A review of synthetic fiber moorings for marine energy applications

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Abstract

Many marine renewable energy (MRE) conversion systems including wave, floating wind, Ocean Thermal Energy Conversion (OTEC) and some tidal energy devices, are moored in place. The choice of mooring system is critical as it directly affects installation, energy take-off, and long term reliability, and hence has a significant influence on costs. Installation has been estimated to account for 27% of lifetime cost for a tidal turbine [1]. This is an area where the other marine industries, notably offshore oil and gas, have extensive experience, but the high energy regions in which MRE devices are deployed pose particular installation difficulties and operating conditions. There has been a strong movement towards replacing steel with synthetic fiber ropes offshore in recent years, particularly in deep water off Brazil and in the Gulf of Mexico [2,3]. Lightweight materials can simplify handling and reduce vessel and crane size but this is not the prime mover towards synthetic fiber moorings for marine energy. The main arguments are the possibility to adapt the mooring to the large movements of floating devices, using rope compliance to reduce peak loads while minimizing energy loss, and reduced cost. This requires both a detailed knowledge of the material options and design tools which can optimize stiffness, strength, damping and long term behavior. The large range of fibers and rope constructions available offers extensive possibilities for tailoring the mooring to the response of the device and maximizing energy recovery.

1. INTRODUCTION

Synthetic fiber ropes are being used today for mooring several prototype marine energy devices. While details are mostly confidential, one MRE device known to be using synthetic ropes is Carnegie Wave Energy's CETO device [4]. This is a sub-surface buoy, 11 meters in diameter in the CETO5 version, which is linked to a pump by a synthetic tether. The tether is an integral part of the system and its long term reliability is essential for the efficient performance of the device.

Because the design requirements of MRE mooring systems are unique, detailed investigation as well as offshore experience will be required before widespread adoption and certification can be achieved in this new application.

The application of synthetic ropes for MRE is quite a recent occurrence and most device prototypes have been designed for short trial periods at sea. Much of the current marine experience of fiber ropes comes from the offshore oil and gas industry, where large diameter (150mm or more) polyester ropes have now been in service as mooring lines for floating offshore platforms for more than 15 years. This has provided a wealth of experience with regards to design, qualification, installation and behavior [2,3,5-7]. In general however, synthetic fiber ropes have been chosen for deep water moorings (beyond 1000 meters depth). While this may be of future interest for thermal ocean energy or possibly for offshore wind turbines, the

majority of MRE applications currently being considered are in tens of meters depth, close to the coast. For such locations the loadings are quite different to those encountered in deep water oil and gas production.
Whilst failure of a mooring line could lead to catastrophic loss of the MRE device (e.g. the Oceanlinx MK3PC system in 2010 [8]), the consequences of such an event occurring are generally lower for MRE devices which are mostly unmanned (e.g. leakage of internal fluids, beaching or collision of devices with other marine craft) than for offshore structures; reliance on existing offshore standards could therefore potentially result in over-engineered and expensive MRE mooring system designs.

The choice of fiber and construction is not simple as these devices operate in a very severe environment and are subject to highly dynamic loading. This paper will first describe the candidate materials, then discuss some of the particularities of fiber ropes compared to steel, describe specific features of MRE devices, and finish with some thoughts on durability. A more detailed paper is available elsewhere [9].

2. AVAILABLE SYNTHETIC FIBERS AND ROPE CONSTRUCTIONS

Synthetic fibers used for rope-making can be broadly grouped in two categories; fibers produced by melt spinning such as polyamides, polypropylenes, polyesters, and high performance fibers produced by other techniques such as solution or gel-spinning, including aramids and high modulus polyethylenes (HMPE). It must be emphasized that these are all families of fibers, which each include a large range of grades which can possess very different properties. Nevertheless Figure 1 shows some typical fiber tensile properties.

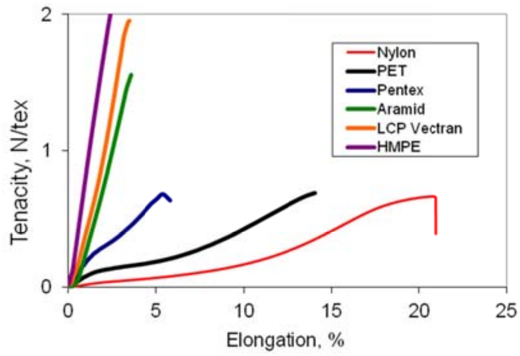

Figure 1. Examples of single filament tensile properties [9].

The ordinate in Figure 1 indicates applied stress in N/tex, (tex is a linear density textile unit, 1 tex = 1g/km). This plot shows the very wide range of mechanical properties available.

In addition to the choice of fiber, the second choice to be made is the rope construction. Ropes are hierarchical structures composed of filaments twisted together to form yarns, which are in turn twisted together to form assembled yarns and then strands. These strands may then be braided or twisted to form either braided or twisted ropes. Figure 2 shows an example of each, but again there is a wide range of possible constructions and the choice will often be a compromise between low angles to optimize stiffness and high angles for handling and to optimize damping. To produce large ropes it is common practice to group together several braided or twisted ropes (often called sub-ropes) in a jacket, Figure 3. More details can be found in [10].

Figure 2. Examples of twisted and braided rope constructions

Figure 3. 400 ton break load parallel sub-rope construction. Braided jacket removed to show twisted 3-strand nylon sub-ropes.;

In order to examine different fiber and construction options commercial software is available, [11]. This has been used in various studies, both to predict stiffness properties [12] and to investigate how twist can be induced under tension loading by some asymmetric twisted constructions [13].

The fiber properties such as those shown in Figure 1, together with the experience of rope-makers and the results from rope models, provide a first indication of what can be expected in a full size rope. Nevertheless, testing is usually required to validate predictions for critical marine applications. Figure 4 shows an example of a test on a 700 ton break load rope for a floating offshore platform mooring. There are few large test machines available and those that exist were usually designed for steel cables with very small piston displacements.

Figure 4. Full size rope test

More details of test procedures and testing facilities can be found in [14].

3. FEATURES OF SYNTHETIC FIBER ROPES COMPARED TO STEEL

There are several important differences to be borne in mind when considering the use of synthetic mooring lines. Figure 5 shows a typical load-extension plot for a new nylon rope subjected to load-unload cycles.

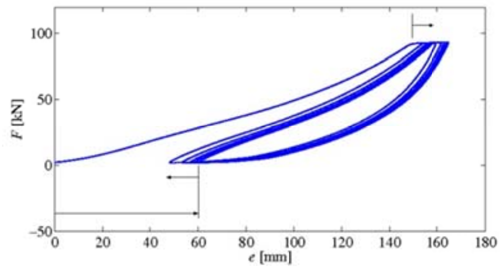

Figure 5. Example of first loading cycles applied to a new polyamide rope [15].

The rope was loaded to 20% of its break load then 5 load-unload cycles up to the same load were applied. This plot reveals several features. The response is clearly non-linear, with a different response between the first and second cycles. This corresponds to a “bedding-in” effect which occurs when fiber ropes are loaded for the first time; it involves a re-alignment of both the molecular chains at the filament level and of the rope construction. Partly recoverable, this can result in significant increases in stiffness and reductions in damping capacity and must be considered in design.

A second major difference between the behavior of synthetic fiber and steel wire ropes is the strong dependence of the response of the former on cyclic load parameters. It has been shown that rope stiffness varies primarily with mean load and load range and to a lesser extent load frequency, so it is no longer possible to employ the steel design approach based on a single stiffness value for all conditions. The synthetic fibers considered here are also polymers and polymers all exhibit viscoelastic behaviour to some extent so that for a constant elongation the load will drop with time (relaxation) and this may require re-tensioning in service.

A third feature of fiber rope behaviour is the possibility to tailor damping. The size of the hysteresis loops in Figure 5 depends on both the fibre type and the rope construction so both can be used to adjust this. Johanning has shown the importance of considering damping in the design of wave energy converter (WEC) moorings [16].

Overall, more detailed characterization is needed for fiber ropes compared to steel, and mooring design software must be able to accommodate their dependency on load level, amplitude and loading rate. The characterization of commonly-used materials such as polyester has already been performed during their development for offshore moorings. An ISO document is available [17] and many test data have been published. However this may not be entirely relevant for the loading conditions experienced by MRE mooring systems.

4. SPECIFIC ASPECTS OF MRE MOORINGS

The large mooring ropes used by the offshore oil and gas industry are designed to work in a frequency regime outside the resonant frequency of the floating platform, Figure 6.

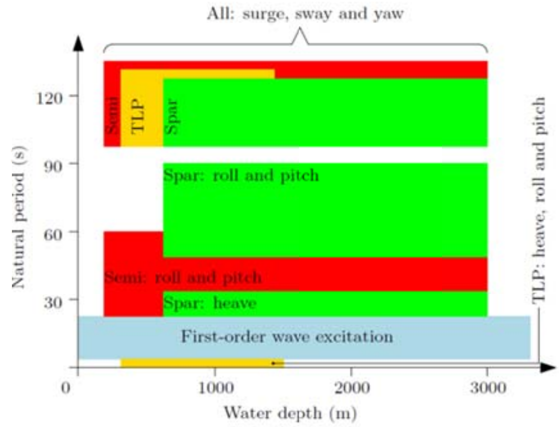

Figure 6. Typical natural periods of spar, semi-submersible and Tension leg Platform (TLP) structures, data from [18].

This is also the case for large floating MRE structures (e.g. floating offshore wind and OTEC). Many WECs on the other hand are based on recovering resonant energy, and work best when subjected to large displacements. This may therefore require a mooring system which can sustain loads originating from first order wave excitation. The mooring must be matched to the device movement, allowing large movements while damping peak loads to reduce fatigue loading. There are various possible configurations, shown in Figure 7 below.

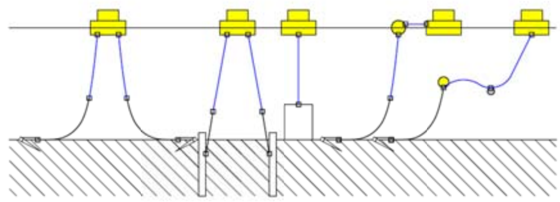

Figure 7. Possible mooring arrangements for MRE devices: Catenary and taut-moored, involving ropes and chains (blue and black lines respectively).

Finding an optimal configuration is not simple, and will of course be device dependent, but most work to date has focused on compliant lines to accommodate large movements. For example, in a Carbon Trust funded study Ridge et al examined the use of polyamide (nylon) ropes [19] for WECs. They first examined the design of a mooring system with different configurations such as those shown in Figure 7. The study indicated that a combination of nylon with steel wires or chains could provide a cost-effective solution. They then performed wet cyclic tests and showed that the new nylon sub-rope offered significantly improved long term behavior than conventional nylon ropes, Figure 8.

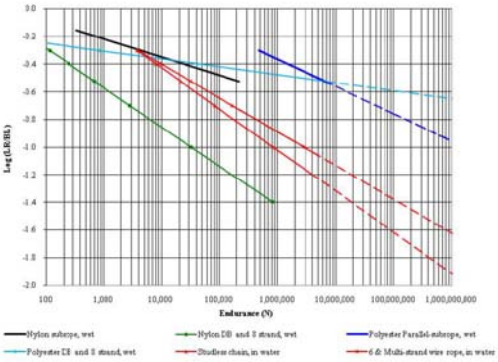

Figure 8. Log (Load range/Break load) versus log(cycles to failure) [19].

A fatigue analysis then indicated that while conventional double braid nylon would last about 3 months in this application the service life of the improved nylon would exceed 2000 years.
In another study it was found that the loading imposed on a WEC by a mooring line can be greatly reduced by careful material selection. For example, introducing synthetic rope into a mooring to replace some of the chain can provide increased elasticity to the line thus reducing loads by up to 20% [20]. Reducing loads reduces the need for very strong and heavy components, which in turn may significantly reduce the cost of the mooring line.

In parallel with system optimization using mooring software and existing materials, some specific mooring line developments are underway to integrate both stiffness and damping functions through the association of a synthetic fiber rope with an elastomer tether [21]. This extends the range of possibilities considerably, as the material can be tailored for a specific device.

5. DURABILITY OF SYNTHETIC FIBER ROPE MOORINGS

Long term reliability is a major objective for all MRE components and is essential to minimize maintenance costs. It is a key issue for all offshore structures, where at least a 20 year lifetime is usually required. When polyester ropes were first proposed for offshore station keeping over 20 years ago concern was expressed over their fatigue behaviour. The durability of individual synthetic fibers has been studied by various authors e.g. [22-24]. This is the basic “material” level, and specific fatigue mechanisms have been observed under certain conditions. When these fibers are used in ropes additional damage mechanisms are observed, related to interactions between the various hierarchical levels. Durability of mooring ropes has been one of the main areas of research for the offshore oil and gas industry where it has been shown by extensive testing that the tension-tension fatigue life of polyester is so long compared to steel that it will never be of concern for moorings [25,26].
The influence of sea water has also been investigated. Kenney et al showed that immersion in sea water during fatigue or creep loading reduced the strength of nylon 6,6 single fibres, yarns and small ropes by approximately 10% in most cases, compared with an ambient air environment [27].
Weller et al. [28] have also studied the behaviour of nylon in sea water, including samples which had been at sea for 18 months. They also showed that both stiffness and damping behaviour evolve with water ingress, Figure 9.

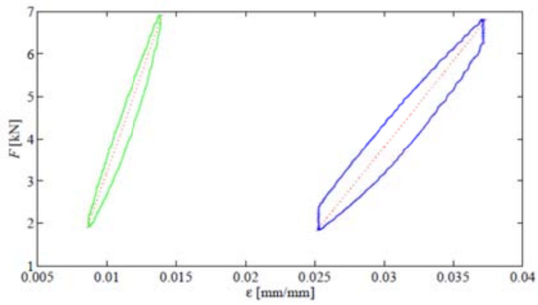

Figure 9. Comparison between response of dry (green) and wet (blue) rope samples subjected to harmonic loading.

Durability of nylon fibers is generally not as good as that of polyester, Figure 8, but as noted above Ridge et al have shown that by judicious choice of construction and marine finish it is possible to significantly improve nylon rope fatigue lifetime compared to that of traditional braided and double braid nylon ropes [19]
There has also been considerable work on the high performance fibres in sea water. For example, Derombise showed that aging in sea water affects both the static fracture and the viscoelastic behaviour of aramid fibers [29,30]; for HMPE fibers there are fewer published data but these are generally believed to be less sensitive to sea water exposure.

6. CONCLUDING REMARKS

There is a wealth of experience concerning the use of synthetic fiber ropes in marine applications, some of which can be directly applied to the mooring of floating offshore wind and thermal energy structures. However, wave energy converters and some tidal turbines will be subjected to highly dynamic loads and for these applications it is essential to optimize the response of the mooring and to base design on a full characterization of the time dependent properties of these materials. When this is done they can offer great potential to reduce capital and installation costs, improve energy production and reduce maintenance of MRE devices.

7. ACKNOWLEDGEMENTS

This paper is partly based on research conducted as part of the “Marine Energy in Far Peripheral and Island Communities” (MERiFIC) project, funded by the European Regional Development Fund through the Interreg IV-A programme, (http://www.merific.eu/).

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