Guidance on the use of synthetic fibre ropes for marine energy devices

Deliverable 3.5.2 from the MERiFIC Project

A report prepared as part of the MERiFIC Project
"Marine Energy in Far Peripheral and Island Communities"

Ifremer reference: RDT CSM 13-232

September 2013

Written by:
Sam Weller (S.Weller@exeter.ac.uk), University of Exeter
Peter Davies (peter.davies@ifremer.fr), IFREMER
Lars Johanning (L.Johanning@exeter.ac.uk), University of Exeter
Stephen Banfield (banfield@tensiontech.com), Tension Technology International, Ltd

france (manche channel) england interreg

European Regional Development Fund
The European Union, investing in your future

Fonds européen de développement régional
L'union Européenne investit dans votre avenir

MERiFIC was selected under the European Cross-Border Cooperation Programme INTERREG IV A France (Channel) – England, co-funded by the ERDF.

The sole responsibility for the content of this report lies with the authors. It does not represent the opinion of the European Communities. The European Commission is not responsible for any use that may be made of the information contained therein.

Executive Summary

This report is a deliverable of MERiFIC Work Package 3: *'Dynamic Behaviour of Marine Energy Devices'* involving the collaboration of IFREMER (Institut français de recherche pour l'exploitation de la mer) in France and the University of Exeter in the United Kingdom.

Although synthetic ropes have been used for the station-keeping of offshore structures for the past two decades predominantly by the oil, gas and shipping industries, there is considerable interest in their utilisation for the station-keeping of marine renewable energy (MRE) devices. Differences in application between typically small, highly responsive devices (e.g. Wave Energy Converters or WECs) and large slow-moving platforms necessitate a unique approach to mooring system design and dedicated mooring component test programs, both guided by relevant certification standards. It is the intention of this report to provide an introduction to synthetic mooring ropes in the context of previous usage in the offshore industry and also to highlight factors which should be considered for their use in MRE mooring systems.

The document begins by setting the scene to give background on the fundamental differences between previous applications of synthetic mooring ropes and MRE devices. In Section 2 a brief overview of commercially available ropes is then given. The distinct properties of synthetic materials and rope constructions are summarised with emphasis placed on issues which are likely to be relevant for MRE devices. In the absence of specific advice for this emerging industry, conventional approaches to applying safety factors to synthetic ropes are then introduced. Section 3 highlights in-service considerations relevant for the different lifecycle stages of ropes, from installation and operational procedures (such as maintenance and inspection) to decommissioning. Specific modelling approaches for synthetic ropes are then summarised in Section 4, followed by a summary in Section 5. This document is not intended to be an exhaustive account of all aspects of synthetic mooring ropes and in light of this further references are provided for the interested reader.

Contents

Introduction

The MERiFIC Project

MERiFIC is an EU project linking Cornwall and Finistère through the ERDF INTERREG IVa France (Manche) England programme. The project seeks to advance the adoption of marine energy in Cornwall and Finistère, with particular focus on the island communities of the Parc naturel marin d'Iroise and the Isles of Scilly. Project partners include Cornwall Council, University of Exeter, University of Plymouth and Cornwall Marine Network from the UK, and Conseil général du Finistère, Pôle Mer Bretagne, Technôpole Brest Iroise, IFREMER and Bretagne Développement Innovation from France.

MERiFIC was launched on 13th September at the National Maritime Museum Cornwall and runs until June 2014. During this time, the partners aim to

- Develop and share a common understanding of existing marine energy resource assessment techniques and terminology;
- Identify significant marine energy resource 'hot spots' across the common area, focussing on the island communities of the Isles of Scilly and Parc Naturel Marin d'Iroise;
- Define infrastructure issues and requirements for the deployment of marine energy technologies between island and mainland communities;
- Identify, share and implement best practice policies to encourage and support the deployment of marine renewables;
- Identify best practice case studies and opportunities for businesses across the two regions to participate in supply chains for the marine energy sector;
- Share best practices and trial new methods of stakeholder engagement, in order to secure wider understanding and acceptance of the marine renewables agenda;
- Develop and deliver a range of case studies, tool kits and resources that will assist other regions.

To facilitate this, the project is broken down into a series of work packages:

WP1: Project Preparation
WP2: Project Management
WP3: Technology Support
WP4: Policy Issues
WP5: Sustainable Economic Development
WP6: Stakeholder Engagement
WP7: Communication and Dissemination

Disclaimer:

It is the intention of this document to provide introductory guidance for the use of synthetic mooring ropes for marine renewable energy (MRE) applications. Readers are actively encouraged to also seek guidance from certification agencies before embarking on the specification of mooring components and the design of mooring systems. The authors of this document cannot be held liable for any damage, loss or injury resulting from use of these guidelines.

Related documentation:

As a result of the MERiFIC WP3.5 study *Dynamic behaviours of marine energy devices* the following documents have either been produced or are in preparation:

Conference and journal publications	MERiFIC deliverables
Weller SD, Davies P, Thies PR, Harnois V, Johanning L. (2012) Durability of synthetic mooring lines for ocean energy devices, Proceedings of the 4th International Conference on Ocean Energy, Dublin, Ireland	D3.4.2: Cross border laboratory and field test procedures
Thies PR, Johanning L, Gordelier T, Vickers A, Weller S. (2013) Physical component testing to simulate dynamic marine load conditions, Nantes, France, 9th - 14th Jun 2013, Proc. of 32nd ASME Int. Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes, France.	D3.5.1: Testing of synthetic fibre ropes
Weller S.D., Davies P. and Johanning L. (2013) The Influence of Load History on Synthetic Rope Response. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark	D3.5.2: Guidance on the use of synthetic ropes for marine energy devices
Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. Synthetic Rope Responses in the Context of Load History: Operational Performance. *Submitted to Ocean Engineering*	D3.5.3: Best practice report - mooring of floating marine renewable energy devices
Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. Synthetic Rope Responses in the Context of Load History: Conditioned Performance. *In preparation*	
Harnois, V., Weller, S., Le Boulluec, M., Davies, P., Le Roux, D., Soule, V. and Johanning, L. Experimental and Numerical Investigation of a Small-scale Mooring Test Facility model. *In preparation*	

1 Background

Over the last two decades synthetic fibre mooring ropes have been utilised by the oil and gas industry for the station keeping of offshore equipment and platforms. The shift away from conventional technologies (i.e. chains and wire ropes) has been driven by the need to specify economical mooring systems that are sufficiently robust to withstand mooring loads of equipment moored in deep and ultra-deep water locations. Compared to existing mooring components, synthetic ropes have particular advantages, including low cost and mass (per unit length) and load-extension properties that can be harnessed to reduce peak loadings [1]. Their adoption is also driven by examples of fatigue failure and wear of steel components [2]. Extensive operational experience has been acquired from the application of these materials for subsea mooring components and hawsers in a wide range of environments across the globe. This coupled with laboratory test programmes to determine the operational and fatigue performance of components has shaped offshore guidelines such as those produced by the Det Norske Veritas (DNV-OS-E301 and DNV-OS-E303 [3,4]), Bureau Veritas (NI432DTOR01E [5]), American Bureau of Shipping [6], International Standards Organisation (ISO18692:2007 and ISO/TS14909:2012 [7,8]) and American Petroleum Institute (APIRP2SM [9]).

Based on the accumulated knowledge of an established offshore rope industry, marine renewable energy (MRE) device developers are keen to utilise the inherent properties of synthetic ropes for the mooring systems of their devices. Unfortunately it is not a straightforward matter to apply existing offshore guidelines or practices to this emerging industry due to fundamental differences, such as those listed in Table 1. This disparity is the subject of on-going work within the MERiFIC 3.5 work package *Dynamic behaviours of marine energy devices*[1] [10-12]. One caveat to this generalisation is that similarities will exist for MRE devices which are based on large floating platforms (i.e. semi-submersible, tension leg platform: TLP or spar floater geometries) for floating wind turbines and multi-purpose projects.

Whilst the design of a floating MRE device will depend on the mode of operation[2], in general devices which are small compared to the incident wave length will dynamically respond to first-order and second-order (low frequency) wave loading as well as the combined effects of wind and currents. The loads experienced by an MRE mooring system will therefore be heavily influenced by the motions of the device to the extent that the response of the mooring system and device are closely coupled [14-16]. Conversely the mooring system of a large floating platform will have the primary function of station keeping whilst allowing low frequency motions (within permissible, small amplitude limits). Hence although a degree of commonality exists between the two areas of application (i.e. mooring system types), the loads experienced by the mooring system will clearly differ, necessitating a new approach to MRE mooring system design and analysis.

[1] Highlighted in MERiFIC deliverable *D3.5.1: Testing of synthetic fibre ropes*

[2] For example wave energy converters (WECs) are typically classified using terms such as *point absorber*, *attenuator* and *terminator* [13]

	Existing offshore equipment	MRE devices
Water depth	Deep and ultra-deep *Semi-submersible* (60m to 3km) *Spar platform* (down to 2.4km, e.g. Perdido platform in the Gulf of Mexico)	Near-shore, intermediate and deep *Pelamis* (greater than 50m) *AWS-III Wave Swing* (around 100m) *WinFlo* (greater than 40m)
Design natural period	Less than 4s or greater than 20s (avoiding first-order wave periods)	Wave Energy Converters (WECs) tuned to first-order wave periods Platforms supporting MRE devices are designed with a similar approach to existing equipment
Mooring system footprint	Large[3] *Catenary system* (e.g. 2.8km radius in 1.2km water depth) *Taut moored system* (e.g. 1.7km radius in 1.2km water depth)	Relatively small due to water depth (e.g. a catenary system may have a 75m radius footprint in 30m water depth)
Number of mooring lines	Many (e.g. 16 may be used for catenary or taut-moored systems)	Typically 3-4, although single point moorings have also been proposed
Synthetic rope material of choice	Polyester[4]	Polyester and Nylon (to-date)

Table 1: Discernible differences and similarities between existing offshore equipment and marine renewable energy (MRE) devices in the context of mooring systems.

[3] Examples from *Final Report and Recommendations to the 22nd ITTC Committee on Deep Water Mooring 1999.*

[4] Nylon, HMPE, Aramid and hybrid constructions have also been utilised, but polyester ropes are the most widely used.

2 Design, Analysis and Usage Considerations

2.1 Synthetic Ropes as Mooring Components

A catenary system is the most likely choice for the station keeping of small buoy-like MRE equipment (Figure 1). Synthetic ropes tend to be used for the mid or upper sections (i.e. from the fairlead). These materials are usually buoyant in water, therefore in order to provide sufficient horizontal and vertical restoring forces at the fairlead(s), chains are used for the lower sections which are connected to anchors. Utilising chains for the lower mooring line sections also prevents the synthetic rope(s) from coming into contact with the seabed, which would over time result in wear through abrasion.

A taut moored system differs from a catenary system in that the restoring forces are a result of axial stretching rather than geometric changes of the complete mooring system. This type of system, which comprises one or more synthetic ropes, may be used to moor a stable platform in locations with small tidal ranges (e.g. a floating platform to support tidal energy devices). Alternatively synthetic ropes can be used to provide a compliant link between the power take-off unit and buoy of a WEC (i.e. the Carnegie Wave Energy's *CETO* device[5]).

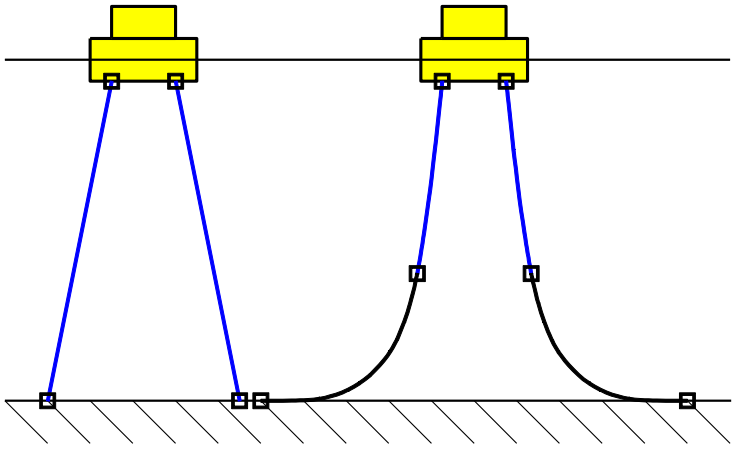

Figure 1: Schematic of (*left*) taut-moored and (*right*) catenary mooring systems showing possible MRE device mooring arrangements comprising synthetic ropes and chains (blue and black lines respectively)

Other mooring geometry layouts, including the use of auxiliary buoys, or interconnected systems for arrays of devices are possible. Further guidance on the design and analysis of mooring systems can be found in the MERiFIC deliverable *D3.5.3 Best practice report - mooring of floating marine renewable energy devices.*

[5] http://www.carnegiewave.com/ (accessed online: 09/09/2013).

2.2 Materials and Constructions

Ropes used in the offshore environment can be made from a wide range of natural and synthetic organic fibres, with materials such as cotton, flax, hemp and sisal used since the early days of sail. The focus of this document is on commercially available rope materials which are likely to be adopted by MRE developers based on their usage in the offshore industry. Materials which are used commercially include:

- Nylon (Polyamide or PA)
- Polyester (PET)
- Polypropylene (PP)
- High-modulus, high-tenacity fibres (i.e. Aramid)
- Liquid crystal polymers (LCPs)
- Hybrid materials
- Polyolefins (i.e. HMPE or HPPE)

Material	Density (g/cm^3)	Melting /charring point (°C)	Moisture (%)[6]	Modulus (N/tex, GPa)	Tenacity (mN/tex)	Strength (MPa)	Break extension (%)
Hemp	1.5	~150	8	21.7, 32.6	470	705	1.8
Steel	7.85	1600	0	20, 160	330	2600	2[9]
HMPE	0.97	150	0	100, 100	3500	3400	3.5
Aramid	1.45	500	1-7	60, 90	2000	2900	3.5
PET	1.38	258	<1	11, 15	820	1130	12
PP	0.91	165	0	7, 6	620	560	20
PA6[7]	1.14	218	5	7[6], 8[8]	840[6]	960	20

Table 2: Selected properties of several synthetic fibre materials (values from [17]). Steel and the natural fibre hemp are included for reference

For comparative purposes, material properties are listed in Table 2 and of this list, particular materials are more likely to be used for MRE mooring systems. Nylon and polyester are the most commonly used rope materials for applications which require moderately high strength and ductility. Polypropylene has similar elasticity to these materials but poor cyclic loading characteristics and can be affected by changes in temperature. Natural fibres such as flax and hemp possess similar strengths to nylon and polyester but synthetic materials are favoured as their performance is more predictable in demanding applications including the effects of weathering [17]. Materials such as high modulus polyethylene (HMPE), high performance polyethylene (HPPE), liquid crystal polymer (LCP) and aramid have considerably higher breaking strengths which are comparable to steel and are stiffer than nylon and polyester. The combined high strength and low mass of these materials makes

[6] At 65% rh and 20°C.

[7] PA6.6 has a higher melting point (258°C) than PA6.

[8] The modulus and strength of nylon is approximately 15% lower when wet [17].

[9] Yield point of steel.

them an attractive choice for taut-moored applications as an alternative for steel wires [18]. The combination of several polymers (i.e. through copolymerisation or co-extrusion) to obtain desirable performance characteristics has received some attention, such as the combined extrusion of polypropylene and polyethylene, or polypropylene and polyester melt mixes, but few commercially available examples exist.

Due to their favourable properties and previous use in offshore applications nylon and polyester are two materials which are likely to be used for MRE mooring ropes. The properties of these materials depend on the behaviour of molecule bonds which vary when subjected to heat (and humidity in the case of nylon). In typical offshore operating conditions the flexibility of nylon is provided by free rotation of carbon bonds in amorphous regions of the structure. Saturation of the rope will result in increased mobility of hydrogen bonds in the amorphous regions, leading to a reliance on the crystallite regions for structural integrity. Although nylon has good temperature and abrasion resistance when dry, both these characteristics reduce once saturated (i.e. there is typically a 15% strength reduction when wet [17]). Comparatively the structure (and hence strength) of polyester is unaffected by water ingress unless at elevated temperatures, (i.e. similarly to nylon the crystallite structures begin to melt above 260°C [17]). Whilst in offshore applications ambient temperatures of this magnitude are unlikely (unless the rope is in close proximity with an extreme heat source), localised internal temperature rises are possible due to hysteresis heating.

Material	Ductility	Strength (Wet/Dry)	Resistance				
			UV	Temperature	Abrasion[10]	Creep	Tension/compression fatigue
HMPE							
Aramid							
PET							
PP							
PA6							
LCP							

Table 3: Indicative properties of several synthetic rope materials[11], classified by colour as poor, average and good. Actual performance will depend on the rope construction and application.

The basic elements of a rope are shown in Figure 2. Most ropes have a hierarchal construction comprising repeating assemblies, sub-assemblies and elements. In the case of the nylon rope shown in Figure 2, the parallel-stranded construction comprises 7x subropes each comprising 3x strands. Each strand is made up of 8x rope yarns and each rope yarn is made up of several hundred spun nylon fibres or filaments. Fibres are therefore the smallest element used in ropes, each of which can range in diameter from 10 to 50µm for multi-filament yarns or 0.2 to 0.5mm for monofilament yarns [17]. All of the hierarchal levels are

[10] Nylon has good abrasion resistance when dry but poor resistance when wet.

[11] Indicative properties from [1,17] and author experience.

assembled with a helical twist or braid angle. Laid and braided constructions with high twist angles are suited for general purpose use, with plaited and single braid constructions typically comprising 8x to 12x strands (Figure 3). These and double braided constructions are commonly used for mooring applications since they do not twist when loaded and are straightforward to splice. Low helical angle ropes tend to be used for high load applications which comprise multiple sub-ropes or braided assemblies inside a protective braided jacket. Parallel yarn or filament constructions have also been manufactured which are torque balanced to minimise twisting during loading. Hybrid rope constructions can be divided into two categories:

- *Hybrid construction techniques,* e.g. a braid-on-braid outer with parallel subrope core, or differing lay lengths throughout the structure
- *Mixed material constructions,* which have a similar purpose to co-extruded or copolymerised constructions but the rope elements are made from different materials (i.e. fibres or yarns)

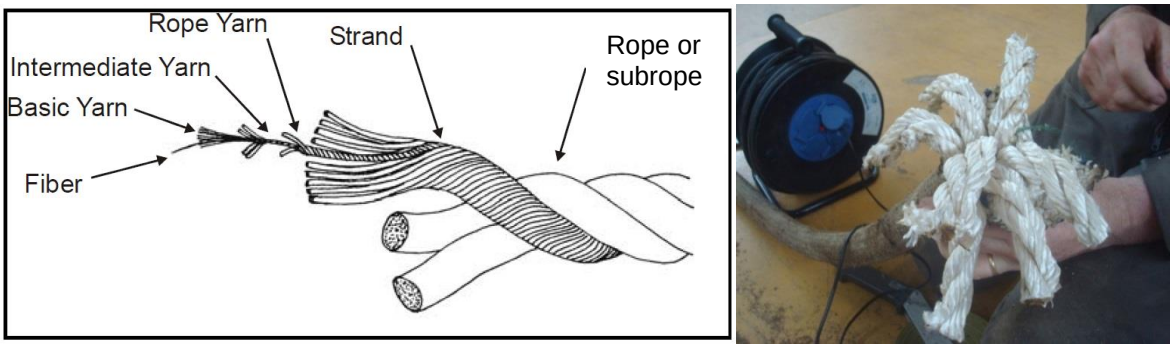

Figure 2: (*left*) Typical rope construction hierarchy (image adapted from [19]) and (*right*) Nylon parallel-stranded rope used in MERiFIC WP3.5

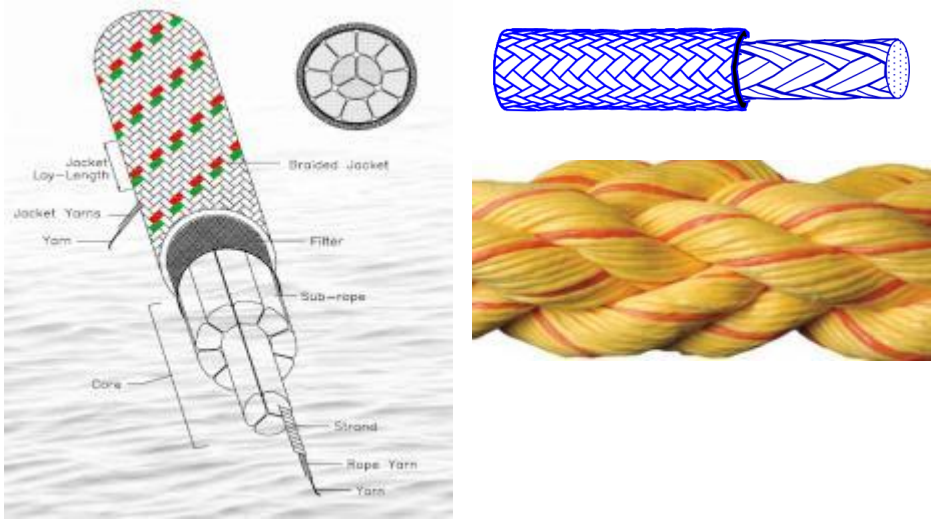

Figure 3: Examples of rope constructions; (*left*) schematic of Lankhorst GAMA 98® deep water rope with multiple subropes and outer jacket, (*top right*) schematic of Bexco double-braid rope with outer jacket and (*bottom right*) Lankhorst TIPTO®EIGHT 8-strand plaited rope[12]

[12] Images from Lankhorst and Bexco product literature (accessed online: 10/09/2013).

2.3 End Terminations

The ends of ropes are usually terminated with eye splices, providing an attachment point for shackles and other hardware. Although many ropes have a protective jacket (such as the one studied in the MERiFIC WP3.5), an additional sheath made from hard-wearing material (Figure 4) or a metal eye provides extra protection against wear from connecting hardware. In the case of nylon ropes, direct contact between steel components and load-bearing fibres would not be advisable due to the possibility of material degradation occurring from abrasion and rust contamination. Splicing is usually carried out by the rope manufacturer to specified eye-to-eye rope lengths. The process is highly skilled because the splice must be made such that the applied load is distributed evenly to each of the load bearing components of the rope.

2.4 Properties

A brief overview of rope properties is included in this section and for more detailed insight the reader is referred to more comprehensive texts such as the *Handbook of Fibre Rope Technology* [17]. Further information regarding synthetic rope testing procedures, relevant guidelines and test facilities can be found in the MERiFIC deliverable *D3.5.1 Testing of synthetic fibre ropes.*

2.4.1 Mass and Cost

Synthetic ropes have a very low density in comparison to steel mooring components (Table 2). Due to their low mass per unit length mooring ropes are usually partially buoyant[13] in sea and fresh water even after saturation and are therefore considerably easier to handle than steel components. Assuming that a rope with equivalent strength characteristics can be found for the application, the direct replacement of chain sections with synthetic ropes will result in lower pre-tensions at the device fairleads. It is therefore possible that the use of synthetic ropes can therefore reduce the load bearing requirements of the moored structure.

One key advantage of synthetic fibre ropes over chains and wires is their relatively low cost. Ridge et al. in [1] carried out comparative cost and mass analysis of several single-line catenary and taut-moored arrangements including several different anchor configurations. The comparison highlighted the advantages in using lightweight, but durable mooring components to replace conventional mooring chains. For example, the ability of nylon to reduce peak loadings would allow smaller gauge mooring chain to be used in anchor-chain-surface buoy-rope-device configurations. The study notes that by adopting this design the overall mass of this system could be to be reduced by 88kg/m and the cost by over £90K per mooring line. These reductions would partly be attributable to the specification of lower capacity components, such as anchors. Clearly in practice the feasibility of using a particular mooring system and actual cost savings that are achieved will depend on the case in question. However, cost savings are potentially scalable to multiple devices in array or ‘farm’ layouts.

[13] Of the main materials used, nylon is negatively buoyant, whereas polyethylene and polypropylene are positively buoyant.

2.4.2 Breaking Strength

Breaking strength is defined as the ability to withstand increased loading until a sufficient number of fibres have been damaged that total failure of the rope will occur with continued loading. The load at which this occurs is often quoted by rope manufacturers as the minimum break load (MBL) and will depend not only on the applied load rate but also the condition of the rope. In terms of strength, the rope that is selected will depend on the expected extreme loads of the mooring system and required safety factor (see Section 2.5). The DNV-OS-E301 *Position Mooring* guidelines [3] define the strength (S_c) of steel wire, chain and synthetic components based on the mean value of breaking strength (μ_s) and the coefficient of variation of breaking strength (δ_s):

$$S_c = \mu_s[1 - \delta_s(2 - 6\delta_s)]$$

With δ_s typically less than 0.10. When μ_s and δ_s have been quantified from a component testing program, the statistical uncertainty of obtained values depends on the number of tests (n) performed. In this instance, a modified value of component strength is calculated:

$$S_C^* = S_c[1 - 2.0\left(\frac{\delta_s}{n}\right)]$$

The reader is directed to the DNV-OS-E301 *Position Mooring* guidelines [3] and associated literature for further information regarding testing procedures, including the MERiFIC deliverable *D3.5.1: Testing of synthetic fibre ropes.*

Figure 4: The inevitable result of a load-to-failure test of a new nylon mooring rope sample (test conducted at IFREMER as part of the MERiFIC WP3.5 study)

2.4.3 Viscoelastic and Viscoplastic Behaviour

Under constant load, synthetic materials tend to extend or creep (Figure 5). The extension of the material may be recoverable (i.e. viscoelastic behaviour) or permanent (viscoplastic) and this will depend on the applied load conditions and condition of the rope. Both creep

and recovery can either occur immediately or be delayed [19]. If a newly manufactured rope is loaded for the first time, constructional rearrangement of the rope will also result in permanent extension, which can be thought of as a ratchet. It is for this reason that tension-tension testing programmes used to determine the operational and fatigue properties of ropes typically commence with a number of creep and relaxation cycles to allow constructional rearrangement to occur enabling the rope to be tested at a known initial state. This stage is often referred to as 'bedding-in'. Even after bedding-in, the rope construction may permit extension in the form of recoverable twisting. In addition to dynamic loading, an important consideration for mooring system design and testing is the level of expected creep in-service. It is possible that non-recoverable extension of the rope will result in a significantly different mooring geometry and lower pre-tension. Unless the mooring lines are subsequently re-tensioned the station keeping abilities of the mooring system will be reduced, resulting in a potentially damaging change to the dynamics of the moored device, particularly for taut-moored systems [18]. In extreme cases creep failure may occur at loads lower than the minimum break load of the rope.

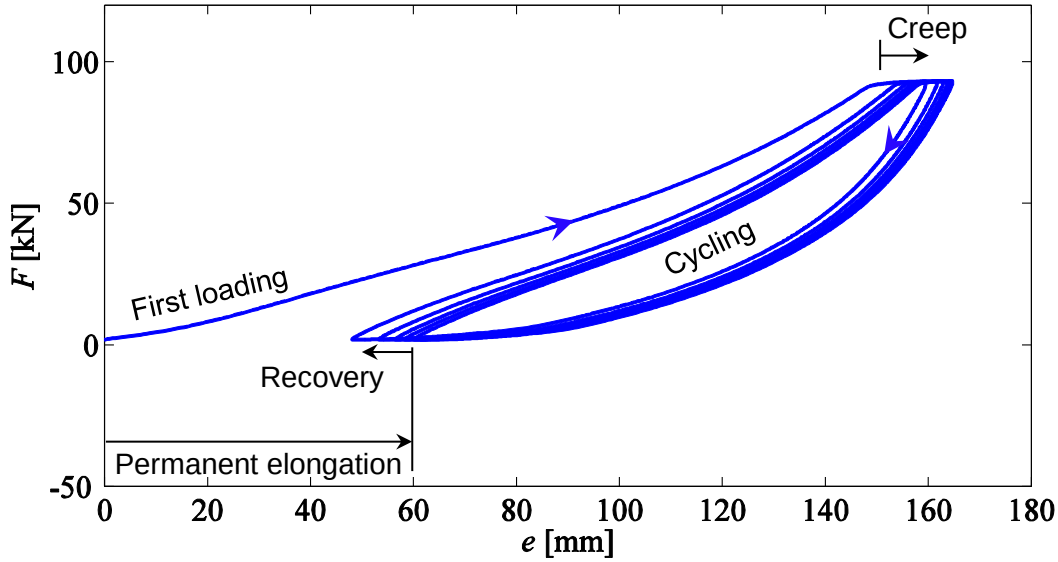

Figure 5: Load-extension behaviour of a new Nylon mooring rope sample subjected to 10 cycles of bedding-in at IFREMER (part of the MERiFIC WP3.5 study)

2.4.4 Axial Stiffness

As mentioned in the previous section the load-extension behaviour of synthetic ropes can be attributed to both material and constructional changes. The ability to absorb tensile energy and elongate to a far greater level than more rigid components (i.e. steel chains and wires) is favourable as the magnitude of peak loads will be lower than if rigid components were used. For comparative purposes, the specific stress-elongation properties of a range of synthetic rope materials are shown in Figure 6. It is clear from this graph that nylon and polyester are capable of large compliance compared to stiffer materials such as steel and aramid, with nylon fibres capable of extensions between 15-20% before failure. In assembled rope form, greater extensions may be possible due to rearrangement of the rope structure under loading. Another key point is that unlike rigid materials, such as metals which tend to display a linear load-extension relationship in their elastic phase (i.e. Hooke's

law), the viscoelastic phase of synthetic materials is highly non-linear, particularly for polyester and nylon.

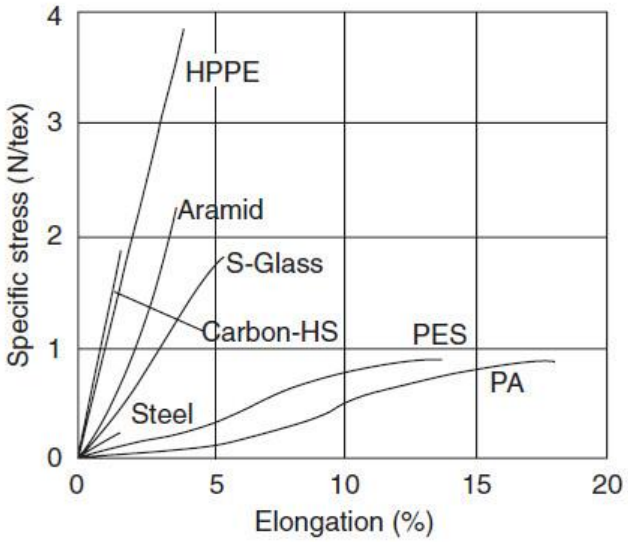

Figure 6: Specific stress-extension curves for various synthetic fibres; aramid, steel, nylon or polyamide (PA), polyester (PES), high strength carbon (Carbon-HS), high strength fibreglass (S-Glass) and gel spun high modulus polyethylene (HPPE). Note: *tex* is a measure of mass per unit length (g/km) [17]

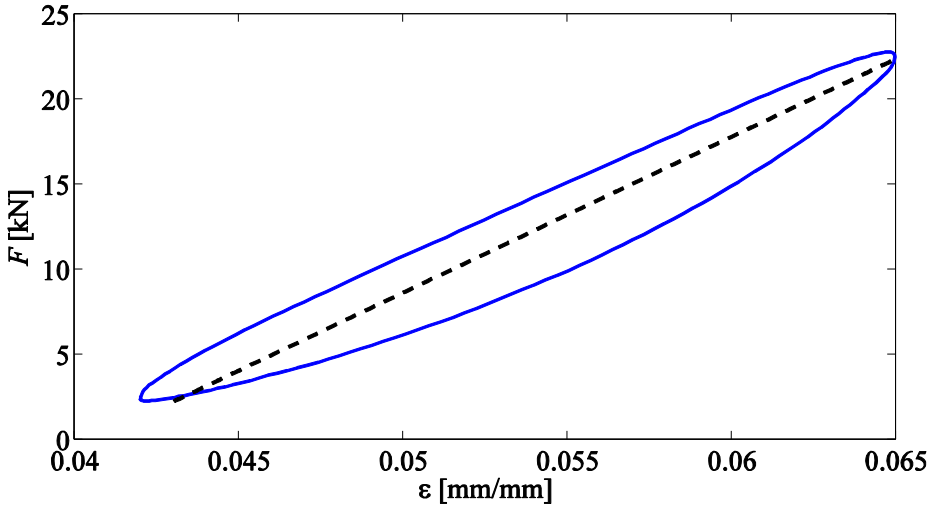

Figure 7: Load-strain response (blue line) of a new nylon rope sample subjected to harmonic loading as part of the MERiFIC WP3.5 study. A single degree-of-freedom line fitted to the response is shown as a dashed black line

Offshore guidelines dictate that the average axial stiffness of the rope (defined as *EA*, units: kN) is determined after repeated harmonic loading and calculated from the gradient of a line fitted to maximum and minimum load and strain values. An alternative approach (reported in [10]) which appears to result in closer agreement, is to fit a single degree-of-freedom trend line to measured values (e.g. Figure 7).

Note that bending stiffness is not covered in these guidelines but may be relevant for lines which are subjected to significant different motions at each end, or are routed via hawse or winches. In this case, guidelines covering bend-over-sheave testing should be consulted.

2.4.5 Axial Damping

2.4.5.1 Forced Response

Viscoelastic materials demonstrate hysteresis, where there is a delay (or phase difference) between changes to the applied load and resulting extension or recovery. This is perhaps best illustrated through considering one load-extension loop of a nylon rope sample subjected to harmonic loading (Figure 8). The energy expended during loading and unloading can be estimated from the area contained within the loop (further details can be found in [10-12]). The energy absorbed and dissipated is related to the damped response of the rope (defined as damping rate *B*, units: kNs/m), which will contribute to the overall damped response of the moored system.

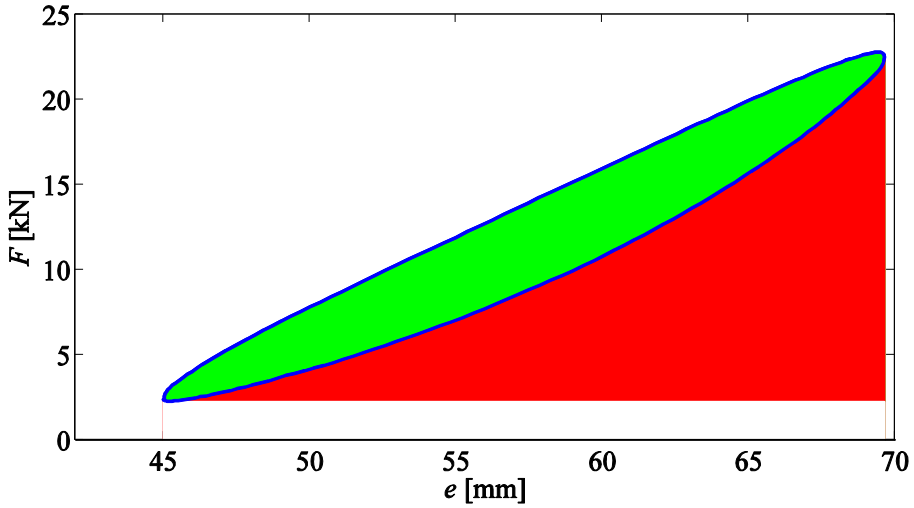

Figure 8: Load-extension response (blue line) of a new nylon rope sample subjected to harmonic loading as part of the MERiFIC WP3.5 study. The area enclosed within the hysteresis loop (green region) can be used to estimate the damped behaviour of the rope

Drag damping resulting from the motion of the line through the water not mentioned in these guidelines but information regarding aspects of numerical modelling is given in the MERiFIC deliverable *D3.5.3 Best practice report - mooring of floating marine renewable energy devices*.

2.4.5.2 Free Response

Resonant responses tend to be avoided in structural design to avoid the effects of load amplification[14]. Synthetic ropes and steel wires, particularly those used in taut-moored applications may be subjected to vortex induced vibration (VIV) and vortex induced motions

[14] Often quantified as Dynamic Amplification Factors (DAFs).

(VIM) induced by turbulence shedding in current flows. High frequency cyclic loading may have implications for the fatigue life of mooring components. Guidance is provided in the DNV-OS-E301 *Position Mooring* guideline [3] to determine the response of mooring lines using rigid body assumptions. However, because no information is provided in [3] or the DNV-OS-E303 *Offshore Fibre Ropes* guideline [4] on how to quantify the natural period of synthetic ropes, a short investigation was carried out as part of the MERiFIC WP3.5 study at IFREMER. On the basis that the free response of a rope subjected to an impulse load can be used to determine the damping behaviour of the rope, tests were conducted on an aged rope sample (Figure 9). With one end of the rope supported by an overhead crane and load cell, a 3kN mass at the lower end was used to provide a pre-tension. A small mass (10.7kg) was then dropped onto the large mass to induce a decay response which was recorded by the load cell (sample rate: 10kHz). Repeated tests indicated a natural period of approximately 0.2s[15], significantly different from the response of the crane without the rope in place (natural period: 0.07s). Assuming that the rope is oscillating in a single degree-of-freedom, the natural period and applied load can be used to approximate the spring stiffness. For the aged rope sample this was found to equal 276.8kN/m (note different units from axial stiffness: *EA*).

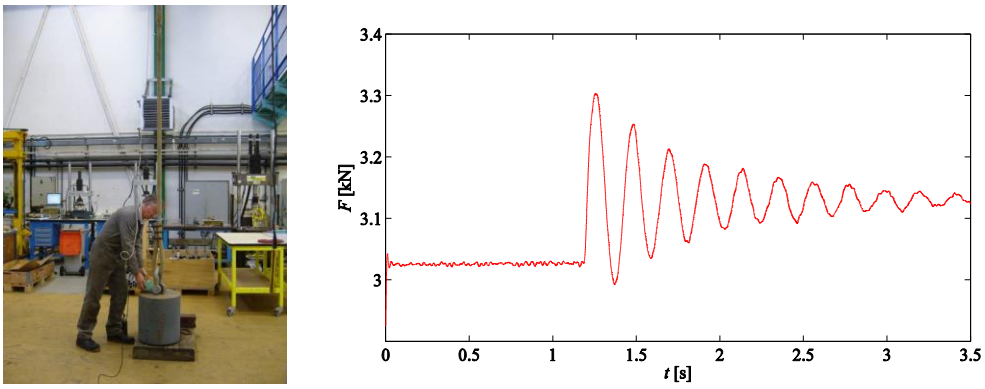

Figure 9: Axial natural period tests conducted at IFREMER as part of the MERiFIC WP3.5 study; (*left*) experimental set-up, (*right*) filtered load cell response after impulse excitation

2.4.6 Variation of Properties with Usage

2.4.6.1 Short-term Changes

If a synthetic mooring rope is subjected to many hundreds or thousands of identical harmonic load cycles then the performance of the rope will eventually reach a steady-state[16]. The standardised approach to determine the average stiffness of the rope is to use the final 5-10 cycles of steady-state response. Prior to reaching a steady-state, the response of the rope will be transient and the evolution of strain (e.g. Figure 10) is related to

[15] Natural periods and spring stiffness values were also calculated for a higher pre-tension level; 5kN (0.3s and 268.8kN/m respectively).

[16] Continued loading will eventually lead to failure through fatigue.

the changing properties of the rope[17]. The mooring system of a dynamically response MRE is unlikely to experience repeated harmonic loading unless it is in a deep water location and very long period swell waves are a common occurrence. Furthermore, steady loading around the pre-tension level of the system will only occur in calm conditions. As a direct result of the stochastic nature of ocean waves, mooring loads for dynamically response equipment tend to be highly irregular and of varying amplitude, phase and mean load (which is partially influenced by the tide). The instantaneous properties of the rope will depend not only on the applied load history, but also the level of strain achieved [10-12]. In order to accurately predict synthetic rope performance and longevity, it is therefore essential that synthetic ropes are specified in the context of loading regimes relevant to the application, rather than just relying on existing standards.

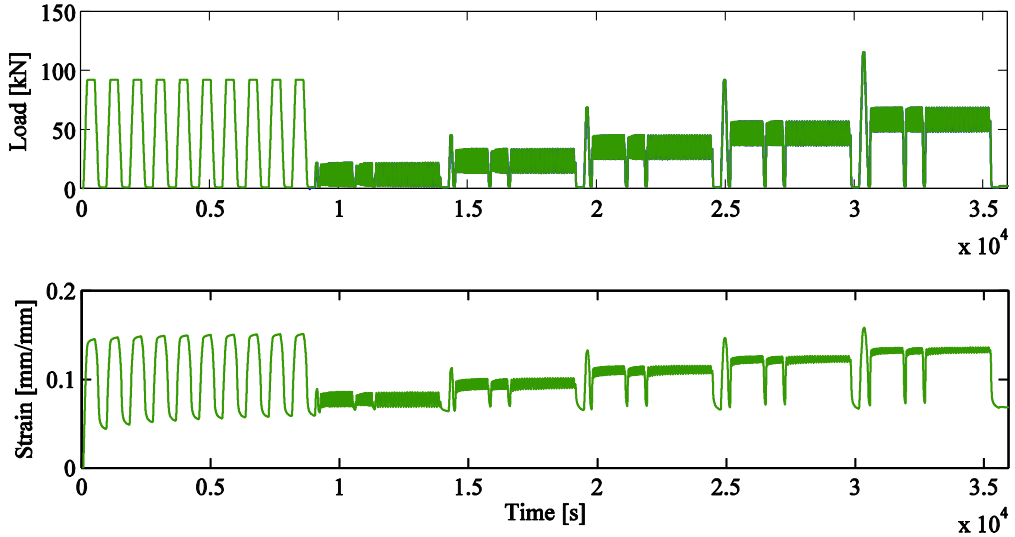

Figure 10: Time-variation of strain of a new Nylon mooring rope sample used in the MERiFIC WP3.5 study using the Dynamic Marine Component (DMaC) facility at the University of Exeter [11]

2.4.6.2 Long-term Changes

A variety of factors will affect the performance of a rope over its lifetime. Investigations conducted as part of the MERiFIC WP3.5 study have compared the performance of new and aged rope samples. The aged rope sample was extracted from a 20m mooring line used during the first 18 month deployment of the South West Mooring Test Facility (SWMTF, further details can be found in [10-12,20,21). Clear differences in performance were observed when the samples were subjected to the same load-time series comprising harmonic loading intervals as well as two irregular time-series based on mooring tensions measured by the SWMTF. Increased compliance and hence strain of the recovered SWMTF rope (Figure 11) indicate mild damage sustained during the first deployment. This damage is likely to be the result of fatigue cycling coupled with a few extreme events (i.e.

[17] For the tests conducted on nylon samples as part of this study, axial stiffness appears to increase and damping reduce with continued loading [10,11].

the last irregular interval shown in Figure 11). Scanning Electron Microscope (SEM) images of fibres support this idea, with wear recesses, caused by fibre-on-fibre friction, present in aged fibres (Figure 12).

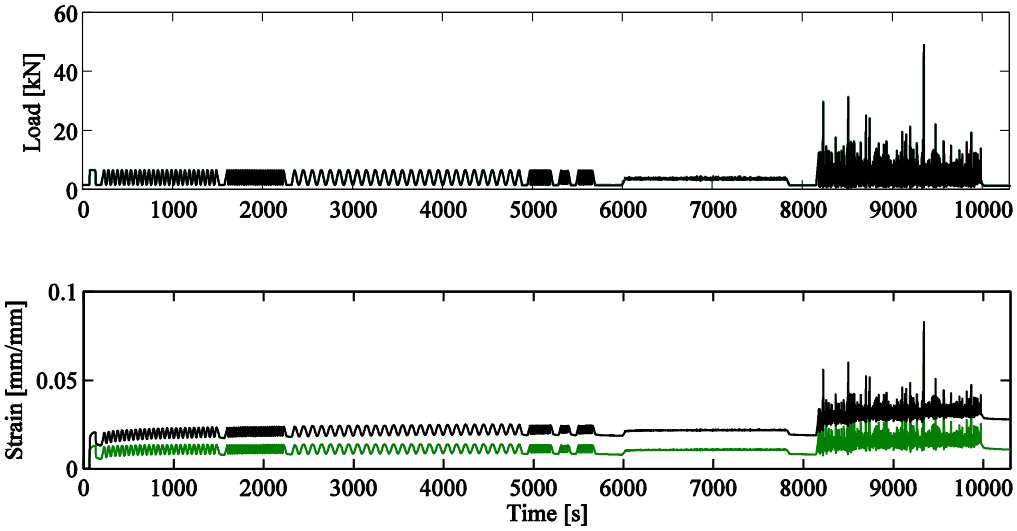

Figure 11: Time-variation of strain of a new (green) and aged (black) nylon mooring rope samples subjected to the same load time-series as part of the MERiFIC WP3.5 study [12]

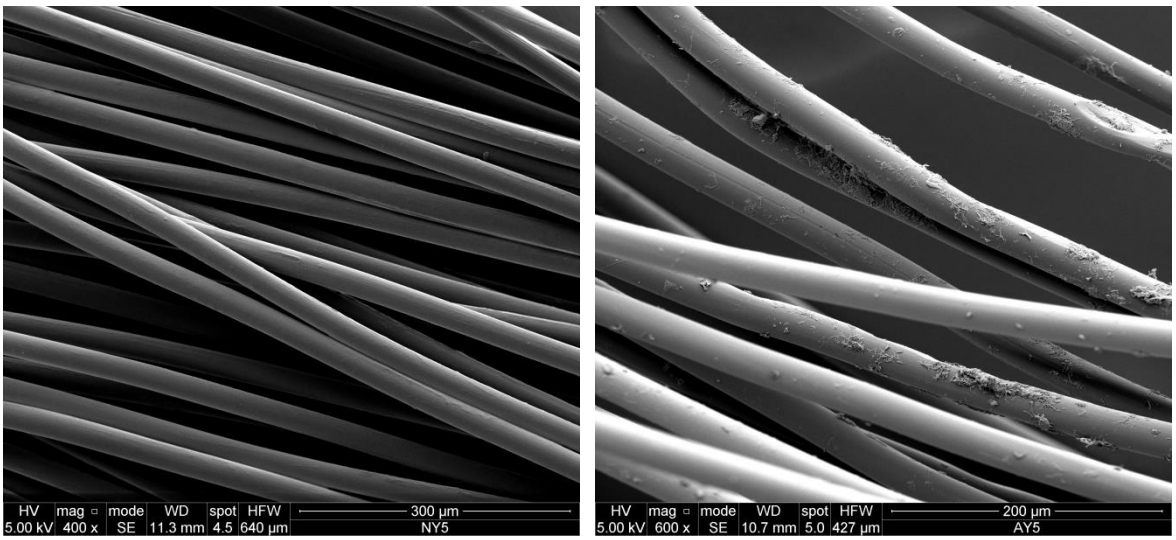

Figure 12: SEM images of (*left*) new and (*right*) aged fibres (analysis conducted at IFREMER [12])

The possibility of failure occurring through repeated, cyclic loading is particularly relevant for synthetic mooring lines operating in highly dynamic environments (i.e. WECs). Fatigue life calculations are typically based on the application of many thousands of harmonic load cycles to ropes or sub-ropes with several different load amplitudes and mean load levels, for example the Oil Companies International Marine Forum (OCIMF) Thousand cycle load level (TCLL) test procedure for single point mooring hawsers [22,23] (example loads are listed in Table 4). As the main fatigue failure mechanism is wear resulting from friction

between adjacent yarns, yarn-on-yarn cyclic tests until failure are also carried out to determine the effectiveness of friction-reducing marine finishes.

Stage	Cumulative load sequence			Equivalent high load levels
	1000 cycles at 50% NWBS	1000 cycles at 60% NWBS	1000 cycles at 70% NWBS	
1	X			251 cycles at 60%
2	X	X		215 cycles at 70%
3	X	X	X	113 cycles at 80%

Table 4: Thousand cycle load level (TCLL) test procedure (from [22]). Load levels are in respect of the average wet break strength (NWBS) of the rope

Whilst the standardised approach of fatigue calculation [3,4] may be applicable for the mooring systems of large, slow moving equipment it is clearly questionable for mooring lines subjected to loads which are highly variable in amplitude and duration. Therefore as with the pertinent need to determine the operational performance of synthetic ropes using loading regimes which are relevant to MRE devices, existing fatigue testing practices must be altered to suit this new application perhaps through the use of accelerated testing. The published work carried out to-date suggests very promising fatigue performance for certain synthetic ropes (Figure 13).

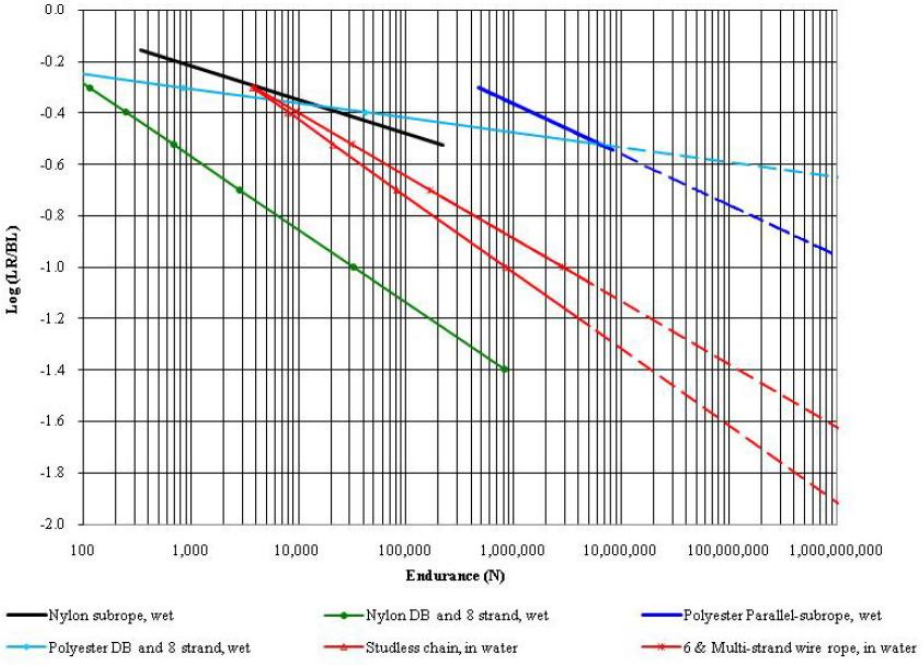

Figure 13: Fatigue results for several mooring components (from Ridge et al. [1]). Dashed lines indicate extrapolated values

The ingress of fine grit, debris or living species into the rope structure will accelerate fibre-on-fibre friction wear and this can even occur if the rope is covered in a protective jacket (Figure 14). To mitigate particulate ingress, particular rope manufacturers include filtration screens to block particles larger than 1 micron. Whilst plant-based bio-fouling is unlikely to cause damage to unjacketed synthetic fibres, a build-up of hard-shelled species such as barnacles, mussels and limpets may result in fibre cutting or abrasion.

The hysteresis response of viscoelastic materials results in heating of the rope as energy is dissipated through the structure [24]. Heat can also be generated by slip occurring between fibres. In extreme cases when the rate of heat transfer is not sufficiently high, localised melting and peeling of the fibre surfaces can occur [25], weakening the structure of the rope and providing a rough surface which will induce wear. Even moderate changes in temperature are likely to change the properties of the fibre materials at a local level [26] and clearly in the context of the energetic responses which may be experienced by MRE mooring systems this topic requires further investigation.

Figure 14: Juvenile mussel shells found on the inside of the projective jacket of the aged rope sample used for the MERiFIC WP3.5 study

Exposure of the outer surface of the rope to ultraviolet (UV) light will lead to material degradation over time, demonstrated through brittle and discoloured fibres which are weaker than their internal counterparts. Polypropylene is particularly susceptible to prolonged UV exposure. For subsea lines, the level of exposure decreases with depth. A non-load bearing protective jacket will prevent exposure as long as it remains intact. Lines which are partially submerged or subjected to continuous salt spray and soaking from waves will experience wetting and drying cycles. As mentioned in Section 2.2 the strength properties of nylon alter with both moisture content and temperature. Fatigue performance will also be influenced, as demonstrated for nylon 6.6 fibres by Kenney, M.C. et al. [27]. Salt crystals which remain after drying are likely to be an abrasive medium between contacting fibres.

Steady	Cyclic	Infrequent
Creep	Fatigue/friction	Exceedance of the MBL
UV exposure	Heating	Heating
	Wetting/drying	Compression fatigue
	UV exposure	Shock loading

Table 5: A summary of possible damage mechanisms. Further information on these mechanisms is available in the literature (e.g. [17,28])

If the motions of the device are highly dynamic then it is probable that the mooring components will experience shock or snatch loading. Rapidly changing loads may be large in amplitude, ranging from slack (i.e. close to zero tension) to peak load to low load in very short intervals. Although the compliant properties of synthetic ropes are suited to reducing the magnitude of peak loadings, it is possible that rapidly applied loads will result in permanent elongation (i.e. the ratchet analogy introduced in Section 2.4.3) and localised rapid heating which could result in damage. During low loads it is possible that fibres, yarns or strands may buckle resulting in fatigue concentrations if the hinges of the kink flex regularly. This is referred to as axial compression fatigue and the occurrence of buckling will depend on the rope construction and loading conditions. In general the fibres of stiffer materials such as aramids or HMPE will fail more readily than more compliant materials such as polyester if the buckled areas are flexed.

2.5 Safety Factors

When specifying a synthetic rope it is important that a factor of safety is specified which reflects the expected environmental and loading conditions that the rope will experience during its lifetime. In the absence of explicit guidelines, safety factors for MRE mooring equipment are currently based on existing certification guidelines which are necessarily high based on the risks associated with catastrophic failure of oil and gas exploration equipment (i.e. the mooring failure of the *Argyll Transworld 58* in 1981 [2]). The consequences of mooring component failure of a MRE device will depend on its location, proximity to other equipment or water-users, whether it is manned[18] and if redundancy has been built into the system[19]. Generally the impact of component failure will be considerably less than oil or gas exploration equipment (which may result in loss of life or environmental disaster) even if station keeping ability has been lost. The application of existing guidelines may therefore be

[18] For MRE devices this will only be the case during installation, maintenance and recovery operations which would be conducted during favourable weather windows (i.e. during calm conditions); hence the percentage of time that a device will be manned will be extremely small.

[19] Higher safety factors must be used for systems which do not have redundancy.

unnecessarily onerous and costly and a new approach is needed which reflects the fundamentally different requirements and features of MRE mooring systems[20].

At present there is a lack of specific guidance for the use of synthetic ropes with MRE devices, for example the DNV guideline DNV-OSS-213 *Certification of Tidal and Wave Energy Converters* [29] refers to the broader DNV-OS-E301 *Position Mooring* guideline [3]. Safety factors for synthetic ropes do not feature in the DNV-OS-E303 *Offshore Fibre Ropes* guideline [4], but are contained within [3]. In this document only the elements of [3] relevant to synthetic fibre ropes are reported.

In the DNV-OS-E301 *Position Mooring* guidelines safety factors are classified based on the consequence of mooring system failure; Class 1: *"Where mooring system failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking"* and Class 2: *"Where mooring system failure may well lead to unacceptable consequences of these types."* The required strength of mooring components[21] (S_c) for Ultimate Limit State (ULS) and Accident Limit State (ALS) scenarios is calculated using the following equation based on mean and dynamic loadings ($T_{c\text{-}mean}$ and $T_{c\text{-}dyn}$). Related safety factors are listed in Table 6:

$$\boldsymbol{S_c - T_{c-mean}\gamma_{mean} - T_{c-dyn}\gamma_{dyn} \geq 0}$$

When characteristic strengths are not available, S_c is determined from the minimum break strength of new components ($S_c = 0.95S_{mbs}$). The same approach is effectively taken in the recently published DNV-OS-J103: *Design of Floating Wind Turbine Structures* guideline [30] which contains further information about selecting dynamic and mean tensions based on 50 year values. In this guideline different consequence class terms are defined (*Normal* and *High*), which appear to be equivalent to Classes 1 and 2 in [3] (although it should be noted that this is not explicitly stated). It is interesting to note that whilst the ALS mean and dynamic safety factors for the floating wind turbine guidance are the same as in [3], the ULS safety factors are between values in [3] recommended for dynamic and quasi-static analysis. This may be indicative of the conservative approach being taken to floating wind turbine design at present. Separate guidance for the characteristic tensile capacity of tendons used in taut-moored applications is given in [30].

[20] For example, the requirements of a mooring system for a floating wind turbine will differ from a resonantly operating WEC, especially if multiple devices are to be deployed in array or 'farm' layouts

[21] The statistical uncertainty of strength characteristics based on test statistics has to be accounted for [3].

DNV-OS-E301 *Position Mooring*	**Mean tension factor (γ_{mean}) ULS, ALS**	**Dynamic tension factor (γ_{mean}) ULS, ALS**
• Dynamic (CC1) • Dynamic (CC2) • Quasi-static (CC1) • Quasi-static (CC2)	• 1.10, 1.00 • 1.40, 1.00 • 1.70, 1.10 • 2.50, 1.35	• 1.50, 1.10 • 2.10, 1.25 • 1.70, 1.10 • 2.50, 1.35
DNV-OS-J103 *Design of Floating Wind Turbine Structures*	**Mean tension factor (γ_{mean}) ULS, ALS**	**Dynamic tension factor (γ_{mean}) ULS, ALS**
• Normal • High	• 1.30, 1.00 • 1.50, 1.00	• 1.75, 1.10 • 2.20, 1.25
BV NR493DTR02E *Classification of Mooring Systems for Permanent Offshore Units*[22]	**Minimum safety factors (Quasi-static analysis)**	**Minimum safety factors (Dynamic analysis)**
• Intact • Damaged • Transient	• 1.75 • 1.25 • 1.25	• 1.67 • 1.25 • 1.20

NS 9415.E:2009 (fish farms)	**Material factor (γ_{mat})**	**Load factor (γ_T)**	**Combined safety factor**
• Static • Quasi-static • Dynamic	3.0	• 1.6 • 1.15DAF • 1.15	• 4.8[23] • 3.45DAF[13] • 3.45[13]

Table 6: Example safety factors applicable to synthetic ropes as specified in offshore standards. Relevant certification agencies should be consulted for up-to-date guidance

The Bureau Veritas NR 493DTR02E *Classification of Mooring Systems for Permanent Offshore Units* [31] guideline takes a different approach to specifying safety factors. Whilst separate values are also used for quasi-static and dynamic analysis, different mooring system conditions are accounted for. Ropes used for hawser applications (which may be applicable to MRE mooring systems with auxiliary surface buoys are covered by NR 494DTR02E *Rules for the Classification of Offshore Loading and Offloading Buoys* [32].

Paredes, G.M. et al. in [33] drew attention to the similarities between fish farm platforms and MRE equipment, both of which function remotely and are unmanned for long intervals. It is likely that the failure of MRE equipment will however incur higher costs due to loss of expensive equipment and incapability to generate electricity. In [33] it is reported that the

[22] Safety factors for synthetic sections of the line should be increased by 10% and 20% for polyester and nylon ropes respectively. Several other caveats to these values are included in the guidelines. For brevity they have not been included in this document.

[23] Values inferred from NS 9415.E:2009 as reported by Paredes, G. M. et al. in [33].

Norwegian NS 9415.E:2009 guidelines for fish farms use a simpler partial coefficient method which does not distinguish between mean and dynamic tensions. In the following expression material and load factors (γ_{mat} and γ_T respectively) are used in conjunction with the expected tension (T_c) and strength of the component (S):

$$\frac{\boldsymbol{S}}{\boldsymbol{\gamma_{\mathrm{mat}}}} - \boldsymbol{T_c \gamma_T} \geq \mathbf{0}$$

For synthetic materials a material factor of 3.0 is specified[24] in NS 9415.E:2009. When conducting quasi-static analysis a dynamic amplification factor (DAF) greater than one (and typically at least 1.1) is used. As mentioned in Section 2.4.6.2 the fatigue performance of synthetic ropes subjected to cyclic loading must be determined in order to accurately estimate the long-term durability of these components. In addition to the ultimate and accident limit states, the DNV-OS-E301 *Position Mooring* and DNV-OS-J103 *Design of Floating Wind Turbine Structures* guidelines [3,30] use a fatigue limit state (FLS) to calculate accumulated damage incurred through fatigue load cycling.

For synthetic ropes a slightly different approach to determining fatigue capacity is adopted. Instead of S-N (stress-number of cycles) curves, the ratio of tension range to characteristic strength (R) to number of cycles is used for tension-tension cycling:

$$\mathbf{log}(\boldsymbol{n_c}(\boldsymbol{R})) = \mathbf{log}(\boldsymbol{a_D}) - \boldsymbol{m}.\mathbf{log}(\boldsymbol{R})$$

Example gradient and intercept parameters for the R-N curve of polyester rope are given in the guidelines as a_D = 0.259 and m = 13.46. A similar approach is also adopted in the Bureau Veritas *Classification of Mooring Systems for Permanent Offshore Units* guidelines [31]. The fatigue life of other synthetic rope materials can be found in the literature, for example in Ridge et al. [1] and the American Petroleum Institute guidelines [9]. For fatigue design a single safety factor is specified in the DNV-OS-E301 *Position Mooring* guidelines [3]:

$$\mathbf{1} - \boldsymbol{d_c \gamma_F} \geq \mathbf{0}$$

Where d_c is the characteristic fatigue damage accumulated during the design life as a result of cyclic loading. A fatigue safety factor of γ_F = 60 is specified for polyester which is considerably higher than what is used for steel components (usually between 1 and 10) due to the apparent large variability of fatigue test results and the typically larger exponent (m) on the R-N curve. Lower fatigue life factors are permissible if fibre rope segments are replaced on a routine basis. Further discussion regarding offshore certification guidelines features in the MERiFIC deliverable D3.5.3 *Mooring of floating marine renewable energy devices*, including commentary on the forthcoming IEC TC114 IEC/TS 62600-10 Ed. 1.0 guidelines [34].

[24] For reference, the material factor of new chains and chain components is 2.0, increasing to 5.0 for used chains [3]

3 In-service Considerations

Estimates of synthetic rope performance and life expectancy determined from numerical modelling and physical testing are valid only if correct in-service procedures are followed. In this section several generic considerations are proposed to aid planning of installation, maintenance and decommissioning procedures.

3.1 Installation

To avoid damage during storage prior to installation, synthetic ropes should be stored in a suitable location avoiding prolonged exposure to extremes of temperature, UV light and degrading chemical agents as well as damage from auxiliary equipment. Care should be exercised during handling to minimise or avoid damage to the surface, either through cuts or abrasion. This is more of an issue with unjacketed ropes.

The installation procedure for the entire mooring system will be planned prior to the deployment date and should include contingency for unexpected events (i.e. sudden changes in weather and the failure of equipment). The installation of synthetic ropes will either be part of an entire mooring system installation or be a recovery/replacement procedure as mentioned in the next section. Due to their prior in the offshore industry, it is sensible to utilise existing installation guidelines, even if the scale of installation differs. For example, the *Floating production system JIP FPS mooring integrity* report produced by Noble Denton Europe Limited in 2006 includes practical advice on polyester rope installation [2]. Following installation it may be prudent to perform bedding-in loading on each mooring line to settle the rope structure, perhaps utilising the installation vessel. Bedding-in of the rope will clearly be more difficult to perform at sea in comparison with the laboratory environment, but will mean that the mooring lines will not have to be re-tensioned in-service (if the MRE device has this capability[25]). Additionally for mooring systems which utilise drag anchors, bedding-in could form part of the anchor embedment process. If bedding-in is not carried out during installation, then structural rearrangement of the rope may occur in-service, leading to a change in the stiffness and station keeping abilities of the mooring system [35].

3.2 Maintenance and Inspection

Access to subsea mooring lines will be considerably more difficult than for surface lines between devices and/or auxiliary buoys. Larger maintenance and detailed inspection procedures require the recovery of mooring lines onto the deck of the work boat utilising crane and winch equipment. For catenary mooring systems it may be possible to inspect the ropes without disturbing the anchors if there is sufficient slack in the mooring line and favourable tidal conditions (an example operation is illustrated in Figure 15). For a taut-

[25] Chain jacks are used on Floating Production, Storage and Offloading (FPSO) vessels. For MRE devices without chain jacks, line re-tensioning may be possible by shortening sections of chain. Alternatively, self re-tensioning may be built into the system (i.e. lazy-wave mooring configurations, see MERiFIC deliverable *D3.5.3: Best practice report - mooring of floating marine renewable energy devices*).

moored system a dive team would be required in addition to a work boat for rope recovery. Clearly large operations such as these require significant expenditure, favourable weather windows and available equipment. It is therefore sensible that such operations are combined with other maintenance procedures. A potentially lower cost alternative is the scheduling of visual inspections using divers and/or remote operated underwater vehicle (ROV) equipment. These operations will only give the condition of the rope surface and terminations (i.e. wear through abrasion, chaffing and cutting, as well as degradation due to UV exposure) and therefore internal damage may be obscured by bio-fouling during long deployments. Measures to prevent bio-fouling have been successfully tried, for example the use of polyurethane as a rope coating (Figure 16).

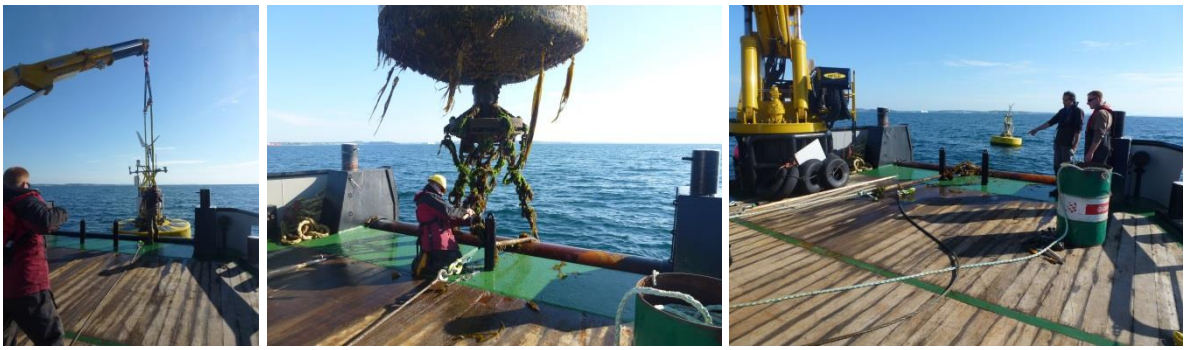

Figure 15: Example operation showing recovery of one SWMTF mooring rope using on-board crane and winch of the work boat

As yet an in-situ inspection technique to determine internal damage or the condition of terminations and splices does not exist. This is particularly an issue for jacketed ropes. Removal of the jacket to inspect the internal rope components is not advisable unless protective measures can be reinstated afterwards. Efforts have been made to gain insight into changes to the structural integrity of polyester ropes through the use of short sections of rope (or 'inserts') as part of the mooring limbs of floating platforms (e.g. [36,37]), with periodic removal (i.e. every 2.5 years) for laboratory testing. In the mid-1990s Petrobras was the first to use this technique for mobile offshore drilling units and production facilities and more recently the use of inserts has been required for particular locations (i.e. in the Gulf of Mexico [36]). However, the effectiveness of this approach to determining the condition of permanent mooring systems has been questioned [37] and it is not clear how relevant separate inserts would be for MRE mooring systems located in considerably shallower water depths. Instead, it would be more feasible for ropes to be recovered in their entirety and tested as part of an on-going monitoring program, with the data yielded used to inform the development of numerical modelling tools.

	Wear, fatigue	UV exposure	Bio-fouling	Creep	Shock-loading	Axial compression
Check	Cuts and chaffing, broken or pulled fibres may give a fuzzy appearance, rope compaction, localised melting. Damage to splices/terminations	Brittleness and discolouration of outer fibres for unjacketed ropes	Significant bio-fouling[26]	In the absence of in-situ elongation measurements a significant change in pre-tension may indicate creep	Usually not discernible from visual inspection, hence check load measurements	Bulges may appear in ropes with a tight jacket. Damaged fibres will have a kinked or 'Z'-shaped appearance or be severed.
Action	Replacement may be necessary if damage is excessive. Consider removing rope and testing in the laboratory	Sample fibres to be removed for tension-testing	Periodic removal of growth may be necessary to avoid change of system dynamics	Re-tensioning may be necessary due to change in mooring system dynamics. Excessive creep will necessitate rope replacement	Line to be replaced if tension or expected damage is excessive.	Line to be replaced if tension-tension testing indicates unacceptable strength reduction

Table 7: Example considerations for a generic inspection and maintenance program as part of condition management. Further guidance is given in [38-40]

Neither the DNV-OS-E301 nor the DNV-OS-E303 guidelines [3,4] contain a great amount of detail on inspection apart from emphasising the need for a documented condition management program. More detailed information can be found in the DNV-RP-E304 *Damage assessment of fibre ropes for offshore mooring* guideline [38]. For synthetic ropes used in MRE mooring applications, inspection and replacement intervals will depend on the material used and loading conditions experienced. The *International Guideline CI 2001-04 Fiber Rope Inspection and Retirement Criteria* [39] comprises a comprehensive summary of fatigue and damage mechanisms as well as inspection procedures. It is likely that a conservative approach will be taken initially based on reliability predictions and lifecycle

[26] The effects of bio-fouling on synthetic rope performance will depend on the rope construction, species and level of growth (the latter two of these factors are location dependent). Particular species may be invasive even for jacketed ropes (see Section 2.4.6.2). Significant growth will affect the dynamics of the system due to the increased inertia (submerged and added mass) as well as drag of the mooring line. Further work is therefore required to define the limits of bio-fouling which are acceptable in the context of MRE devices and if preventative measures should be taken (Figure 16).

analysis, the accuracy of which could be improved by the measurement of mooring loads and environmental conditions. In the absence of specific guidance, Table 7 lists particular considerations which may be applicable for synthetic mooring ropes used in MRE applications.

Figure 16: (*left*) Recovered nylon mooring rope used during the first deployment of SWMTF. Considerable bio-fouling in the form of mussel growth and kelp can be observed, (*middle*) removal of fouling using the on-board crane. (*right*) An example of bio-fouling prevention; polyurethane coated polyester riser protection net after four years of service on the Heidrun TLP.

3.3 Decommissioning

Due to the irreparable damage occurred in-service, ropes which have reached the end of their usable life must be disposed of properly. The DNV-OS-303 guidelines specify that fibre ropes should be taken out of service if loads exceeding 70% MBL have been measured [4] with more general guidance given in [39]. A similar approach is adopted for lifting equipment to avoid the possibility of accidental usage. Synthetic ropes are comparably lower in cost compared to steel components, but that should not encourage an irresponsible attitude to disposal at the end of their service life. Recycling programs such as the one launched by Lankhorst Ropes in March 2011 are part of a 'cradle-to-grave' approach to rope manufacture. Whilst the processed granulate is a sellable commodity (the Lankhorst Ropes program cites several potential applications such as landing stages, bollards, bridges and picnic sets), the reasons why this is not carried out on a wider scale by other rope manufacturers are two-fold: a) there are a large number of offshore ropes in-service which have yet to be retired and b) the recycling process is not straightforward due to issues with contamination.

4 Modelling Approaches for MRE Mooring Systems

4.1 Numerical

Numerical modelling approaches can be split into two key areas; i) synthetic rope modelling tools and ii) mooring system software.

Several approaches have been taken to model the various aspects of synthetic fibre rope performance, for example the creep of HMPE [18] and the heat build-up [24,26] and cumulative damage of polyester [40]. These studies have either been based on the development of theoretical curves utilising coefficients based on experimental measurements (e.g. [41]) or the development of complex modelling tools using viscoelastic/plastic formulae, finite element and continuum methods (e.g. [42-44]). Fibre Rope Modeller (FRM) developed by Tension Technology International (TTI) is a commercially available modelling program based on early work by Leech et al. [45]. The program uses yarn properties to predict the performance of ropes in terms of extension, torque and twist[27] by adopting a hierarchal calculation approach. The program is also capable of predicting the effects of cycling and certain damage mechanisms (i.e. creep, hysteresis, abrasion and fatigue) on long-term rope durability. Whilst FRM has primarily been used to model large mooring ropes for deep water offshore applications (e.g. [19]), the application of this program for MRE mooring systems is a recent occurrence.

There are several commercial programs which are available to carry out static, quasi-static and dynamic analysis of complete mooring systems, including (but not limited to) *Orcaflex* by Orcina[28], *Optimoor* by TTI[29] and *Deeplines* by Principia[30]. TTI have also produced an online *Rope Selection Calculator*[31] and formulae which can be used in the initial stages of mooring system design. Examples of commercially available simulation software designed specifically for MRE devices are few, (e.g. for WECs there is *WaveDyn* by GL Garrad Hassan[32]). An introduction to mooring system software is not given here, but features in the MERiFIC deliverable D3.5.3 *Best practice report - mooring of floating marine renewable energy devices*. It is mentioned in this section to highlight the current disparity between detailed synthetic rope modelling approaches and mooring system software. It is typical in the currently available mooring system software for the stiffness and damping properties of elements of the mooring line (whether they are synthetic ropes, cables or chain) to be specified by single values. Some programs allow the specification of non-linear load-strain properties, but even this does not take into account the possible change in stiffness (or

[27] For twisted rope constructions.

[28] http://www.orcina.com/SoftwareProducts/OrcaFlex/ (accessed online: 05/10/2013).

[29] http://www.tensiontech.com/software/optimoor.html (accessed online: 05/10/2013).

[30] http://www.principia.fr/expertise-fields-software-products-deeplines-126.html (accessed online: 05/10/2013).

[31] http://www.tensiontech.com/tools_guides/rope_selection_calculator.php (accessed online: 05/10/2013).

[32] http://www.gl-garradhassan.com/en/software/25900.php (accessed online: 05/10/2013).

damping) that is typical of synthetic ropes with usage and conditioning [10-12]. It is therefore important that sensitivity of the moored system to changes in both stiffness and damping is determined during the analysis stage of mooring system design.

4.2 Experimental

MRE device concepts are typically tested using reduced scale models in wave and/or current flumes, with the selected model scale governed by scaling criterion and the physical dimensions of available facilities. A Froude scaling regime is usually adopted for the representative dimensional and dynamic quantities of components and assemblies. For small-scale modelling of mooring cables and chains, the two most important criteria to satisfy are the correct submerged mass and geometry of each mooring system element in order for the inertia and drag of the line to be representative. Single or multiple axial springs are often used to achieve the correct axial stiffness[33] of the mooring line [46]. It is possible that the non-linear axial stiffness of a synthetic mooring line can be achieved using multiple springs, however a more prudent approach may be to use the same material from which the rope is constructed to also give a more accurate representation of material damping. As far as the authors are aware this approach has only been attempted twice, once to represent polyester mooring ropes [47] and once as part of this MERiFIC work package for nylon mooring ropes. In the MERiFIC study, 1:5 scale model tests of the SWMTF were conducted in IFREMER's salt water wave basin with small-scale representations of new and bio-fouled lines comprising nylon rope yarns (Figure 17, further details can be found in [48]). Previous tension-tension tests on the nylon yarns indicated that they gave a good representation of the full-scale rope axial stiffness through Froude scaling. The results of this experimental study will feature in a forthcoming publication [49] which will include comparison to simulations carried out using *Orcaflex*.

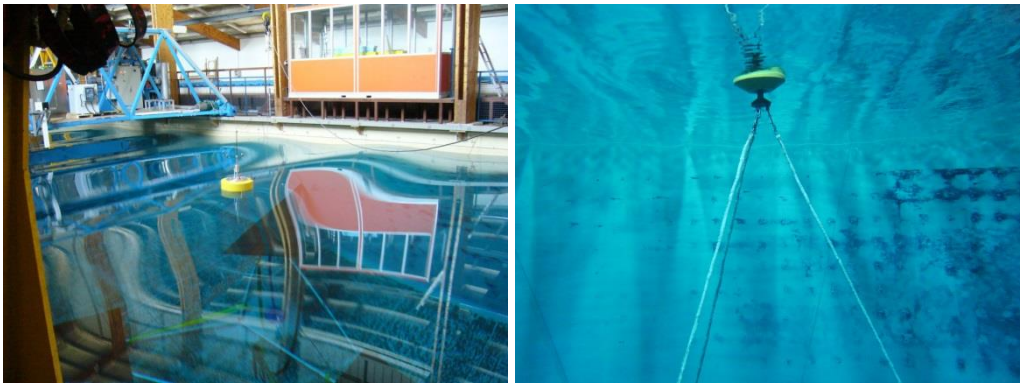

Figure 17: (*left*) 1:5 scale model of the SWMTF tested in the salt water basin at IFREMER, (*right*) underwater view of small-scale lines with representative bio-fouling [48].

[33] Bending stiffness will need to be considered for umbilical cables and may also need to be considered for MRE devices undergoing highly dynamic motions

5 Summary

It has been the intention of this document to give background information on synthetic fibre ropes which may be used for MRE mooring system design. Whilst the short and long-term performance of these materials is more complex than conventional ferrous materials used in mooring applications, there are distinct advantages to using synthetic ropes instead of steel components including low cost, low mass and an inherent ability to absorb energy. It is possible that they are an enabling technology in the design of economic mooring systems. Although used in a wide range of offshore applications for the past two decades, this new application has unique challenges and detailed investigations will be required before widespread adoption and certification can be achieved.

At the time of writing (October 2013) guidelines which are relevant to synthetic mooring ropes for MRE devices have yet to be published by the main offshore certification agencies. Instead device developers must use existing guidelines which were written for other offshore applications and hence the relevance of such information is at least questionable, if not inappropriate. Due to the relatively recent application of synthetic ropes for MRE devices, there are a number of uncertainties about the performance and reliability of these ropes operating in conditions which (of the few examples which have been deployed to-date) are highly specific to the application. It is perhaps unsurprising that the current approach is very conservative; using large factors of safety and specifying standard rope materials and constructions.

Figure 18: MRE device examples which utilise synthetic mooring ropes; (*from left*) *WinFlo* concept (source: WinFlo), *CETO* wave energy device (source: Carnegie Wave Energy) and *CORES* oscillating water column [50]. Images accessed online: 21/09/2013

Over time more devices will be deployed and a greater insight will be gained into the durability of synthetic ropes in this new application, with mooring loads measured in-service used to inform laboratory test programmes as well as reliability and lifecycle analysis. As confidence is increased more suitable factors of safety can be applied to MRE mooring components, which can take into account the distinct differences between unmanned MRE equipment and safety critical equipment used in other offshore applications (i.e. by the oil and gas industry). It is encouraging that there are already several examples of MRE devices which have used (i.e. in sea-trials) or are planning to use synthetic fibre ropes, such as *WinFlo*, *CETO* and the *CORES* project (Figure 18).

6 References

[1] Ridge, I.M.L., Banfield, S.J. and Mackay, J. (2010). Nylon Fibre Rope Moorings for Wave Energy Converters. In Proceedings of the OCEANS 2010 conference, Seattle, USA

[2] Noble Denton Europe Limited (2006) Floating production system JIP FPS mooring integrity. Research Report 444 prepared for the Health & Safety Executive

[3] Det Norske Veritas (2010). DNV-OS-E301: Position Mooring

[4] Det Norske Veritas (2013). DNV-OS-E303: Offshore Fibre Ropes

[5] Bureau Veritas, (2007). Certification of fibre ropes for deepwater offshore services. 2nd edition. NI 432 DTO R01E

[6] American Bureau of Shipping (1999) Guidance notes on the application of synthetic ropes for offshore mooring

[7] International Standards Organisation (2007) Fibre ropes for offshore stationkeeping: Polyester. ISO18692:2007

[8] International Standards Organisation (2012) Fibre ropes for offshore stationkeeping: High modulus polyethylene (HMPE). ISO/TS14909:2012

[9] American Petroleum Institute (2001) API RP 2SM: Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring

[10] Weller S.D., Davies P. and Johanning L. (2013) The Influence of Load History on Synthetic Rope Response. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark

[11] Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. (TBD) Synthetic Rope Responses in the Context of Load History: Operational Performance. *Submitted to Ocean Engineering*

[12] Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. (TBD) Synthetic Rope Responses in the Context of Load History: Conditioned Performance. *In preparation*

[13] Harris, R.E., Johanning, L. and Wolfram, J. (2004) Mooring systems for wave energy converters: A review of design issues and choices. 3rd International Conference on Marine Renewable Energy, Blyth, UK

[14] Johanning, L. and Smith, G.H. and Wolfram, J. (2007) Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. Ocean Engineering (2007), 1918-1934

[15] Fitzgerald, J. and Bergdahl, L. (2008) Including moorings in the assessment of a generic offshore wave energy converter: A frequency domain approach. Marine Structures, 23-46

[16] Cerveira, F., Fonseca, N. and Pascoal, R. (2013) Mooring System Influence on the Efficiency of Wave Energy Converters. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark

[17] McKenna, H.A., Hearle, J.W.S. and O'Hear, N. (2004) Handbook of Fibre Rope Technology. Woodhead Publishing Limited

[18] da Costa Mattos, H.S. and Chimisso, F.E.G. (2010) Modelling creep tests in HMPE fibres used in ultra-deep-sea mooring ropes. International Journal of Solids and Structures 48 (2011) 144–152

[19] Flory, J.F., Banfield, S.J. and Petruska, D.J. (2004) Defining, Measuring, and Calculating the Properties of Fibre Rope Deepwater Mooring Lines. Proceedings of the 2004 Offshore Technology Conference, Houston, USA. OTC 16151

[20] Weller, S. Davies, P. Thies, P.R., Harnois, V. and Johanning, L. (2012) Durability of synthetic mooring lines for ocean energy devices. Proceedings of the 4th ICOE, Dublin, Ireland

[21] Johanning, L. Thies, P. and Smith, G. (2010) Component test facilities for marine renewable energy converters. Proceedings of the Marine Renewable and Offshore Wind Energy Conference, London, UK

[22] OCIMF (2000) Oil Companies International Marine Forum) Guidelines for the purchasing and testing of SPM hawsers

[23] Flory, J.F. (2000) The revised OCIMF SPM hawser guidelines. Proceedings of OCEANS 2000 MTS/IEEE Conference, Providence, USA

[24] Bosman, R.L.M. (1996) On the Origin of Heat Build-up in Polyester Ropes. Proceedings of the 1996 MTS/IEEE Oceans Conference. Fort Lauderdale, USA. 332-338

[25] Flory, J.F., Leech, C.M., Banfield, S.J. and Petruska, D.J. (2005) Computer Model to Predict Long-Term Performance of Fiber Rope Mooring Lines. Proceedings of the 2005 Offshore Technology Conference, Houston, USA. OTC17592

[26] Overington, M.S. and Leech, C.M. (1997) Modelling Heat Buildup In Large Polyester Ropes. International Journal of Offshore and Polar Engineering 7, 1, March 1997

[27] Kenney, M.C., Mandell, F.J. and McGarry, F.J. (1985) The effects of salt water and concentrated salt solutions on the fatigue of nylon 6,6 fibres. Journal of Materials Science 20 (1985), 2060-2070

[28] Backer, S., McGarry, F.J. and Williams, J.H. (1981) Deterioration of Synthetic Fiber Rope During Service. Report A131684

[29] Det Norske Veritas (2012). DNV-OSS-213: Certification of Tidal and Wave Energy Converters

[30] Det Norske Veritas (2013). DNV-OS-J103: Design of Floating Wind Turbine Structures

[31] Bureau Veritas (2012) Classification of Mooring Systems for Permanent Offshore Units. NR 493DTR02E

[32] Bureau Veritas (2006) Rules for the Classification of Offshore Loading and Offloading Buoys NR 494DTR02E

[33] Paredes, G. M., Bergdahl, L., Palm, J., Eskilsson, C. and Pinto, F.T. (2013) Station keeping design for floating wave energy devices compared to offshore oil and gas platforms. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark

[34] IEC/TS (2013) Marine energy - Wave, tidal and other water current converters - Part 10: The assessment of mooring system for marine energy converters (MECs). IEC/TS 62600-10 Ed. 1.0 *In preparation*

[35] Foulhoux, L., Pennec, S., Damy, G. and Davies, P. (1999) Testing of a large diameter polyester rope offshore west Africa. Proceedings of the International Offshore and Polar Engineering Conference, Brest, France

[36] Otten, J.D. and Leite, S. (2013) Thunder Hawk Mooring Rope Particle Ingress, Break, and Fatigue Testing. Proceedings of the 2013 Offshore Technology Conference, Houston, USA. OTC24080

[37] Tension Technology International & Stress Engineering Services (2004) Effective Use of Inserts in a Mooring Line Rope Integrity Management System “INSERT JIP”

[38] Det Norske Veritas (2005). DNV-RP-E304: Damage Assessment of Fibre Ropes for Offshore Mooring

[39] Cordage Institute (2001) International Guideline CI 2001-04 Fiber Rope Inspection and Retirement Criteria Guidelines to Enhance Durability and the Safer Use of Rope. CI 2001-04 First Edition

[40] Steckel, M.G. (1984) Tensile fatigue behaviour of polyester yarns in ambient and sea water environments. MS thesis, Massachusetts Institute of Technology

[41] François, M., Davies, P., Grosjean, F., Legerstee, F. (2010) Modelling of fibre rope load-elongation properties - Polyester and other fibres. Proceedings of the 2010 Offshore Technology Conference, Houston, USA. OTC 20846

[42] Chailleux, E., Davies, P. (2003) Modelling the Non-Linear Viscoelastic and Viscoplastic Behaviour of Aramid Fibre Yarns. Mechanics of Time-Dependent Materials 7, 291–303

[43] Davies, P., Lacotte, N., Kibsgaard, G., Craig, R., Cannell, R., Francois, S., Lodeho, O., Konate, K., Mills, S., Francois, M., Defoy, A-L., Durville, D., Vu, D., Gilmore, J. and Sherman, D. (2013) Bend over sheave durability of fibre ropes for deep sea handling operations. Proceedings of the 32nd International Conference on Offshore Mechanics and Arctic Engineering, Nantes, France

[44] Ghoreishi, S.R., Cartraud, P., Davies, P. and Messager, T. (2007) Analytical modeling of synthetic fiber ropes subjected to axial loads. Part I: A new continuum model for multilayered fibrous structures. International Journal of Solids and Structures 44 (2007) 2924–2942

[45] Leech, C.M., Hearle, J.W.S., Overington, M.S., Banfield, S.J. (1993) Modelling tension and torque properties of fibre ropes and splices. Proceedings of the Third International Offshore and Polar Engineering Conference Singapore

[46] Cozijn, J.L. and Bunnik, T.H.J. (2004) Coupled mooring analysis for deep water CALM buoy. Proceedings of the 23rd International Conference on Offshore Mechanics and Arctic Engineering, Vancouver, Canada

[47] Fernandes, A.C. and Rossi, R.R. (2002) On the model scaling of polyester mooring lines for offshore applications. Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering, Oslo, Norway

[48] Le Roux, D. and Le Boulluec, M. (2012) Etude d'un ancrage textile pour la bouée SWMTF destineé à l'analyse du comportement des systèmes houlo-moteurs. Projet de Mastère Spécialisé Energies Marines Renouvelables, ENSTA, Bretagne

[49] Harnois, V., Weller, S., Le Boulluec, M., Davies, P., Le Roux, D., Soule, V. and Johanning, L. (TBD) Experimental and Numerical Investigation of a Small-scale Mooring Test Facility model. *In preparation*

[50] CORES (2011) Components for Ocean Renewable Energy Systems: Final Publishable Summary Report 213633