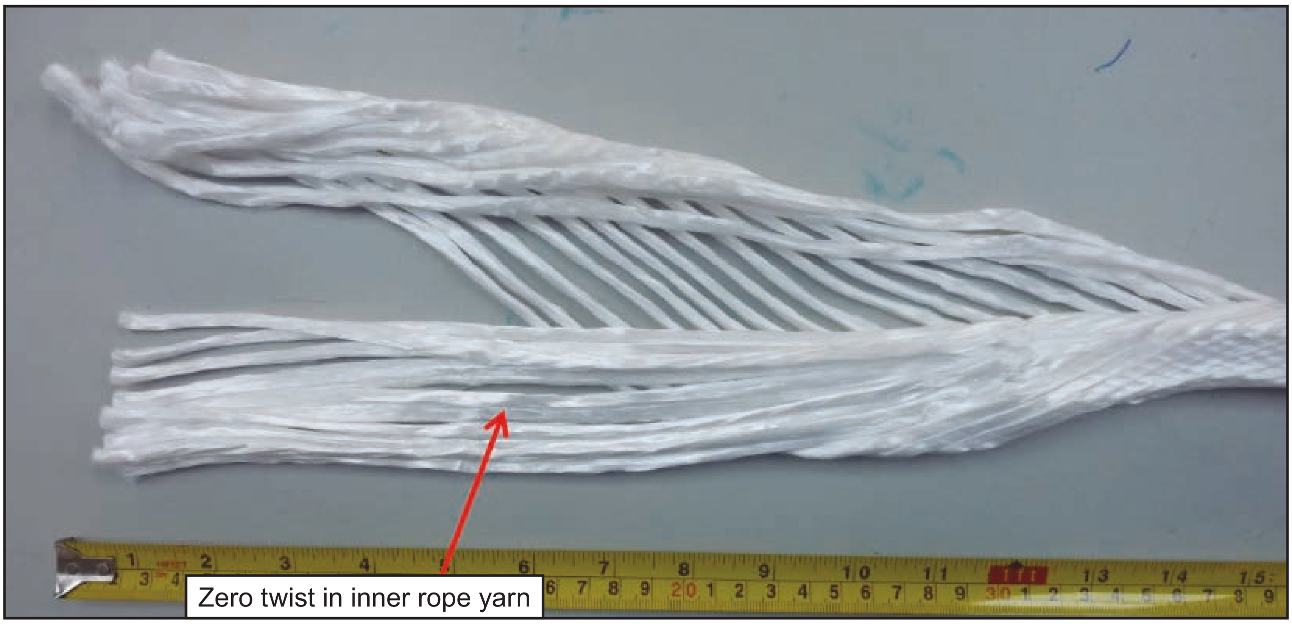

Figure 38: Inner rope yarns with zero twist

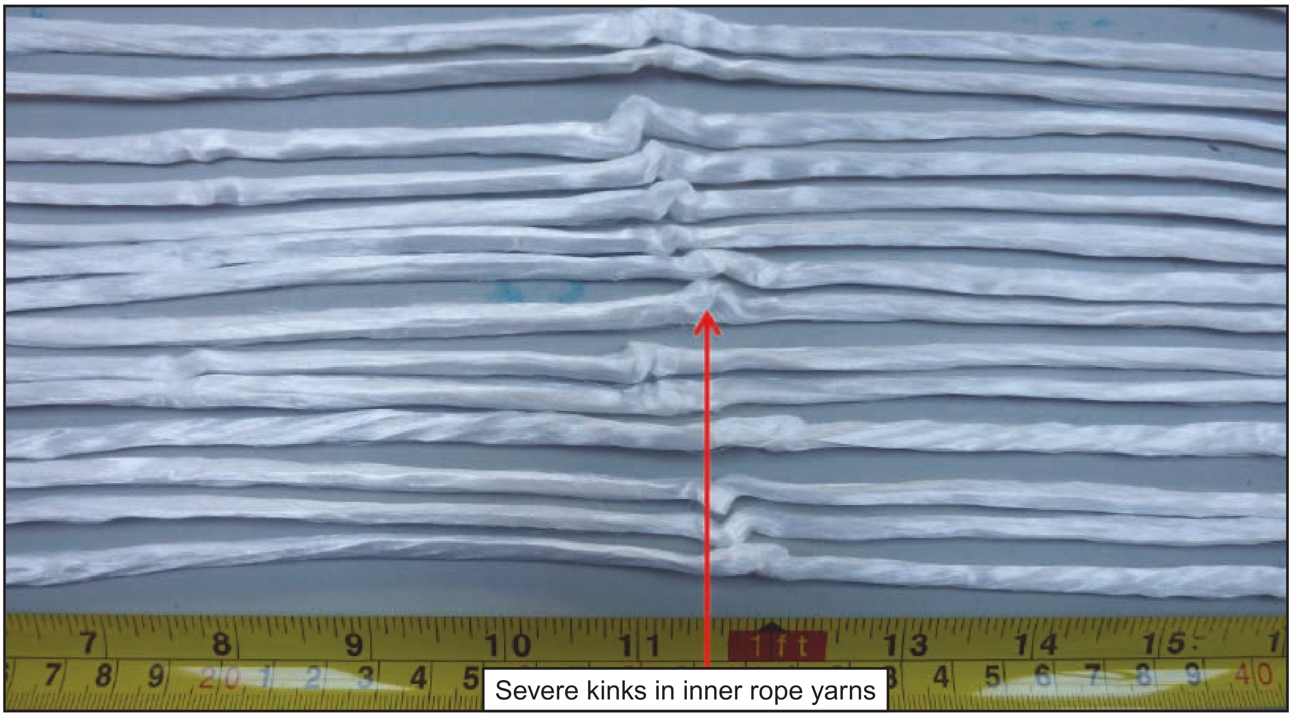

Figure 39: Severe kinks in inner rope yarns

Given that both samples failed in the splice area, TTI estimated that the actual full break strength efficiency could have been approximately 5% higher, but was still below the specified MBL, and was in agreement with the yarn 85% realisation strength calculations.

1.17.6 Report discussion and recommendations

The final series of practical tests conducted in support of this investigation led TTI to conclude that:

> *The results of the FRM modelling and the investigations clearly indicate that the Bridon rope design has been optimized for strength and that due to the low twist level in the inner yarns it 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 kink bands have also been identified in other jacketed HMPE rope constructions including 12-strand sub-core ropes with long lay strands and low twist yarn levels.*

and,

> *…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 focussed on the materials being used as mooring lines for deepwater mooring platforms. Here the ropes are produced in relatively long lengths that sit between the anchor on the seabed and the rig or vessel… Apart from during deployment or recovery and even then at very low loads these ropes never come in to 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.*

The report recommendations were:

- *Ropes to be used in this application need to be 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 be 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 where 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.*

TTI's final report is at **Annex K**.

1.18 MOORING EQUIPMENT GUIDELINES (MEG)

1.18.1 Overview

OCIMF first published its Mooring Equipment Guidelines in 1992. Subsequent work by the group resulted in the publication of MEG-2 in 1997 and MEG-3 in 2008. The initial publication and later editions sought to refine, unify and update selected guidance and essential information. This included the design performance of mooring deck equipment, ease of rope handling and safety of personnel. The guidelines were widely accepted as the recommended minimum standard for ships' mooring arrangements by ship designers, surveyors, and ship and terminal operators.

1.18.2 MEG-2

Zarga was built with reference to the requirements of MEG-2. MEG-2 did not contain specific recommendations for modern, low elongation, synthetic materials such as HMPE and aramid.

Within its recommendations for ship designers, MEG-2 stated that:

- *Loads in any one mooring line should not exceed 55% of the MBL.*

- *Wire ropes should be the standard mooring equipment for all large tankers and it is recognised that wire ropes greater than 44mm diameter may require special handling arrangements in terminals.*

- *Winch brakes should provide a minimum holding capacity of 60% of the MBL of the wire on the first layer of wire of a split drum winch …*

- *Minimum safety factors listed in Table 4.3 are based upon the appropriate design criteria and loading assumptions, and should be incorporated in all new equipment and mooring fittings.*

The minimum safety factors listed in Table 4.3 of MEG-2 for steel wire and synthetic fibres was 1.82 and 2.0 respectively. MEG-2 defined the SWL of a deck fitting as the maximum load that should normally be applied during service conditions. The guide also stated that the test load for pedestal and universal roller fairleads should be the SWL multiplied by the safety factor of the rope, i.e. the rope's specified MBL.

The guide recommended, *as a general rule*, a minimum deck fitting to steel wire rope D:d ratio of 12. It also stated that:

> *Where this would create problems with the size of the fitting, a ratio of 10 is an acceptable compromise for items such as universal roller fairleads.*

MEG-2 indicated that the strength loss due to bending was not as critical for conventional synthetic fibre lines as for steel wire, but warned that newer types of synthetic fibres such as aramid were more bend radius sensitive. The guide went on to explain that:

> *As for all fibres the strength loss and durability factors may depend upon the specific material and construction. The rope manufacturer's guidelines should be consulted for each specific application.*

1.18.3 MEG-3

MEG-3 was produced following a major review of the guidance contained in MEG-2 and included more detailed information on HMSF rope. The substantive changes included:

- Guidance for site-specific analysis of the impact local environmental conditions at terminals will have on mooring patterns and equipment.
- Relevant extracts from the OCIMF publication *Guidelines on the Use of High-Modulus Synthetic Fibre Ropes as Mooring lines on Large Tankers*[38].

The recommendations for ship designers stated that:

> *Wire or HMPE ropes should be the standard mooring equipment for all large tankers and gas carriers. …*

The guidance on safety factors and mooring line loads with respect to percentages of rope MBL remained the same for HMPE, but the SWL for deck fittings was redefined. With regard to SWL, MEG-3 explained that:

> *It is worth repeating that, in these guidelines, the SWL is defined by the MBL of the line and not by the force exerted on the fitting by the line. Further, it is the SWL of the fitting rather than a safe working load for the line. At the SWL of a fitting, the line is at its MBL. As defined, the SWL is approximately twice the maximum force in the line in normal service… It is a tension that will only be reached in rare and extraordinary circumstances. In everyday service the line tension is unlikely to be more than 20% of MBL.*

In respect of the strength criteria, MEG-3, section 6.1.2 included:

> *Ship designers will normally have determined the mooring restraint requirements for large ships under standard environmental criteria assuming all mooring lines are steel wire ropes.*
>
> *More vessels are being outfitted from new with HMPE ropes. The higher Safety Factor (SF) of 2.0 for HMPE…may result in larger deck equipment being required than for equivalent wires (SF 1.82) particularly when fittings are on the borderline of that size range.*

[38] Superseded and removed from print as a result of MEG-3.

Current practice has been to replace steel wire ropes with HMPE lines having the same MBL where operating limits and experience has been found to be adequate. In these cases, the implied SF of the HMPE line is 1.82 assuming that the vessel is moored in the same environmental conditions as when equipped with steel wire ropes.

The rope manufacturing industry advocates a higher SF for HMPE than for steel wire since they have to apply it to a wide range of materials and constructions. The higher SF is also believed to result in a longer service life and higher residual strength at end of life.

Section 6.4.7.4 provided guidance on fatigue and service life, which included:

…Life expectancy is determined by a number of factors such as SF's, D:d ratios (bending diameter: diameter of the rope) … It has been shown that a small increase in SF can result in a significant increase in service life.

Bend fatigue will be impacted by load levels and the diameter of contact surfaces. High modulus ropes generally require a larger bend radius to achieve the same fatigue life as steel.

Section 7 (Figure 7.3) provided a method for calculating mooring line MBL and the relationship to winch parameters:

Ship Size and Hull Form (Input data from Shipyard/Ship Designer)
Mooring Force Calculation
Mooring Restraint Requirements
Mooring Restraint Requirements ÷ Number of Mooring Lines in Same Group = MBL of Mooring Line
MBL gives 'Design Rope' *Table 7.1 and ISO 3730*
Design Rope Leads to following Winch Parameters: *Brake Design Load = 80% of line MBL* *Brake Holding Load = 60% of line MBL* *Winch Pull = 22 – 33% of line MBL* *Drum diameter = 16 X line diameter* *Width of tension part = 10 X line diameter*

Section 7.5 – Winch Performance, provided further explanation, which included:

7.5.1 Rated Pull (also called drum load or hauling load)

The listed values should not be less than 22% and not more than 33% of the design line's minimum breaking strength. This value assures adequate force to heave in against environmental forces. On the other hand, it is low enough to prevent line overstressing in the stalled condition…

MEG-3's guidance on rope retirement, included:

Localised areas of stiffness along a rope normally indicate that the rope has been subjected to shock loads. Shock loads are simply a sudden change in tension from a state of relaxation or low load to one of high load. The rope should be considered for retirement.

1.19 GUIDE TO PURCHASING HIGH MODULUS SYNTHETIC FIBRE MOORING LINES

The *HMPE Users Group LNG Mooring Line Failures Final Report* concluded that the HMSF rope procurement specification, which was used at the time of *Zarga*'s build, placed an over reliance on MBL. The report's recommendations regarding the HMPE rope procurement specification stated that:

- A rope should have sufficient HMPE content to maintain longevity when exposed to prolonged periods of high load and temperature.
- Standardised operating conditions should be established.
- Creep performance should be modelled.
- To avoid changes from prototype to current production, actual rope break load tests should be conducted for each contract.

In response to the HMPE Users Group report, the Society of International Gas Tanker and Terminal Operators (SIGTTO) and OCIMF produced the *Guide to Purchasing High Modulus Synthetic Fibre Mooring Lines* **(Annex L)**. The guide provided generic information about rope failure modes, factors affecting rope fatigue life and operational considerations. These included:

1.2.5 Creep and heat exposure

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 40C or greater. …Manufacturers or suppliers should be consulted as the effect of creep can be mitigated by rope design, fibre or increased size.

Although the guide specifically stated that axial compression fatigue was applicable to aramid fibres only, the related guidance included:

1.2.7 Axial compression

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. …*

__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.

The operational considerations included:

- Mooring at exposed berths and the effect of first and second order wave forces (larger ships experience proportionally higher tension loads from the wave induced motions compared to smaller ships).
- The importance of load sharing between multiple lines (incorrect tending results in more stress being put on the higher-loaded line); and
- The need to maintain records of rope service, including significant events such as brake rendering or passing vessel surge.

The purchasing guidance made reference to the rope's intended application, including: vessel type/size; winch design and arrangements; and information on fairleads. Rope MBL was stated to be a critical performance criterion when procuring rope. However, the HMPE Users Group report recommendation for actual rope break tests was not implemented.

With regard to jacketed constructions, the guide included:

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.

and,

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

1.20 GUIDANCE PROVIDED BY THE NAUTICAL INSTITUTE

The Nautical Institute publication, *Mooring and Anchoring Ships Vol 2 – Inspection and Maintenance* was published in 2009. Chapter 1 – *Mooring Ropes*, included the following:

Creep

Taking into account that safety factors for marine applications are of three or higher and as ropes will generally not be working continuously against their working load limits, the continuous operational loads acting on a mooring rope can generally be expected to be in the range of 20% or even less.

Selecting the right rope for the job

In view of the variety of applications for mooring/towing/offshore ropes in the marine industry, it will be clear that the application for which the rope will be used should be well defined and understood. Efforts should therefore be made to identify as many factors as possible that may influence the performance of the rope.

Working loads and safe working loads

In order to ensure that a rope can safely withstand loads in excess of its normal or safe working load and remain safe to use after a certain amount of wear has affected the rope, a Safety Factor (SF) will have to be considered. .. It is widely accepted that the normal working load of a mooring rope is not more than 20% of its new breaking strength. This is because mooring applications generally require a safety factor of three or four and because mooring ropes will generally be used for loads well below their safe working load.

Shock loads

Normally, loads are considered to be shock loads when the load in question is in excess of 10% of the rope's normal working load and when this load is applied suddenly…If a load is not applied suddenly, but over a longer period of time, this would be 'overloading' rather than 'shock loading'. However, from a damage point of view, any rope that has been subjected to overloading or shock loading should be considered as shock-load damaged. It should be remembered that, when being overloaded or subjected to shock loads, a rope may have sustained damage and may part at a later stage, even when being used under its normal working conditions.

Stiffness

When ropes have been exposed to shock loads, they tend to become more rigid and stiff, which means an alteration in properties which will have an effect on the rope's strength and behaviour during handling…

Discard criteria: Using ropes which are stiff in places is dangerous and these ropes should be considered for retirement. Although the stiffened area will be the part that is most affected, it is important to remember that the whole rope, or considerable parts of it, may have been overloaded.

1.21 OFFSHORE MOORING APPLICATIONS

1.21.1 General

HMSF ropes have been used as mooring restraints for offshore oil and gas structures for more than 30 years. They are typically used in deep-water oil and gas fields because steel wire ropes generally reach their self-weight limit at depths of about 2000m.

In order to mitigate the potential consequences of mooring restraint failures, the offshore industry commissioned a series of studies to examine various factors that affected the fatigue performance of the synthetic materials. The results of the studies were used by classification societies to develop mooring rope performance standards. The aim was to ensure that the HMSF ropes used to restrain offshore platforms met a prescribed set of performance criteria; this included a calculated life expectancy.

1.21.2 Rope classification and certification

In February 2013, DNV-GL[39] produced its *Offshore Fibre Ropes (DNVGL-OS-E303)* standard. The standard, one of a number of classification/certification routes for offshore fibre ropes, set out DNV-GL's materials, design, manufacture and testing requirements for aramid, polyester, HMPE, LCAP[40] and polyamide ropes and tethers. The standard discouraged the use of rope MBL as the overriding performance criterion, and promoted other methods such as the *Tension, Time and Temperature* (3-T) performance criteria. The 3-T performance criteria were introduced to help assess the ability of synthetic fibre rope to withstand load. On 3-T, the standard stated:

> *The ability of a synthetic fibre line to carry load depends on the magnitudes and durations of tensions to be applied, the magnitudes and durations of preceding loading, and on the associated temperatures within the load bearing material.*

and;

> *The 3-T performance characteristics shall be established by testing, whereby design curves are established for the relevant combinations of these parameters (tension, time and temperature).*

The 3-T design curves could be used to support an assessment of a rope's residual life.

In September 2015, DNV-GL published the recommended practice: *Design, testing and analysis of offshore fibre ropes (DNVGL-RP-E305)*[41]. The recommended practice emphasised:

- *Offshore fibre rope should be analysed on the basis of amount of load bearing material in the cross section, and the characteristics of the material used.*

- *The tension versus stretch behaviour of synthetic rope, which is fundamentally different to that of steel wire rope.*

- *The strength and endurance of synthetic rope and steel-wire rope are governed by fundamentally different mechanisms.*

[39] The standard was originally produced by Det Norske Veritas (DNV); DNV merged with GL in September 2014.

[40] Liquid crystal aromatic polyester.

[41] Based on the findings of a number of joint industry projects involving oil majors, rope manufacturers and fibre producers.

The recommended practice categorised the loading of offshore fibre ropes in two ways: point-to-point loading[42] and combined loading[43]. The document also explained that the design of an offshore fibre rope will depend on the intended application, and that the ropes can be manufactured as a bundle of parallel elements (subropes or assembled yarns). Additionally, it stated that:

> *Parallel-element designs rely on a jacket to hold the bundle of load bearing elements together, and are usually intended for point-to-point loading only.*

For combined loading, it stated:

> *…lifting lines for deepwater deployment and recovery systems (DDRS) will be working as part of a hoisting device. This entails working of the rope over sheave(s) and thus it is loaded more complexly than in pure tension. The loading will include both bending and twisting.*
>
> *Lifting lines should be made in a construction of load bearing strands to keep the rope together when it is loaded in tension, bending or twisting. The rope should not rely on a jacket to keep its elements together. On that basis, parallel-element lines are generally not considered suited as DDRS lifting lines; however specially engineered exceptions might exist.*

The guidance further compares steel and synthetic fibre under tension, noting that the failure of a steel element will largely depend on the magnitude and not the time or temperature while under tension. For steel, the same ultimate capacity remains after loading, whereas, for synthetic fibre, the combined effect of tension and temperature will cause failure after a corresponding time. On 3-T endurance, the recommended practice explained that:

> *The time that a synthetic filament can carry tension without breaking depends on what the tension is and what it has been before, and what the temperature is and what it has been before.*
>
> *For example, for the same tension, increasing the temperature will reduce the time before the filaments fail. For the same temperature, reducing the tension will increase the time before the filaments fail.*
>
> *The 3-T load bearing endurance should be managed by a design curve approach.*

The associated guidance note included:

> *As the criticality of each parameter depends on the other two critical parameters, all three can be seen as a single, three-dimensional, critical parameter…*

---

[42] *Point-to-point loading means pure, axial tension, where for example a mooring tether is part of a taut-leg mooring system, or a pendant line is used for a lifting operation.*

[43] Combined loading involves additional bending or twisting.

1.21.3 International standard for fibre ropes used for offshore stationkeeping

The characteristics and test methods for HMPE fibre ropes used for offshore stationkeeping were specified in the international technical standard ISO 14909:2012 *Fibre ropes for offshore stationkeeping – High-modulus polyethylene (HMPE)*[44]. The standard included specifications for rope material (core and jacket), rope properties (MBL, minimum core tenacity, creep properties), rope layout and construction, rope testing, certification and marking.

The standard contained guidance on tests for both cyclic loading and creep. With regard to cyclic loading tests, the standard required the rope to be maintained in a wet condition in fresh water at a temperature no greater than 30°C. The test required the rope to be cycled up to a load of 50% MBL. The creep test parameters included a maximum temperature of 25°C and a tension not exceeding 55% MBL.

The standard also provided rope handling guidance, which included:

> *Occasional bending and running over rollers is allowable during deployment. The rope should not be repeatedly cycled around rollers for prolonged periods of time. The rope should also not be left curled for prolonged periods around bends under dynamic loading conditions.*

1.22 OFFSHORE INDUSTRY AND OTHER RESEARCH AND GUIDANCE

1.22.1 Fibre Tethers 2000 Report

In 1995, the results of a joint industry tension-tension fatigue study were published in the *Fibre Tethers 2000 Report*. In the study, a selection of ropes with MBLs of 5t and 120t were subjected to tension-tension fatigue testing over a variety of load ranges. The ropes were made in a variety of different synthetic fibres, including aramid, HMPE, LCAP and polyester. When cycled between high and low tensions evidence of axial compression fatigue was found. The axial compression fatigue was attributed to several different causes, including twisting and differential component length. In one rope, axial compression fatigue was attributed to radial tension in the braided jacket.

Many of the samples failed during the tests but the HMPE sample completed a million cycles at 20±19.5% break load without breaking. The longevity of the HMPE sample was attributed to a combination of lower peak load, higher resistance to axial compression fatigue and quality of construction. Nevertheless, all the yarns showed signs of buckling and severe kink banding at filament level. Yarns on the outer strands retained between 40 and 95% of new strength while breaks were found in the centre yarn. In respect of buckling fatigue due to axial compression, the report stated: *In order for the damage caused by a low minimum load to cause complete rope failure, it must be combined with a high enough maximum load*.

The study's restrained yarn buckling tests found that HMPE suffered detectable strength loss after 20,000 low load cycles and severe strength loss after 200,000 cycles **(Table 4)**.

[44] Developed by EUROCORD.

Number of cycles for:		
	Detectable strength loss	**Severe strength loss**
Aramid	1,000	20,000
HMPE	20,000	200,000
Polyester	50,000	1,000,000

Table 4: Restrained yarn buckling tests

In respect of rope twisting, the report included:

> *One consequence of twisting is that some components will be forced into axial compression and this leads to the observed kink band failures. An increase in twist shortens the rope and tends to put straight core yarns into compression, whereas a decrease in twist tends to put outer yarns in to compression.*

Following on from the Fibre Tethers 2000 Report, TTI undertook further research into the buckling of rope fibres and yarns. The conclusions in TTI's subsequent report included:

> *Because oriented fibres have low compressive yield stress, which causes a low plastic bending moment, the buckling results in sharp kinks, which fail after repeated cycling.*
>
> *The model… predicts that groups of saw-tooth buckles will be separated by straight slip lengths. The forces involved are the axial compressive load, the frictional resistance to axial slip, and the lateral restraint of radial pressure. The yarn modulus and the friction coefficient have a role in determining the displacement in the slip zone, which affects the axial compressive force, but the dominant yarn properties are the bending stiffness, which sets the pattern of initial plastic buckling, and the bending yield moment, which determines the formation of plastic hinges.*

1.22.2 Guidelines for the Purchasing and Testing of Single Point Mooring Hawsers

In 2000, OCIMF published its *Guidelines for the Purchasing and Testing of SPM Hawsers*[45]. The guidelines provided information to help purchasers and manufacturers to identify the most appropriate ropes for use as single point mooring (SPM) hawsers. The guidelines contained a range of tests and procedures that could be used to determine the suitability and performance of a rope for SPM applications **(Annex M)**.

One of the performance tests described in the OCIMF guidelines was the *Thousand Cyclic Load Level* (TCLL) test, which was designed to establish the approximate peak cyclic load required to cause failure after 1000 cycles. The test included cycling the load up to 50% of its *new wet breaking strength* (NWBS)[46], while soaked in water of between 10°C and 25°C. If the rope survived 1000 cycles, the cyclic load level was increased to 60% for a further 1000 cycles, and then at 70% and 80% if it remained intact.

[45] The publication was a revision and consolidation of the three volumes of the OCIMF 1987 Hawser Guidelines.

[46] The specimen is load cycled to 50% of its estimated NWBS and its change in length is measured before the specimen is loaded until it breaks. The residual strength at break is given as a percentage of the rope's NWBS.

The other tests included yarn shrinkage and creep. For the creep test, reference loads were suspended by fibre samples over a period of time and their lengths accurately measured. The tests are conducted at temperatures of between 15°C and 25°C over a period of up to 24 hours.

Bridon's technical literature indicated that the *Steelite Superline Xtra* rope had originally been designed for use in the offshore industry as tethers for exploration drilling rigs and mobile offshore drilling units.

The TCLL test, although designed for SPM hawsers, was commonly referred to by rope manufacturers as a means of expressing rope strength and durability. The HMPE Users Group report stated, within its failure hypothesis:

> *"OCIMF TCLL shows these ropes should not fail under short term very high loading".*

1.22.3 Engineers' Design Guide – Deepwater Fibre Moorings

In July 2002, Noble Denton Europe Ltd and TTI produced the first edition of The *Engineers' Design Guide – Deepwater Fibre Moorings*. The guide dealt with the practical design aspects of offshore mooring systems that incorporate fibre ropes. The production of the guide was supported by oil companies, classification societies, government agencies, design contractors, rope manufacturers, installation contractors and fibre producers.

In respect of this investigation, the relevant sections of the guide stated:

> *This section is concerned with fatigue effects occurring within ropes under cyclic loading. Creep… is invariably involved in the final stages of failure when other mechanisms have caused yarns to fail, so that the residual tensions on the remaining yarns reach levels at which creep rupture becomes important. Creep is very sensitive to temperature. Note that the creep rate scale is logarithmic: creep Hysteresis heating …will reduce yarn strengths and is likely to accelerate other fatigue modes. The tension-tension fatigue mechanism …should not occur in mooring lines maintained under tension.*
>
> *Axial compression fatigue was a major source of strength loss and of failure during fatigue tests in the Fibre Tether 2000 (1995) joint industry study …*
>
> *Axial compression fatigue is a potential problem, and it is certainly a cause for concern with high-modulus fibres.*
>
> *Axial compression fatigue occurs when a rope component goes into compression, and causes buckling of fibres into sharp kinks. On the inside of the bends in the fibres, internal molecular kink-bands develop, and after repeated cycling these lead to rupture.*

The guide provided temperature limits for different fibre materials **(Table 5)**.

Safe Working Temperature	Polyester	Aramid	HMPE (Dyneema® fibre grade SK60. Current fibre grades used in mooring lines include SK75 and SK78)	Nylon
Long term (1 month +)	*50°C*	*N/A*	*60°C*	*60°C*
Short term (up to 10 minutes)	*200°C*	*N/A*	*80°C*	*70°C*
Melting point	*258°C*	*430°C*	*150°C*	*260°C*
Approximate values (over 0 to 50°C range) for:-				
Drop in strength per 10°C	2.5%	N/A	6%	2.5%
Drop in modulus per 10°C	3%	N/A	4%	3%

Table 5: Engineers' Design Guide fibre safe working temperatures

1.22.4 Appraisal of ropes for LNG moorings

In 2015, at the International Organization for the Study of the Endurance of Ropes conference in Stuttgart, an appraisal of ropes for LNG moorings was presented. The appraisal compared the TCLL test results of an HMPE rope with those of three other ropes constructed of an aramid synthetic fibre against more representative service in hot climates.

The report **(Annex N)** summary included the following:

> *In the tensile fatigue tests (TCLL), the three Aramid samples showed very consistent behaviour for both 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 – (all at a TCLL level of about 70%). The HMPE sample performed well in the OCIMF TCLL test (a TCLL level of about 75%), but performed poorly in the tests at elevated temperature (TCLL level of ca. 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), while 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 the work showed that the HMPE rope performed poorly at elevated temperatures when compared to the Aramid ropes.

1.22.5 Cordage Institute

The Cordage Institute is a US-based association of rope, twine and related manufacturers, their suppliers and affiliated industries. The institute's technical committee develops international standards, guidelines, test methods and other technical documents for rope, cordage and twine products. These included *CI1500-2015: Test methods for Fiber Rope* and *CI-2001: Fiber Rope Inspection and Retirement Criteria*.

The institute's guidance document, *Fiber Rope Inspection and Retirement Criteria*, provided practical guidance on rope types, inspection processes and retirement. Key sections relevant to this accident investigation included:

- *Terminology*

  <u>Working Load Limit (WLL):</u> The working load that must not be exceeded for a particular application as established by a regulatory or standards setting agency. The WLL is calculated by dividing the new rope minimum breaking strength by a design factor. Absent any official publication of a WLL for an application, design factors should be established by a qualified person. Design factors for rope commonly vary between 5 and 12.

  <u>Overloading</u>: exceeding the WLL by 2 or more times or loading a rope in excess of 50% of its published breaking strength.

- *Excessive Tension/Shock Loading*

  Overloading or shock loading a rope above a reasonable working load limit can cause significant loss of strength and/or durability. However, the damage may not be detectable by visual or tactile inspection. The usage history of a rope is the best method to determine if excessive tension or shock loading has occurred. Overloading and shock loading are difficult to define and the inspector must take a conservative approach when reviewing the history of the rope. Repeated overloading will result in similar damage as that caused by cyclic fatigue as described in Section 6.3. Shock loading may cause internal melting of fiber [sic].

- *Cyclic Tension Wear*

  Ropes that are cycled for long periods of time within a normal working load range will gradually lose strength. This loss of strength is accelerated if the rope is unloaded to a slack condition or near zero tension between load cycles. The subsequent damage is commonly referred to as fatigue.

- *Flex Fatigue – Pulleys, Rollers, Chocks, Fairleads, Blocks*

  Constant bending of any type of rope causes internal and external fiber abrasion. This is frequently caused by running on pulleys. But, other types of flexing such as frequent bending over a small radius surface can also cause fatigue damage… [sic]

- *Axial Compression and Kink Bands*

  Ropes that have a braided or extruded jacket over an inner load bearing core are subject to axial compression as manifested by kink bands. This occurs mostly in ropes with a very tight jacket. In severe cases, the rope will have bulges in zones where kinks are concentrated (bulges often repeat at a uniform cycle length). If the inner core can be inspected, bands of kinked fibers or yarns that have a Z appearance may be seen. If damage is severe, the filaments at the Z points will be severed as with a knife. If the jacket cannot be opened for internal inspection, destructive inspection or testing may be the only means of evaluation.

The publication's evaluation guide indicated that where an internal inspection has identified Z shaped kinks within jacketed ropes, the rope should be retired.

1.23 SIMILAR SNAP-BACK ACCIDENTS

1.23.1 *Probo Bear*

On 10 April 2006, an able seaman was fatally injured when he was struck by a mooring line while operating a winch on the fo'c's'le of the oil/bulk/ore carrier *Probo Bear* during a shift ship operation.

During the shift ship operation, the master noticed that one of the forward spring lines became taut, but he was unable to determine which of the two spring lines it was. The master ordered the forward mooring party OiC to slacken the taut spring line, but he did not receive a reply, and the spring line did not become slack. The master then ordered dead slow astern on the main engine to halt the ship's movement. Slightly less than 1 minute later, he noted that the taut spring line had suddenly become slack, and he ordered the engine to be stopped.

A short time later, the able seaman (who had been) operating the number two forward spring line winch was found lying on the fo'c's'le deck to the port side of the spring winch platform. He had severe head injuries and his safety helmet had been split in half. The 24-strand polypropylene/polyethylene line had parted while the casualty was operating a winch.

The investigation[47] found that a lack of preparedness, communication and supervision, and the incorrect use of the mooring winch brake, were contributing factors to the accident. In particular, the report concluded that:

- The shift ship operation started before the crew on the fo'c's'le were ready.

- The OiC's position during the shift ship operation meant that he did not have a clear view of the spring lines or the crew members operating the spring winch.

The report recommendations included:

Ship managers and masters should ensure that personnel supervising mooring operations are stationed such that they can clearly sight all operations that they are responsible for.

[47] Australian Transport Safety Bureau - Marine Occurrence Investigation Report No.230.

1.23.2 *Dublin Viking*

On 7 August 2007, the ro-ro passenger ferry *Dublin Viking* was preparing to leave its usual berth for a scheduled sailing. Wind and tidal conditions were benign, but in the process of letting go the stern line the operator of the stern line winch heaved in the line instead of paying out slack. The stern line parted with a loud crack, and snapped back, striking the legs of the mooring party's OiC. Both of his legs were broken and his left leg was almost severed. The recoil also dislocated a shore worker's shoulder and elbow. The OiC was evacuated to hospital, where he died 6 days later.

The investigation[48] found that the stern line was a composite of steel chain, HMPE and polypropylene lines. The relatively low elongation chain and HMPE line resulted in the majority of the elasticity being provided by the short length of polypropylene, which failed. The condition of the polypropylene line had deteriorated to approximately 50% of its specified MBL, and the lead changed direction either three or four times, each of which caused localised wear and loading. Examination of the parted line showed some areas where yarns had been fused together by heat generated in localised overloading.

The report conclusions included:

- *It was apparent that the shore and ship supplied parts of the stern line had evolved in isolation and the implications of each element on the performance of the whole system had not been considered.*

- *The lack of specification for mooring lines in the purchasing system left the selection and supply of replacement ropes open to interpretation and variation in what was procured.*

- *The arrangement …made the aft mooring deck extremely cramped. This, combined with the number and arrangement of mooring lines created several overlapping snap-back zones if any of the lines were to part. The 2/O was obliged to move in and out of these because he relayed orders to line-handlers and maintained visual contact with his own crew.*

1.23.3 *Morraborg*[49]

On 3 July 2011, the cargo ship *Morraborg* was preparing to berth. A forward spring line was passed ashore from the starboard side and the ship was then manoeuvred by running against the spring line with the rudder hard to port to get the stern closer to the quay. During the operation, the spring line parted and struck the C/O. He subsequently died of his injuries. The 6-month old spring line was an 8-strand plaited polypropylene/polyethylene mix with an MBL of 441kN.

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[48] MAIB Report No. 7/2008 - Report on the investigation of the parting of a mooring line on board *Dublin Viking* alongside at Berth 52 in the Port of Dublin, Ireland, resulting in one fatality, 7 August 2007.

[49] Final Report RS 2014:03e - Fatal accident on board the *Morraborg* in the port of Holmsund, in the county of Väster botten, Sweden, 3 July 2011

1.23.4 *Merito*

On 9 December 2014, a 3/O from the container vessel *Merito* was fatally injured when he was struck by one of the vessel's 56mm 8-strand polypropylene mooring ropes. The 3/O was inspecting the vessel's mooring lines ashore during gale force winds when the line parted.

The investigation[50] conclusions included:

- *The mooring rope parted as it was subjected to a snatch load when it took up the weight of the vessel.*
- *The 3/O was probably not aware of the stern moving off the berth and may have not realised that he was standing in the snap back zone and was in imminent danger if the mooring rope parted.*
- *The aft mooring arrangements did not allow all mooring ropes to have equal tension on them.*
- *The mooring ropes were routinely subjected to abrasion damage thus lowering their designed breaking strength.*
- *The Company did not provide inspection guidance and retirement criteria to identify worn ropes.*

[50] Transport Malta Safety Investigation Report No. 32/2015 - MV *Merito* parting of mooring ropes resulting in one fatality in the port of Algiers 9 December 2014.

SECTION 2 - ANALYSIS

2.1 AIM

The purpose of the analysis is to determine the contributory causes and circumstances of the accident as a basis for making recommendations to prevent similar accidents occurring in the future.

2.2 OVERVIEW

Zarga's forward spring lines were being used to heave the vessel aft along its berth when the inboard line parted and struck the OiC of the mooring party.

The OiC had positioned himself within the snap-back zone of the mooring line either because he did not realise he was standing in a danger zone or because he had underestimated the risk he was taking. Factors that might have influenced the OiC's decision to stand where he did, included:

- Guidance provided in the vessel's SMS and by the rope manufacturer.
- Insufficient manpower.
- Perceived time pressures and a desire to get the job done.

At the time of failure, the tensile load recorded in the line was less than a quarter of the rope's specified MBL.

The factors that contributed to the rope's reduction in residual strength, and its failure, included:

- The rope design and construction.
- *Zarga*'s mooring deck layout and the diameter of its fairleads.
- The environmental conditions at the vessel's LNG terminals.
- The vessel's mooring line maintenance and condition monitoring regime.

2.3 SNAP-BACK TRAJECTORY AND POSITION OF THE CASUALTY

Zarga's forward inboard spring line parted on the forward mooring deck about 2m inboard of its deck pedestal roller fairlead. The outboard section of the HMPE rope recoiled violently towards its *Euroflex*® tail while the inboard section stiffened and fell to the deck. The evidence indicated that the OiC was positioned aft of the spring line shipside roller fairlead when the rope parted; however, his unconscious body was found lying on the deck forward of the fairlead.

Generally, after failure, a rope held between two connections in a straight line will recoil along that line, perhaps with a snaking pattern. Depending on the energy stored in the rope and its elasticity, it could travel beyond and behind the connection points, perhaps as far as the length of the failed section. If the failed end strikes an object during the recoil it may be deflected in another direction. When a rope is around one or more deck fittings, the potential snap-back zone during the recoil becomes very complex as any changes in the direction of a rope's lead can introduce new danger zones.

TTI's computer modelled snap-back analysis indicated that the outboard end of *Zarga*'s parted spring line recoiled around the pedestal roller fairlead and looped outboard and aft of the spring line's ship's side roller fairlead. It then whipped inboard and forward, striking the OiC on the back of his head before passing through the fairlead into the water **(Figure 35)**. It is likely that the force of the impact knocked the OiC forward of where he was standing.

The trajectory analysis also indicated that the rope struck the OiC about a quarter of a second after it parted. Given his position and the environmental conditions, the OiC, unlike his signaller, would not have heard the rope rattling on the mooring deck immediately before it parted; and given the speed and route of trajectory the OiC would not have seen the approaching broken part before it struck him.

2.4 SNAP-BACK CHARACTERISTICS OF HMPE ROPES

HMPE rope has an elongation characteristic of about 2.5% before failure, which is slightly more than steel wire rope. Because of its low elasticity, the consequence of an HMPE rope failure was generally considered to be less hazardous than other synthetic ropes with little or no snap-back at failure. This point was made by the rope and material manufacturers in their promotional literature and reflected in safety guidance provided by STASCo.

It was apparent that the vessel operator and *Zarga*'s crew had not fully recognised the risk of snap-back introduced by the elasticity of the mooring line tails. *Zarga*'s onboard risk assessments had identified snap-back as a hazard to mooring deck crew. However, the risk assessments had not been reviewed following the change to mooring arrangements, in this case the change in mooring line tails.

2.5 IDENTIFICATION OF SNAP-BACK ZONES

The most recent industry guidance, which was reflected in the 2015 edition of COSWP, acknowledged the limitations of traditional snap-back assessment methods and the complexity of modern mooring decks. The guidance recommended that the entire area of a mooring deck be considered as potentially dangerous and advised against painting snap-back zones on decks.

The area aft of the spring line ship's side roller fairleads was a designated safe zone, and guidance provided by STASCo to reassure crew following previous rope failures stated that:

> *The elasticity required in the system is provided by the mooring tail. So as long as persons are not standing between the mooring winch and the fairlead at the ships side they are not in danger of being caught by whiplash.*

This guidance was supported by the danger zones highlighted on *Zarga*'s snap-back plans **(Figure 23)**.

It was apparent that the shipbuilder and vessel operator had not fully considered the consequences of mooring line failures occurring on deck. The vessel's snap-back zone plans only considered break points at the shipside fairleads. The guidance provided by STASCo also enforced the crew's perception that parted sections of HMPE ropes do not snap back.

The complex snap-back trajectory and dynamics of the outboard section of the failed spring line could not have been accurately predicted without the type of practical test-based data and computer modelling software used by TTI. However, had more thorough snap-back assessments been carried out for the mooring deck's high risk failure points, such as the pedestal rollers, it would have been apparent that the area aft of the ship's side fairleads was a potential snap-back danger zone **(Figure 40)**.

2.6 THE CONDUCT OF THE MOORING OPERATION

2.6.1 Planning and execution

STASCo's standard plan for berthing its Q-Max vessels at the South Hook LNG terminal was to attach 10 mooring lines fore and aft during the last hour of a rising tide. This allowed the crew to use the flood tide to help tension the mooring lines. The standard mooring line configuration of 3-5-2 (three head/stern lines, five breast lines and two spring lines) fore and aft was briefed by the master to the chief officer, mooring party OiCs and the bosun prior to arrival at Milford Haven. However, contradictory instructions were provided on the day of arrival in the vessel's daily work plan. This disparity, which was not identified or challenged, led the bosun and his deck crew to prepare nine lines fore and aft in a 3-4-2 configuration.

Prior to coming alongside, the OiC at the aft mooring station identified and rectified the mooring line arrangement disparity, but the forward mooring party's OiC did not. The bosun and the forward mooring party's OiC had not been to South Hook before, which probably contributed to the deck crew's initial rigging of only nine mooring lines and the OiC's failure to identify the problem. However, with better communication and control, the initial error could have been resolved before *Zarga* reached the berth. Had the OiC at the aft station told the bridge or the forward mooring party that his lines had been prepared incorrectly, or had the bridge team asked the mooring parties to confirm their line arrangements, the consequences of the earlier misunderstanding would have been avoided.

The strength of the wind during *Zarga*'s transit through the Haven to South Hook was at or just over the port limits for an LNG carrier. The winds increased when the vessel reached the berth and it was slack water when the first lines were passed ashore. It was almost 2 hours after high tide when *all fast* was declared and the tugs released. By this time, the vessel had already moved 40cm forward of its target position. The forward mooring party then spent a further 25 minutes fitting chafing guards around the mooring lines at the fairleads. During this time, *Zarga* moved forward a further 1.1m.

The requirement to rearrange the forward mooring lines caused a significant delay during the mooring operation but was not the cause of the vessel's misalignment. During the 2-hour period it took to secure the vessel on the berth, the dominant effect of the westerly winds over the ebbing tide caused the vessel to move forward of its target position on the berth. Regardless of the delay caused by the need to

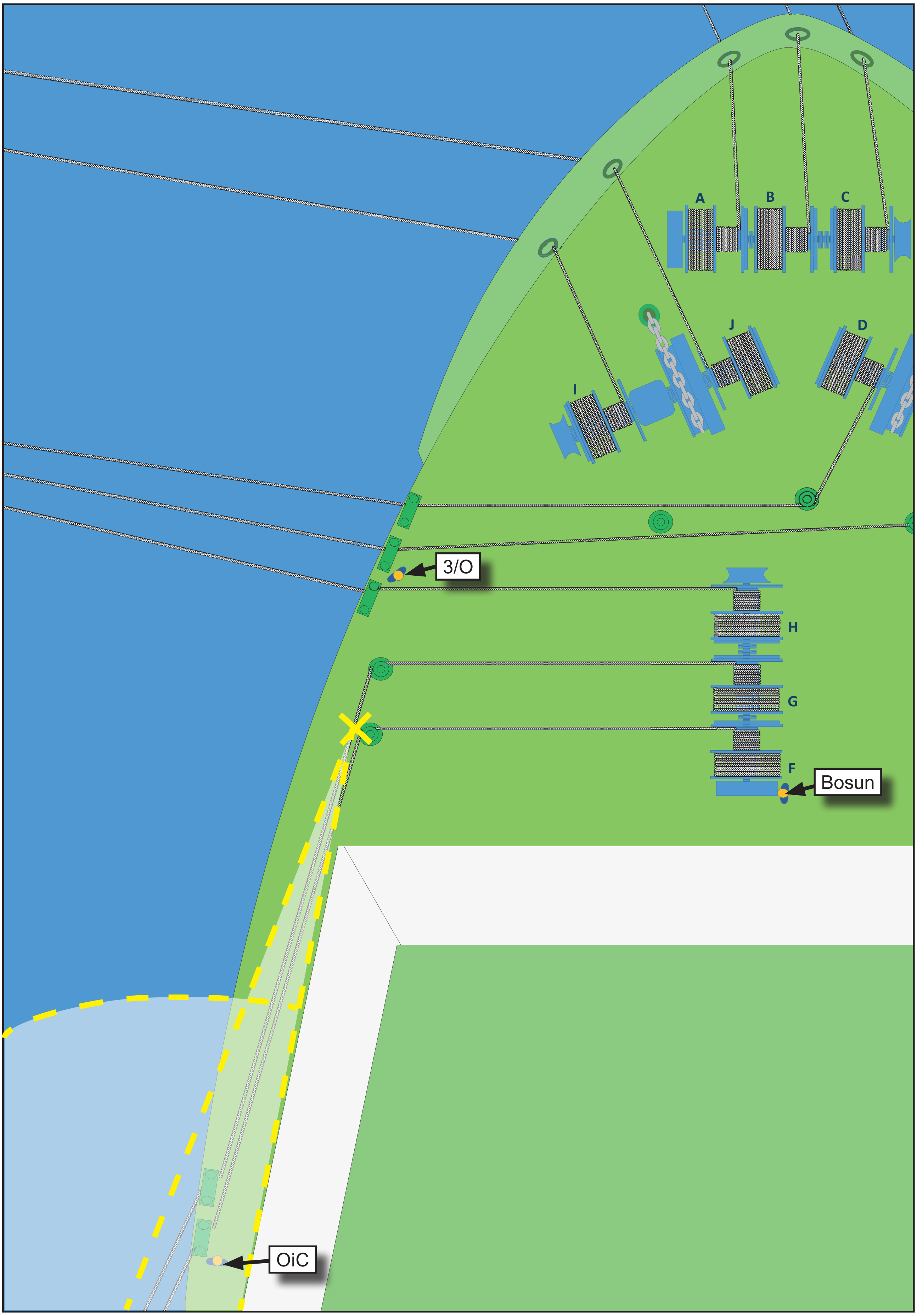

Figure 40: Simplified illustration of snap-back zone for spring line break point at deck pedestal roller fairlead

reconfigure the forward mooring lines, the decision to release the tugs before the chafing guards were fitted was key to the eventual misalignment of the vessel. Had the effects of the wind and falling tide been fully appreciated, the master might have waited until the mooring operation was fully complete before declaring *all fast* and releasing the tugs.

2.6.2 Repositioning the vessel on the berth

When the terminal staff informed the C/O that *Zarga* was out of position by 1.5m, the forward mooring party crew members had already been released. When the OiC was told of the problem and the master's decision to use the forward springs to reposition the ship, he, the other 3/O and the bosun were still at the forward mooring station. The OiC decided to retain control and follow the master's orders without recalling the rest of his mooring party. The OiC put the bosun at the winch controls and, using the other 3/O as his signaller, positioned himself aft of the spring lines' shipside fairleads.

The use of the spring lines to reposition the vessel on the berth had been successful during previous port visits and the decision to do it on this occasion, rather than recall the tugs, was supported by the pilot on board. However, as soon as the bosun started to heave in on the spring lines, it became apparent that the task would not be simple. The winch continually stalled and rendered, and the order to heave in on both spring lines at the same time was difficult to accomplish and went against the safety guidance provided by OCIMF.

Given the environmental conditions, the initial decision to release the tugs was taken too quickly, and the subsequent decision not to recall them to help realign the vessel placed the deck crew in an unnecessarily hazardous position. The decision not to re-muster the forward mooring party elevated the level of risk because it led to the OiC taking a direct part in the tensioning of the spring lines. Once actively involved, he lost his overall perspective of the mooring operation. This diminished his ability to supervise the operation, communicate with the bridge, and recognise the dangers that he and his team were in.

2.6.3 Positioning of the mooring party

In order to monitor *Zarga*'s mooring lines and the vessel's movement along the berth, the OiC positioned himself aft of the spring line shipside roller fairleads. This was a location that was regularly used by OiCs to monitor mooring lines and had previously been identified by the vessel operator as a safe zone. However, this meant that the OiC could not see the bosun at the winch controls and led him to task the 3/O to act as his signaller. Although *Zarga*'s SMS contained a procedure for the use of a signaller in such circumstances, the position taken up by the 3/O to relay the OiC's orders was clearly within the identified snap-back zones for the forward spring lines.

Mooring decks are extremely hazardous places, and it is readily apparent from similar accidents (paragraph 1.23), and the statistics highlighted by the IMO, that this type of accident is not uncommon, and often has fatal consequences. Standing in the bight or the snap-back zone of a rope when it suddenly tightens or parts is the most common cause of injury or death on mooring decks. Factors that often contribute to mooring deck accidents are lack of communication and control, insufficient training and experience, and the person-in-charge becoming directly involved with a particular aspect of the operation. All of these factors were evident in this case:

- The forward mooring party was not fully mustered.
- Onboard guidance indicated that the area aft of the spring line roller fairleads was a safe zone.
- The OiC was relatively inexperienced.
- The OiC became directly involved and lost his ability to oversee events.

The OiC was considered to be a competent, conscientious and promising young officer; however, it is clearly apparent that both he and his signaller placed themselves in dangerous snap-back zones when safer options were available. For instance, the OiC could have been positioned on top of the tank casing **(Figure 41)**, where he would have had direct line of sight of the bosun. It is almost certain that a number of other factors had an influence on the OiC's judgment and decision-making processes. These included the length of time he had spent on the mooring deck in cold and wet conditions, perceived time pressures and a personal desire to take responsibility for the earlier delays.

Figure 41: Alternative position, outside snap-back danger zones, for coordination and control of mooring line operations

2.6.4 Designing out the risk

As ships have increased in size, the identification of mooring deck danger zones has become more complex. Larger vessels require more ropes to hold them in position and, as a result, more deck winches, fairleads and bollards are needed. This increases the number and sizes of mooring line snap-back danger zones.

It is imperative that a holistic approach to mooring deck design is taken that emphasises the paramount safety of the crew. This issue has been recognised by the IMO (paragraph 1.11.3), which is exploring the potential of innovative solutions to engineer out the risk. Some of the innovations being considered include the locating of winches at the ship's side or on the berth; fitting of cages, snap-back barriers and raised safety platforms; and use of remotely operated systems.

2.7 EMERGENCY RESPONSE

Once the accident had happened, the response of the crew and the terminal staff was immediate; the emergency services were alerted, and medical first-aid was provided swiftly. The injuries suffered by the OiC were life threatening, but because of the efforts of his crewmates, the emergency service paramedics and hospital surgeons, he survived.

2.8 ROPE FAILURE MODE

2.8.1 Overview

Zarga's forward inboard spring line parted under tension on the fo'c's'le deck, about 2m inboard of its pedestal roller fairlead. The hook load of 24t, recorded at the time of failure, was 17.5% of the rope's specified MBL.

As the mooring winch was heaving on the spring line when it parted, it is likely, taking into account the frictional resistance of the roller fairleads, that the tension in the rope at its failure point would have been significantly higher than that recorded at the dolphin hook. Nevertheless, given the winch pull, this would still have been less than a quarter of the rope's specified MBL and below the vessel operator's accepted WLL.

The break load tests carried out by TTI established that the residual strength of the failed rope, remote from the break point, was as low as 35% of its specified MBL. This demonstrated that the spring line could easily have failed under normal working conditions at other points along its length.

Various factors such as previous shock loadings, tension-tension fatigue, flex fatigue, creep, heat and twisting would almost certainly have contributed to the rope's progressive loss of strength. However, the internal examination of the rope identified axial compression fatigue as the predominant mode of failure. Tensile overload of the remaining yarns would ultimately have caused the rope to fail suddenly.

2.8.2 Axial compression fatigue

Prior to this accident, it had been widely accepted across the rope manufacturing industry that HMPE was not susceptible to axial compression fatigue. So much so, that a number of international standards stated that it should not be considered when designing rope systems. However, the internal visual examinations of the failed rope identified the presence of yarn kinks at regular intervals along the entire length of the HMPE spring line. The kinks were found to be more severe in the inner yarns of the load bearing core. Subsequent SEM examination of the textile yarns discovered kink bands in the fibre filaments at the location of the yarn kinks. The examinations also identified a total of 13 broken yarns remote from the break point; all of which had occurred in locations where kinks had formed. The type of kinks and damage found in the rope yarns was typically associated with axial compression fatigue that can be a consequence of the manufacturing process, rope design and operational application.

If a rope as a whole is subjected to an axial compression force, it will bend into a radius that is too large to cause yarn or fibre damage. However, when individual components within a tensioned rope are forced into compression and are restrained by neighbouring components, damage can be caused. This can occur during manufacture if individual rope components have differing lengths[51], or in service when a rope undergoes cyclic loading, is bent around a tight radius, or is twisted.

The high failure rate of HMPE mooring lines on LNG carriers post-2007 had largely been attributed to the high cyclic load range experienced at exposed terminals, such as South Hook, and relatively low HMPE fibre content, as found in Bridon's long-lay jacketed ropes. However, TTI's review of its previous research identified that axial compression fatigue might have been a causal factor in these earlier HMPE rope failures. The combination of cyclic loading of HMPE rope, leading to axial compression fatigue, and a high enough maximum load sufficient to cause complete rope failure, had been identified in the Fibre Tethers 2000 report. Nevertheless, the perceived high number of cycles required to achieve severe strength loss was generally considered by the report's authors to rule out axial compression fatigue as a cause for concern for the offshore sector. It is apparent that the risks associated with axial compression fatigue identified in this report for HMPE mooring lines, and other HMSF ropes, need to be fully understood by both rope manufacturers and ship operators, and reflected in industry guidance.

2.8.3 Cyclic loading

The continuous cyclic loading of a rope can induce tension-tension and axial compression fatigue that reduces the rope's residual strength and service life. At low loads this can be particularly destructive to an HMSF rope as not all the fibres will be equally loaded and individual components can be subject to axial compression even when the rope as a whole is under tension.

Over half of the mooring line failures recorded on board the STASCo managed Q-class vessels between 2010 and 2015 occurred at the UK's South Hook and Isle of Grain LNG terminals. It was therefore evident that the environmental conditions at these more exposed LNG terminals increased the likelihood of failure. The

[51] Such as the level of twist imparted by the strander between the outer and inner yarns.

strong winds and tidal range at South Hook presented a high cyclic load range and increased the risk of shock loading. Both these outcomes would have accelerated the fatigue and strength reduction processes.

To reduce the likelihood of shock loading and tension-tension fatigue, STASCo fitted longer mooring line tails, and this intervention appears to have extended the longevity of the HMPE mooring lines. However, the evidence indicates that the fitting of longer nylon rope mooring line tails to mooring lines with pre-existing fatigue damage due to high loads, did not address the unforeseen risk of axial compression fatigue failure.

2.8.4 Bending and twisting

Bending and working a rope under tension around small diameter fairleads can cause significant damage and sudden unexpected failure. Localised friction at the bend can cause heat build-up within the rope core, resulting in melting of fibres and weakening of the rope. The smaller the D:d ratio the greater the effect. Operating a rope at high tensile loads around deck fittings with too small a D:d ratio will also induce a high degree of axial compression and tensile load within separate components of the rope. This will significantly increase the risks associated with inter-fibre abrasion, heat generation and flex fatigue. Long-lay constructions, with low or zero helix angles and tightly bound jackets, are particularly prone to damage.

Twisting of a rope, particularly one which has a low yarn twist, will also create axial compression. Depending on the direction of twist, this could put either the inner or outer yarns in to compression. Bridon identified an area of twisting in the failed spring line close to its spliced eye, but evidence of twisting was not found close to the break point.

The bending of *Zarga*'s spring line around the vessel's deck fairleads at angles approaching 100° was a significant factor in the reduction of the line's load-carrying capabilities as well as its loss of strength over time. In addition, the arrangement of the mooring decks on board the Q-class LNG carriers almost certainly contributed to the fleet's high mooring line failure rate.

In order to reduce the risk of axial compression and flex fatigue, it is essential that mooring decks are designed to remove or minimize the number of bends in a mooring line; ideally point-to-point loading should be the aim. Larger diameter and well maintained fairleads will also improve a rope's life and it is critical that the rope manufacturer's minimum recommended D:d ratios are not exceeded.

2.9 ROPE DESIGN AND CONSTRUCTION

2.9.1 Overview

There is a vast variety of rope designs and constructions readily available off the shelf for purchase. For complex applications, rope manufacturers often design and construct bespoke ropes to order.

Design and construction are fundamental to a rope's resilience and longevity, and should be optimised to meet the challenges of the rope's intended application. A long-lay length jacketed HMSF rope provides higher tensile strength for a given diameter than an unjacketed braided rope, and requires less fibre content. However, long-lay jacketed ropes are more susceptible to axial compression and flex fatigue.

DNV-GL considered two loading categories for ropes used in offshore applications: point-to-point loading and combined loading. According to the classification society's recommended practice, long-lay jacketed ropes are best suited for point-to-point loading applications and should not generally be exposed to combined loading.

2.9.2 Long-lay jacketed construction

Long-lay ropes have several advantages over traditional braided ropes, not least a greater strength to size ratio. However, long-lay ropes require jackets to maintain their structure and prevent them unravelling. Jackets will protect the load bearing core from external abrasion damage; however, tightly bound jackets impart radial compression on the load bearing core. This radial compression constrains the axial movement of the rope yarns and fibres, promotes the formation of kinks by preventing fibre load equalisation, and increases the risk of further internal abrasion.

Similar yarn kinks to those identified in *Zarga*'s failed rope have often been found in new HMSF long-lay jacketed ropes. This was the case when TTI examined the *Steelite Superline Xtra* rope manufactured by Bridon to support this investigation. This phenomenon had previously been seen as almost exclusively a concern of Aramid ropes, and was not considered to be a significant concern as the expectation was that the yarn kinks would pull out under tension and that HMPE had a high resistance to axial compression fatigue. The failure of *Zarga*'s mooring line has proven this assumption to be wrong, and it is clear that serious consideration needs to be given to the suitability of low-twist jacketed ropes for use in ship-shore mooring applications.

2.10 MINIMUM BREAKING LOAD, SAFETY FACTORS AND WORKING LOAD LIMITS

The shipyard specification for *Zarga*'s mooring lines stipulated 44mm diameter HMPE rope with an MBL of 137t and an eye spliced at one end. The calculated rope strength for the failed rope was 151.47t and its specified MBL was 137t. Break load tests of sections of *Zarga*'s failed rope resulted in residual rope strengths of between about 35% and 64% (47tf and 85tf) of the specified MBL.

A minimum safety factor of 2 for 'other synthetic' mooring lines was recommended in OCIMF's MEG-2; this allowed a WLL of 50% MBL, which was 68.5t for *Zarga*'s mooring lines. Changes in the number of lines required by the OPTIMOOR tool from 18 to 20 indicate that the tool did not reflect reality. This was due to the limited data input requirements in the MEG to enable an effective assessment to be conducted. Furthermore, the OCIMF Safety Factor of 2 for synthetic ropes meant that the OPTIMOOR assessment would indicate a successful result with all lines equally loaded to 68.5 tonnes. Not only was this load in excess of Bridon's guidance on working loads, but it was unrealistic to assume that the load on all 20 lines could be maintained equally.

Although specified from the outset to be used with HMPE ropes, the mooring equipment fitted on board the Q-Max and Q-Flex LNG carriers had been, in effect, designed and sized to accommodate steel wire rope in terms of diameter, MBL and SF. It was apparent that the shipbuilders and vessel operators considered HMPE rope to be a direct replacement for steel wire. This was because steel wire and HMPE ropes had similar size to strength ratios. However, the resilience and durability of the ropes under dynamic loading were very different. MEG2 and MEG3 showed the strength reduction in steel wire rope when the bending ratio around deck fittings was reduced. At a D:d ratio of 12:1, the percentage of original breaking strength was in the region of 91%-93%. At a D:d of 9, the rope strength had reduced to between about 85% and 87%. The guidance indicated that high modulus fibre ropes would require a larger bend radius to achieve the same fatigue life as steel. It is clear from the above that steel wire rope would also have suffered strength loss when operating on *Zarga*'s mooring deck. Nevertheless, it is apparent that HMPE ropes come in a range of fibre grades, and have a wide range of constructions. Some are considered to be more resilient than steel wire rope to cyclic tensile loading and to not suffer more from bend strength loss. However, sufficient information to purchasers on HMSF rope suitability under varying operating conditions has been lacking.

Safety factors of less than five are rarely applied for HMSF ropes outside the shipping sector, and safety factors of 10 and higher are often used for high-risk dynamic applications where the expected loads are typically more well controlled, measured and understood. In the ship-shore mooring environment, loads are not always accurately or consistently measured, and inherently not controlled as the vessel mooring environment is affected by tidal height and loading condition. A higher safety factor will reduce a rope's WLL as a percentage of MBL, and therefore reduce its exposure to stress and increase its working life. This logic is simple and obvious, however, increases in mooring line safety factors could have serious impacts on vessel design. Higher safety factors will require an increased number of mooring lines or increased rope strength. Only the latter of these options is potentially available to the Q-Max vessels.

2.11 SUITABILITY OF BRIDON'S *STEELITE SUPERLINE XTRA* ROPE FOR THE MOORING LINE APPLICATION

2.11.1 Overview

The vast majority of the 45 mooring line failures that occurred on board STASCo-managed Q-Max and Q-Flex vessels between 2009 and December 2015, were 3-strand *Steelite Superline Xtra* ropes. Of the 90 failed mooring lines analysed in the HMPE Users Group study, 99% were of a long-lay jacketed construction and 92% were manufactured by Bridon/Marlow. According to the data recorded, the operating life of the failed mooring lines ranged between 62 and 1940 hours, with the average being 1011 hours.

Given these overwhelming statistics, the suitability of the Bridon *Steelite Superline Xtra* rope for use as a ship-shore mooring line needs to be closely examined. In particular, its application on board *Zarga* and the other Q-Max and Q-Flex vessels.

2.11.2 Rope construction

TTI identified rope construction as a contributory factor in the development of kinks and axial compression fatigue in *Zarga*'s failed rope. The internal examinations of the failed spring line and the new and unused *Steelite Superline Xtra* rope established that the helix angles of the rope's inner and outer yarns were zero and 15° respectively.

As discussed in paragraph 2.9.2, the tightly bound jacket and parallel and low twist elements within the load bearing core would have had a detrimental effect on the ropes' strength. However, it was apparent that the manufacturing process also introduced weaknesses and stress raisers within the yarns. It is possible that the kinks induced during the manufacturing process, when subsequently subjected to axial compression, became more severe due to an increase in the local fibre density. With the inability to expand due to the tight jacket and surrounding fibres, internal friction increased, leading to extreme abrasion and subsequent overload.

The internal examination of the new rope identified unequal yarn lengths and visible kinks. SEM examination of the textile yarns discovered the formation of kink bands at filament level. The Cordage Institute's rope evaluation guide recommended the retirement of a rope where internal inspection of the load bearing core has identified distinctive Z shaped kinks. If this criterion was applied, the new *Steelite Superline Xtra* rope would have been rejected.

2.11.3 Minimum breaking load

Bridon's three-strand, 44mm diameter *Steelite Superline Xtra* rope was originally designed and marketed by Marlow in 2003. The test data for Marlow's original MBL calculations could not be found, however the rope manufacturer's quality assurance test methodology document **(Annex B)** indicated that a realisation factor of 0.998 had been used to achieve a specified rope MBL of 127t. Bridon used the same realisation factor to calculate an un-spliced realised strength of 151.47t for *Zarga*'s failed mooring rope. If the realisation test methodology set out in ISO 2307:2010 was applied, the calculated MBL for the spliced rope would have been 136.3t (151.47 x 0.9). Similarly, had this been applied to the test results for a subsequent batch of ropes (paragraph 1.7.3) the spliced MBL of those ropes would have been 131T.

TTI calculated an MBL of 122.3t for the new spliced rope supplied by Bridon, using the manufacturer's realisation factor of 0.998. This was 14.7t less than the specified MBL of the failed rope. During the actual whole rope break load tests the two test samples parted at 101.46t and 105.64t. These were 20.8t (17%) and 16.7t (14%) less than the new rope's actual whole rope break load. Given the variances in yarn strengths found during TTI's testing, the whole rope break tests carried out on the new rope clearly demonstrated that a realisation factor of 0.998, effectively an equal translation of yarn to rope strength, was inappropriate. TTI's report suggested that a realisation factor of 0.85 was more appropriate.

TTI's test results raise significant concerns about the validity of Bridon's original realisation test results. It is difficult to explain how Bridon's realised test results for *Zarga*'s ropes were so much higher than those achieved with the new rope and those previously achieved by Marlow. This is especially so as the rope was constructed using the same design specification, manufacturing plant and grade of Dyneema® fibre. Furthermore, the specified MBL of 137t for the spliced rope was higher than the indicative MBL of 134t for the same un-spliced rope quoted by Bridon in its technical brochures.

The evidence clearly demonstrates that Bridon's specified MBL of 137t for its spliced 44mm diameter, three-strand, *Steelite Superline Xtra* rope was, at best, optimistic. The calculated MBL of 137t was significantly higher than that stated in Marlow's test sheet (127t un-spliced) and subsequently achieved by TTI, and it is clear that the use of a realisation factor of 0.998 was inappropriate. Regardless of the veracity of previous MBL calculations, it is apparent that the rope's current design specification does not deliver the MBL required for the Q-Max and Q-Flex vessel mooring lines.

2.11.4 Safety factors and working load limit

In accordance with the guidance provided in MEG-2 on safety factors for *other synthetic fibre* ropes, the WLL applied to *Zarga*'s mooring lines was 68.5t (50% MBL). However, MEG-2 also warned that specific recommendations had not been made for newer low stretch synthetic materials, and recommended that rope manufacturers' guidelines be considered. Bridon's HMSF rope manual stated that the life of its ropes could be adversely affected when exposed to working loads above 20% of MBL. The manual also defined a shock load as one that exceeded the working load by more than 10%.

If the guidance set out by the rope manufacturer had been followed and a safety factor of five applied, the WLL of *Zarga*'s mooring ropes would have been 27.4t and loads above 30.1t would have been considered shock loads. On the day of the accident the spring line experienced prolonged loading above 27.4t and peaked at 40t. Although well within the WLL recommended by OCIMF, it could be argued that the rope experienced a degree of shock loading immediately prior to its failure.

Had the safety factor recommended by Bridon been applied during the tendering process, the 44mm *Steelite Superline Xtra* rope would have been eliminated. Indeed, had the safety factor been applied, an MBL in excess of 300t would have been required and this would have meant a bigger rope diameter. Furthermore, as other rope manufacturers recommended similar safety factors, it is unlikely that any type of 44mm diameter rope would have been considered suitable for the application.

2.11.5 Deck fitting and mooring line D:d ratios

Zarga's inboard spring line was bent around two sets of roller fairleads and was subjected to three directional changes between its winch drum and the terminal's dolphin hook. As the line parted about 2m inboard of its pedestal roller fairlead, its break point would have passed around the pedestal roller while under load shortly before the failure. It is also likely that the same section of the rope would have been worked around the fairleads on a regular basis.

The minimum D:d ratio specified in Bridon's Fibre Rope Catalogue for *Superline* ropes was 12:1, which was in accordance with generic guidance provided by OCIMF and other industry bodies. The diameters of the rollers fitted to *Zarga*'s pedestal and universal fairleads were 450mm and 400mm respectively. As a result, the D:d ratio between the deck rollers and the mooring lines were:

Pedestal fairlead roller D:d ratio	= 450:44	= 10.2:1
Universal fairlead roller D:d ratio	= 400:44	= 9.1:1

These D:d ratios were significantly less than those recommended by the rope manufacturer. However, this obvious safety-critical issue was not highlighted during the investigations into the LNG carriers' previous mooring line failures. Furthermore, the arrangement of the mooring deck and D:d ratio incompatibilities was not included in the scope of the HMPE Users Group study.

The D:d ratios between the deck fittings and the mooring lines were too small, and for that reason alone the *Steelite Superline Xtra* rope should not have been considered suitable for use on the Q-Max and Q-Flex vessels. However, the manufacturer was not consulted during the rope procurement process and its published guidance was ignored. It is apparent that mooring deck design needs to be considered as a system instead of individual components assessed and chosen independently.

2.11.6 Deck fitting safe working loads

The SWL of *Zarga*'s pedestal and universal roller fairleads was 74t. This was above the WLL of the mooring lines and in accordance with the guidance contained in MEG-2. However, if MEG-3's revised guidance on SWL is retrospectively applied, the SWL of the fairleads would need to be almost doubled to 137t; equal to the specified MBL of the lines.

2.12 ROPE MAINTENANCE MANAGEMENT

2.12.1 Onboard inspection and maintenance regime

Zarga's failed spring line had been in service for 5 years and had 1342 recorded working hours. The rope was initially used as a head line and operated for 520 hours with an 11m tail. It was then operated for a further 655 hours as a head line with its 22m *Euroflex* tail and end-for-ended twice before being rigged as a spring line in October 2014. During this time, the rope had been inspected at 4-monthly intervals by the ship's crew, and on several occasions by the rope manufacturer's service staff. Several areas of localised stiffness and evidence of heavy loading on the fairleads were observed during the non-destructive examination of the parted rope. However, on all occasions the overall condition of the rope, remote from the break point, was assessed to be good.

A review of *Zarga*'s mooring line maintenance records revealed that the crew had regularly identified areas of localised rope stiffness during their routine mooring line inspections. To remedy this, and taking into account guidance from Bridon representatives, the ropes were often flexed around bollards and fairleads and, on occasion, they were softened by being hammered with wooden mallets.

Guidance provided in *Zarga*'s SMM warned that localised stiffening was indicative of shock loading. The guidance went on to recommend that ropes suspected of being shock loaded (in excess of an unspecified WLL), or when winch brake rendering had occurred, should be condemned. Similar warnings and guidance was provided by industry bodies such as the Nautical Institute. Bridon had advised STASCo that ropes will become hard during normal operation without detrimental effect. However, hook load data for *Zarga*'s mooring lines indicated that many of the vessel's mooring ropes had experienced some degree of shock loading and overloading.

Tightly bound jacketed ropes are naturally stiffer cross-sectionally than unjacketed constructions, and assessing rope stiffness, and its impact on the rope's potential longevity, is subjective and dependent on the assessor's knowledge and experience. There is no universal agreement on how to respond to localised stiffness in sections of HMSF rope. However, beating jacketed ropes with mallets should not be considered an acceptable practice as this can only result in increased internal damage.

The aim of the STASCo's mooring line maintenance management regime was to ensure that ropes were removed from service before their strength was substantially reduced. The residual strength of *Zarga*'s parted spring line and the incidence rate of rope failures on board the STASCo managed Q-class vessels demonstrated that this aim was not being met. This was because the company's recommendations relating to localised rope stiffness and shock loading were not fully implemented. It was also indicative of the difficulties associated with the through-life monitoring of the condition of HMSF ropes, and tightly jacketed ropes in particular.

2.12.2 Rope condition monitoring and retirement

Most rope manuals and guidance documents make reference to rope longevity and predicted working life but, despite this, rope manufacturers do not provide life expectancies for their products. Furthermore, unlike lifeboat falls, there are no regulatory obligations for the periodic replacement of ships' mooring lines. Instead, mooring line retirement or replacement is typically condition based, and relies largely on continuous through-life monitoring.

STASCo's policy was to rotate spring ropes with other ropes every 2 years and to end-for-end the mooring lines after 4 years, which indicates that the company's expectation was that the ropes would last at least 8 years. The company relied primarily on external visual inspection to determine the condition of their mooring lines. However, several of the rope rejection criteria listed in *Zarga*'s SMM, such as broken strands, abraded yarns and fused fibres, required internal examination of the rope. To do this, the jacket needed to be removed and therefore sections of the rope destroyed.

The periodic internal examination of *Zarga*'s mooring lines might have identified yarns kinks and some of the discard criteria listed in the vessel's SMM, but it would not have established the condition or status of the macro-molecular fibres. The rope fibres might have sustained damage through a variety of means during the rope's working life, and currently there are no recognised NDT methods for assessing the overall condition of HMSF ropes. Indeed, kink banding in the fibres can only be seen under SEM.

In addition to working hours, STASCo recorded environmental conditions at the LNG terminals and hook loads when ropes failed. The LNG terminals recorded the hook load data. However, these time, tension and temperature data were not used meaningfully to assess rope condition and trigger retirement. Mooring line shock loading and overload incidents went unnoticed or were not recognised, and therefore many ropes were operated until failure. It is apparent that a robust condition-based rope-management-monitoring system needs to be developed and implemented. To achieve this, the vessel operators and rope and fibre manufacturers need to work together to collect and analyse the necessary data in order to generate threshold criteria for discarding lines.

2.12.3 End-for-ending

The periodic end-for-ending of steel wire ropes is a well-recognised practice for lifeboat falls and mooring lines on board ships. It ensures that the same sections of rope are not constantly exposed to the highest dynamic loads, and extends their working life. *Zarga*'s PMS required the mooring ropes to be end-for-ended every 4 years. The failed spring line was end-for-ended twice in 4 years.

It is unknown why the rope was end-for-ended after 2 years, but end-for-ending it a second time might have put a previously weakened section of rope to work in a location where it would be exposed to high dynamic loads. This assessment is supported by the fact that the rope only achieved a further 167 hours as a spring line.

2.13 THE USE OF HIGH MODULUS SYNTHETIC FIBRE ROPES AS SHIPS' MOORING LINES

2.13.1 General

A wide variety of ropes is currently in use as mooring lines on board ships. Synthetic fibre ropes have many well publicised advantages over traditional steel wire ropes, but they also have disadvantages. For instance, Polyamide ropes absorb more elastic energy than HMSF ropes for a given displacement, but their elasticity can have serious consequences when they part under load. Conversely, low elongation ropes, such as HMPE, store a lower amount of elastic energy but might be more susceptible to undetectable damage during dynamic loading.

It is crucial that ship owners, operators and builders choose the right type of rope for a given application. To do this they need to have a full understanding of the properties and limitations of each type of HMSF rope. Complex failure modes, such as axial compression, tension-tension and flex fatigue, as well as the effect temperature and tension have on the creep rate of a given fibre need to be fully understood.

When considering the use of steel wire ropes, the shipping industry has a great deal of collective knowledge, and there are well established rules relating to their inspection, maintenance and retirement. Ambient air temperatures have little or no effect on the residual strength of steel wire rope; broken strands are easily detected, as are internal and external abrasion and corrosion. The same cannot be said for all HMSF ropes. As discussed earlier in this section, jacketed ropes cannot readily be internally inspected, and the rate of strength loss over time can vary significantly depending on ambient temperatures, induced heat, load, and bending and twisting.

The parting of a mooring line under tension is one of the most dangerous occurrences on board ship and one that happens all too often. The condition of HMSF ropes needs to be monitored closely to ensure they are retired or discarded well before their residual strength approaches the WLL for the application. To do this, operating data such as temperature, tension and time need to be recorded. This is not currently done and there are limited non-destructive methods available to determine the overall condition of HMSF ropes. This is an area that would benefit significantly from further research.

2.13.2 High modulus synthetic fibre mooring line purchasing guidance

When SHI sought tenders for the Q-fleet's HMPE mooring lines, it specified a maximum rope diameter of 44mm, an MBL of 137t and a splice at one end. It did not provide a WLL or details of the vessel's deck fittings, and nor was this information requested by the rope suppliers to ensure suitability. The specification followed the standard approach to rope purchase at that time, with rope MBL being the key parameter in determining suitability. The HMPE Users Group report recognised that this was a common approach taken by many purchasers and was too simplistic for HMSF rope. In February 2014, in response to a recommendation made in the HMPE Users Group report, OCIMF and SIGTTO produced and distributed the *Guide to Purchasing High Modulus Synthetic Fibre Mooring Lines* **(Annex L)**.

Although an improvement on previous guidance, the revised HMSF rope purchasing guide was constrained by the contents of MEG-3. It did not discuss minimum D:d ratios, safety factors and WLLs, and specifically stated that HMPE was resistant to axial compression fatigue.

Taking into account all the issues highlighted in this investigation report, it is essential that the purchasing guidance for HMSF mooring lines is subject to a thorough review, and amended where appropriate. The offshore sector has demonstrated that an engineering design approach needs to be applied when purchasing HMSF mooring lines. Had SHI specified a WLL for the mooring lines and provided the details of the mooring deck fairleads, Bridon would have had the opportunity to consider its recommended safety factors and minimum D:d ratios when submitting its tender.

2.13.3 Comparison with the offshore sector

There is, and has been for many years, a considerable body of guidance, recommended practices and standards for the application of fibre ropes and tethers in the offshore sector. This has been developed with the involvement of the oil majors, classification societies, rope manufacturers and synthetic fibre producers through joint industry projects. Understandably, the consequences of an offshore platform or other structure breaking loose from its moorings was unacceptable. Therefore, an engineering design approach was applied, whereby the factors affecting the equipment's 'fitness for purpose' were designed, tested and analysed. This ensured that under the specified operating conditions, the equipment would meet the required standards (paragraph 1.21).

It is also apparent that mooring lines for the shipping industry and, in particular the newer generation of HMSF ropes, have not been considered in the same way. On the contrary, HMSF ropes have been considered as an almost direct replacement for steel wire ropes, but without the negative aspects of steel wire. Heavy reliance was placed on the results of testing carried out for the offshore sector, but which is clearly not appropriate for ship mooring lines, in particular the reliance given to the TCLL. It is not the case that HMSF ropes are wholly unfit for purpose but, to make them fit the task they should be assessed as being suitable in similar ways to those used in the offshore sector. This important element in the selection process was, and in some respects still is, lacking.

The ropes or tethers in the offshore sector operate with lower WLLs under controlled loading with much higher D:d ratios; MBL is not considered a primary parameter to assess suitability and parallel core jacketed ropes are not considered appropriate for bending or twisting operations, and they are subjected to lower operating temperatures in submerged conditions. By comparison, jacketed mooring ropes on board ships can be subjected to cyclic loads at low factors of safety, while working on relatively small bend radii in, sometimes, hot and dry conditions. Consequently, the failure rate of these ropes found on board these ships is, perhaps, not surprising.

SECTION 3 - CONCLUSIONS

3.1 SAFETY ISSUES DIRECTLY CONTRIBUTING TO THE ACCIDENT THAT HAVE BEEN ADDRESSED OR RESULTED IN RECOMMENDATIONS

1. The OiC of the forward mooring party was seriously injured because he was standing in the snap-back zone of the forward spring lines when one of them parted. [2.2]

2. The decision to attempt to reposition the vessel using the spring lines, rather than recalling the tugs, placed the mooring parties in an unnecessarily hazardous position, particularly given the strength and direction of the winds. [2.6.2]

3. Had STASCo assessed the consequences of the forward spring lines parting at or close to their deck pedestal roller fairleads, it would have been apparent that the designated safe area that the OiC was standing in when he was injured, was a potential snap-back danger zone. [2.5]

4. Had the master, C/O and OiC fully assessed the situation a much safer way of conducting the task might have been identified. [2.6.3]

5. The mooring line ultimately failed due to tensile overload after its residual strength had reduced. [2.8.1]

6. The tensile load on the mooring line when it parted was less than a quarter of its specified minimum breaking load and below its accepted working load limit. [2.8.1]

7. Although the Q-Max and Q-Flex LNG carriers were specified from the outset to have HMPE mooring lines, the shipbuilder and vessel operator did not take into account the recommended safety factors. This critical omission resulted in the high rate of rope failures experienced across the Q-class fleet. [2.10]

8. The *Steelite Superline Xtra* ropes were not suitable for use as mooring lines on board *Zarga* and the other Q-Max vessels. They did not have the required minimum breaking load, the diameter of the vessel's deck fittings was too small and, given the rope manufacturer's recommended safety factor, the required working load limit was too high. [2.11]

9. Mooring line maintenance management and condition monitoring regimes were ineffective. Onboard inspections regularly identified evidence of shock loading but, contrary to company and industry guidance, the ropes were not discarded. [2.12.1]

10. The condition of the load bearing core of jacketed ropes cannot be adequately assessed on board ship. Several of the rope discard criteria listed in *Zarga*'s safety management manual, such as broken strands, abraded yarns and fused fibres could not be identified without destroying sections of the rope. [2.12.2]

3.2 SAFETY ISSUES NOT DIRECTLY CONTRIBUTING TO THE ACCIDENT THAT HAVE BEEN ADDRESSED OR RESULTED IN RECOMMENDATIONS

1. The vessel operator and its mooring deck crew underestimated the risk of snap-back. This was because the vessel's snap-back assessments did not fully consider the consequences of a rope parting on deck and the elasticity introduced by the HMPE mooring rope's Euroflex® tail. [2.3, 2.4, 2.5]

2. The progressive reduction in the spring line's residual strength would have been the result of a combination of factors, such as shock loading and tension-tension fatigue. However, the predominant factor identified in this case was axial compression fatigue. [2.8.1]

3. Axial compression fatigue had not previously been considered as a likely failure mode or significant cause of strength loss in HMPE rope by the rope manufacturing industry. [2.8.2]

4. The test methodology and calculations used by Bridon to achieve the required specified MBL for *Zarga*'s mooring lines were flawed. The realisation factor applied was unrealistic and results were much higher than those previously (Marlow) and subsequently (TTI) achieved for the same design of rope. [2.11.3]

5. Neither the builders of the Q-Class LNG carriers nor the rope suppliers asked the necessary questions or provided the detailed information required to ensure suitable ropes were purchased for mooring the vessels. [2.13.2]

6. The *Guide to Purchasing High Modulus Synthetic Fibre Mooring Lines,* issued in 2014, did not adequately address some of the issues discussed in this report. [2.13.2]

3.3 OTHER SAFETY ISSUES NOT DIRECTLY CONTRIBUTING TO THE ACCIDENT

1. The arrangement of *Zarga*'s mooring deck meant that its entire fore deck area was a snap-back danger zone. In order to ensure the safety of life, deck crews need to be removed from such danger. This can only be achieved through better ship mooring system and mooring deck design. [2.6.4]

2. *Zarga*'s mooring lines were especially susceptible to axial compression fatigue because of their long-lay jacketed construction, the effects of bending around the ship's deck fittings and the high levels of cyclic loading experienced at exposed LNG terminals such as South Hook. [2.8.3, 2.8.4]

3. The tightly bound jacket fitted around Bridon's *Steelite Superline Xtra* rope's load bearing core increased the radial compression acting on the inner yarns. This constrained relative movement between the yarns and increased the likelihood of axial compression fatigue. [2.9.2]

4. Potentially damaging kinks within the core of the *Steelite Superline Xtra* rope were introduced during the manufacturing process. [2.11.2]

5. The tensile strength of HMSF rope will diminish steadily over time regardless of how well it is maintained. For this reason, appropriate safety factors and anticipated life expectancies need to be applied, and parameters such as time, tension and temperature need to be closely monitored. Without these, the ropes will only be discarded on failure. [2.12.2]

SECTION 4 - ACTION TAKEN

4.1 MAIB ACTIONS

The **Marine Accident Investigation Branch** has:

- Issued Safety Bulletin SB 1/2015 **(Annex J)** warning of the increased dangers of snap-back on mooring decks when high elasticity synthetic tails are fitted to HMPE mooring lines.

- Issued Safety Bulletin SB 1/2016 **(Annex O)** explaining the difficulty of assessing the condition of the load bearing core of tightly bound jacketed ropes.

4.2 ACTIONS BY OTHER ORGANISATIONS

Shell International Trading and Shipping Company Ltd has:

- Worked closely with the MAIB throughout the investigation process and has used the data gathered during the snap-back trials and assessments to reassess the danger zones on the mooring decks of its vessels.

- Installed physical barriers to protect deck crew within designated safe areas.

- Replaced the *Steelite Superline Xtra* mooring lines on its Q-class vessels with new 12-strand unjacketed HMPE ropes.

- Replaced the forward spring lines on all its managed vessels and examined the ropes for yarn failure.

- Engaged with OCIMF's Ports and Terminal Committee to examine the safety issues relating to the accident and identify future safety initiatives.

Bridon International Ltd has:

- In association with STASCo, set up a working group to examine *Zarga*'s failed mooring line and inspect other ropes of a similar operating profile.

- Removed *Steelite Superline Xtra* rope from sale during 2015.

- Begun a programme of product validation and revalidation using external standards where available.

- Improved the naming conventions of its products.

- Taken a leadership role in both the Eurocord and OCIMF task forces relating to mooring ropes to assist in the dissemination of lessons learned from this accident to the wider fibre rope industry.

The **Oil Companies International Marine Forum** has:

- Produced and distributed an information paper **(Annex P)** highlighting the issues identified in the MAIB safety bulletins and undertaken to update the OCIMF/SIGTTO guide on purchasing high modulus synthetic fibre mooring lines for integration within MEG-4.

- Formed working groups to:

  - Review and enhance the information contained in its Mooring Equipment Guide.

  - Develop minimum requirements for the initial testing and certification of HMSF mooring ropes.

  - Develop HMSF rope through-life condition-based monitoring recommendations.

  - Assess the impact of wind, tidal streams and vessels' drag coefficients on mooring line load.

  - Undertake a detailed review of the design and ergonomics of current mooring decks and submitted comments to the fourth session of the IMO's Sub-committee on Ship Design and Construction regarding amendments of SOLAS II – 1/3-8 and the development of guidelines for safe mooring operations for all ships.

The **Marshall Islands Maritime Administration** has:

- Undertaken to engage with the IMO's Sub-committee on Ship Design and Construction (SDC) Correspondence Group on Safe Mooring Operations.

Milford Haven Port Authority has:

- Issued Notice to Mariners No.45 of 2015 – Ship Movements within Milford Haven[52], reminding masters of the requirement to obtain permission of the harbourmaster for moving between berths, shifting ship on a berth or to enter or depart berths.

[52] This applies to vessels of 20m length and over.

SECTION 5 - RECOMMENDATIONS

Bridon International Ltd is recommended to:

2017/117 Review and enhance its guidance and instructions for the monitoring, maintenance and discard of HMSF mooring ropes, and bring this to the attention of its customers. The revised guidance should emphasise the importance of:

- Deck fitting and rope D:d ratios.
- Applying appropriate safety factors for given applications.
- Understanding the causes of kinking and the potential impact of axial compression fatigue on the working life of HMSF rope.
- Rope fibre examination and testing as part of the assessment of fibre fatigue degradation and discard.

2017/118 Conduct whole rope break tests, where practicable, to establish accurate realisation factors for its HMSF ropes.

Shell International Trading and Shipping Company Ltd is recommended to:

2017/119 Review the mooring arrangements on board its vessels and ensure that the mooring lines and the deck fittings are compatible.

2017/120 Develop robust mooring line procurement criteria to ensure rope manufacturers' recommendations on safety factors and D:d ratios are carefully considered.

2017/121 Provide its ships' crews with comprehensive guidance on the inspection of HMSF mooring ropes.

2017/122 Investigate methods for monitoring the through-life condition of HMSF rope mooring lines with the aim of ensuring ropes are retired and replaced before their residual strength drops below their expected working load limit.

The **Oil Companies International Marine Forum** is recommended to:

2017/123 Consider the safety issues identified in this report during the revision of its Mooring Equipment Guidelines, in particular:

- The complex nature of mooring rope snap-back, and actions that can be taken to mitigate injury to the crew.
- Factors such as axial compression, cyclic loading, creep, flexing and twisting that will contribute to the loss of strength in HMSF ropes over time.
- Adoption of a safe minimum D:d ratio for all deck fittings using HMSF mooring ropes.
- Through-life monitoring of HMSF mooring rope operating conditions and maintenance to achieve managed discard timescales.

2017/124 Promulgate the safety issues identified in this investigation to its members.

2017/125 When updating its OCIMF/SIGTTO guide on purchasing high modulus synthetic fibre mooring lines, ensure the limitations of the tests contained within its "Guidelines for the Purchasing and Testing of SPM Hawsers" are recognised, and that rope performance tests verify an HMSF rope meets a prescribed safe working life.

EUROCORD is recommended to:

2017/126 Consider the inclusion of the following criteria during the next revision of ISO2307:2010:

- Full load break tests to be applied to all new rope designs/constructions and when the molecular properties of fibre material have been significantly altered.
- Clarification that yarn break testing and the resultant realisation-factors, as a means of determining rope strength, be treated only as supporting evidence to full rope break testing.
- Indicative realisation factors for HMSF.
- The effects of yarn twist levels on rope strength and fatigue life under varying operating conditions.

Safety recommendations shall in no case create a presumption of blame or liability

Marine Accident Report

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