A novel mooring tether for peak load mitigation: Initial performance and service simulation testing

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Abstract

One of the main engineering challenges for floating marine renewable energy devices is the design of reliable, yet cost-effective mooring solutions for the harsh and dynamic marine environment. The mooring system must be able to withstand the ultimate limit state during storm conditions as well as the fatigue limit state due to the highly cyclic wave induced motions.

This paper presents the performance and service simulation testing of a novel mooring tether that combines the material properties of elastomeric and thermoplastic elements. This allows to 'tailor' the load-extension curve to exhibit a low stiffness response for the expected normal, operating, load conditions and a high stiffness response for the envisaged extreme, storm, conditions. The experimental results demonstrate the working principle of

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the mooring element and show good agreement between the theoretical load extension curve and the conducted performance tests with a distinct hysteresis effect caused by the thermoplastic element. The hysteresis is dependant on the applied pre-tension and load cycle amplitude of the element and to a lesser extent on the cycle frequency. The relaxation of the elastomeric element is quantified, giving insight into the expected long-term performance of the tether. The demonstrated working principle and the possibility to tailor the mooring response allows engineers to load- and cost-optimise the mooring system of floating marine energy converters.
Keywords: elastomeric mooring, component testing, offshore renewable energy, peak loads, reliability

Contents

1. Introduction

The development of wave and tidal energy holds the potential to alleviate issues of energy security, reduce carbon emissions and to build a new industry. The progress so far has been confined to the installation of prototypes and small-scale demonstration projects. However, recent activities in the UK where the Crown Estate has leased marine energy sites for large commercial-scale developments with a total capacity of 1.6GW are very promising. The 11 projects in the Pentland Firth and Orkney waters are expected to be installed during 2014-2020. Floating wave energy applications are planned with an installed capacity of 400MW [1]. Another area of application that is incresingly considered is the mooring of floating offshore wind installations [2, 3].

1.1. Cost reduction potential for mooring systems

One of the most critical components for all floating offshore devices is the mooring system. The requirements and design issues are discussed in [4–6]. Some of the key points which need to be accommodated are:

- Survival in extreme load conditions
- Allowing dynamic motions under operational conditions for power conversion
- Long-term reliability
- Cost-effectiveness

The capital cost of present mooring systems is estimated to incur about 10% of the capital cost of a typical marine energy converter installation [7]. This cost estimate dates back to 2004 and may be overly optimistic for more exposed sites with water depth larger than 50m. As a consequence, mooring floating structures in exposed sites is expensive and needs to drop in costs for devices to become viable. The mooring systems are typically being adapted from oil and gas applications and carry high safety factors, while they are not being optimally designed to accommodate the requirements for wave energy devices. In particular for oil and gas installations peak loads are of concern, as the mooring must be able to withstand the highest loads expected in storm conditions, which typically lie an order of magnitude above the operational load conditions. This leads to an asymmetrical situation for the case of marine energy converters where the mooring system carries the capital expenditure for extreme conditions, while the potential for generated income is constrained through operating conditions.

The mooring cost estimated by Johanning et al. [8] identifies mooring lines and chains as the main cost factors with up to 70% of the overall mooring system cost. The specific cost of mooring lines/chain is approximately linear to the required minimum breaking load (MBL). As such, peak loads have a direct impact on the mooring cost. Or, to put it optimistically, the mitigation of peak loads are of immediate benefit for the cost-efficiency of the mooring system.

The mitigation of peak loads without incurring excessive MBL requirements of conventional mooring ropes can be achived with innovative mooring designs. One such technology has been developed by Techology from Ideas (TfI), proposing a soft elastomeric, rubber element to provide the required compliance during normal operaion and a much stiffer thermplastic compression spring to absorb the peak loads in storm conditions. This type of mooring tether is cobining the two required functions named above, i) sufficient compliance during normal sea states and ii) Stiff mooring response in extreme load conditions.

1.2. Brief review on use of rubber moorings

Elastic mooring configurations using rubber materials have been developed for surface and near-surface buoy systems since the mid 60's [9]. The main feature of such elastic, taut buoy systems is the capability to absorb forces induced by the wave action and tidal variations.

A direct comparison between elastomeric tethers and a catenary chain configuration carried out by Paul et al. [10] indicates that the former reduce the dynamic tensions in severe sea states by about a third. The use of elastic tethers results in a more moderate buoy motion, increasing the survivability of mooring hardware and instrumentation on the surface buoy [11].

As such, one of the most prevalent applications is found in wave buoy moorings [12]. The requirements and applications for wave and navigation buoys are well described in [13]. The mooring system must allow the buoy to track the orbital wave motion, necessitating a highly flexible material. In addition, the elasticity must be relatively constant across the range of extensions. Both aspects are satisfied by rubber, enabling wave buoys to accurately measure the wave profile. A specific example are the non-directional Waverider buoys from Datawell, for which a 15m rubber cord (hardness of 45 to 50 Shore) is recommended [14].

Another application are so-called 'snubbers' [15] which denote rubber inserts in mooring configurations to absorb wave energy. Results from field trials for a buoy based seafloor observation system are reported in [16]. In all three mooring designs the snubber inserts protect the electro-optical cables from undue strains.

The use of flexible mooring systems has also been considered for floating marine renewable energy devices. Eight companies that may potentially employ this mooring solution for commercial deployments are identified in [17]. The challenge in incorporating flexible mooring systems to floating marine energy devices is to complement the elastic behaviour in a defined extension range with a non-linear stiff response once the extension exceeds the specified elastic operational limits.

A number of systems are proposed to combine these characteristics, among which are the Seaflex buoy mooring system [18] and the Exeter Tether [19, 20]. The preliminary results of a third system, the TfI mooring tether [21] are reported in the remainder of this paper.

1.3. Scope and structure

The key technical consideration for mooring lines is their performance regarding reliability and stiffness characteristics [22]. The testing has been a joint effort of Technology from Ideas (TfI) as technology provider, the wave energy device developer Ocean Power Technologies (OPT) as potential end-user and the University of Exeter who conducted the experiments. The mooring tether combines soft elastomeric and stiff thermoplastic material components within a single assembly. This allows a soft, elastic response through the elastomeric component during operational conditions and a stiff, non-linear response through the thermoplastic component to withstand higher loads during storm conditions. Figure 1 shows the design drawing (1(a)) and the assembled prototype (1(b)). The elastomeric part is connected to the centre of two end plates. At the outside of the end plate are two steel wires connected, which are shackled to three compressive elements each. In normal, operating conditions the load response is governed by the elastic component. The steel wires and the compressive elements carry no load in operating conditions. Once the elastomeric element extends to a length where the steel wires are engaged and tensioned, the compressive elements will resist the elongation of tether in a non-linear fashion.

The potential of such a combined load response to reduce the peak loading of typical mooring arrangements is described in [21]. For the modelled configurations, the maximum tension was reduced up to 90%. The primary purpose of the tests presented in this paper was to confirm the mooring tether could be built to a designed response curve. Industry standard mooring packages used by OPT predicted a load reduction by approximately 70% for the chosen design curve. Moreover, the mooring tether was experimentally tested to assess the load behavior and component performance in different operating conditions.

The remainder of the paper describes the experimental set-up and procedure (section 2), followed by the test results of the conducted performance tests (section 3.1), amplitude and frequency hysteresis tests (section 3.2) and the service simulation tests (section 3.3) for the extreme and fatigue load case. The paper closes with a discussion of the main results and outlines the implications for further development (section 4).

2. Experimental set-up and procedures

The objective of the tests were to assess the behaviour and performance of the mooring element and to establish confidence that the required performance can be delivered in the field. Four specific performance characteristics were assessed:

1. Load extension response curve of the mooring element

2. Element operation and performance across a range of sea states
3. Performance and survival in extreme sea states
4. Indication of fatigue performance

All tests have been carried on the Dynamic Marine Component test rig (DMaC), a unique facility to replicate the forces and motions that components and sub-systems are subjected to in (floating) marine applications [23–25]. It comprises of two hinged gimbles with a backplate, termed 'moving headstock' which is capable to replicate motions in three degrees of freedom and a linear actuator to provide the axial loading on the specimen. The reaction frame resists the forces and motions induced by the actuators and allows to adjust the linear actuator for a variable test bed length.

The experimental set-up of the tether in the rig is shown in fig. 2 and fig. 3. The mooring element was connected to the coupling plate interfaces of the test rig using a series of shackles at both ends, the actuator (fig. 2(b)) and the moving headstock (fig. 2(c)). The length of the test bed was adjusted, so that the linear actuator was fully extracted with the mooring element at its original, unstretched, length. Through this set-up a full 1m stroke of the linear actuator was available for the test. The initial length of the unloaded mooring tether (without connectors) is $l_0 = 670mm$, thus a maximum length of $l_{max} = 1670mm$ at a target extension of 149% could be provided by the experimental arrangement.

Five different test types have been carried out which are briefly described in the following and are summarised in table 1.

1. *Performance testing*: The load extension curves were measured for slow displacements (10s period) and velocities matching the scaled

wave period (3.88s period). The tether was cycled from zero tension at 0m extension to the maximum 1m extension and relaxed again in a smooth manner over a period of 10 seconds. This performance test was repeated throughout the entire test programme to assess potential performance variations. The tether was also cycled from zero tension at 0m extension to a series of target extensions (0.2, 0.4, 0.6 and 0.8m).

2. *Hysteresis amplitude testing*: The stress-strain response at non-zero pre-tension levels was measured for a range of different amplitudes. From a zero displacement position the tether was pre-tensioned to target levels of 0.2, 0.3, 0.4 and 0.5m, from which 5 load cycles with amplitudes of 0.1, 0.2 and 0.3m were imposed. The cycle periods were chosen at full-scale periods (8 and 10s) as well as scaled periods (2.4 and 3.0s).

3. *Hysteresis frequency testing*: This series of tests set out to measure the hysteresis behaviour of the tether for varying wave frequencies/periods. The tether was cycled at two pre-tension levels (0.2 and 0.3m) which are likely to be expected during field operation in a taut mooring system, with a cycle amplitude of 0.1 and 0.2m over a range of wave periods (1.2s to 16s).

4. *Extreme sea state/storm condition testing*: In order to be confident in the reliable operation of the tether in extreme sea states, it is essential to test the behaviour and integrity in the elastic/thermoplastic transition region of the tether response. The conducted tests included a combination of load cycles replicating a group of five waves, load cycles under high pre-tensions (0.9m) and storm sea conditions using the load signal from a 3-hour numerical simulation.

5. *Fatigue testing*: These tests aimed to accelerate the fatigue of the mooring element to deliver confidence that its performance lifetime will be acceptable. The chosen test parameters were based on the expected operational profile with a typical pretension of 0.2m extension and cycle amplitudes of between 2.1s and 3.6s and cycle amplitudes with a peak displacement between 0.23m and 0.62m.

   The fatigue test were carried out in three blocks, amounting to over 1,200 cycles. It is being recognised that the fatigue limit was not being reached during those simulation tests. However an indicative fatigue behaviour could be evaluated.

All tests were carried out indoors with room temperatures between 15-20 degrees. The test specimen was kept dry, i.e. all tests were conducted in air. It should be noted that all tests were performed on one test specimen.

3. Results

3.1. Performance tests

The performance test aimed to establish a reference for the tether behaviour for a full extension. The test was carried out for the individual and coupled elements. The results shown in fig. 4 are plotted for the complete (combined) tether and for the individual elements. This allows identifying the different contributions to the combined tether load response. It can be seen that the load response of the fully assembled tether is initially governed only by the elastic element and with increasing load (extension) the thermoplastic element engages from about 120% elongation onwards. The results shown have been corrected to exclude the 'rig disturbance' which is caused by stiction forces in the bearings.

Table 1: Test plan summary

Test series	Description	Displacement [m]	Cycle period [s]	Total number of cycles
100	Performance testing	0.2 - 1	3.88, 10	11
200	Hysteresis amplitude testing	0.1 - 0.3	2.4 3.0, 8, 10	93
300	Hysteresis frequency testing	0.3 - 0.5	1.2, 2.1, 3.0, 4, 7, 10, 13, 16	19
400	Extreme/storm testing	0.5 - 1	3.9, 10	18
500-800	Fatigue testing	0.03 - 0.82	2.1, 2.7, 3.0, 3.6, 10	1265

The 'modelled' line is a superposition of the individual material stiffness characteristics. The general behaviour is validated through the tests, but the tests reveal two further aspects: i) the mooring tether is slightly softer than expected and that ii) the thermoplastic element shows a considerable hysteresis effect.

The hysteresis effect represents the damping provided by the mooring tether, i.e. the energy dissipation E during a single load cycle. This effect can be quantified through numerical integration of the area enclosed by the load-extension curve.

$$E = \int_b^a f(x)dx - \int_b^a g(x)dx \quad (1)$$

where $f(x)dx$ is the upper part and $g(x)dx$ the lower part of the load extension curve and the parameters a and b are chosen at the intersections of the curves that enclose the hysteresis area. Using the trapezium rule: $f(x)dx$ can be written as:

$$\int_b^a f(x)dx \approx \frac{b-a}{n}\left[\frac{f(a)+f(b)}{2}+\sum_{k=1}^{n-1} f\left(a+k\frac{b-a}{n}\right)\right] \tag{2}$$

$g(x)$ is computed in the same manner for values of $g(a)$ and $g(b)$. The amount of damping that is achieved gives an indication how well the peak loads are damped/mitigated by the thermoplastic element and will thus be presented in the following.

Figure 5 displays the positive correlation between energy dissipation (hysteresis effect) and increased maximum displacements, i.e. extension of the mooring element.

3.2. Amplitude and frequency hysteresis tests

The aim of the hysteresis amplitude testing was to measure the stress-strain response at non-zero pre-tension levels. The general finding for this test series is that the hysteresis effect depends on the applied pre-tension and cycle amplitude and to a lesser extent on the cycle period.

Figure 6 shows the hysteresis values for the three different cycle amplitudes that have been applied for different pre-tension levels. While an increase of pre-tension for a given cycle amplitude induces a moderate increase of the dissipated energy, an increase in the cycle amplitude has a stronger effect.

The hysteresis frequency testing aimed to assess the tether behaviour for varying wave frequencies. The relationship between hysteresis effect and cycle period is summarised Fig. 7. For or a given level of pretension and cycle amplitude a slight increase of dissipated energy can be seen up to a period of 5s, which is the frequency relevant at this scale. For higher cycle periods, (7, 10, 13, 16s) the values for the dissipated energy are very similar, which suggests that the elastomer response is not dependent on the incident wave frequency.

3.3. Service simulation tests

3.3.1. Extreme tests

In order to establish confidence in the reliable operation of the tether in extreme sea states the behaviour and integrity of the tether have been tested in the elastic/thermoplastic transition range. Three different tests were carried out to assess the tether in expected extreme conditions.

- Simulated wave group with increasing pre-tension and maximum displacement that cycles the tether through the elastic/thermoplastic transition.
- Cyclic test with high pre-tension (0.9m) and $\pm$0.1m displacement
- Storm signal using 100 year storm condition load information

Figure 8 shows the simulated wave displacement profile. The five waves peaks and the resulting force are shown where z-axis data denotes the requested displacement and 'linear displacement' denotes the measured displacement. The simulation achieved good agreement for the displacement signal. It can also be observed (at around 24s) how the thermoplastic element engages for displacements $>$0.8m and results in a stiffer load response.

A more artificial signal aimed to cycle the tether within the elastic-compressive transition region. The recorded load signal is shown in Figure 9. The transition from the elastic to the the thermoplastic element is smooth and repeatable for both increasing and decreasing loads. However, the long-term response, i.e. the fatigue and creep behaviour must also be established (see section 3.3.2).

The service simulation appraisal was completed with a load signal derived from a 100-year storm model. In order to convert the force signal to a suitable displacement signal, it has been scaled with a factor of s=3.45 (prototype scale) and normalised with respect to the maximum achievable stroke of 1m. The storm test was run for 45min, equivalent to 3 hours at full-scale. The displacement and force signal for this storm test are shown in Fig 10. The load extension curve largely followed the behaviour established in the earlier tests and the thermoplastic compressive element engaged for some of the peaks demonstrating the working principle of the tether in a realistic load case.

3.3.2. Fatigue tests

The fatigue tests aimed to accelerate the fatigue of the mooring element to gain confidence that its long-term performance will be acceptable. It must be noted here that the scope of the study presented was not sufficient to test the specimens to failure and the number of load cycles have been limited to 50 in 4 cases and 500 in one case. The chosen test parameters were based on the expected operational profile with a typical pretension of 0.2m extension and cycle amplitudes of between 2.1s and 3.6s and cycle amplitudes with a peak displacement between 0.23m and 0.62m (see Table 2). The most severe profile was also tested with $N = 500$ cycles.

The nominal energy dissipation for each cycle is shown in Figure 11 and reveals a slight decrease throughout the test, that appears to stabilise around 5.7% reduction compared to the first load cycle. The fatigue tests

Table 2: Fatigue tests

Test No.	Pretension [m]	Relaxation [m]	Peak Displacement [m]	Cycle period [s]	Number of cycles
510	0.2	0.01	0.23	2.1	50
530	0.2	0.03	0.29	2.7	50
550	0.2	0.06	0.38	3	50
570	0.2	0.14	0.62	3.6	50
805	0.2	0.14	0.62	3.6	500

Table 3: Percentage loss of hysteresis effect for different fatigue tests

	Test number				
N	510	530	550	570	805
50	-5.5%	-5.4%	-4.1%	-3.7%	-7.2%
500					-5.7%

only excercise the elastic element, so the loss of hysteresis is attributed to the relaxation/creep of the tether.

3.4. Creep Analysis

As with all polymer materials there will be some permanent creep deformation to the materials over repeated stress/strain events [26, 27]. The mooring element consists of two separate polymer components, the rubber elastomer and the thermoplastic spring, each with separate creep performance. By plotting the peak force achieved at a defined extension, this creep can be measured in order to estimate the creep for the expected component lifetime. Figure 12(a) shows the results of such a plot on the elastomeric component alone extended by 0.8m. The green dots represent actual measurements with the red line being the curve fitted to those dots. It can be seen that there are inconsistencies where the force drops by substantial amounts over a single extension. These can be traced to experimental changes, where the mooring element has been disassembled or changed in some way between tests. Removing these inconsistencies we obtain the green line.

Figure 12(b) shows the same analysis over the entire component stretched to 1m extension. In this case there are some larger inconsistencies which can be traced to a design issue with the connectors which has emerged through the tests but can be easily mitigated. Once these points are removed a value for the expected creep can be obtained. These results show that the there is a reduction in the peak load at 1m extension of approximately 14% over 10 million cycles. This can be further reduced by preconditioning the component, stretching it at the manufacturing stage before deployment to remove the initial creep, halving the peak load loss at 1m extension. Due to the non-linear nature of the stress/strain response curve, the mooring component only requires an additional 1% extension of the mooring component to reach the original peak load, resulting in creep having very little impact on performance.

4. Discussion and Conclusion

This paper has presented some of the key results for a performance and service simulation test of a novel mooring tether. The working principle has been successfully demonstrated in that the elastomeric elastic element is engaged in normal operating conditions and the thermoplastic compressive element engages for in situations of high/extreme mooring loads. This allows a mooring system with both a 'soft' response to allow the motion of the floating device necessary for many power take-off designs and a 'stiff' response for high load situations, for example during storms. A prototype of this mooring tether was tested for this work, but the main response characteristics and the point of transition from the elastic to the compressive element can be designed for the application at hand. The fatigue and creep analysis work has also indicated the lifetime expectations for such components, suggesting 5-10 year lifetimes are feasible.

The presented behaviour will be very useful for array configuration of devices where the footprint area must be tightly controlled to avoid interference or collision of closely spaced devices [21]. It also overcomes the dilemma that mooring cost is directly coupled to the expected peak load during storm conditions and the required maximum breaking load of the mooring material, as two systems are combined to decouple operational and extreme mooring requirements.

Further tests will have to be conducted to investigate the frequency dependence of the tether under submerged conditions, which are expected to differ from the conditions in air. Beyond the initial assessment presented here, further tests must also validate the fatigue performance in a test-to-failure approach for multiple specimen.

The performance and service simulation tests identified a number of small design changes to be made to the mooring component. Following successful tank testing of the components it is planned to deploy tethers rated to 50kN on a full sized data buoy in Galway Bay, Ireland during 2014.

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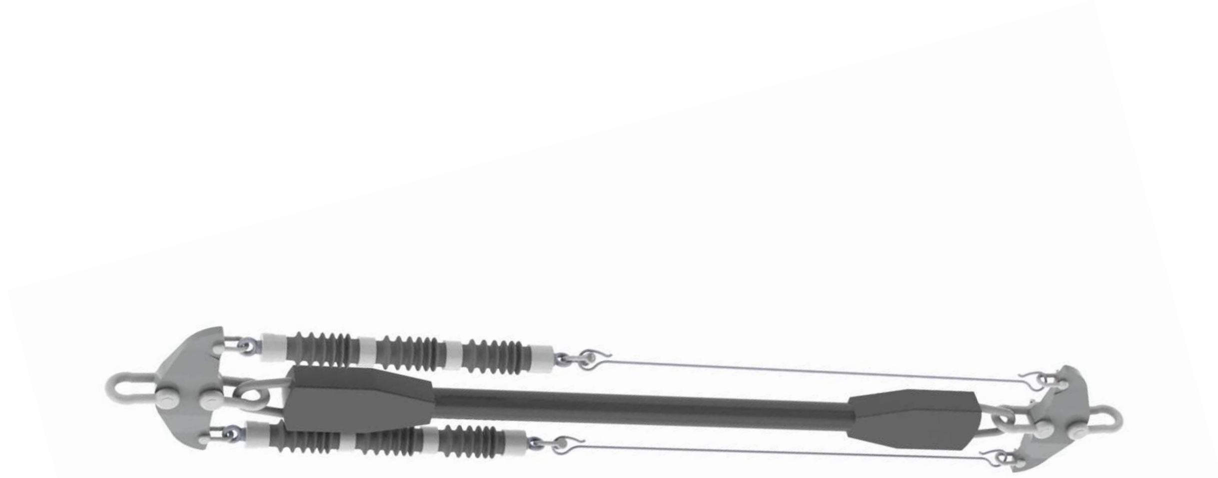
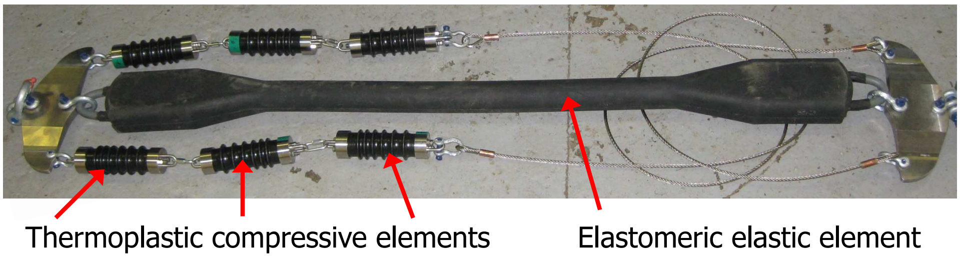
List of Figures

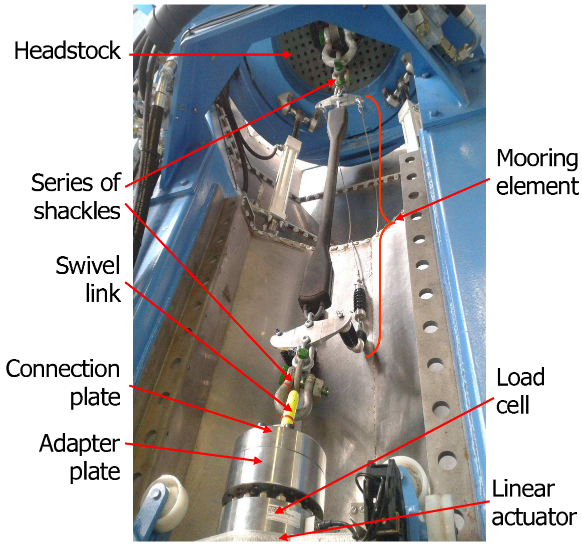


(a) Design drawing for mooring tether



(b) Assembled prototype

Figure 1: Prototype TfI mooring tether combining elastomeric and thermoplastic elements.

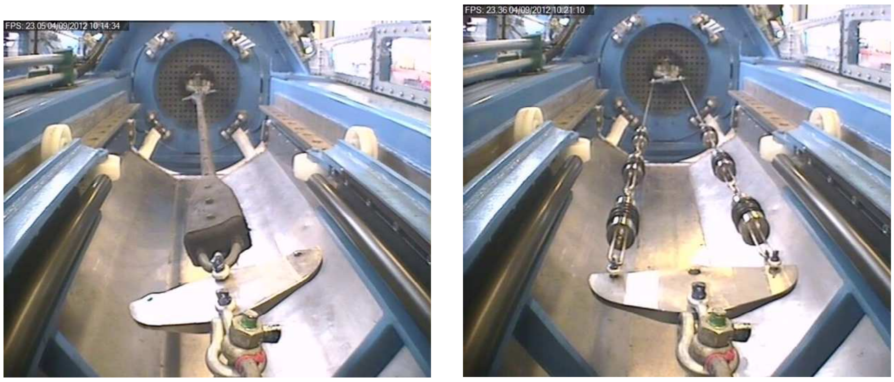


(a) Overview from linear actuator

(b) Connection to linear actuator

(c) Connection to headstock

Figure 2: Experimental set-up of mooring element in Dynamic Marine component test rig (DMaC)



(a) Elastomeric elastic component (b) Thermoplastic compressive element

Figure 3: Test set-up for individual components

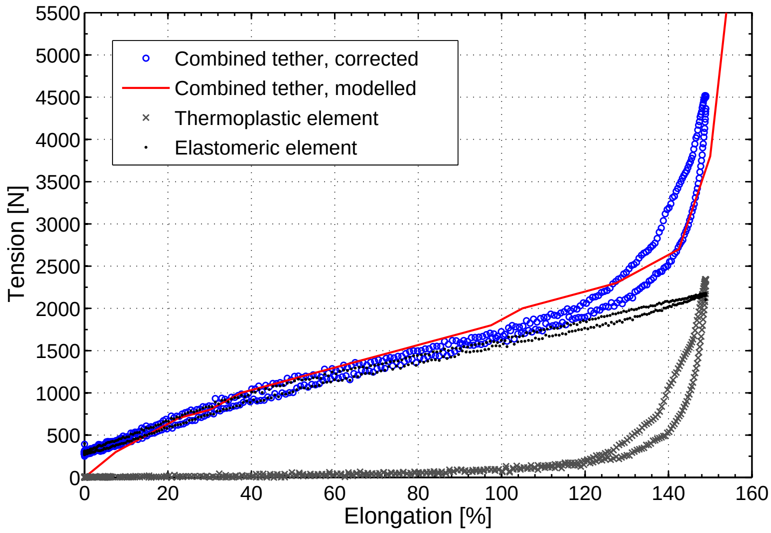


Figure 4: Load-extension performance of individual tether components (elastomeric and thermoplastic characteristics) and combined tether performance (corrected for test rig disturbance). Test rig disturbance has been quantified through a test run without specimen attached. The anticipated modelled behaviour (solid curve) is also shown.

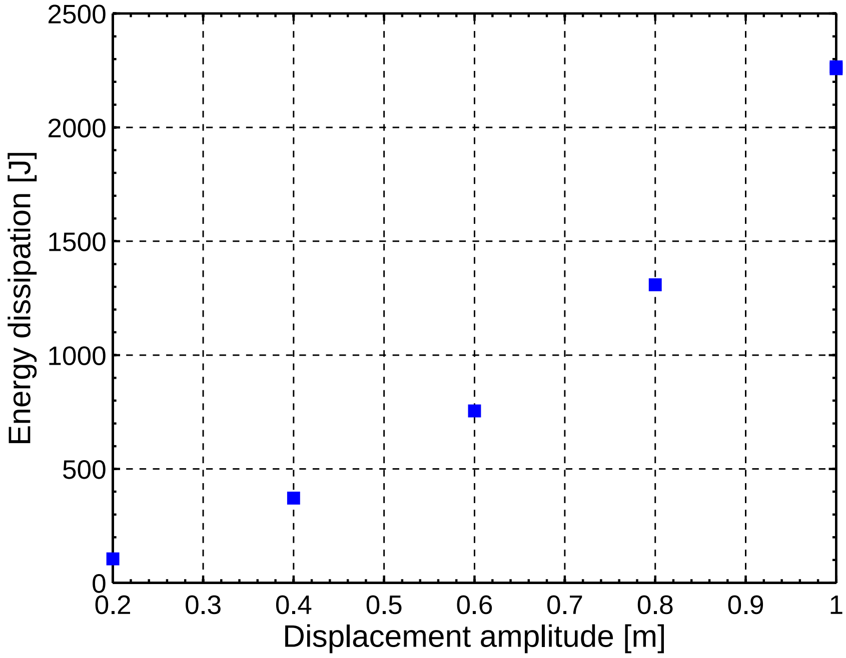


Figure 5: Energy dissipation (hysteresis effect) for increased maximum displacements of the mooring element

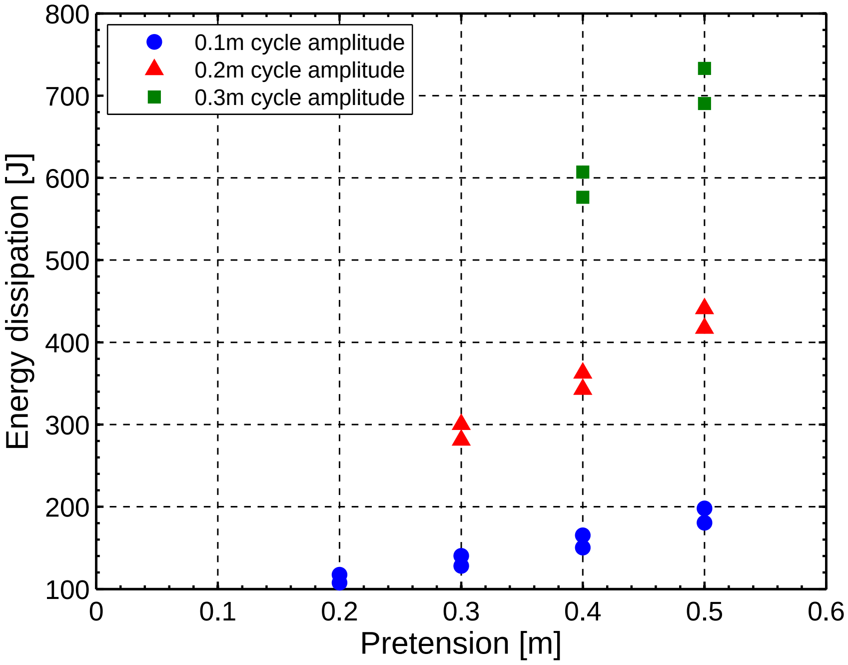


Figure 6: Pretension against Hysteresis for Test 200 series

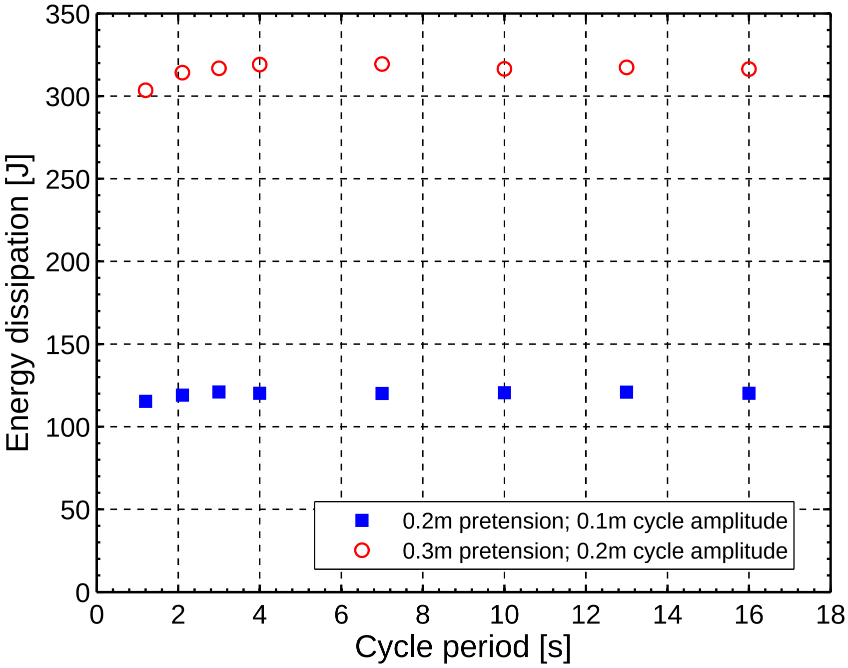


Figure 7: Cycle period against Hysteresis for Test 300 series

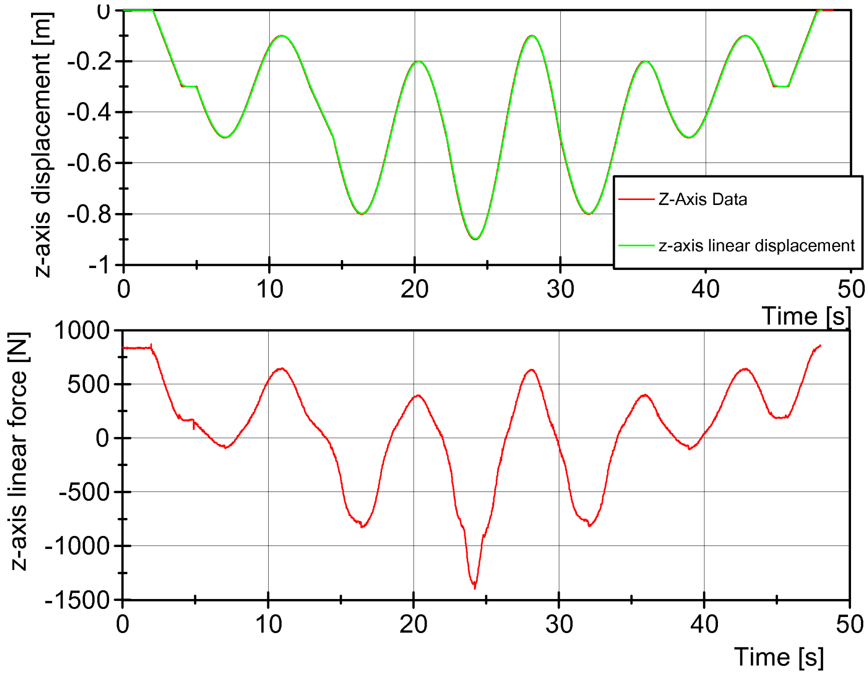


Figure 8: Displacement signal and recorded linear force for simulated wave group test. Thermoplastic element engaged at peak around 24s.

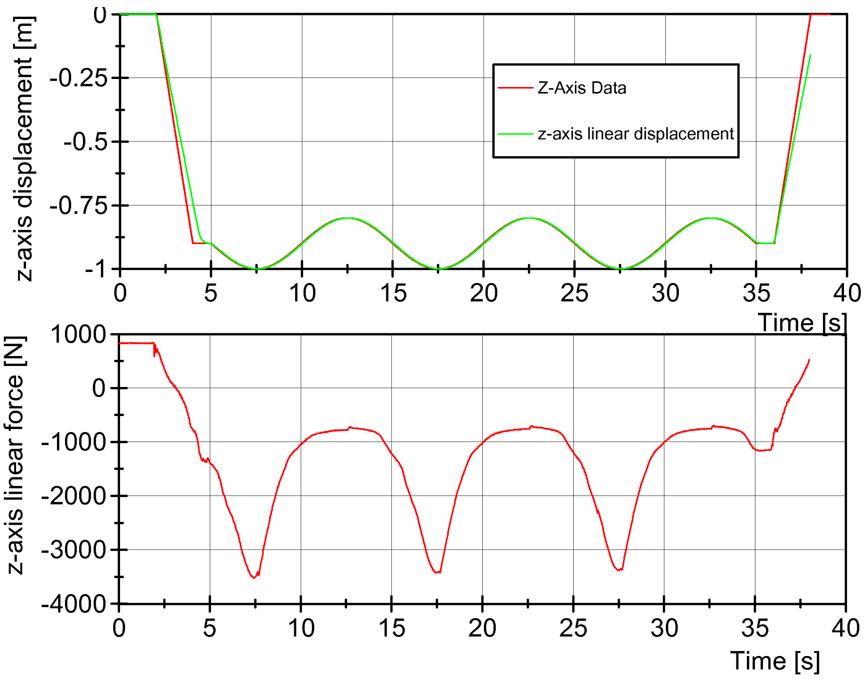


Figure 9: Repeated cycling over elastic-compressive transition.

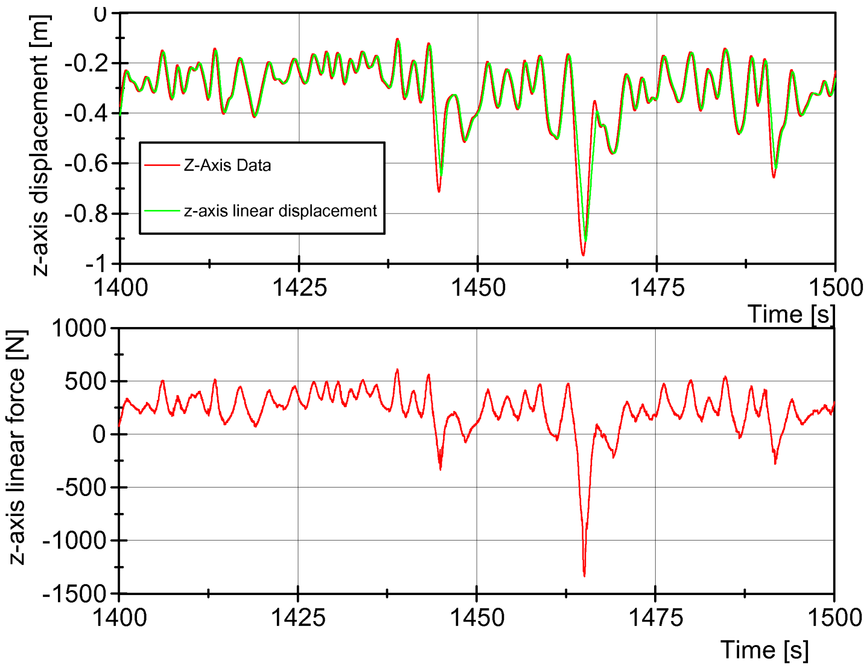


Figure 10: 100 year storm condition test, close-up view

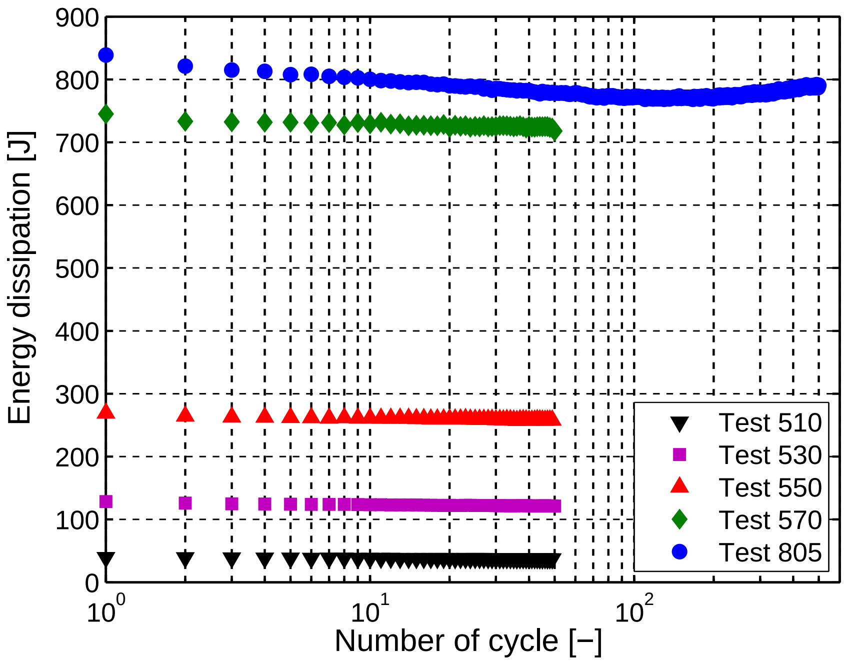
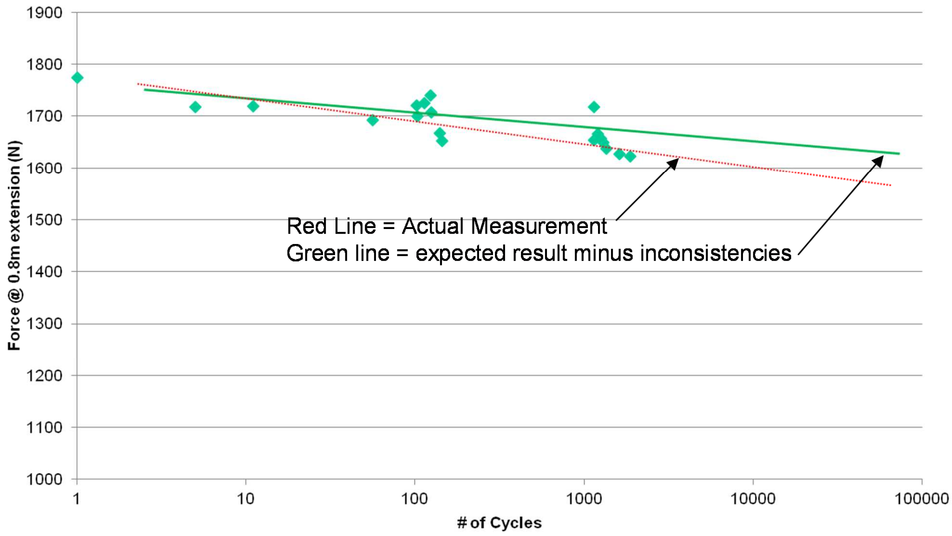
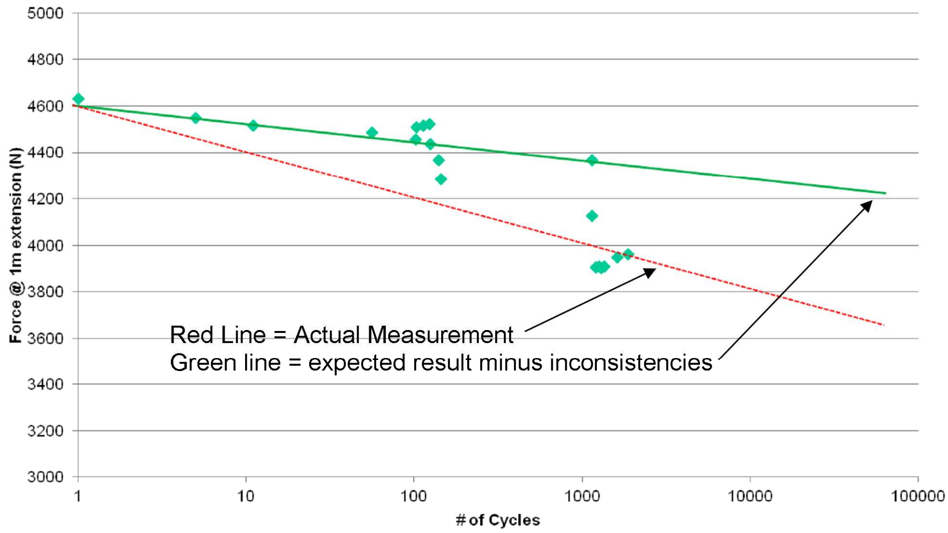


Figure 11: Number of cycles and hysteretic behaviour during fatigue tests



(a) Elastomer, 0.8m extension



(b) Entire tether, 1.0m extension

Figure 12: Analysis of measured and expected creep performance of mooring tether