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Integrity and reliability testing of a HDPE taut mooring system belt

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Abstract — **The integrity of the mooring system is critical for the safe station-keeping of any floating structure. For motion dependent wave energy converters, the additional requirement is to provide sufficient compliance to allow the power take-off working principle to function. This paper presents the physical testing carried out as part of the MARINET2 test programme. The mooring system design for the Calwave wave energy converter is tested in order to validate the actual physical performance of the mooring system. The tests are carried out at the Dynamic Marine Component Test facility (DMaC), capable to replicate the forces (up to 30 tonnes) and motions (up to 1m / 30°) with submersed test specimens of up to 6 meters length. The tests explore the Minimum Breaking Strength (MBS) as a primary measure of integrity, but will also perform repeated cyclic loading, simulating low-cycle fatigue behaviour of the mooring system. The tests also assess the mooring response and integrity under simulated Accidental Limit State (ALS) conditions, where the device's power take-off will be locked and the mooring loads are expected to increase considerably. A key finding of the tests is the importance of the termination pattern and quality, which has a direct influence on the mooring MBS. The static and dynamic stiffness for the tested HDPE belts is also determined. The paper will be of interest to technology developers, mooring designers and stakeholders concerned with the integrity, durability and validation of offshore mooring systems.**

Keywords—**Reliability, Component Testing, Mooring, Shock Load, Tension-tension test.**

I. INTRODUCTION

MOORING systems are one of the most important sub-systems for floating offshore structures, as they warrant the safe station keeping of the installation. Thus, the design and testing of mooring systems has to take into account the technology development status. According to [1] technologies can be classified regarding their technology status (Proven, Limited field history, new/unproven) and their application (known, unknown). The assessment yields a technology class range from 1 - 4:

1. No new technical challenges
2. New technical uncertainties
3. New technical challenges
4. Demanding new challenges

Class 1 and 2 represent well established, demonstrated mooring systems with a track record in the field and multiple monitored installations. For many floating wave and tidal energy technologies the 'application' has to be classed as 'new', as there often is not sufficient field experience with a complete system. This classes the mooring system as category 2 and above, depending on the technology status itself. If the mooring system itself has limited field history (class 3) or is in itself new (class 4) additional design and test work is required to identify, quantify and validate the new technical aspects and challenges. This is a reoccurring issue and as a result dedicated component testing is increasingly used in order to physically test the behaviour and load capacity of sub-systems in general and mooring components in particular.

This paper reports the specifications and results for a tension-tension test, carried out on mooring belts. The belts constitute the critical component of a taut mooring system for the CalWave wave energy converter [2]. The paper is structured as follows. After the introduction, the test objectives, methods and specifications are described in section II. The results regarding the Minimum Breaking Strength (MBS), dynamic response and shock loading behaviour are presented in section III. The test outcomes will be discussed regarding the specific taut mooring design as well as wider technology assessment findings for the sector (section IV).

II. TEST OBJECTIVES AND SPECIFICATIONS

The aim of the mooring component tests were to validate the design assumptions for a taut mooring system. The critical component was identified to be a High Density Polyethylene (HDPE) mooring belt.

Relevant work in the literature includes the seminal paper by Banfield and Casey [3] on the evaluation and

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testing of mooring fibre ropes and their application for in the marine renewable energy sector [4].

As a known material / component in a new application some of the technical uncertainties were sought to be quantified and resolved.

A. *Test Objectives*

The specific objectives were:

1. to determine the quasi-static and dynamic stiffness of the mooring belts,
2. to verify the strength of belt loop terminations,
3. to quantify the belt response and integrity under shock loading.
4. to explore the fatigue life of the belt.

B. *Experimental setup*

The experiment was performed in the Dynamic Marine Component (DMaC) test facility, part of the University of Exeter. The DMaC test rig was designed to replicate operational and fatigue loads on marine components [5]. The tailstock provides linear motion comparable to heave and the headstock generates bending moments similar to pitch, roll and yaw, see Figure 1. In addition, the test samples can be fully submerged in fresh water during testing.

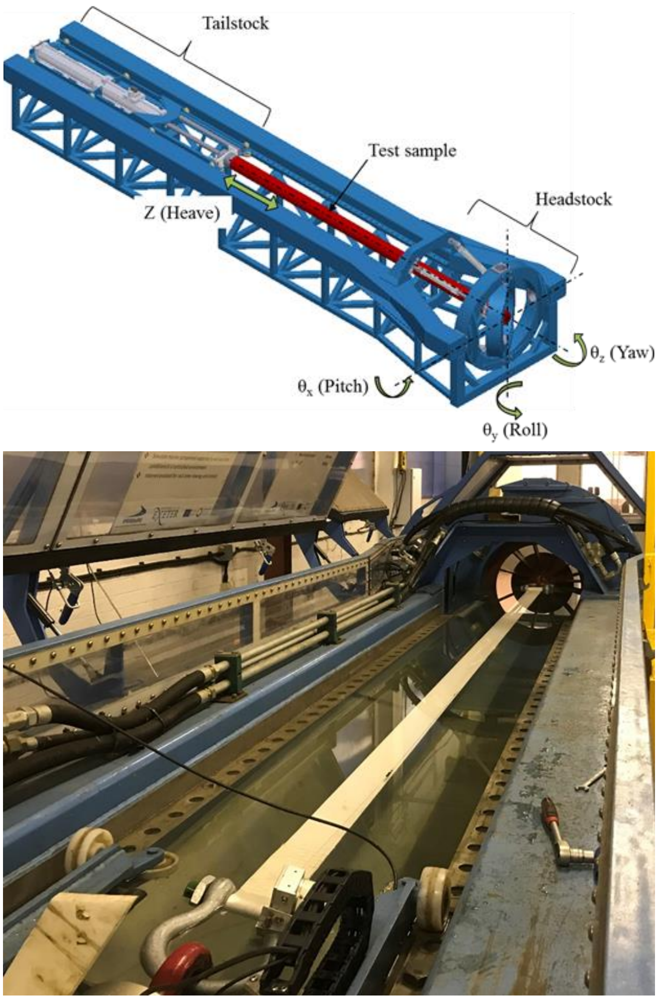

Fig. 1. Experimental setup in the Dynamic Marine Component test rig. Top figure: Engineering Drawing and conventions. Bottom figure: Installed and submerged test sample connection to the hydraulic actuator.

Two belt samples were manufactured, i.e. woven belt and termination stitching, by TTS Inova for the tests (hereafter referred to as 1-TTS and 2-TTS). Both components were a HDPE belt, 100 mm width and 2 mm thickness, see Figure 2. The loop length was 80 mm and the stitch length of 220 mm. The overall length (eye to eye) was ~5 m. The Minimum Breaking Strength (MBS) for the terminated belt was reported by the manufacturer (TTS Inova) to be 180 kN. The mooring belts were connected to test rig using shackles at either end. The shackles provided an inside width of 106 mm to accommodate the 100mm wide belt. The pin diameter was 42 mm.

Following an early failure of sample 1 (see section III), both belts were re-stitched, re-using the same belt material (HDPE, 100 mm width, 2 mm thickness). The loop stitching was carried out by SBK Sails Ltd. The samples were shortened to L = 3 m. Sample 3-SKB was constructed from sample 1-TTS and sample 4-SKB was constructed from sample 2-TTS. The re-stitching had a 40 cm loop length and a 30 cm stitch length, along with a reinforcement strip, see Figure 2.

It should be noted that sample 1-SKB had been pulled to failure at 78 kN (see section III) and sample 4-SKB has been bedded in using an MBS of 20 kN.

Fig. 2. HDPE mooring belts – loop stitching. Left – Sample 1-TTS closeup of loop stitching. Centre: Sample 3-SKB closeup of loop re-stitching. Right: 3-SKB closeup of reinforcement strip in belt loop.

C. *Test Procedure*

The tests followed the procedures of ISO 19336:2015 (Fibre ropes for offshore station keeping – Polyarylate) [6]. The test procedure involves four stages, see Fig 3:

1) bedding in (B.3.1),
2) quasi-static (B.3.5.2),
3) dynamic stiffness (B.3.5.3.A) and
4) breaking strength (B.3.1).

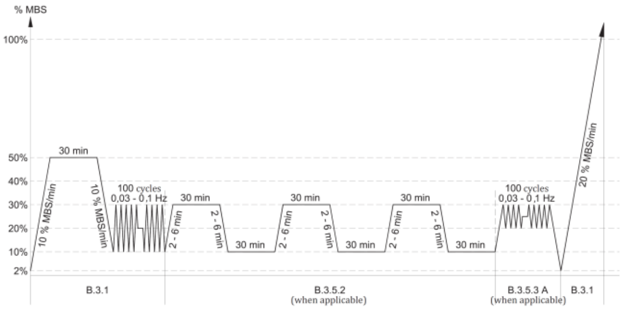

Fig. 3. Quasi-static stiffness, dynamic stiffness and breaking test sequence, B.3; see [6].

The belt response and integrity regarding the shock loading was tested by repeated, sudden tension increases. Theses loads were imposed after the bedding in process (B.3.1). Following the shock loading the ISO 19336 procedure was continued, i.e. quasi-static (B.3.5.2) and dynamic stiffness (B.3.5.3.A), followed by a final break strength (B.3.1) test. The shock load profile was provided through scale-model testing of the prototype device supplied by CalWave. Fig. 4 shows the load profile that was employed for these 'shock loads'.

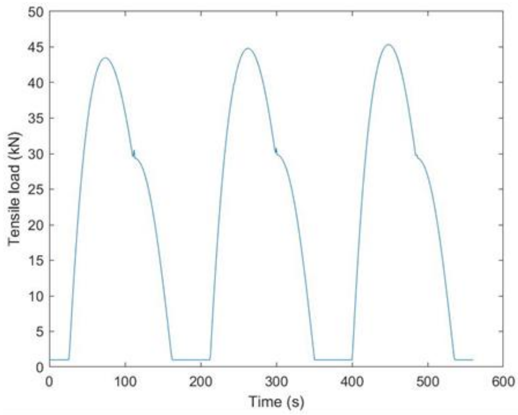

Fig. 4. Shock load profiles for belt integrity tests. The load signal was determined through physical scale-model testing

The complete test sequence of all four samples is summarized in Table I, along with the assumed MBS.

D. *Measurements and calibration*

The tensile load was measured by a DSCC pancake load cell manufactured by Applied Measurement Ltd, UK; full-scale linearity of ±0.039%.

The piston displacement was measured using a LM10 linear encoder manufactured by RLS; resolution of 0.05 mm.

A WS12 draw-wire transducer manufactured by Applied Measurements was used to measure the sample elongation. ISO 19336 requires the transducer be connected at least three rope diameters from the last splice tuck; however, the transducer connection would affect the belt cross-section. Thus, the transducer was clamped to the shackle, see Figure 6. The draw-wire was stitched through the belt using Kevlar thread.

TABLE I
SUMMARY OF TEST SEQUENCE

Sample	Test sequence	MBS [kN]
1-TTS	Bedding in (B.3.1) – Sample failure	180
2-TTS	Bedding in (B.3.1) – Quasi-static stiffness (B.3.5.2) – Dynamic stiffness (B.3.5.3.A)	20
3-SKB	Bedding in (B.3.1) – Quasi-static stiffness (B.3.5.2) – Dynamic stiffness (B.3.5.3.A) – Break (B.3.1)	180
4-SKB	Bedding in (B.3.1) – Shock loading - Quasi-static stiffness (B.3.5.2) – Dynamic stiffness (B.3.5.3.A) – Break (B.3.1)	180

The measurements were recorded using a National Instruments (NI) compact Reprogrammable Input Output (cRIO) 9022 at a sample rate of 50 Hz. Load measurements utilised a NI 9237 C-Series module and displacement measurements used a NI 9205 C-Series module for the cRIO.

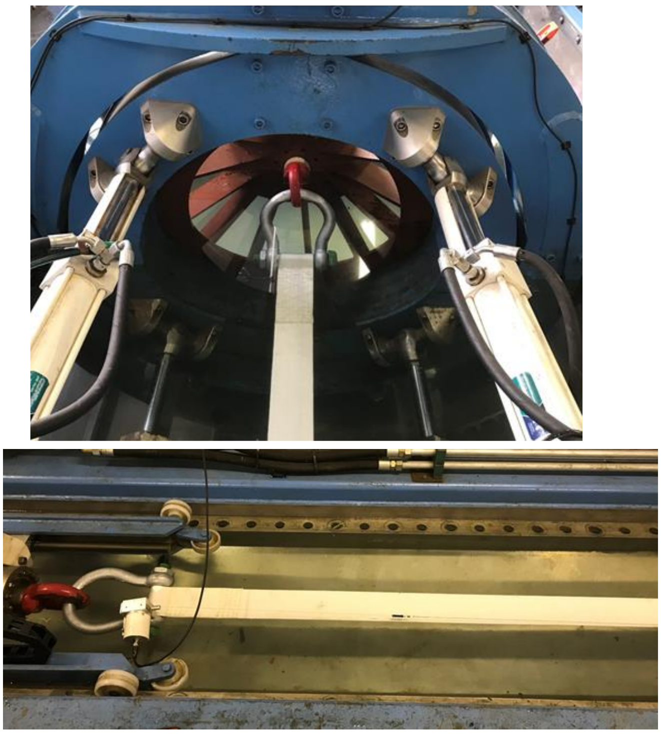

Fig. 5. Experimental setup – connections. Top: Headstock connection. Bottom: Tailstock connection of the belt sample with draw wire potentiometer attached to belt.

The tailstock load cell was calibrated using an external load cell and voltmeter with traceability to National Physic Laboratory. The draw-wire transducer was calibrated against a steel ruler.

TABLE II

SUMMARY OF MOORING BELT TEST RESULTS, MINIMUM, BREAKING STRENGTH (MBS) AND STIFFNESS VALUES, AFTER ISO 19336:2015

Sample	Minimum Breaking Strength (MBS)	Dynamic stiffness (end of bedding in) (K_{rb})	Dynamic stiffness (K_{rd})	Quasi-static stiffness (K_{rs})
Unit	[kN]	[kN/m]	[kN/m]	[kN/m]
1-TTS	78.0	N/A	N/A	N/A
2-TTS	N/A	6.400	12.42	6.397
3-SKB	144.9	2.903	3.989	2.038
4-SKB	205.9	0.976	1.254	0.578

III. RESULTS

E. *Minimum Breaking Strength (MBS)*

Sample 1-TTS failed at 78.0 kN load, see Fig. 6. The stitching on the belt loop started to fail as low as 21.9 kN, indicated by the small load decreases in the time history. Sample 3-SKB failed at 144.9 kN MBS, see Fig. 7, and sample 3-SKB failed at 205.9 kN MBS, see Fig. 8.

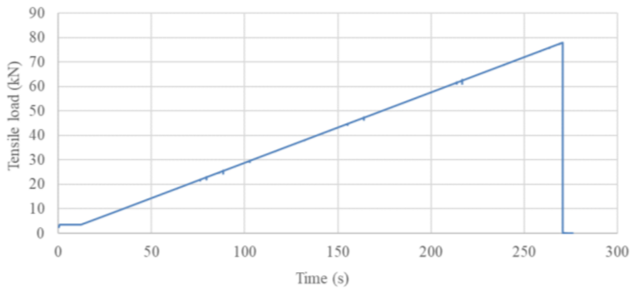

Fig. 6. Time series of tensile load test, sample 1-TTS failure at 78.0 kN. The small load slips indicate the onset of loop failure.

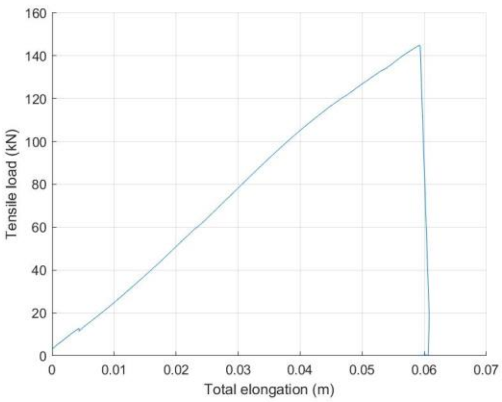

Fig. 7. Sample 3-SKB - load extension plot, with MBS of 144.9 kN.

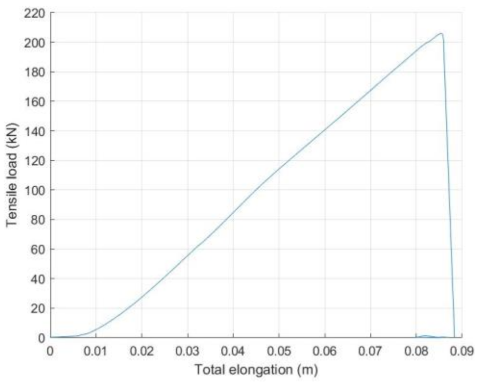

Fig. 8. Sample 4-SKB - load extension plot, showing MBS of 205.9 kN.

F. *Belt Loop failures*

Across all tests, the mooring belts failed at the stitched loop termination. Fig. 9-11 show the three failed samples 1-TTS, 3-SKB and 4-SKB.

Sample 1-TTS failed at a relatively low load of 78kN, which was a factor 2.3 lower than the expected MBS, provided by the manufacturer. Fig. 9 shows the complete failure at the belt loop stitch at one end, as well as the progressed stitch failure at the other end of the belt. Sample 3-SKB failed at a higher MBS of 144.9 kN (see Fig. 10), which can be attributed to the improved loop termination through increased loop diameter/length, reinforcement and extended stitching. Sample 4-SKB reached a higher MBS of 205.9 kN, failing at the stitch, but also showing the onset of an additional failure mode, a transverse tear across the belt (see Fig 11).

Fig. 9. Sample 1-TTS. Belt loop failure. Complete failure at headstock end (upper picture) and partial failure at tailstock end (lower picture).

Fig. 10. Sample 3-SKB. Complete belt loop failure at MBS = 144.9 kN.

Fig. 11. Sample 4-SKB. Complete belt loop failure at MBS = 205.9 kN. Two failure mechanisms were observed; failure of the stitch and a transverse tear across the belt.

G. *Load-Extension curves and mooring stiffness values*

The load-extension curves for sample 3-SKB are shown here as representative results for the quasi-static and dynamic stiffness tests, see Fig. 12-14. All three figures depict the measured elongation using the test rig measurements, rather than the draw wire transducer.

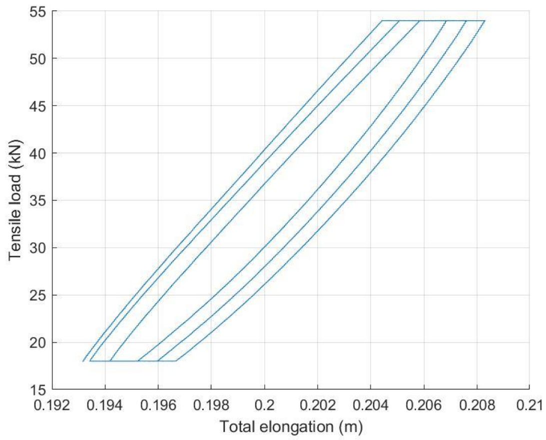

Fig. 12. Sample 3-SKB - Load vs total elongation of quasi-static stiffness test [ISO19336:2015 B.3.5.2].

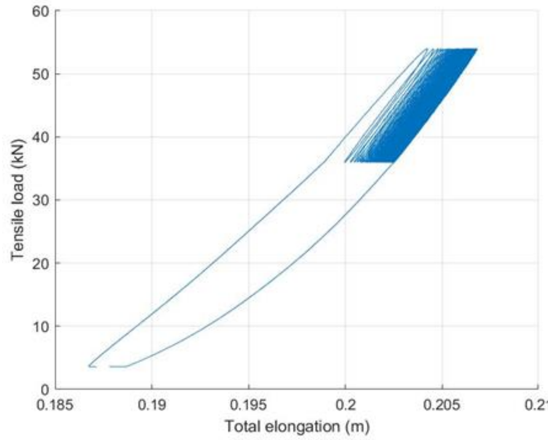

Fig. 13. Sample 3-SKB - Load vs total elongation of dynamic stiffness test [ISO19336:2015 B.3.5.3.A].

Fig. 12 and Fig. 13 show the bedding in of the samples, with increased elongation for repeated cycles. The stiffness remains relatively steady and can thus be calculated as the slope of a single-cycle.

Sample 4-SKB was also subjected to the repeated shock load signal (comp. Fig. 4). The mooring belt response is plotted in Fig 14. The hysteresis of the load extension response is relatively low, as the sample has been fully bedded in for this test, being close to a linear stiffness response.

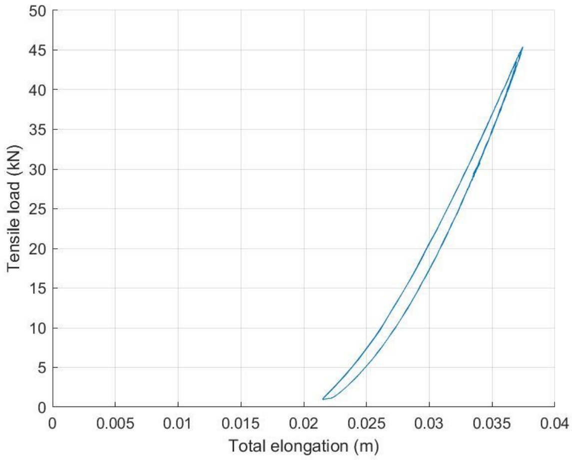

Fig. 14. Sample 4-SKB - Load vs total elongation of last three cycles of shock loads.

The load versus gauge elongation (draw-wire transducer) measurements (B.3.1) are shown in Fig. 15. The draw-wire transducer data is plotted using a 0.2s rolling average to reduce noise.

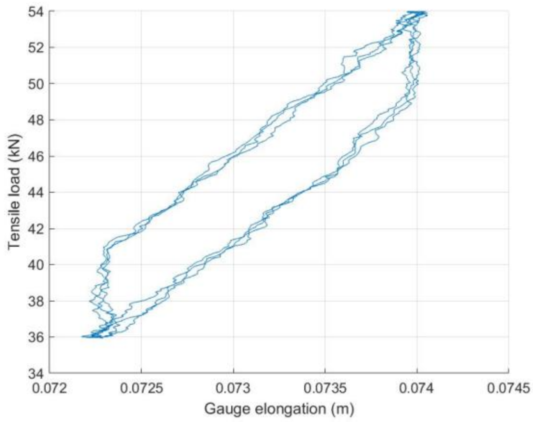

Fig. 15. Sample 3-SKB - Load vs gauge elongation of dynamic stiffness test (last 3 cycles) [ISO19336:2015 B.3.5.3.A].

IV. Discussion and Conclusion

H. *Safety Factors*

Design uncertainty demands the application of increased safety factors. In view of the premature failures (factor 2.3 lower than anticipated), a safety factor in the order of three appears to be justified, in terms of the belt termination. The revised and improved termination stitching was able reduce this factor to 1.2 and 0.9 regarding the expected MBS. The component testing and the subsequent termination improvements were able to demonstrate an improved MBS. It should be noted that this is only the safety factor regarding the specific belt MBS and the termination. The actual field installation will have many more uncertainties (e.g. return wave probabilities, mooring system response) and will thus require an additional probabilistic safety factor analysis for the overall design. It is noteworthy though, that component reliability testing is able to reveal physical failure modes, prior to field installation. This allows design improvements sufficiently early to avoid expensive and potentially critical failures.

I. Loop Termination

The loop termination failure of sample 1-TTS was likely caused by the loop terminations diameter being too small in relation to the shackle pin diameter. This applied non-uniform out-of-plane forces (perpendicular to belt surface) to the stitching causing premature failure.

J. Design Improvements

The belt loop design was initially improved by studying loop termination on lifting strops. The loop diameter was significantly increased from 8 cm to 40 cm and the stitch length was increased by 50%, from 20 cm to 30 cm. It is unclear whether the reinforcing strip had any affect.

K. Stiffness value

The stiffness values of the belt samples, see Table II, vary between 0.578 and 12.4 kN/mm. The highest stiffness values were from sample 2-TTS where the MBS was set to 20 kN, thus the measured stiffness values are only valid for low loads (less than 10 kN). The stiffness values of samples 3-SKB and 4-SKB (MBS 180 kN) had stiffness values ranging between 0.578 and 3.989 kN/mm. The stiffness of sample 3-SKB was between 3 and 3.5 times that of sample 4-SKB, for all values (K_{rb}, K_{rd}, K_{rs}), emphasising the variability in belt behaviour and construction. The belt design and manufacturing tolerances should be controlled as much as possible. For the field installation / mooring design, a physical characterisation of the belt properties is advised, as the load history regarding ageing [7] and operational conditions [8] have an influence on the stiffness of synthetic mooring ropes.

L. Effect of shock loading

The effect of shock loading on stiffness can be explored by comparing the dynamic stiffness before (K_{rb}, B.3.1) and after shock loading (K_{rd}, B.3.5.3.A) of samples 3-SKB and 4-SKB. The dynamic stiffness of sample 3-SKB (without shock loading) increased by 1.37 and sample 4-SKB (with shock loading) increased by 1.28. Thus, shock loading is likely to have had minimal effect of stiffness.

The effect of shock loading on the MBS and stiffness of the samples is unclear. The MBS of sample 4-SKB was 205.9 kN, which had been shock loaded, whereas the MBS of sample 3-SKB was lower at 144.9 kN. This is opposite to expectation because shock loading was expected to reduce the MBS. Additional component tests are required to better quantify the effect of shock loading.

M. Conclusion

This paper has reported the integrity and reliability testing of a HDPE mooring belt. The tests revealed the criticality of the belt loop terminations. The terminations were improved through increased stitch length and pattern and reinforced loop configurations. The improved design could be verified through further tests, showing a twofold increase in MBS, in the region of the manufacturer MBS values.

The static and dynamic stiffness of the mooring components were also determined, but showed some variability across the samples. This will inform the accurate numerical characterisation of the overall mooring system, providing stiffness envelopes for a higher fidelity mooring design.

References

[1] DNVGL-SE-0163 (2015) 'Certification of Tidal Turbines and Arrays'

[2] Kojimoto NC, Lehmann M., Murray, B, Boerner T, Alam, MR, 2017. Model Scale Submerged Hydraulic Power Take-Off With Adjustable Damping for Wave Energy Conversion. International Society of Offshore and Polar Engineers (ISOPE).

[3] Banfield S., Casey, N., 1998. Evaluation of fibre rope properties for offshore mooring. Ocean Engineering, 25(10), pp.861-879.

[4] Weller, SD, Johanning L, Davies P, and Banfield SJ, 2015. Synthetic mooring ropes for marine renewable energy applications. Renewable Energy, 83, pp.1268-1278.

[5] Thies PR, Johanning L. (2010) Development of a marine component testing facility for marine energy converters, 3rd Int. conference on Ocean Energy (ICOE 2010), Bilbao, 6th - 8th Oct 2010, Proc. of 3rd Int. Conference on Ocean Energy [ICOE].

[6] International Standards Organisation (2015). ISO/TS 19336:2015, Fibre ropes for offshore station keeping – Polyarylate

[7] Weller SD, Davies P, Vickers AW, Johanning L. (2015) Synthetic rope responses in the context of load history: The influence of aging, Ocean Engineering, vol 96, pp 192-204, DOI:10.1016/j.oceaneng.2014.12.013.

[8] Weller SD, Davies P, Vickers AW, Johanning L. (2014) Synthetic rope responses in the context of load history: Operational performance, Ocean Engineering, vol 83, pp 111-124, DOI:10.1016/j.oceaneng.2014.03.010.