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

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Contents

1 Background 7
2 Design, Analysis and Usage Considerations 9
2.1 Synthetic Ropes as Mooring Components 9
2.2 Materials and Constructions 10
2.3 End Terminations 13
2.4 Properties 13
2.4.1 Mass and Cost 13
2.4.2 Breaking Strength 14
2.4.3 Viscoelastic and Viscoplastic Behaviour 14
2.4.4 Axial Stiffness 15
2.4.5 Axial Damping 17
2.4.5.1 Forced Response 17
2.4.5.2 Free Response 17
2.4.6 Variation of Properties with Usage 18
2.4.6.1 Short-term Changes 18
2.4.6.2 Long-term Changes 19
2.5 Safety Factors 23
3 In-service Considerations 27
3.1 Installation 27
3.2 Maintenance and Inspection 27
3.3 Decommissioning 30
4 Modelling Approaches for MRE Mooring Systems 31
4.1 Numerical 31
4.2 Experimental 32
5 Summary 33
6 References 34

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.

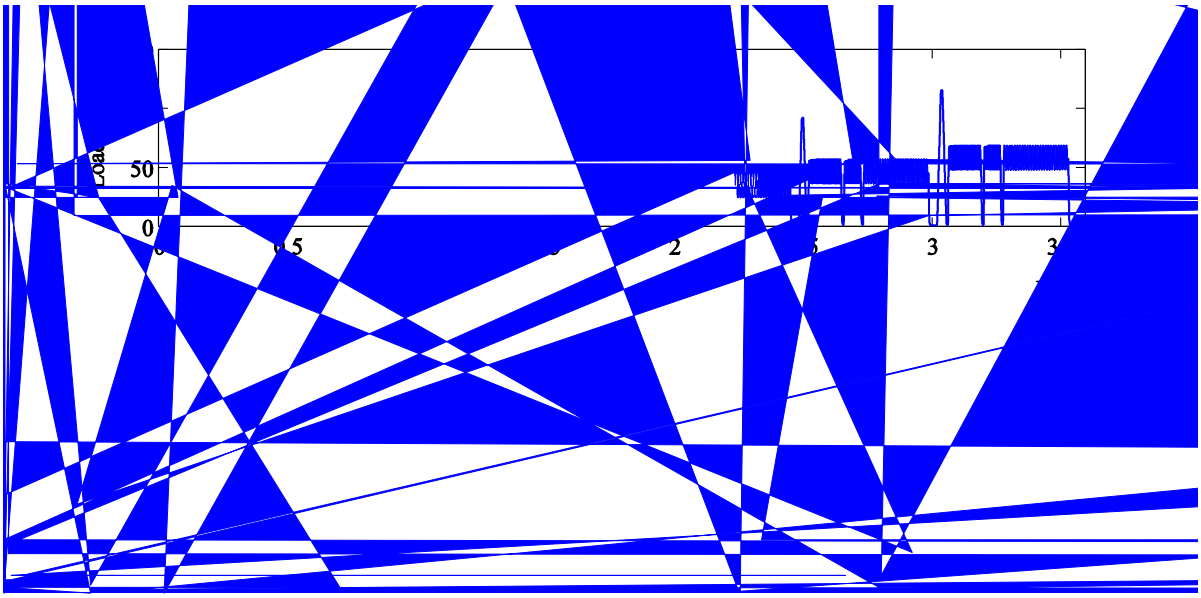

Figure 10: Time-variation of strain of a new Nylon mooring rope sample used in the MERiFIC WP3.5 study using the Dynamic Marine Component (DMaC) facility at the University of Exeter [11]

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].

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

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:

$$S_c = \gamma_m \cdot \gamma_d \cdot T_{c\text{-}mean} + \gamma_d \cdot T_{c\text{-}dyn}$$

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**
x Dynamic (CC1) x Dynamic (CC2) x Quasi-static (CC1) x Quasi-static (CC2)	x 1.10, 1.00 x 1.40, 1.00 x 1.70, 1.10 x 2.50, 1.35	x 1.50, 1.10 x 2.10, 1.25 x 1.70, 1.10 x 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**
x Normal x High	x 1.30, 1.00 x 1.50, 1.00	x 1.75, 1.10 x 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)**
x Intact x Damaged x Transient	x 1.75 x 1.25 x 1.25	x 1.67 x 1.25 x 1.20

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

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

	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 ôZô 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 ócradle-to-graveô 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 IFREMERõs 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*.

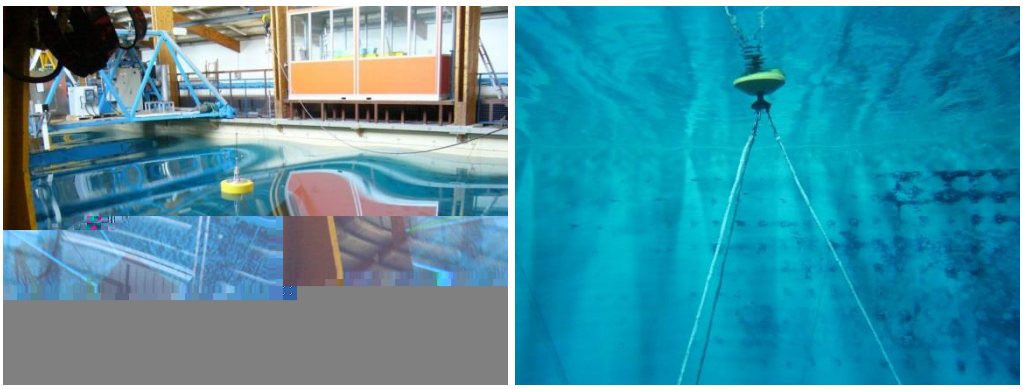

Figure 17: (*left*) 1:5 scale model of the SWMTF tested in the salt water basin at IFREMER, (*right*) underwater view of small-scale lines with representative bio-fouling [48].

[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).

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