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**Abstract.** This paper describes a study of the fatigue characterization of polyamide mooring ropes for floating wind turbines. Under some conditions polyester ropes, which are favoured for offshore oil and gas platform station-keeping, are too stiff for wind turbine moorings, and polyamide may be a suitable alternative. While early studies on fatigue of braided nylon ropes showed very short lifetimes some recent results have indicated that it is possible to significantly enhance lifetime by modifying rope construction and improving fibre coatings. In this paper yarn-on-yarn abrasion testing is used first to evaluate a new yarn coating. Significant lifetime enhancement was noted, so fatigue testing of ropes was then performed. Results confirm that excellent fatigue lifetimes can be achieved, superior to those for steel chain. Finally, failed yarn and rope samples were examined by microscopy, in order to improve understanding of the fatigue mechanisms leading to failure.

Keywords: Fatigue, Rope, Nylon, Mooring, Water, Floating wind turbine

## 1 Introduction

As Offshore Energy Converter systems such as floating wind turbines approach commercial development, there is a need for mooring lines in shallow water (between 50 and 100 m). Since these applications aim at harnessing marine energies, the systems are located in exposed areas, where dynamic loading is significant. In addition, the inherent moderate to low water depth results in a globally stiff behaviour of the mooring system when the standard components for deep-water floating oil and gas platforms (Weller, 2015) are used (steel chains or polyester rope). The system integrity will be maintained by damping the dynamic loadings, requiring the use of more stretchable fibre ropes than polyester order to remain within limited floater offsets to preserve the export cable integrity.

Polyamide 6 (nylon) fibres are a good candidate for these applications because of experience from previous use in other marine applications, low price and high breaking strain (up to 25%). It is first instructive to examine the behaviour of individual nylon fibres. Bunsell developed a single fibre tensile test machine (Bunsell, 1971a), which was used in several fatigue test programmes on nylon (Bunsell, 1971b; Ramirez, 2006; Colomban, 2006), polyester (Le Clerc, 2007; Lechat, 2006) and higher stiffness (Lafitte, 1982; Davies, 2010) fibres. The nylon used in these studies was polyamide 6.6, but a comparison with polyester showed that the tensile fatigue mechanisms are similar (Bunsell, 2009). Both fibres show distinctive failure morphology; fatigue cracks originate at the surface or just below it at inclusions, and run within the fibre in the axial direction producing long characteristic fatigue cracks. In terms of fatigue lifetime, one approach is to define a median number of cycles to failure (the lifetime at which 50% of the samples break, at a given load range). Typically 25-30 fibres are tested for each median value and tests are run dry. Table 1 shows some published values for nylon 66 and polyester fibres obtained in the same laboratory. Overall, the PET lifetimes appear longer, but the fibres tested in the two studies were not identical and this is reflected in differences between the two sets of data. For individual test series such as those with a load range 0-75%, the median lifetimes for PET in (Le Clerc, 2004) and nylon in (Herrera, 2004) are very similar. It should also be underlined that any comparison between nylon and polyester is complicated by the much lower stiffness of the former. All the tests reported in those fibre studies were run under load control; if strain control had been applied the nylon results would probably exceed those for polyester. Finally, it should be noted that it is necessary to apply very large load ranges to obtain failures, well above the usual service loads, indicating that the intrinsic fatigue strength of both these fibres is high.

| Load range, % break load | Polyester | Nylon 66 | Source |
|---|---|---|---|
| 0-70 | 506 | - | Le Clerc (2004) |
| 0-75 | 212 | 86 | |
| 0-80 | 131 | - | |
| 0-75 | - | 214 | Herrera (2004) |
| 0-80 | - | 151 | |
| 0-85 | 434 | 92 | |
| 0-90 | 106 | - | |

**Table 1.** Median lifetimes (in kcycles) for tensile fatigue tests on single fibres.

When ropes rather than single fibres are considered, studies on braided nylon 6 ropes in the 1980's (Kenney, 1985; Mandell 1987) have shown relatively poor fatigue performance compared to polyester, which provided little incentive for developing nylon mooring ropes. Indeed, nylon single point moorings used offshore are typically changed every one or two years. A study published by OCIMF (the Oil Companies International Marine Forum) in 1982 presented results from tests on small and large nylon rope hawsers, both new and after service. These revealed that a semi-log relationship of the type:

$$N = e^{A(100-L)}$$

could be used to represent the data, with N the cycles to failure, A an empirical parameter and L the maximum load as a percentage of break load. The empirical parameter A was found to be in the range 0.14 to 0.16 for ropes tested during that study. For a wet rope this corresponded to only a few hundred cycles at 50% of the break load.

Several other studies in the 1980's and 1990's generated fatigue data on braided nylon ropes. For example, Seo et al. (1997) examined wear and fatigue of nylon and polyester fibres and ropes. They showed yarn-on-yarn (YoY) abrasion data which indicated that while nylon 66 fibres showed better durability than polyester when dry, when tests were run wet the nylon 66 showed significant reduction in wear resistance whereas polyester did not. They concluded that comparisons of YoY wear between nylon and polyester will vary significantly with the loading condition. Nylons are superior at very high tensions whereas at low tensions polyester lifetimes exceed those of nylon. There is a widely perceived idea that polyester ropes have superior fatigue resistance than nylon ropes. Quite recently, however, Ridge et al. (2010; Banfield, 2017) have shown significantly improved fatigue results for twisted nylon ropes; those authors qualified these ropes as ideal for wave energy convertor moorings and Flory et al. (2016) also discussed these applications. Two major differences compared to the earlier fatigue work were the use of twisted ropes with long lay lengths and the application of improved fibre coatings. Both can help to reduce internal abrasion, which was shown by Mandell to be a major failure mechanism during low-load, high-cycle fatigue (Mandell, 1987). At higher loads, creep rupture is the main concern, and this depends on the polymer structure rather than the fibre interactions.

There are few other relevant and recent results for these materials, but Weller et al. (2015) examined a 44 mm diameter parallel twisted strand nylon 6 rope that had been tested at sea for 18 months on a wave energy buoy and showed the importance of loading history and operating conditions on nylon rope performance.

Polyester fibre ropes have been used for mooring deep-water offshore platforms for many years now (De Pellegrim, 1999; Bugg, 2004; Haslum, 2005) and extensive fatigue testing has shown that their fatigue performance is better than equivalent steel components (Banfield, 2000). The idea of using nylon ropes for long-term mooring lines is relatively new as there is little available knowledge on the durability behaviour of such structures. Indeed, as Pham et al (2019) conclude in a very recent study "a comprehensive study on the critical fatigue damage mechanisms of nylon should be the topic of future work." It is therefore essential to generate further data on polyamide mooring ropes, in order to validate their use for this application. It is also of interest to see how these improved nylon rope constructions compare with the polyester ropes currently in use offshore.

The goal of the present study is to provide a better understanding of the mechanical behaviour and the fatigue damage of twisted polyamide ropes compared to other mooring line options, in order to help design floating wind turbine mooring lines. First, the influence of fibre coating is evaluated by yarn-on-yarn abrasion tests. Then results from quasi-static and cyclic tests on rope samples are shown. Finally, failure mechanisms are described and discussed.

## 2 Materials and Test methods

### 2.1 Fibres and ropes

Polyamide 6 (PA6), often described as Nylon 6, in the form of yarns and ropes provided by Bexco Ropes (Hamme, Belgium) have been investigated in this study. The yarns used are supplied by Nexis fibers with a linear weight of 188 tex (g/km), provided with and without a proprietary coating. The nylon rope samples used in this series of tests were specially manufactured for the research project. The rope is a six-meter-long (pin-to-pin) three-stranded rope of outer diameter around 15 millimeters for a nominal break load of 75 kN, with eye-splices at each end. Each strand is composed of the 188 tex yarns twisted together into rope yarns, which are themselves twisted together to form the strand. The strand lay length is similar to polyester sub-rope constructions for deepwater mooring ropes and imposes splices of more than 2 meters at each end of the rope, leaving a 2-meter central section. Ropes were all supplied from the same production run, but in two deliveries, which will be referred to as "Initial batch" and "Final batch"; the coating details are confidential. Only ropes with coated yarn have been tested in this study.

### 2.2 Yarn on Yarn tests

The yarn-on-yarn abrasion tests were performed as described in the CI (Cordage Institute) requirements (2009; Flory, 2013) and ASTM D 6611 (2007). This test is the standard industry method for testing inter-yarn abrasion of synthetic fibers and provides a qualitative value of the abrasion resistance. The only difference from the standard test procedure was that tests were performed in natural sea water here, rather than the tap water defined in the standards.

These tests were carried out with the configuration presented in Figure 1. A yarn is twisted with itself (by turning it by 3.5 turns) between three pulleys. At one end of the yarn a weight is attached to apply a constant tension, and at the other end a motor drives the cable back and forth with a 1 Hz frequency until the yarn breaks due to abrasion in the twisted region. Different weights are applied to vary the applied tension.

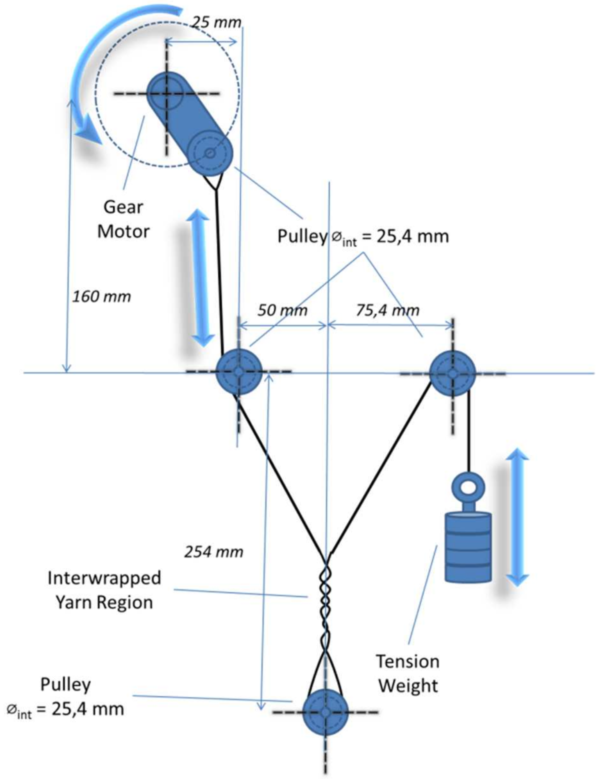



**Figure. 1.** Yarn on yarn test set-up

The inter-wrapped region is immersed in filtered, untreated sea water throughout the test until failure. Two types of specimens have been tested with this test: yarn without coating and yarn with a special marine finish. Results are given as cycles to failure versus the load, expressed in grams per tex where tex is the linear weight of the yarn in grams per km.

### 2.3 Rope fatigue tests

Quasi-static and fatigue testing have been performed on a servo-hydraulic test machine at the IFREMER Marine Structures Laboratory in Brest. This has a load capacity of 300 kN (AEP TC4 load cell, accuracy ± 1 kN) and a piston stroke of 3 meters (a SCAIME wire transducer PT5DC-40, accuracy ±1 mm was used to measure piston movements). Load was introduced to the eye splices through 100mm diameter steel pins. For tests in which strain was measured in the central part of the rope between splice wire displacement transducer (ASM WS10-500, accuracy ±0.5mm) was clamped to the rope over a known length.

It is well known that polyamides are sensitive to water, and moisture has been shown to affect the long term behaviour of polyamide 6 fibres (ISO18692, 2007; Miri, 2009; Hunt, 1980; Humeau, 2018) so it is essential to perform tests in the wet state. Before each test, the rope sample was fully immersed in tap water for 4 hours on the testing machine without load. It was then continuously sprayed with tap water throughout the test as shown in Figure 2.

**Figure. 2.** Rope during a fatigue test

Unless noted otherwise, the fatigue test results presented here were obtained with a mean-load of 40% of nominal break load, and at a cycling frequency of 0.1 Hz. Sinusoidal load amplitude was applied around this mean value. Before each test, a pre-cycling "bedding in" protocol was applied. This consisted of five load-unload cycles up to 50% of nominal break load, with each loading and unloading ramp lasting 2.5 minutes and hold periods of 5 minutes at 10 and 50%.

## 3 Results and discussion

### 3.1 Yarn on yarn abrasion tests

Yarn on yarn abrasion tests were performed up to failure, which occurred in the inter-wrapped section of the yarn in all cases reported on Figure 3. On this curve, each point represents 3 to 8 test repeats at each applied stress level, defined in grams/tex, depending on the scatter. The error bars represent the minimum and maximum numbers of cycles found at each load. The dashed lines show a linear best fit on the semi-log scale. The continuous red line corresponds to values in a Cordage Institute guidance document (Flory, 2013), which recommends a minimum lifetime for each load level for offshore hawsers.

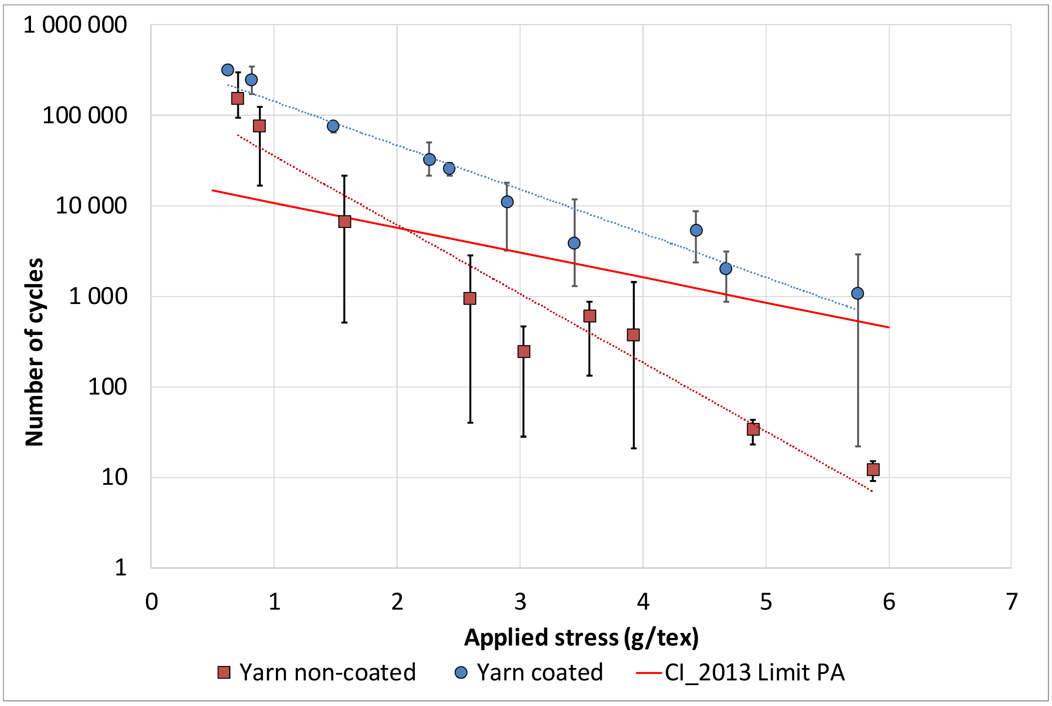



**Figure. 3.** Yarn on yarn results for uncoated and coated polyamide 6 yarns.

Cycles to failure are significantly higher for coated yarn samples and there is more scatter in results for uncoated yarns. There is a minimum performance criterion (number of cycles versus applied tension) defined for polyamide yarns for offshore use in hawsers, given by the CI document (Flory, 2013), which is represented as a red line on Figure 3. The coating enables the mean test values at all applied stresses to satisfy this criterion, though the criterion is only satisfied for all individual test lifetimes below an applied stress of 3g/tex.

A set of yarn-on-yarn abrasion tests was also performed on a 220 tex polyester fibre yarn with a marine finish, currently used in offshore mooring line applications. Figure 4 shows the comparison between the polyester and the nylon. These tests were all performed on the same test machine, in natural seawater, following the same test procedure. It is apparent that the yarn-on-yarn abrasion lifetimes of the coated nylon yarn are similar to those of this polyester yarn.

The main conclusion from these test results is that addition of this special marine coating to yarns results in an increase in lifetime by one or two decades; the coating enables mean lifetimes of this yarn to pass from below to above the CI limit and to achieve similar performance to those of a polyester yarn with marine finish. Given this promising improvement, a set of rope specimens was then prepared from these coated yarns.

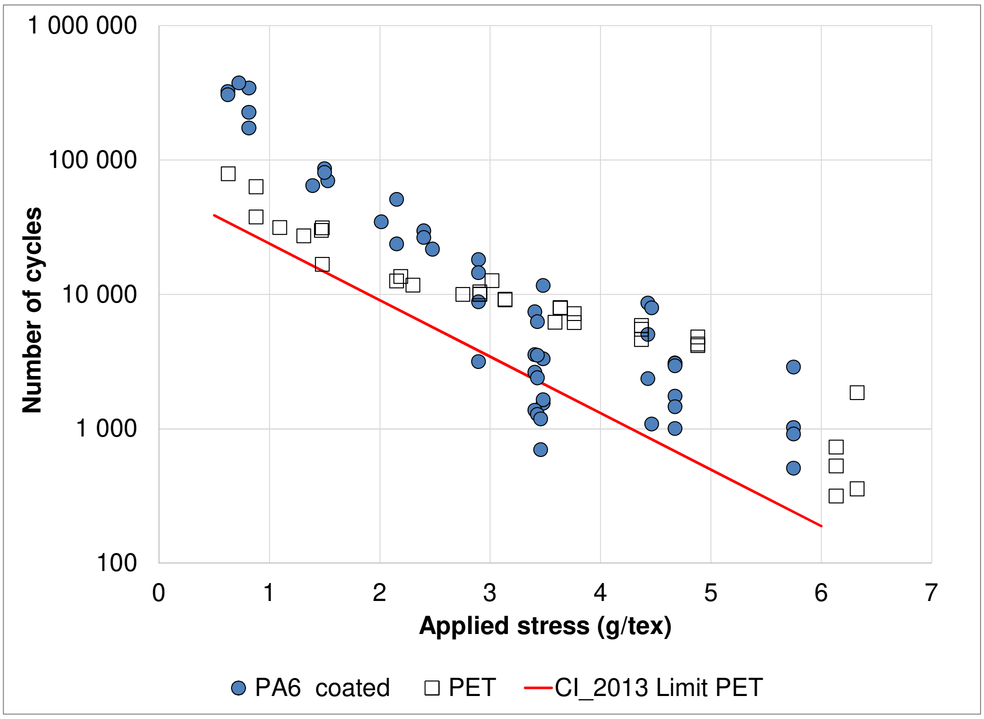



**Figure 4.** Comparison between YoY abrasion test results for nylon 6 and polyester (PET) yarns

### 3.2 Rope quasi-static break test

Wet and dry break tests were performed first, to check nominal reference strength values. On one wet sample the strain to failure was measured by fixing an (expendable) wire transducer gauge to the central section between splices. Table 2 shows the results from these six tests. Figure 5 shows the load-strain plot for the wet break test. This rope sample was subjected to unloading cycles at 20, 40, 60 and 80% of the nominal break load. The other samples were loaded directly to failure at a rate of 20% break load/minute. The load-strain response is very non-linear as has been noted in previous studies.

| Condition | Break loads, kN |
|---|---|
| Dry | 75, 78, 77 |
| Wet | 72, 73, 71 |

**Table 2.** Rope break loads

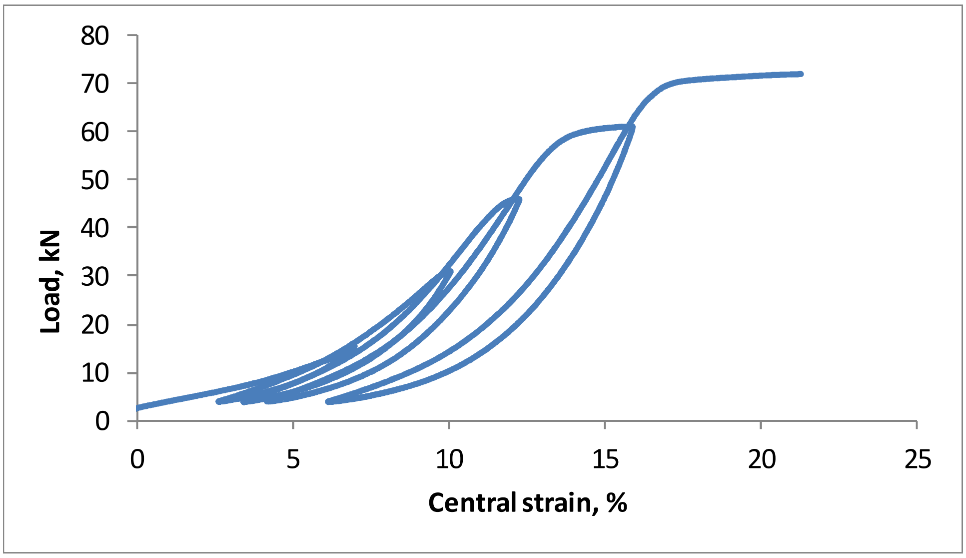



**Figure 5**. Example of force-strain plot for wet quasi-static test to failure.
Test consisted of load-unload cycles to 20, 40, 60 and 80% of nominal break load then ramp to fail.

### 3.3 ISO cyclic tests

In order to compare the behaviour of the improved nylon rope with the polyester used today for offshore moorings two tests were run following the ISO18692 (2007) Procedure for offshore station-keeping. The rope was cycled between 5% and 55%, i.e. a load range of 50%, and 10 000 cycles were applied followed by residual break tests. In fact the ISO test requires the number of cycles, N, to be only 5500 cycles for this load range ($N=166/R^{5.05}$ with R the load range as a percentage of break load) so the tests performed here were more severe than the specified conditions. Table 3 shows the results.

| Sample | Cycles applied | Residual strength after cycling, kN |
|---|---|---|
| 1 Tested dry | 10 000 | 75 |
| 2 Tested wet | 10 000 | 72 |

**Table 3.** Results from ISO 18692 cyclic loading tests on improved nylon rope.

The residual strengths are very close to 100% of the measured dry and wet strengths shown in Table 2. This suggests that the cyclic performance of these ropes satisfies the ISO fatigue requirement for permanent offshore moorings.

### 3.4 Multi-specimen fatigue test results

Twenty-five rope specimens were then tested wet in fatigue, at different load levels, with continuous cycling up to failure at 0.1 Hz. The longest test lasted around 320 000 cycles (37 days). Figure 6 shows examples of the load-time and piston displacement-time recordings for a fatigue test which involved 5 bedding-in cycles to 37.5 kN followed by 4612 cycles between 10 and 50 kN to failure.

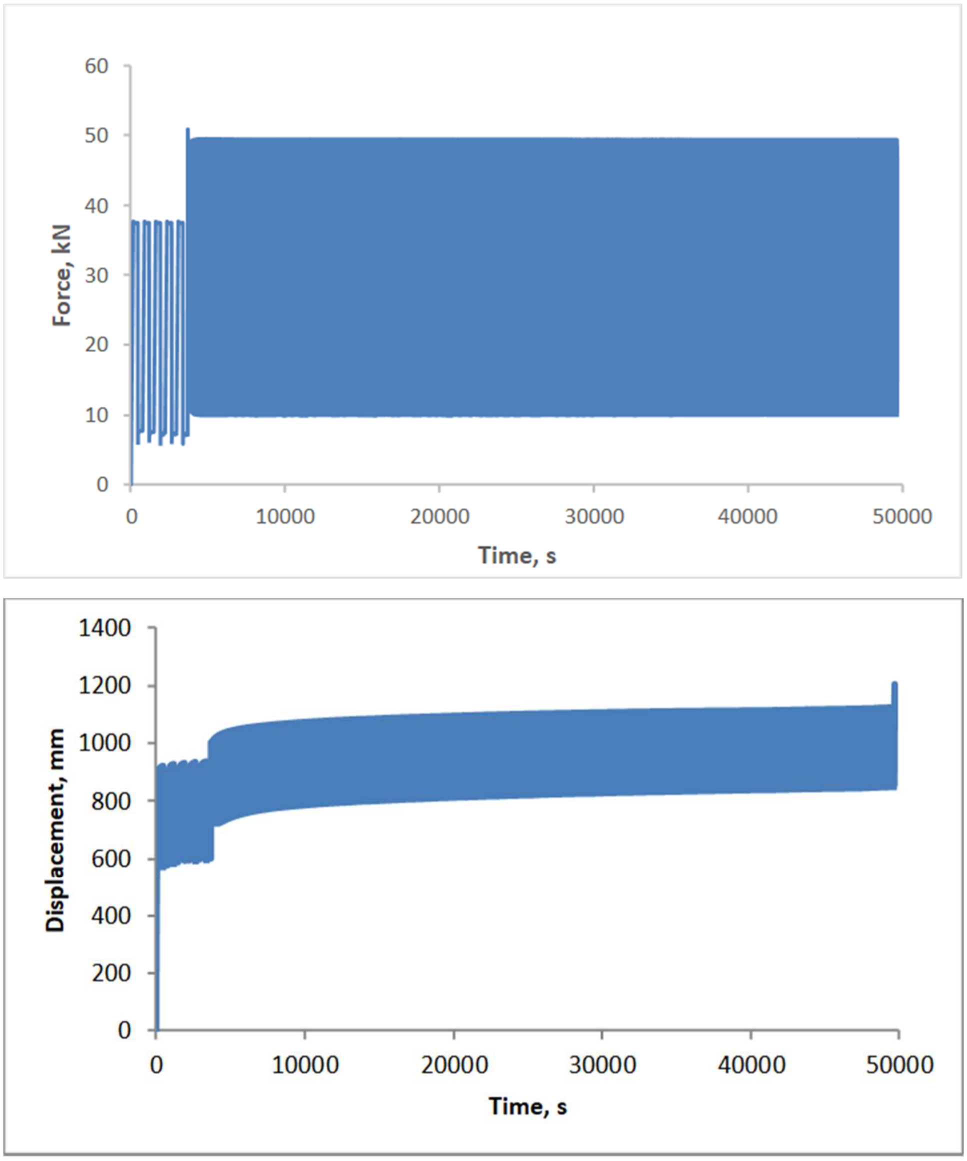
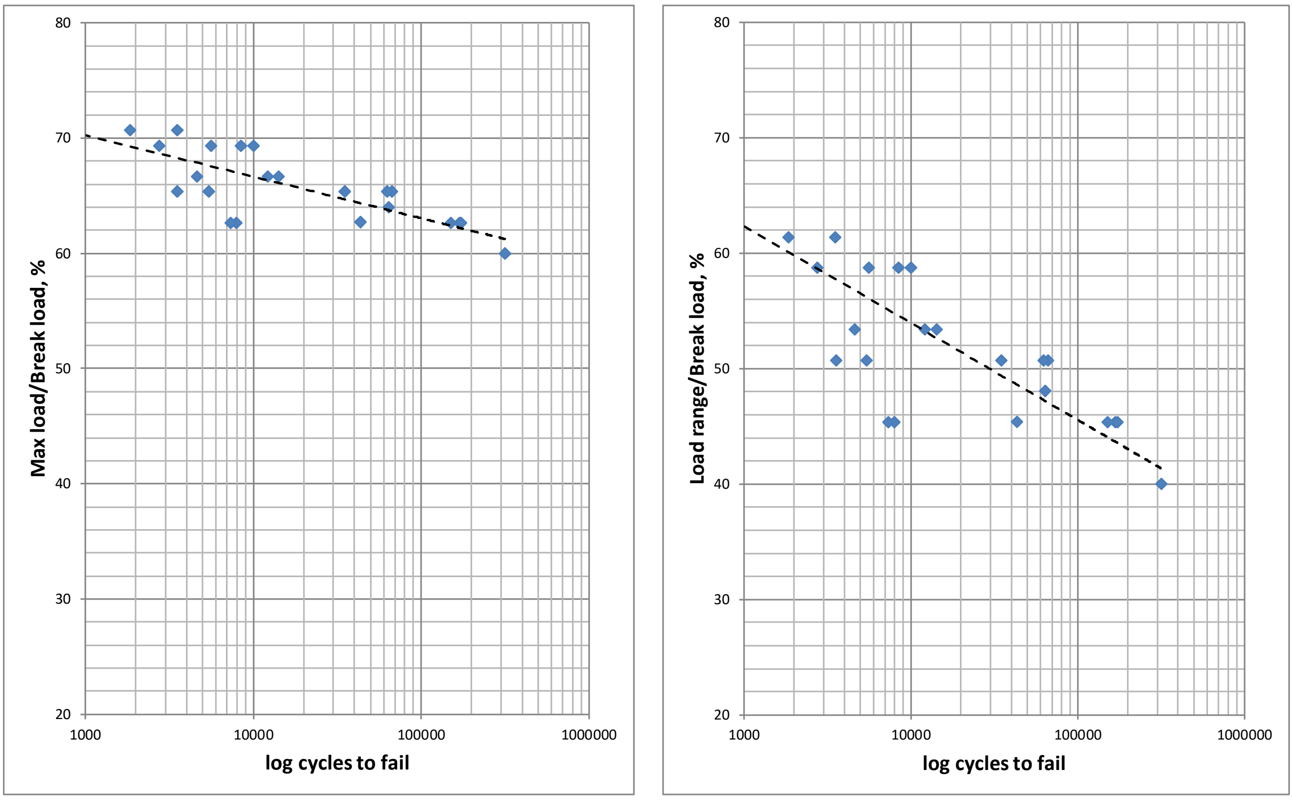



Figure 6. Examples of a) force-time and b) piston displacement versus time raw data from a cyclic rope test to failure after 4612 cycles.

Results are shown first in the traditional S-N format in Figure 7, with cycles to failure plotted versus maximum load (Figure 7a) and load range (Figure 7b), both normalized by the nominal dry break load (75 kN). For all tests reported here failure occurred in the central section of the rope, initiating near the transition between the end of a splice and the central section, with complete separation of the specimen into two parts. A small number of samples failed in the eye splice region at the sample end, and these have been removed from the data set. Figure 8 shows an example of a broken specimen.




(a) (b)

**Figure 7.** Fatigue test results for rope samples. (a) Maximum applied load, (b) Load range, both expressed as percentages of nominal dry break load (75 kN). Dashed lines show linear regressions.

**Figure 8**. Failed sample after test, showing two broken parts superposed.

The fatigue data points are shown in an alternative presentation format in Figure 9, in order to compare directly with the data published by Ridge et al. (2010). Here the load range is normalized by the wet break load (75 kN) and plotted on a log scale.

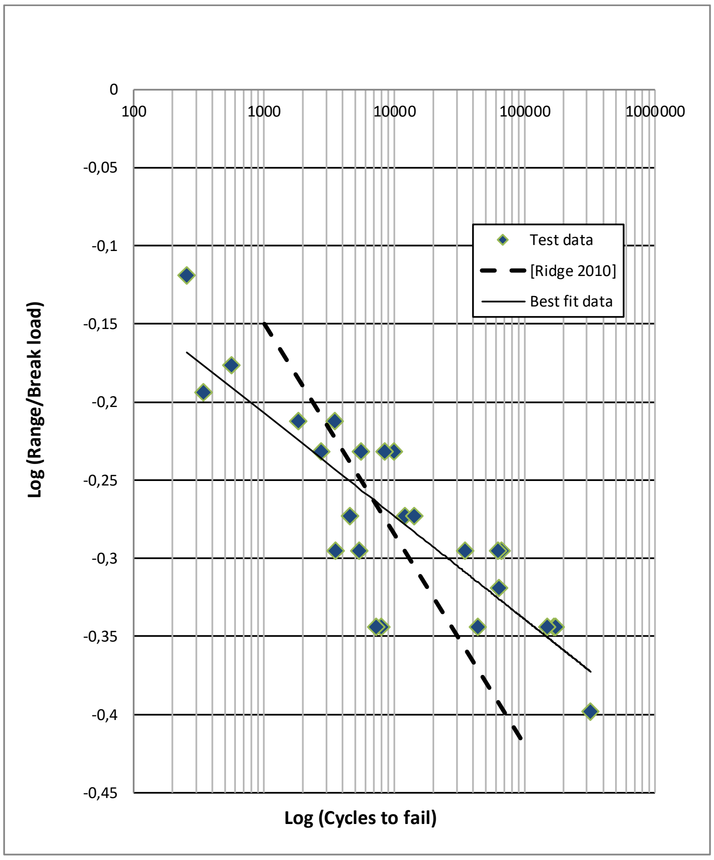



**Figure 9.** Fatigue test results for rope samples and comparison with published data from Ridge et al. (2010) shown as dashed line.

The dashed line in Figure 9 shows the trend line for results from Ridge et al. (2010) on their improved polyamide rope for long term mooring of wave energy converters. The results for the rope from the present study, from a different rope manufacturer to that of Ridge et al. (2010), are grouped around those previous results.

A more detailed analysis of the results from the present tests shown in Figure 9 revealed two populations, as shown in Figure 10. Indeed, when the results are plotted according to their batches, it is apparent that the final batch provides significantly higher fatigue lives and lower variability than the initial batch. The reasons for this difference are currently being investigated.

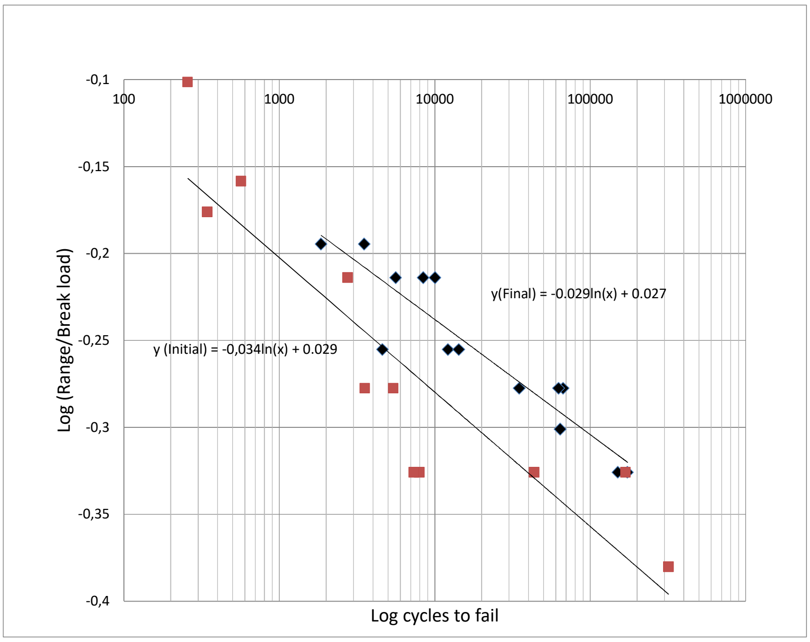



**Figure 10.** Fatigue test results separated according to batches, initial and final.

Figure 11 shows a summary of the results from all tests in this study on nylon sub-ropes, and compares them with published results for nylon (Kenney et al., 1985; Ridge et al., 2010) and polyester ropes (Banfield et al., 2000). A plot is also included which corresponds to S-N behaviour of steel chain (Banfield et al., 2000).

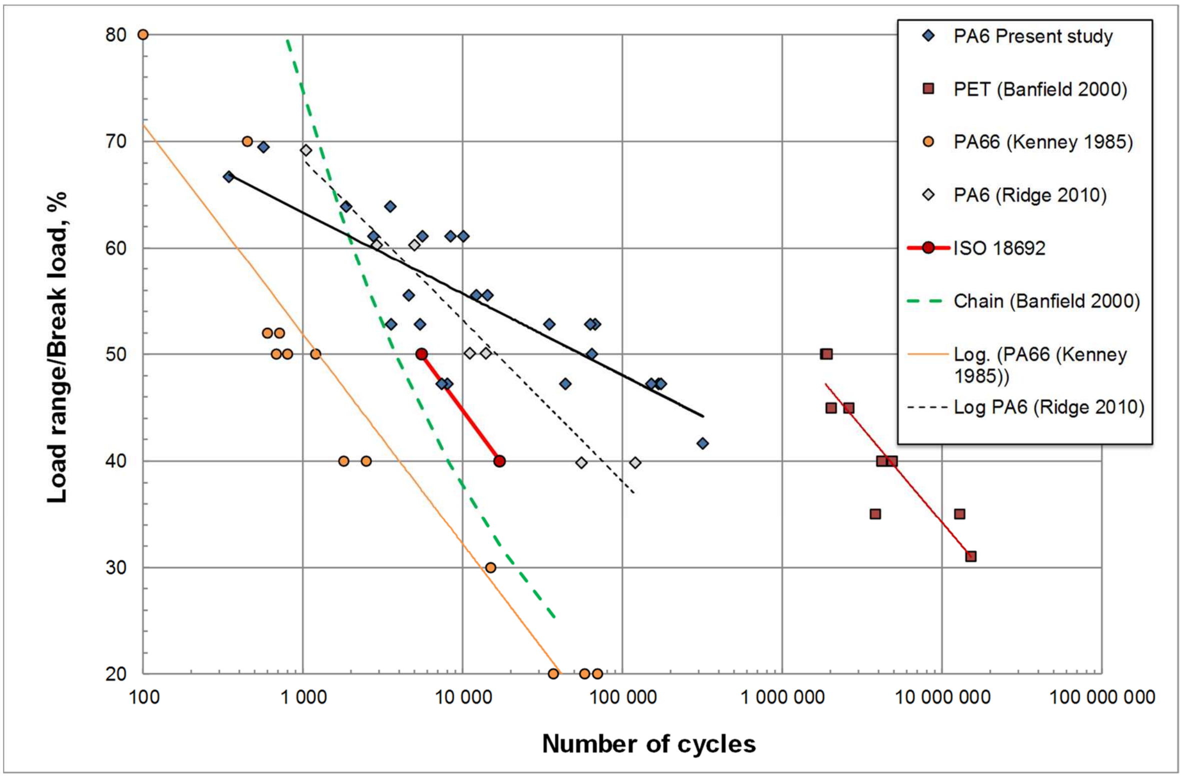



**Figure 11.** Overview of fatigue results, compared to previous tests on nylon, polyester and steel chain.

The coated nylon rope studied here provides considerably better fatigue lifetimes than the early double braid values (Kenney et al., 1985) and a little better than recently published values on coated twisted ropes (Ridge et al., 2010). Values are a little lower than measured polyester offshore rope values but these nylon values exceed the minimum ISO requirement (thick red line), confirming the ISO test results noted previously in Table 3. The fatigue lifetimes of these improved ropes are also considerably better than chain values.

These results reinforce the idea that provided appropriate rope constructions and coatings are adopted, nylon fatigue may no longer be an issue for mooring lines for marine renewable energy applications.

### 3.5 Yarn and rope failure mechanisms

Optical microscopy and Scanning Electron Microscopy SEM (Quanta 200, FEI) were used both to assess the main phenomena behind fatigue failure and to determine if the yarn-on-yarn test samples show the same damage mechanisms as those in rope fatigue testing.

### 3.5.1 *Yarn samples after Yarn on Yarn abrasion tests*

Specimens were analysed after yarn-on-yarn tests. Even at quite low loads some marks are observed on broken fibres, which suggest a peeling mechanism may be acting. Examples are shown in Figure 12. It should be noted that melted fibres were not observed on yarn samples.

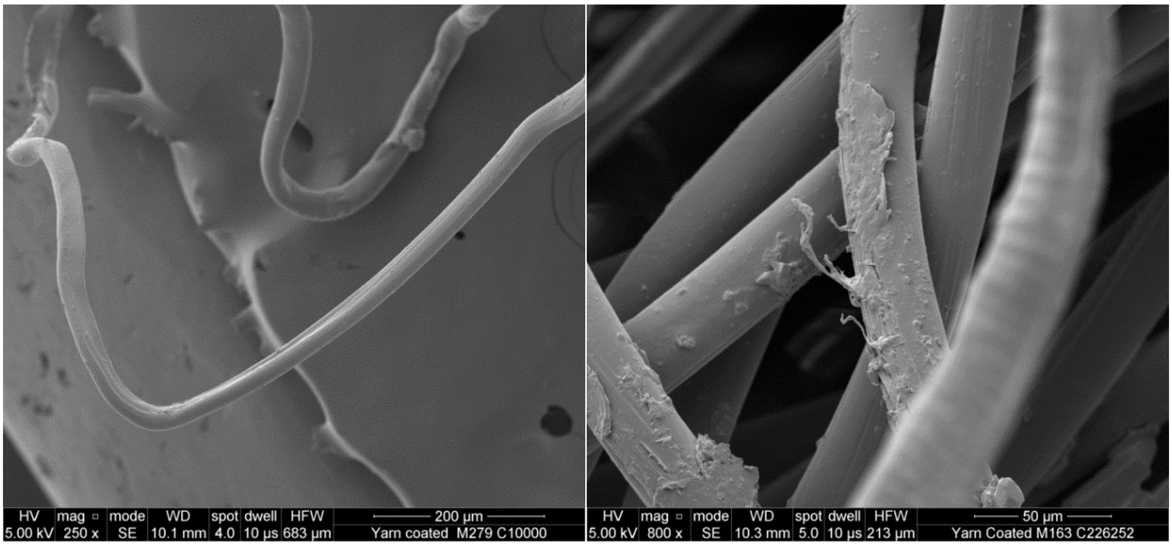



**Figure 12.** Examples of damage to fibres after yarn on yarn testing (coated yarn).

### 3.5.2 *Rope inspection after fatigue testing*

The results discussed by Mandell (1987) suggest that two failure mechanisms dominate cyclic response of nylon ropes. At high loads, creep rupture is the main failure mode, while at low loads abrasion can cause failure, either external abrasion on bollards or internal abrasion between fibres. However, it should be noted that there is not a distinct cut-off between these two mechanisms, both may occur if loading amplitude (and hence relative internal movement within the rope elements) is sufficient. As coatings are improved, one would also expect the abrasion mechanism to be shifted to higher numbers of cycles. Most samples were taken from broken ropes at 200mm from the final failure zone, in order to detect damage but without the final high energy failure mechanisms. Additional observations on samples from tests interrupted before final failure, and from areas of failed samples away from the break region, revealed significant areas of abrasion in the contact areas between the rope strands, Figure 13. The outer surfaces of the strands are intact but the inner surfaces in contact reveal broken fibres.

**Figure 13.** Example of internal abrasion in rope sample (coated)

More detailed examination in a scanning electron microscope revealed areas of surface peeling, similar to those seen in yarn-on-yarn tests (Figure 14), similar features were documented by Hearle (1998).

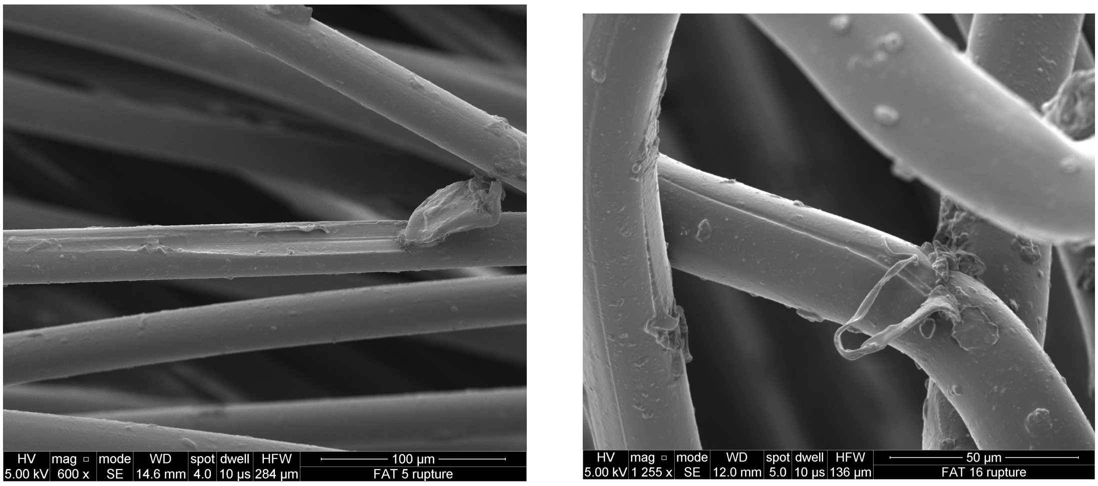



**Figure 14.** Examples of peeled zones on fibres taken from two coated rope specimens after fatigue tests to failure with a range of 52% of break load (coated yarn).

A third significant feature in observations of broken ropes in fatigue in the failure zone is the presence of highly compacted and melted fibres (Figure 15); this probably occurs during the final separation of the rope, when all the stored elastic energy is released.

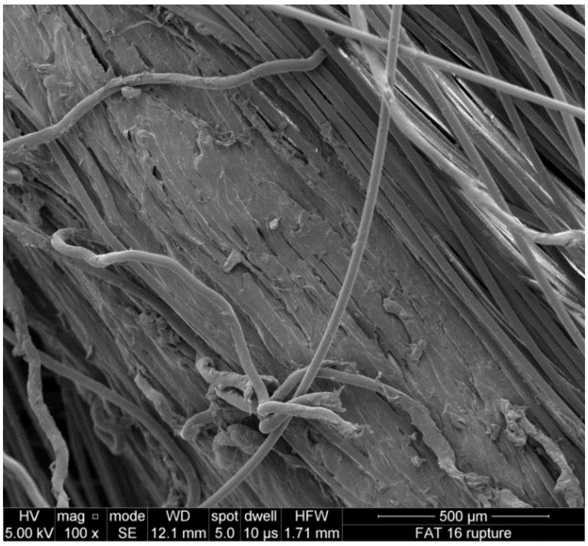



**Figure 15.** Example of compacted zone in a sample taken from failure region of coated rope tested to failure with a range of 52% of break load.

## 4 Conclusion

The results from yarn-on-yarn loading abrasion tests show a significant increase in abrasion resistance by the addition of a specially developed coating. Furthermore, the long lay length rope construction enables these polyamide ropes to exhibit very good fatigue performance, similar to that demonstrated recently for another rope product by Ridge et al. (2010; Banfield, 2017; Flory, 2016) . However, it is also shown here that the fibre coating conditions can significantly affect fatigue performance and must be carefully controlled.

SEM observations show two particular failure mechanisms in ropes; the first and most visible is melted fibres, usually over a large area of the size of a yarn. The second mechanism is the peeling of individual fibres; this is probably indicative of abrasion, as similar features were observed on broken fibres from the yarn on yarn test samples.

These results, and the favourable comparison with polyester ropes currently being used for offshore platform station keeping suggest that, provided appropriate coatings are applied to fibres, fatigue lifetime should not be a limiting factor for mooring floating wind turbines with nylon fibre ropes.

## 5 Funding

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