Performance Comparison of Marine Renewable Energy Converter Mooring Lines Subjected to Real Sea and Accelerated Loads

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***Abstract*— One immediate challenge for the commercial development of floating Marine Renewable Energy Converters is reducing the weight and associated costs of mooring lines in deep water (>75m). Synthetic fibre ropes offer already a solution to the weight problems of using steel lines in deep-water offshore oil and gas installations as they have a very low weight in water.**

The present study focuses on the performance of fibre ropes in shallow waters, subjected to real sea conditions and the replication of the same loads accelerated in time.

Determining fatigue life is one of the most important aspects of long-term mooring analysis. At present, the fatigue analyses are usually based on S-N or T-N curves that are obtained with regular loads even when these loads are completely different to the ones measured at sea by a wave energy converter.

The differences between the standard fatigue test and the real life of a mooring system are mainly the rate in which the loads are applied and the profile of the loads. Here, these two elements are analysed to get the fatigue damage, obtaining important differences in this measure.

***Keywords*— Marine Renewable Energy Converters, taut mooring system, accelerated testing, fatigue analysis.**

I. INTRODUCTION

The oceans are a very important renewable energy source present in various ways: wind, waves, currents and others. Due to the high quantity of devices necessary to harness these energy sources, it is expected that it will be necessary to deploy offshore installations located on sea depths beyond 50 meters. This trend implies that in the near future, a large number of the offshore platforms will be moored and anchored to the seabed, as in [1] and [2]. Fibre rope taut mooring lines represent a new and interesting option for the mooring of Marine Renewable Energy Converters (MREC) in deep-water (see Fig. 1), but with the counterpart of having exclusive requirements regarding their anchoring systems as is indicated in [3].

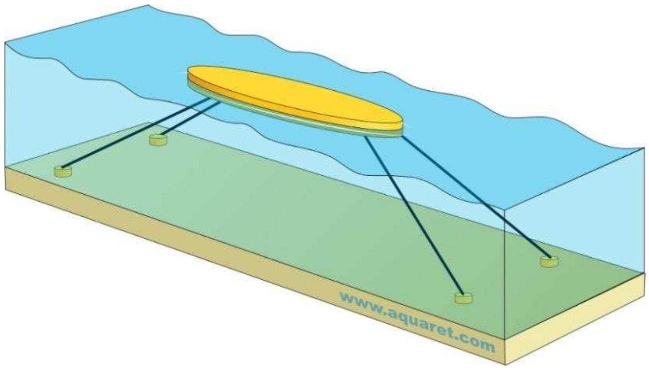

Fig. 1 Example taut mooring configuration [4]

Synthetic fibre ropes offer a solution to the weight problems of using steel lines in deep-water as they have a very low weight in water. Also, compared to steel, there are a large number of synthetic fibre material compositions with a wide range of material properties. A synthetic rope can therefore be designed to have properties that match the mooring requirements.

There are large differences between the dynamics, requirements and dimensions of a Marine Renewable Energy Converters (MREC) and Oil and Gas platforms, for which fibre ropes have been developed over the past two decades. Generally, the dynamics of a MREC are more variable and in some cases the loads are completely different. These devices are typically designed for optimal performance therefore responses close to resonant are possible in one or more modes of motion. This has implications in the mooring system requirements and in the efficiency of the MREC, as in [5].

At present, almost the 100% of the MREC use spread mooring systems, as in [6], [7] and [8]. This means that a large footprint area is needed for only one device. Although this could be problematic for arrays comprising of closely spaced devices, very few small-footprint, taut moored systems have been used to-date. Due to this fact, there is a lack of experience within the sector about suitable taut-moored configurations and which products to use, or even if specialist components needed to be developed for this application.

To this is added the fact that there is not too much information about real loads and that they are related to each specific design. There are a lot of designs of MREC and each design supports different loads, therefore, a mix of concepts MREC-mooring system exist.

To fill this lack, the company WireCoWorldGroup (Lankhorst-Euronete Portugal), synthetic fibre rope manufacturer, along with the Fundación Centro Tecnológico de Componentes (CTC) developed the FIBRETAUT project (Fibre Ropes for Taut Mooring Lines for Marine Energy Converters).

II. OBJECTIVES

The main objective of the FIBRETAUT project was to acquire real load time series and replicate them at different speed rates (same loads but applied in fewer time) in order to compare the fatigue effect.

In parallel, several technical secondary objectives were defined:

- Perform tests of the fibre ropes in two environments, one in real open water conditions and other in a control environment at the laboratory.
- Determine strength limits and the stiffness and damping properties of fibre ropes with cycling at different loads.
- Define the mooring system to be implemented at the SWMTF.
- Implement the rope behaviour and model the mooring system in a commercial FE code (OrcaFlex)
- Validate the model with real data: metocean conditions and measured loads at sea.
- Verify the applicability of fibre ropes for marine energy converter applications.

The South West Mooring Test Facility (SWMTF) and the Dynamic Marine Component (DMaC) facility were selected as the best candidates to acquire and replicate the mooring loads respectively.

III. METHODOLOGY

For the development of the objectives defined in section II, the following Key Points (KP) were considered:

- KP1: Definition of the specifications and base line load cases, in parallel with the numerical models (see Fig. 2).

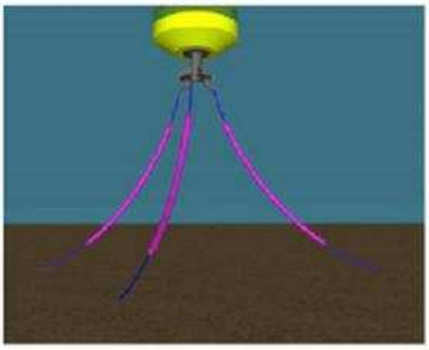

Fig. 2 Example of a numerical model of the buoy and its mooring system [9]

- KP2: Tests at the SWMTF site and collection of the data for the real sea conditions with an Acoustic Doppler Current Profiler (ADCP, see Fig. 3).

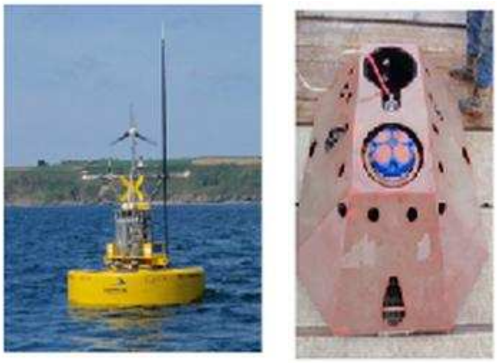

Fig. 3 SWMTF buoy & Teledyne RDI ADCP

- KP3: Application, at the DMaC, of the measured loads in the SWMTF at different speeds (see Fig. 4).

Fig. 4 Dynamic Marine Component test facility (DMaC)

- KP4: Validate the numerical model and correlate the accelerated test in the laboratory (DMaC) with the test at sea (SWMTF).

KP1, 2 and 3 are developed in sections IV and V, meanwhile KP4 is developed in section VI.

IV. SPECIFICATIONS AND MODELLING ACTIVITIES

The first part of the investigation was the definition of the mooring system which would be implemented at the SWMTF site.

According to the specifications of the SWMTF, provided by the University of Exeter (UoE), a specific mooring system was designed. The main constraints for the mooring design were specified by the UoE in terms of maximum design tension load (maximum strength of the mooring lines), total mooring vertical pre-tension (maximum load admissible by the padeye of the buoy) and the maximum elevation angle between the mooring lines and the seabed at the anchor points. Most of these restrictions are due to the fact that all the elements except the fibre ropes were the ones that the SWMTF already had.

Starting from the information provided by Lankhorst-Euronete Portugal several configurations of the mooring system for the SWMTF were performed and based on simulations, an optimal mooring design was obtained.

All the proposed mooring line configurations were modelled in OrcaFlex and subjected to the real sea state conditions.

Among all the fibre ropes offered by Lankhorst, Polyamide was the material chosen for the project due to its high compliance. The final mooring configuration was composed of three lines with the following elements (from buoy to anchor): stud less chain (1m long), polyamide rope (22m long and 30mm diameter), stud less chain (36m long and 24mm diameter) and stud link chain (5m long and 36mm diameter). Fig. 5 and TABLE I show the final design as well as the properties of the rope and chains used.

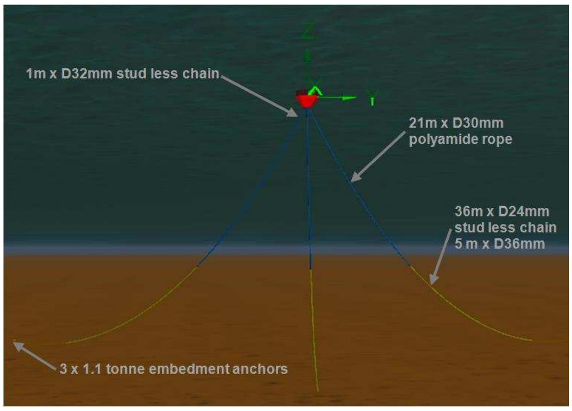

Fig. 5 Final mooring configuration at the SWMTF site

TABLE I
SELECTED ROPE

Material	Diameter (mm)	Weight (kg/m)	MBL (kN)	Design constraint
Polyamide	30	0.585	231	MBL > 207 kN
Steel	24	13.5	320	
Steel	36	29.091	732	

V. TEST PLANS

Before doing the tests, it was necessary to manufacture only the ropes because all the rest elements were part of the standard mooring system of the SWMTF. During May 2014, the preparation and fabrication of three test samples for the SWMTF site and five test samples for the laboratory tests at DMaC were carried out. The only difference between the samples was the length: 22 m (SWMTF) and 4 m (DMaC).

Fig. 6 One of the 30 mm diameter polyamide samples used for DMaC testing

The SWMTF was deployed on 12th June 2014 with the intention of recording line tensions for 30 days.

Fig. 7 Deployment of the mooring system at the SWMTF site

In the case of the DMaC, the test plan is more complex because different task must be done with a tighter schedule.

In order to fulfil the 10 days of the facility access, the following test schedule was defined:

TABLE II
TEST SCHEDULE AT DMAC

Day 1	Day 2	Day 3	Day 4	Day 5
Bedding cycles & Calibration works		Real-time dry testing		Set-up of DMaC for wet testing
Day 6	**Day 7**	**Day 8**	**Day 9**	**Day 10**
Final set-up (filling of DMaC) & Real-time wet testing			Calibration and accelerated wet testing	

This test schedule can be summarised as follows in the next three types of tests:

- Calibration: Two brand-new samples for preliminary testing and calibration of DMaC.
- Real-time: Two brand-new samples for real-time testing. The most loaded line, from the fatigue point of view, was determined and subsequently a time series was applied to the samples.

- Accelerated-time: One brand-new sample for accelerated testing. The load magnitudes applied were the same as were used for the real-time tests, but the time vector was modified to accelerate the load time-series.

TABLE III lists all the tests conducted at DMaC.

TABLE III
DMAC TESTS

Sample Number	Test Number	Wet/ Dry	Code	Notes
1	3	Dry	Sample1Test3	Real (x1) time-series
	4	Dry	Sample1Test4	
2	9	Wet	Sample2Test9	
	10	Wet	Sample2Test10	
	13	Wet	SampleBTest13	Calibration
	14	Wet	SampleBTest14	
	15	Wet	SampleBTest15t	
	16	Wet	SampleBTest16	
3	17	Wet	Sample3Test17	Accelerated (x1,2) time-series

Prior to each time series, five bedding in cycles are applied to stretch the ropes to a working strain. TABLE IV summarizes the load and duration time of each bedding in cycle.

TABLE IV
TEST SCHEDULE AT DMAC

Step	Start Load (N)	End Load (N)	Duration (s)
Bedding in ramp up	2000	46200	150
Bedding in hold	46200	46200	300
Bedding in ramp down	46200	2000	150
Bedding in hold	2000	2000	300

During the scheduled time of 10 days, the sample ropes were tested at DMaC according to the Test Plan described in TABLE II. The time series of tension obtained from the OrcaFlex models were used as input data for DMaC. Fig. 8 shows one fully-submerged rope which was tested at DMaC during the 8th December 2014.

Fig. 8 Submerged rope sample at DMaC

VI. RESULTS

A. Results from SWMTF

The data from the SWMTF was collected at the planned time, 30 days after deployment. Although two new load cells were installed and checked prior to the deployment at SWMTF, load cell 1 failed in the fifth day, therefore, the tension data was only collected for the first five days of the deployment. Owing to this failure, UoE and CTC were obliged to improvise with the available information to generate realistic line tension time series to use at DMaC.

Due to the SWMTF has a system called MotionPak that measures and stores the accelerations of the buoy, it was possible to impose the MotionPak-based displacements (in the 6 degree of freedom) into OrcaFlex, in order to estimate mooring line tensions during the test period at SWMTF. The method with the MotionPak based-data inputted in Orcaflex gave reasonable results and a good correlation was achieved to obtain a representation of the missing data.

Fig. 9 shows the comparison between the measured data at SWMTF (recorded when load cell 1 was initially working) and the Orcaflex simulation results based on displacements derived from the MotionPak data.

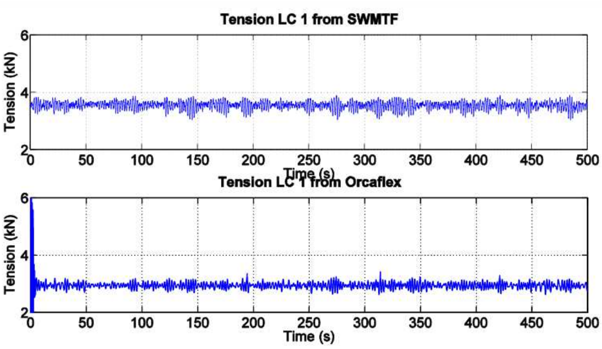

Fig. 9 Validation of mooring line tensions using MotionPak-derived displacements provided by UoE

Fig. 9 shows a large difference in the mean tension. This discrepancy is due to the tide range wasn't included in the simulations. This figure also shows the typical high frequency loads of a MREC.

B. Results from DMaC

The results obtained from DMaC were time series of tension and displacements. The information of the samples was processed with Matlab in order to generate plots that show the behaviour of each sample. As an example the following figures for Sample 1 are shown:

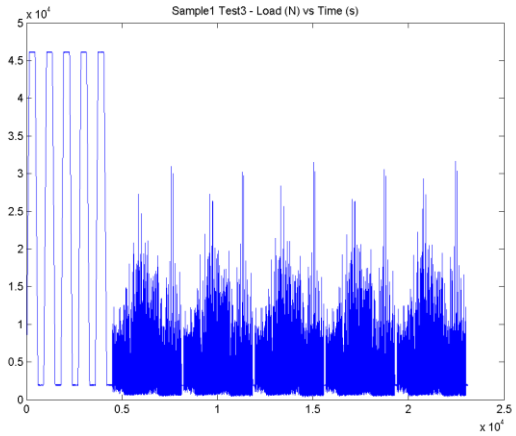

Fig. 10 Sample 1 Test 3 – Load (N) vs. Time (s), [10]

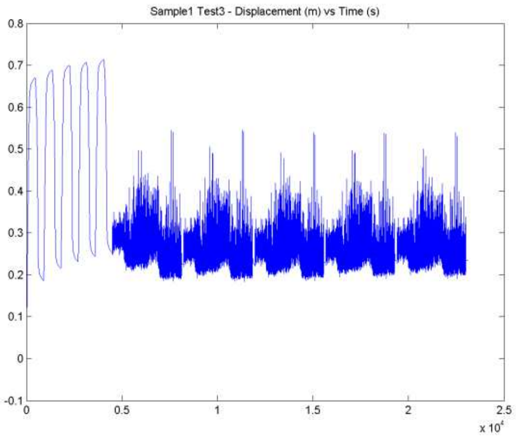

Fig. 11 Sample 1 Test 3 – Displacement (m) vs. Time (s), [10]

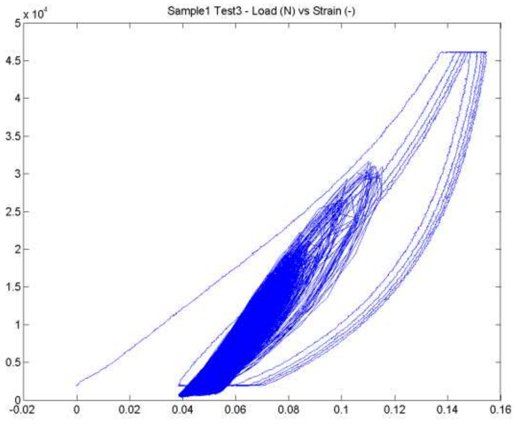

Fig. 12 Sample 1 Test 3 – Load (N) vs. Strain (-), [10]

Preliminary tests identified some differences between the input and output values of tension. These differences can be seen in Fig. 13, where the output data imposed by DMaC is lower than the input.

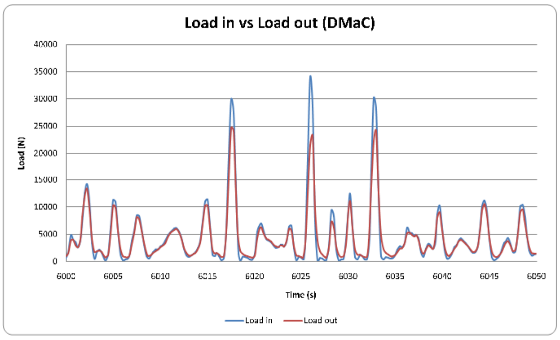

Fig. 13 Load in vs. Load out (DMaC) , [10]

Additional tests were carried out to obtain a better calibration of the DMaC's control system with the aim of reducing these discrepancies.

In order to validate the obtained results, the output displacements from DMaC were implemented in the OrcaFlex models to obtain a comparison in terms of tension. A good correlation between the DMaC and OrcaFlex output was obtained. Fig. 14 - Fig. 19 show this correlation for each sample:

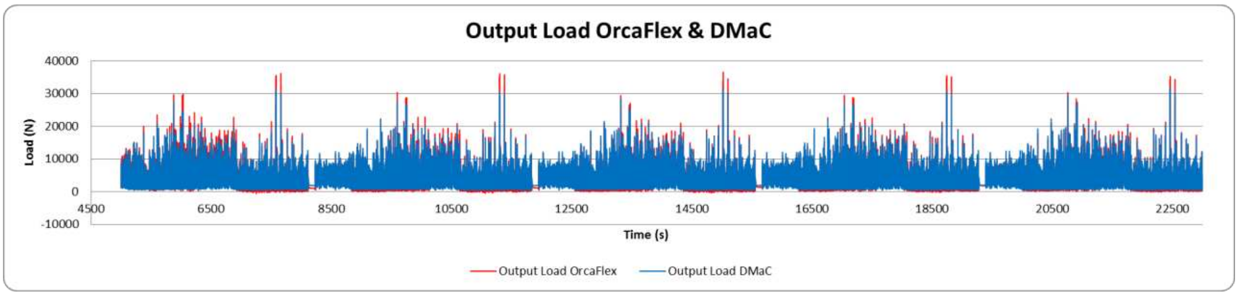

Fig. 14 Sample1Test3. Output Load DMaC vs. Output Load OrcaFlex, [10]

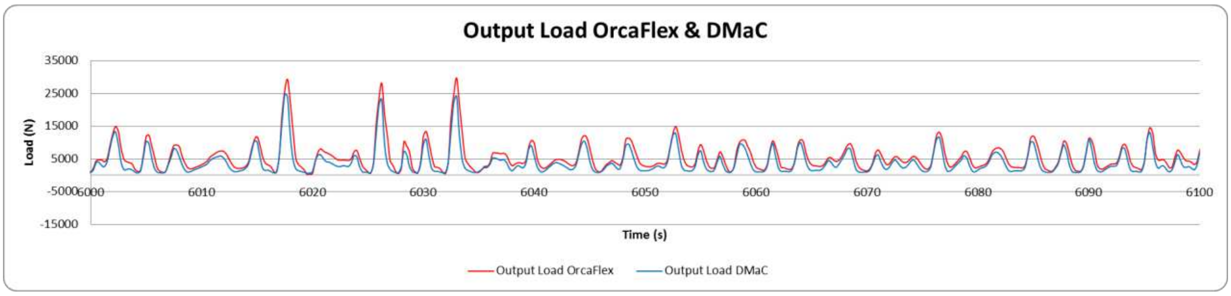

Fig. 15 Sample1Test3. Detail of Output Load DMaC vs. Output Load OrcaFlex, [10]

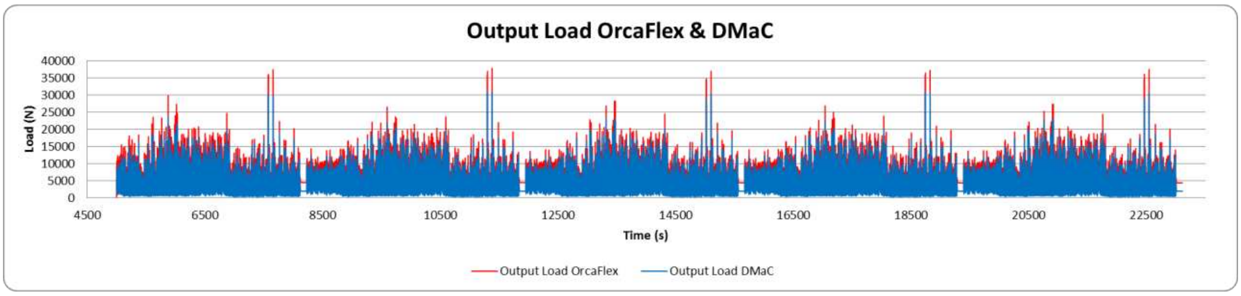

Fig. 16 Sample2Test9. Output Load DMaC vs. Output Load OrcaFlex, [10]

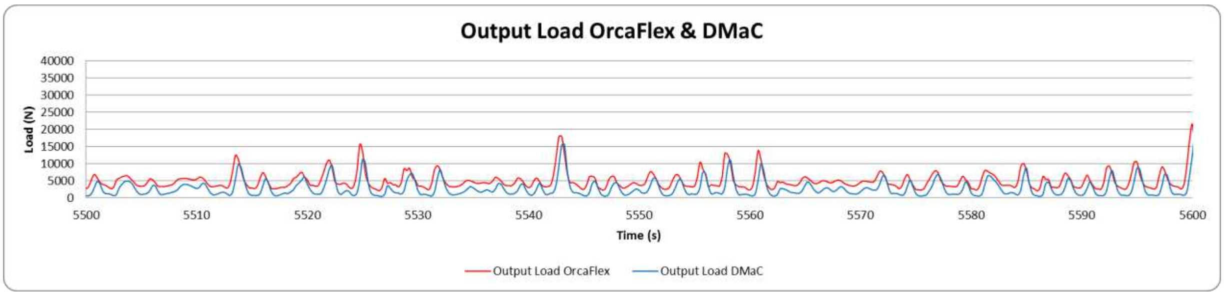

Fig. 17 Sample2Test9. Zoom of Output Load DMaC vs. Output Load OrcaFlex, [10]

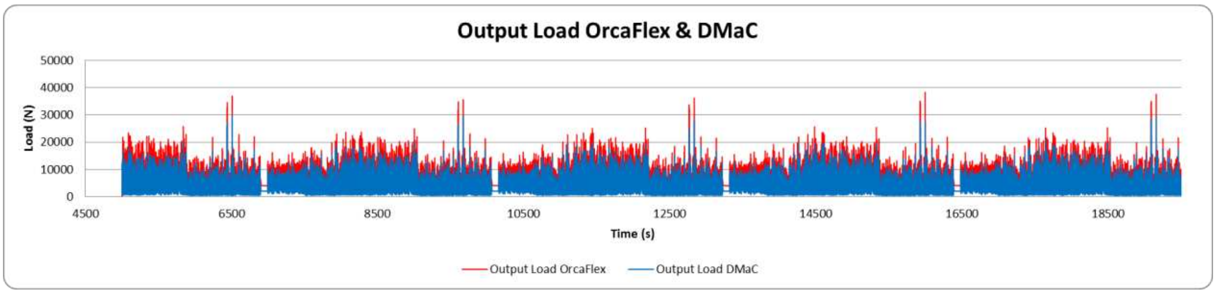

Fig. 18 Sample3Test17. Output Load DMaC vs. Output Load OrcaFlex, [10]

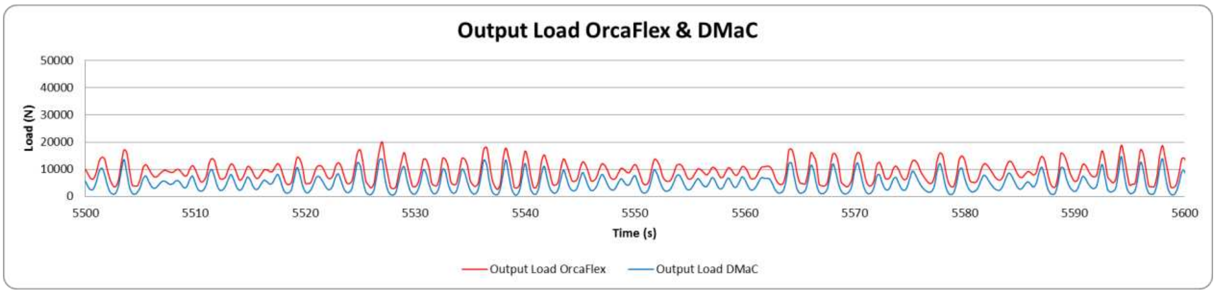

Fig. 19 Sample3Test17. Zoom of Output Load DMaC vs. Output Load OrcaFlex, [10]

In some parts of the simulations discrepancies between the numerical model and the test occurred. In Fig. 15 a lack in the hysteresis model can be seen in the discharges while in Fig. 17 and Fig. 19 the mean tension is a little bit lower in measured loads. This fact can be answered by two reasons: the creep phenomenon or the smaller axial stiffness of the wet conditions than dry conditions.

The information contained in the charts Load vs Strain was transformed to obtain the mean curves of the stiffness of each sample. During this post-processing, different behaviour of the same samples was observed. There are large differences between the results obtained during the first and second days of testing for each sample. In day 1, there is roughly a 4 – 5% of elongation during initial loading; however, in day 2 the behaviour is more or less linear. This effect can be observed in Fig. 20 and Fig. 21:

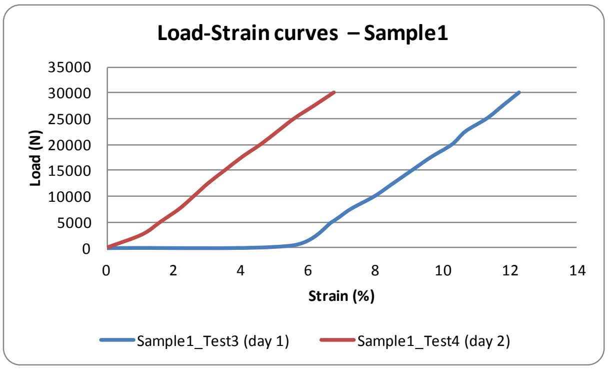

Fig. 20 Load-Strain curves for Sample 1 (day 1 and day 2) , [10]

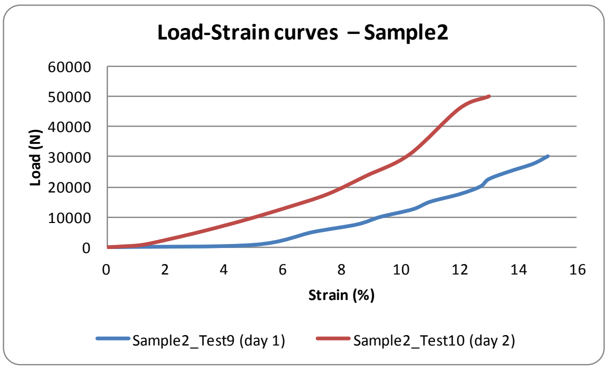

Fig. 21 Load-Strain curves for Sample 2 (day 1 and day 2) , [10]

These differences are due to the previous loading experienced by each sample (bedding in cycles and day-1 loads). It is standard practice to apply bedding in cycles prior to testing to enable the rope to be conditioned from its manufactured state to one to which is known. The end result of this realignment and viscoplastic deformation is residual strain. Therefore, when applying bedding in cycles to samples for the first time, it is expected that some permanent extension will occur, mainly due to 'pull-out' or constructional rearrangement of the rope. From the DMaC test results it can be concluded that whilst 5 bedding in cycles were selected due to the length of test time available, the samples were not fully bedded in.

In a study of larger diameter nylon ropes, an increment of strain of around 6% after bedding in was noted [11].

Another result achieved from the analysis of the information provided by DMaC is related to the influence of the testing environment. Fig. 22 shows the behaviour of the 3 identical samples which only differ in the testing environment and the speed of load application.

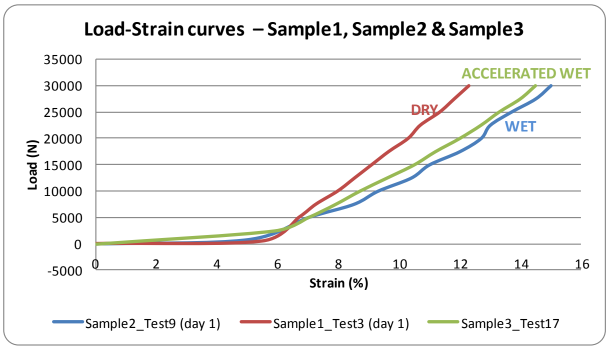

Fig. 22 Behaviour of the 3 samples, [10]

Finally, fatigue analysis using the Rainflow method was conducted in OrcaFlex in order to determine the fatigue damage resulting from the DMaC tests. Fig. 23 show the fatigue damage of the five tests conducted during the exposure time for each sample.

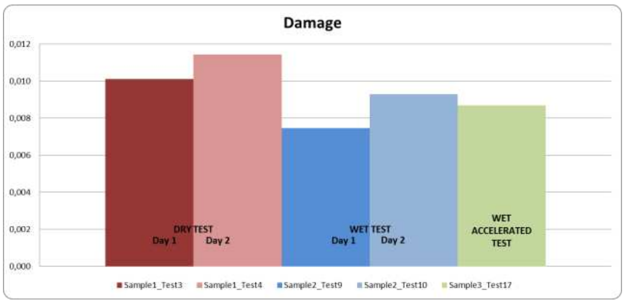

Fig. 23 Damage obtained in Fatigue Analysis, [10]

Similar levels of fatigue damage were expected, however different values were obtained. Two differences were obtained. The first difference is that, in all the cases, the fatigue damage during the second day of testing was higher. These discrepancies may be due to the differences in the stiffness. The second difference is that higher values of fatigue damage were obtained in dry testing conditions. A difference of a 24% in terms of fatigue damage was obtained. This discrepancy may have arisen due to the fact that the same S-N curve was used for all the analysis (wet and dry conditions), or the parameters used in the counting cycle algorithm.

It can be concluded that the use of water in the tests is a determining factor, even though the samples were not fully saturated prior to testing; however a notable decrease in axial stiffness was observed which is typical of wet nylon (e.g. [12]). This difference should be considered when designing MREC mooring systems comprising nylon ropes. Likewise, it was deducted that accelerating the application of loads causes a small increase in the axial stiffness of the rope. Whilst it has been noted that a mild effect of load rate on axial stiffness before in previous tests conducted by the UoE, further testing would be required before firm conclusions could be drawn.

Intuitively it makes sense; the sample has less time to recover between each load cycle.

VII. CONCLUSIONS

The main and secondary objectives set at the beginning of the project were met in full. On the other hand, the key points were met, since the definition of the base line load cases and the development of numerical models based on the rope properties have been achieved. Also, despite the unexpected drawbacks, (the failure of a load cell), the tests at the SWMTF and the data collection for the real sea conditions were carried out.

The main conclusions of the tests carried out in the South West Mooring Test Facility (SWMTF) are:

- Although load cell 1 failed after some days and the tension data couldn't be measured, due to the SWIFT has displacement sensors on board it could be possible to generate the line tensions through simulations, although this means an extra effort of data processing.
- The response characteristics of a MREC result in higher frequency loads than an Oil & Gas platform, so this must be taken into account carefully.

The accelerated tests at DMaC based on the real load cases obtained in the test site in open water were conducted and the validation of the numerical model and the correlation of the accelerated tests in the laboratory (DMaC) with the test at sea (SWMTF) were accomplished.

The main conclusions of the tests carried out in the Dynamic Marine Component Test Facility (DMaC) are:

- The behaviour of the ropes has been obtained for random loads, what is not easy to obtain for rope manufacturers.
- A good correlation between the measured DMaC output and OrcaFlex time-series was observed.
- The numerical model of the rope behaviour has been validated and (after further validation) could be used in commercial projects.
- Prior load history is very important. The standard bedding in cycles didn't achieve full conditioning of the samples.
- Different behaviour of the ropes in dry and wet conditions was demonstrated. The use of water is very important in this type of tests, necessitating samples to be fully saturated prior to testing.
- A decrease in axial stiffness was noted for the samples tested in wet conditions in comparison to those tested in dry conditions.

In the long-term, it is expected that cost-effective fibre rope taut mooring lines in deep water applications will be developed for the emerging MREC industry. This will provide a new market for rope manufacturers and help advance the MREC industry further into deeper and more energetic wave environments.

At present, the MARINET post-access reports are available at the web site of MARINET as FibreTaut#1 and FibraTaut#2 [13].

VIII. FURTHER WORK

The decommissioning of the ropes is scheduled to be performed after the winter season (Summer 2015). The ropes will be sent to Lankhorst-Euronete Portugal to be subjected to further testing and analysis in order to consolidate the conclusions reached so far and even to develop some more.

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