Evaluation of Wire-Lay Nylon Mooring Lines in a Wave Energy Device Field Trial

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***Abstract*— A 1/7 scale wave energy conversion (WEC) device was installed in Puget Sound for over a year in a realistic scale wave environment. The objectives of the trial were:**

- **Evaluate the behavior of the WEC**
- **Assess the performance of a wire-lay nylon mooring line anchor system. This paper reports the results of the mooring system.**

The costs of mooring systems for offshore marine renewable energy devices are a critical component in developing an economically feasible installed system. Several factors contribute to this, including the fact that conventional mooring technologies and components have been applied to renewable energy systems with little attention paid to optimizing the overall system. The Puget Sound scale WEC installation offered an opportunity to evaluate the performance of an unconventional mooring line construction for a WEC in field conditions.

Offshore WEC systems are typically located in shallow water (depth<50m), high-energy wave environments. Typically the wave loads drive the mooring configuration, size and cost. In order to minimize dynamic wave loads, options have included using very long or heavy catenary moorings, sinkers, subsurface buoys or long lengths of polyester synthetic lines to lower system modulus. The resulting mooring systems become complicated and costly to install and often occupy a large footprint on the seabed.

Use of traditional laid or braided nylon lines provided high elasticity to help dissipate load but at the expense of poor fatigue behavior. Wire-lay nylon offers high elasticity with greatly increased fatigue life. Successful demonstration of wire-lay nylon in WEC moorings had the potential for significant reductions in material and installation cost.

Sound & Sea Technology, Inc. designed and installed the mooring with Whitehill Manufacturing Corp. wire-lay nylon mooring lines. Whitehill's wire-lay lines are designed specifically to be used in applications where a combination of low elastic modulus and high fatigue durability are required. The line construction differs substantially from laid ropes and braided constructions. Wire-lay lines have the following advantages compared to conventional line constructions:

- **No strand crossovers to eliminate internal abrasion in the body of the rope. For braided constructions, internal abrasion at the strand crossovers results in rope strength reduction and poor fatigue performance.**
- **Individual protective strand jacketing to minimize abrasion between strands in the splice region. These jackets also provide protection from UV, foreign particle ingression, and external damage to maximize rope service life.**

This paper reviews the design criteria for the Puget Sound WEC mooring configuration. The physical characteristics of the wire-lay mooring lines used for the initial modeling and analysis of the mooring design and their influence on the final mooring design are described.

The data acquisition system provided wave height, period, and mooring loads. After the WEC was taken out of the water the mooring lines were recovered and tested in Whitehill Manufacturing's laboratory.

Residual tensile strength was measured, and any physical degradation was noted. Cyclic tests were conducted to predict remaining rope fatigue life.

This field trial demonstrates the utility of wire-lay mooring lines for wave energy, and by extension, other at-sea moored systems that require low elastic modulus, long fatigue life mooring configurations.

Keywords—mooring, nylon, synthetic, rope, wave energy conversion, alternative energy

I. INTRODUCTION

Synthetic ropes have long been used in the marine and offshore industries for various applications from reusable moorings for vessels to permanent moorings for oil drilling and pumping units [1,2]. The critical criterion of these applications is that movement is minimized. This calls for a taut mooring system with a high elastic modulus. WEC devices represent applications where movement is instead essential. The Puget Sound WEC field trial device operates optimally with a system that applies minimal vertical forces. A low tension tri-moor, described in further detail later, is used to apply restoring forces almost entirely in the horizontal plane.

The nylon mooring lines of the field trial were evaluated. An overview of fatigue life, modulus data and mooring

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configuration will be presented. This data can be used as a resource for future alternative energy applications requiring a low elastic modulus such as wind, wave, tidal, and thermal energy converters. Fig.1 below is the WEC device used in this field trial.

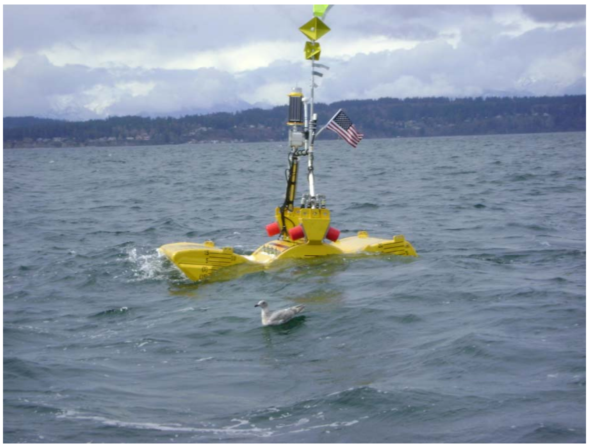

Figure 1. WEC device installed in Puget Sound for over a year.

II. Rope Design and Modulus Values

Whitehill Manufacturing Corp. designed and manufactured a high-performance wire-lay nylon 3-strand rope for the WEC device application. A polyester braided jacket was applied to each individual strand as an abrasion and UV protective element. The experimental data outlined below is provided as a reference for the design of the synthetic mooring.

A. Nylon Properties

1) Permanent Elongation

Synthetic rope has a degree of permanent elongation that can affect a mooring configuration. When a line is loaded to a particular load level whether that occurs deliberately during installation or inherently from environmental conditions the line has an amount of permanent elongation, resulting from its load history. Load levels are evaluated as a percentage of the minimum break load (%MBL). Fig. 2 below is an example of an installation procedure that leaves the line permanently elongated.

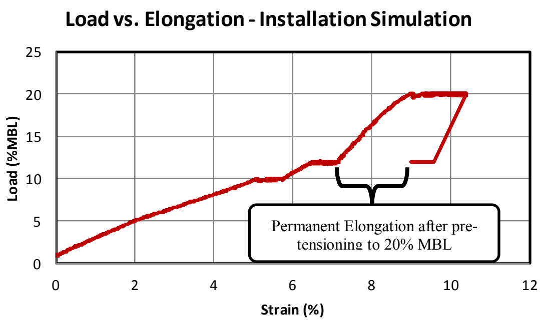

Figure 2. Installation procedure for a nylon rope using a 12% working load and a 20% pre-tension.

The Puget Sound WEC trial used a mooring design with line loads around 2% MBL and no pre-tensioning procedure. With these characteristics, rope permanent elongation was negligible. However, full scale designs may see an increase in these and therefor an increase in permanent elongation. There are also other types of WEC devices that are optimized using taut moorings [3]. These systems will also need to consider permanent elongation when designing a mooring and developing an installation procedure.

2) Static Modulus

Static modulus is the rope's response to long-term environmental forcing functions. These are typically winds, currents and tides that maintain a constant elevated velocity. When exposed to prevailing environmental conditions the device shifts its position relative to the seabed. This is known as an offset. Offsets are important depending on what subsurface connections are in place. Fig. 3 below displays the static modulus of a nylon rope up to 20% MBL.

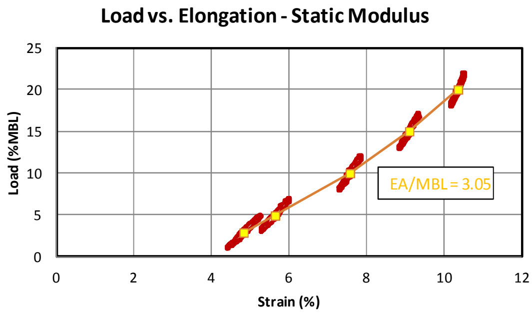

Figure 3. The nylon line is cycled at several different mean loads as it is brought up to a maximum mean load of 20% MBL.

3) Dynamic Modulus

Dynamic modulus is the rope's response to shorter periodic forcing functions such as waves and vortex induced motion (VIM). The dynamic modulus is utilized by mooring engineers when determining responsible safety factors. A lower dynamic modulus leads to lower mooring loads. Fig. 4 depicts several different load amplitudes around 10% mean load. Fig. 5 is a similar graph around 15% mean load.

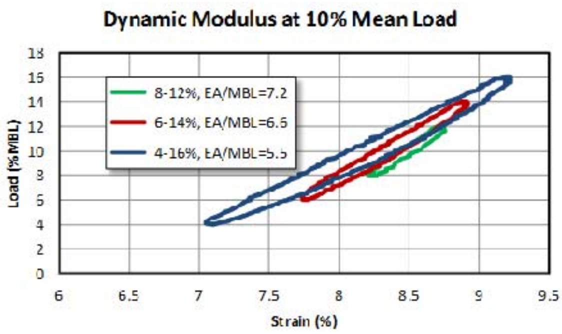

Figure 4. Three different dynamic modulus numbers are determined by cycling the nylon line around a 10% mean load.

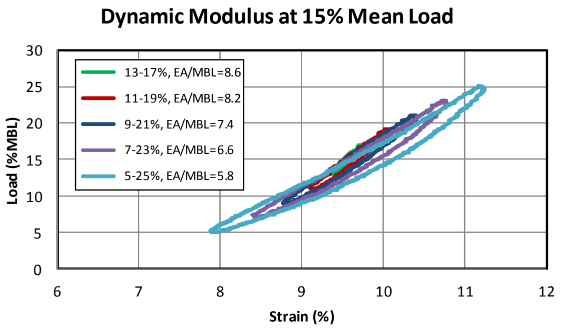

Figure 5. Five different dynamic modulus numbers are determined by cycling the nylon line around a 15% mean load.

B. *Rope Construction*

Nylon is the material of choice in applications like the WEC device, which call for a low elastic modulus. The low elastic modulus serves to reduce loads in high-energy environments where WEC systems are deployed. However, when choosing a synthetic rope, the construction of the line is also a major design factor to take into consideration. Rope construction can greatly affect fatigue characteristics as seen in Figure 6 below. Load levels are recorded as a percentage of average break strength (%ABS). The increase in fatigue life of wire-lay nylon has been proven in the marine industry. Wire-lay nylon hawsers have been used in vessel to vessel moorings with significantly improved fatigue life as compared to braided constructions [4].

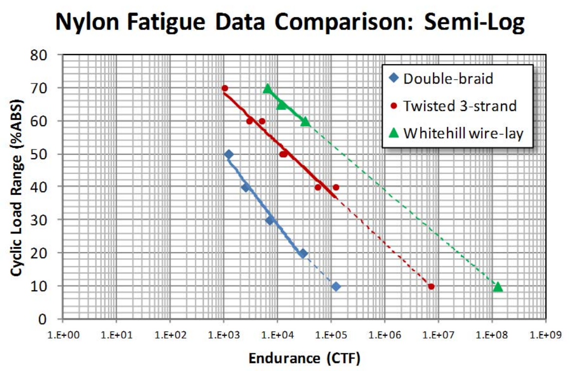

Figure 6. Fatigue life comparison of double-braid, twisted 3-strand and Whitehill wire-lay [5].

III. Mooring Design

In February 2011 a WEC device was installed in Puget Sound. It needed a mooring system that would maintain a fixed global position while allowing for large vertical movements to maximize energy generation. This is accomplished using a conventional tri-moor with surface floats and deadweight anchors. Figure 7 shows the WEC mooring configuration designed and installed by Sound & Sea Technology, Inc. The horizontal lines are wire-lay nylon rope, and the vertical legs are 6-strand steel wire rope. As part of the design process, the mooring was analyzed for loads using ANSYS AQWA. These simulated loads were then compared to the field-measured loads recorded over the duration of the installation, and found to be in good agreement.

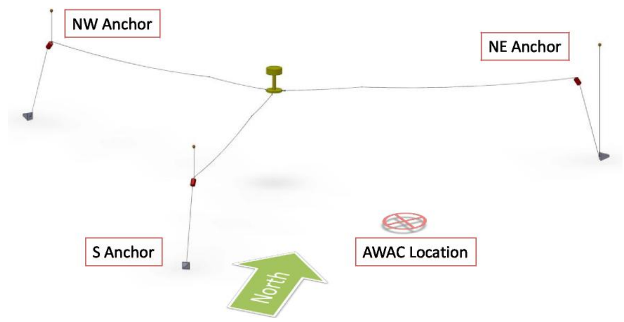

Figure 7. Puget Sound WEC device trial mooring configuration.

IV. Mooring Field Trial Results

The trial WEC device was left in service for 400 consecutive days. The lines were handled several times throughout the trial including the removal of the WEC device once for servicing. The mooring lines were left in place while only the WEC device was removed. It is important to note any handling, because excessive handling can increase chances of damage and may decrease line service life.

The Puget Sound mooring lines were returned with no sign of abrasion due to mishandling.

The average wave period during this field trial was 2.08 seconds causing approximately 16.6 million tension-tension fatigue cycles over the service life of the mooring lines. Fatigue cycles had a low mean load and small cycle amplitude compared to conventional moorings. Tensions remained below 3% MBL for nearly the entire trial. This level of tension is significantly lower than taut mooring systems which operate from 10%-20% MBL [6]. For WEC systems there are a wide range of optimal mooring configurations and tensions specific to each energy generation system from the low tensions seen in this field trial to semi-taut and taut moorings [7]. Fig. 8 is load level data for one mooring line over the course of the trial. There are some periods where data collection ceased. Fig. 9 is load data over a typical day.

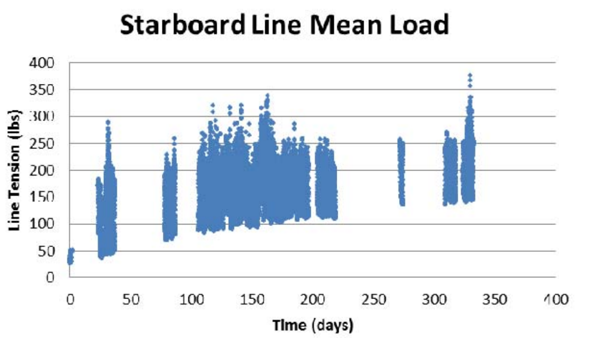

Figure 8. Mean mooring line tension data for the starboard line over a year.

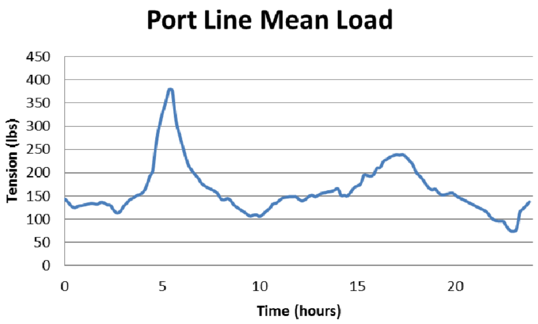

Figure 9. Mean mooring line tension data for the port line over a day.

The maximum load on any line was 1,078 pounds. This load corresponds to less than 5% of the lines rated strength. This demonstrates that load levels were well below the rated strength of the lines. With this low-tension mooring configuration, the risk of overloading the lines is extremely low.

V. Mooring Line Test Results

Mooring lines were removed at the end of the trial period and were tested for residual strength and remaining fatigue life. Fig. 10 below is one of the original eyes used in the mooring assembly. The mooring lines were cut into sections and new eyes were spliced as necessary to create samples with at least a 10 ft. gage.

Figure 10. Original nylon mooring line eye.

A. *Break Strength Results*

To quantify the safe working loads of the used ropes a break strength test is conducted. Samples were loaded ten times to a nominal load to bed-in new splices. Then the ropes are loaded until failure. Fig. 11 and Table 1 summarize the break strength test results.

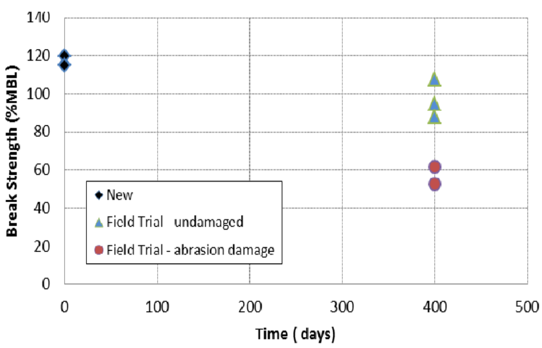

Figure 11. Whitehill wire-lay nylon mooring lines residual break strength.

TABLE I. Break Strength Results

Break Strength (lbs)	Comments
23,960	New
23,090	New
23,000	New, Exposed to the elements for 2 ½ months
12,330*	Used, NE leg "Anchor eye", 25 lay lengths of damage, one original eye
10,510*	Used, South leg "Anchor eye", visible damage, one original eye
17,600	Used, South leg two new eyes, middle of longer leg
21,520	Used, NE leg, used with no damage, one original eye
18,930	Used, NE leg two new eyes, middle of longer leg

* Strength loss due to abrasion damage caused by floats.

Two break strength results, denoted with asterisks in Table 1, were much lower than our expected values due to tension-tension fatigue alone. A visual inspection of these test samples revealed signs of external abrasion. The location of the abrasion within the mooring assembly lead to the conclusion that contact with the surface floats was the cause of the abrasion. It is possible that the rope came into contact with the float and over millions of cycles began to wear through some of the load-bearing fibers. Although the strength of the rope did fall markedly, the safety factors were great enough that the system performance remained unaffected. However, when moving to a full-scale system it would be advisable to employ a remedy for this abrasion issue, such as increased line tension, additional abrasion protection, and/or additional hardware to create separation between the rope and the surface floats..

B. *Fatigue Results*

Residual break strength is not enough to fully characterize the wear done to a synthetic rope. Mooring lines can often retain high break strengths even though cyclic fatigue life has suffered significantly. J. Flory's progressive failure model is a standard for comparison of fatigue life test results [8]. Fig. 10 is a comparison of Flory's model to the results for the unused 3-strand nylon lines. As shown in fig. 12, if tension-tension fatigue is the only mode of fatigue present, the Whitehill nylon lines will outlast the standard.

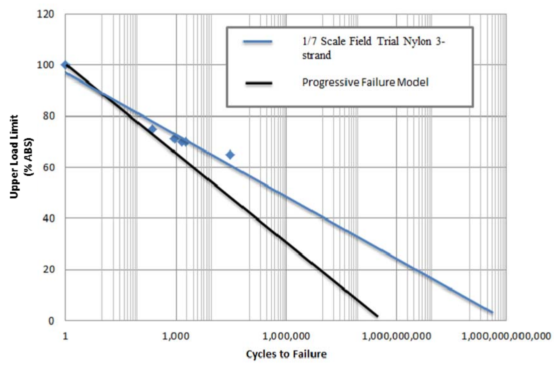

Figure 12. Fatigue results for new Whitehill 3-strand nylon wire-lay mooring lines compared to Flory's progressive failure model.

Fatigue tests were carried out on the lines returned after the Puget Sound field trial to determine the remaining fatigue life of the lines. These results were compared to results of the fatigue life of new lines. Fig. 13 below graphically summarizes the fatigue results.

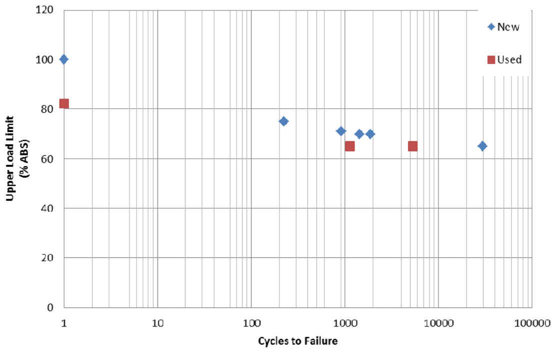

Figure 13. Fatigue results for new and used Whitehill 3-strand nylon wire-lay mooring lines.

VI. CONCLUSIONS

The 400 day long wave energy conversion device field trial using high-performance wire-lay nylon 3-strand rope is a great opportunity to accrue data for both moorings and alternative energy applications. During the trial a large array of data was collected, such as mooring load levels for all three lines, wave heights, wave heading, current and wind speed, water depth, etc. This data will serve as a basis for future testing and design of promising new technologies in a rapidly-growing market.

This paper offers a broad overview of the mooring design process and can serve as a rope selection example when looking for low elastic modulus, long fatigue life mooring lines.

The low tensions under which this field trial was conducted make it a unique and interesting mooring configuration to study. Break strength data produced residual strengths from 74%-91% MBL. Fatigue tests were run to build a used rope database. Further fatigue testing and modeling will be done to create a complete understanding of the fatigue mechanisms present.

Wire-lay nylon rope offers a cost-effective solution to mooring systems operating in high energy wave environments. Use of low modulus nylon lines results in lower mooring loads, which translate to lower mooring and installation costs. The wire-lay construction extends the life of the lines making it an economically viable solution. With the success of this field trial full scale WEC moorings have been designed using Whitehill wire-lay nylon rope constructions.

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