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TENSION-TENSION TESTING OF A NOVEL MOORING ROPE CONSTRUCTION

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ABSTRACT

Synthetic fibre ropes are in widespread use in maritime applications ranging from lifting to temporary and permanent mooring systems for vessels, offshore equipment and platforms. The selection of synthetic ropes over conventional steel components is motivated by several key advantages including selectable axial stiffness, energy absorption (and hence load mitigation), fatigue resistance and low unit cost. The long-term use of ropes as safety critical components in potentially high dynamic loading environments necessitates that new designs are verified using stringent qualification procedures. The International Organization for Standardization (ISO) is one certification body that has produced several guidelines for the testing of synthetic ropes encompassing quasi-static and dynamic loading as well as fatigue cycling.

This paper presents the results of tension-tension tests carried out to ISO 2307:2010, ISO 18692:2007(E) and ISO/TS 19336:2015(E) on three different 12-strand rope constructions manufactured by Ashimori Industry Co. Ltd from polyester and Vectran® fibres. The purpose of the tests was to characterise the performance of a novel 12-strand construction and compare this to a conventional 12-strand construction. Utilising the Dynamic Marine Component test facility (DMaC) at the University of Exeter several key performance metrics were determined including; elongation, minimum break load (MBL) and quasi-static and dynamic stiffness. During the ISO 2307:2010(E) test programme the samples were tested dry and during the ISO 18692:2007(E) and ISO/TS 19336:2015(E) test programmes the samples were fully submerged in tap water after being soaked for at least 24 hours. Two methods were used to quantify sample extension: i) an optical tracking system and ii) a draw-wire potentiometer. Axial compression fatigue and cyclic loading endurance tests were also carried out on two Vectran® samples. Further load-to-failure tests and sample analysis were also carried out by Ashimori Industry Co. Ltd.

It was found that the MBL of the samples exceeded the values specified by the manufacturer (by 7.7-29.5% for the polyester samples) with failure occurring at the splices in all cases and minor abrasion noted in several locations. The measured MBL of the novel polyester Straight Strand Rope (SSR) construction was up to 16% higher than the conventional construction with increases of quasi-static and dynamic stiffness of up to 6.8%. Differences between the viscoelastic and viscoplastic behaviour of the samples were also noted. The data obtained during these tests will provide insight into the behaviour of these materials and different rope constructions which will be of use to rope manufacturers, mooring system designers in addition to offshore equipment and vessel operators.

INTRODUCTION

Synthetic fibre ropes have widespread use in the offshore sector. Several decades of use in challenging offshore environments has demonstrated their suitability for temporary and permanent mooring systems and lifting equipment for offshore equipment and vessels (i.e. [1]). For example the continued use of polyester (PET) mooring ropes enabled Lloyds Register to lower the required safety factor by 20%.

Procedures for the manufacture, classification, testing and use of mooring ropes have been developed by a number of certification agencies including (for testing) Bureau Veritas [2], Det Norske Veritas [3], International Standards Organisation [4, 5, 6], American Petroleum Institute [7] and American Bureau of Shipping [8]).

This paper summarises a series of tests carried out on three 24 mm diameter, 12-strand rope constructions (8 samples in total): i) a conventional polyester construction (specified minimum break load MBL_s = 120 kN), ii) polyester SSR (MBL_s = 169 kN) and iii) Vectran-SSR (MBL_s = 458 kN). Referring to Figure 1 the SSR variants tested were a novel construction (US patent application 20150152594 [9]) featuring twisted stands each of which comprised a core bundle of fibres inside "…a tubular woven fabric woven with warp and weft yarns made of synthetic fibers…". According to [9] the motivation for this innovation was to provide:

1. A high-tensile rope with low percentage elongation with an improved strength utilization rate.
2. A stable rope structure of which the lay length can be readily determined.
3. A scalable design for large diameter ropes.

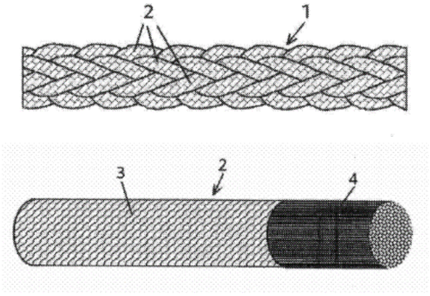

Figure 1: Schematic diagrams of the rope (1) showing individual strands (2) with tubular woven jacket (3) and fibre core (4), from [9].

With a view towards international certification of the design, the tension-tension tests reported in this paper focused on the performance of the three rope constructions based on the test procedures laid out in ISO 2307:2010(E) and ISO 18692:2007(E). Additional testing was also carried out to ISO/TS 19336:2015(E) to determine the cycling loading endurance and axial compression fatigue of two Vectran-SSR samples. Because the specified breaking load of the Vectran samples was above the maximum achievable DMaC load, Ashimori Industry Co. Ltd subsequently carried out load-to-failure tests on the Vectran samples from each ISO test. These tests were witnessed by ship classification society Nippon Kaiji Kyokai.

In the following section the experimental setup including the tension-tension equipment and measurement system are introduced. The experimental results are then summarized before conclusions are made.

NOMENCLATURE

ε_b	Failure strain	[%]
F_{ref}	Reference load (2% MBL)	[kN]
F_{max}	Maximum load achieved	[%MBL$_s$]
F_X	Minimum load during cycling	[kN]
F_Y	Maximum load during cycling	[kN]
K_{rb}	Dynamic stiffness at the end of bedding in	[-]
K_{rd}	Dynamic stiffness after cycling	[-]
K_{rs}	Quasi-static stiffness	[-]
l_2	Gauge length at F_{ref}	[mm]
l_3	Gauge length at 50% MBL	[mm]
L_U	Effective length at zero load	[mm]
L_X	Gauge length at minimum load	[kN]
L_Y	Gauge length at maximum load	[kN]
MBL_m	Measured minimum break load	[kN]
MBL_s	Specified minimum break load	[kN]

EXPERIMENTAL SETUP

Dynamic Marine Component (DMaC) test facility

The DMaC test facility is owned and operated by the University of Exeter (Figure 2a). Its main role is to replicate the dynamic operational and fatigue loads that offshore components typically experience in service (e.g. [10, 11, 12]). The facility includes a hydraulically powered tailstock for the application of user-defined loads (harmonic and irregular time-series) with a hydraulically powered headstock, providing an additional three degrees-of-freedom (roll, pitch and yaw). This feature is particularly useful for the testing of subsea components which are subjected to bending or torsion at one end (for example cables, umbilical assemblies and risers, e.g. [13]). Furthermore

DMaC has been designed so that components can be fully submerged in fresh water during testing. Further details of the facility can be found in [14].

During the ISO 2307:2010(E) test programme the samples were tested dry and during the ISO 18692:2007(E) and ISO/TS 19336:2015(E) test programmes the samples were fully submerged in tap water after being soaked in water for at least 24 hours. The bedding-in tests were carried out with DMaC in force-controlled mode whilst the load-to-failure tests were carried out with DMaC set to displacement-controlled mode.

Ashimori Industry Co. Ltd test facility

Additional load-to-failure tests were carried out on Vectran-SSR samples using tension-tension equipment operated by Ashimori Industry Co. Ltd (Figure 2b). The hydraulic machine, manufactured by Shimadzu Seisakusho Ltd. is capable of applying tensile loads up to 1000 kN and has been certified by the classification society Nippon Kaiji Kyokai.

Measurement system

DMaC comprises a synchronised control and data acquisition system which enables both specified and measured values to be appended, at each time step, to a single results file. For the tests reported here the axial load and displacement experienced by the main hydraulic actuator were simultaneously logged at a sample rate of 50 Hz. In addition to data logging, the DMaC data acquisition system was used to monitor actuator displacement and axial load during test setup, allowing the reference tension (F_{ref}) of 2% MBL to be set prior to testing. The axial load was measured by a DSCC pancake load cell manufactured by Applied Measurements Ltd with an accuracy of 98.1 N.

Two different methods to measure the time-variation of gauge length were used during the tests. An OptiTrack motion tracking system (manufactured by NaturalPoint Inc.) was used to monitor sample elongation during the ISO 2307:2010(E) tests (throughout the bedding-in and load-to-failure stages). Four motion tracking cameras were used to track the position of spherical targets (7/16” diameter) positioned on the gauge length of the sample (l_2) at a sample rate of 120 Hz. In accordance with ISO 2307:2010(E) the attachment points of the targets were at least three times the rope diameter from the end of the splices. Prior to each test the motion tracking system was calibrated by following a procedure defined by the manufacturer. For the test setup used a mean residual error of <0.2 mm was achieved.

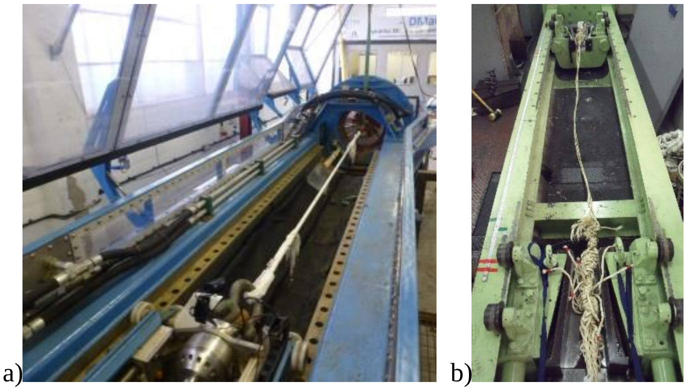

Figure 2: a) DMaC test facility with a polyester rope sample installed. b) Ashimori Industry Co. Ltd test facility

A WS-12 IP67-rated draw-wire transducer manufactured by Applied Measurements Ltd was used to measure gauge length elongation during the bedding-in and dynamic stages of the ISO 18692:2007(E) and ISO/TS 19336:2015(E) tests at a sample rate of 50 Hz. With the transducer body clamped to the sample using a custom-made clamp, the end of the draw-wire was attached to the sample using a bungee cord (via an additional length of wire) in order to provide a gauge length greater than 1.2 m. In accordance with ISO 18692:2007(E), the attachment points of the transducer body and wire were at least three times the rope diameter from the end of the splices. The transducer has been used extensively for rope testing in the past and possesses a high level of measurement linearity ($R^2 > 0.99$) and a resolution of 15.3 µm. To avoid damage to the transducer it was removed prior to running the load-to-failure test stage.

For the ISO 18692:2007(E) tests, the dynamic stiffness at the end of bedding in (K_{rb}) was calculated. To do this the approach in section B.3.6.2 of the standard was applied, utilising the recorded variation of load over the 100th cycle, the specified sample MBL and strain over the 100th cycle. A similar approach was used to determine dynamic stiffness after cycling (K_{rd}; B.3.6.3 of ISO 18692:2007(E)). Quasi-static stiffness (K_{rs}) of each sample was calculated using the last quasi-static ramp cycle using the approach in B.3.6.4 of ISO 18692:2007(E). Table 1 summarises the parameters used in Equation 1:

$$K_{rb,rs,rd} = \frac{\frac{F_Y - F_X}{MBL}}{\frac{L_Y - L_X}{L_X}} \qquad (1)$$

	X	*Y*	**Cycle**
K_{rb}	10.0% MBL	30.0% MBL	100th
K_{rs}	10.0% MBL	30.0% MBL	3rd
K_{rd}	40.0% MBL	50.0% MBL	100th (of 40-50% MBL interval)

Table 1: Stiffness calculation parameters.

Load schedules used for each test are listed in Annex A. Following the ISO/TS 19336:2015(E) tests carried out at DMaC, the minimum break load (MBL_m) of the two Vectran samples was determined from load cell measurements at Ashimori Industry Co. Ltd.

TEST RESULTS

ISO 2307:2010(E) results

In accordance with the ISO 2307:2010(E) standard the effective length (L_U) and gauge length (l_2) of each sample were measured prior to the test at zero load and a reference tension of 2 kN (Table 2). The OptiTrack measurements of gauge length were used to determine gauge length l_3 of the polyester samples at 50% MBL, during the first bedding in cycle. Due to the capabilities of DMaC this quantity was measured at 44.8% MBL for the Vectran sample. Examples of measured time histories for the PET-SSR sample are shown in Figure 3.

Type	L_U **[mm]**	l_2 **[mm]**	l_3 **[mm]**	MBL_m **[kN]**	ε_b **[%]**
PET	2384.0	1506.0	1945.0	170.303	14.8
PET-SSR	2294.0	1508.0	1603.0	183.065	9.8
Vectran-SSR	1963.0	1265.0	1288.0	N/A	N/A

Table 2: Measured and calculated parameters from the ISO 2307:2010(E) tests.

Following bedding in, the polyester samples were loaded to failure. The break loads achieved were notably higher than those specified by the manufacturer (PET: $MBL_m = 1.42MBL_s$; PET-SSR: $MBL_m = 1.08MBL_s$). The failure strain (ε_b) of the PET sample was higher than its SSR variant. From visual inspection it appears as though the PET sample failed on the splice nearest to the DMaC headstock (Figure 4) with one subrope remaining intact showing the point of failure. Failure of the PET-SSR sample occurred at the headstock end of the sample where it parted approximately mid-way along the eye. Minor abrasion damage also occurred to the tailstock end eye.

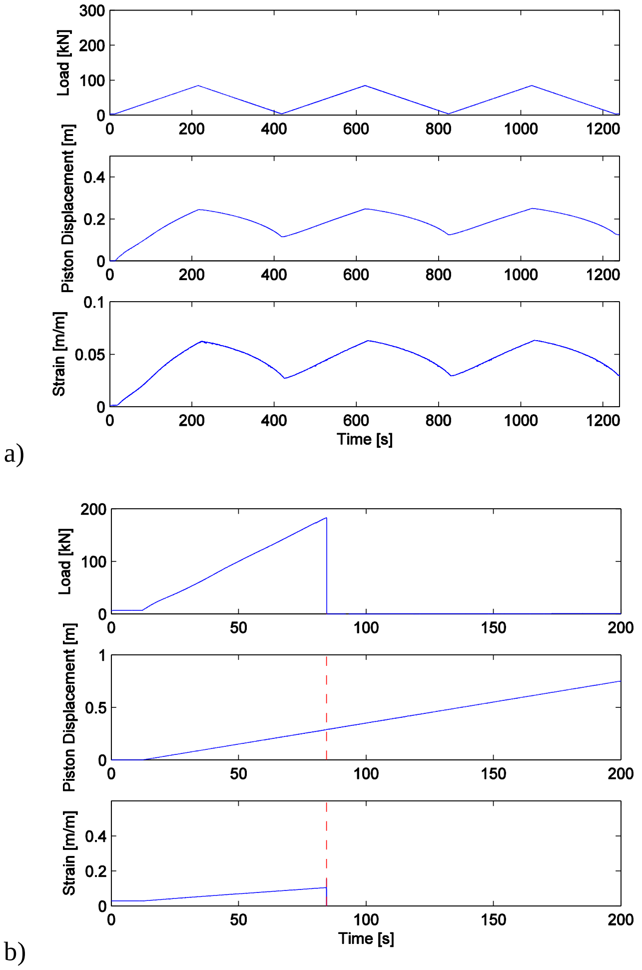

Figure 3: Examples of measured time-series for the PET-SSR sample during ISO 2307:2010(E): a) bedding in and b) load-to-failure test.

The maximum load measured with the Vectran-SSR sample was 206.1 kN, hence failure of this sample was not achieved during the test.

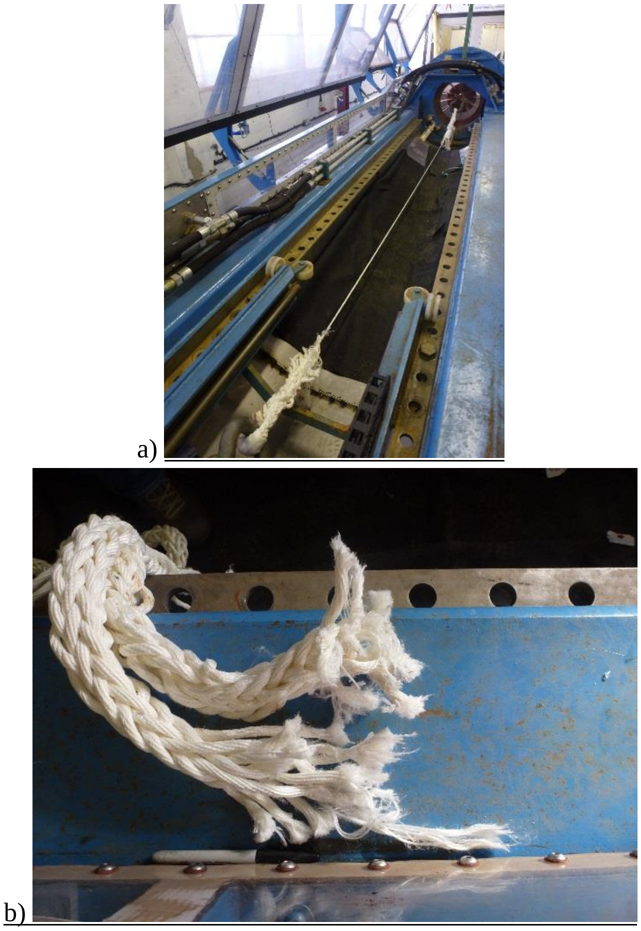

Figure 4: a) PET and b) PET-SSR samples after load-to-failure ISO 2307:2010(E) tests.

ISO 18692:2007(E) results

The focus of the ISO 18692:2007(E) tests was to quantify the stiffness of the samples after three loading intervals; bedding in, quasi-static loading and dynamic loading as well as the minimum break load. Table 3 lists stiffness values calculated using the last cycle of each loading interval. It can be seen that the PET-SSR variant stiffness values are slightly higher than the conventional PET construction. As expected the Vectran-SSR stiffness values are significantly higher than those calculated for the polyester samples and this is illustrated in the example provided in Figure 6.

Type	l_2 **[mm]**	K_{rb} **[-]**	K_{rs} **[-]**	K_{rd} **[-]**	MBL_m **[kN]**
PET	1518.0	21.961	17.077	34.817	160.693
PET-SSR	1523.0	23.558	17.78	35.226	191.371
Vectran-SSR	1510.0	63.254	56.239	103.869	N/A

Table 3: Measured and calculated parameters from the ISO18692:2007(E) tests.

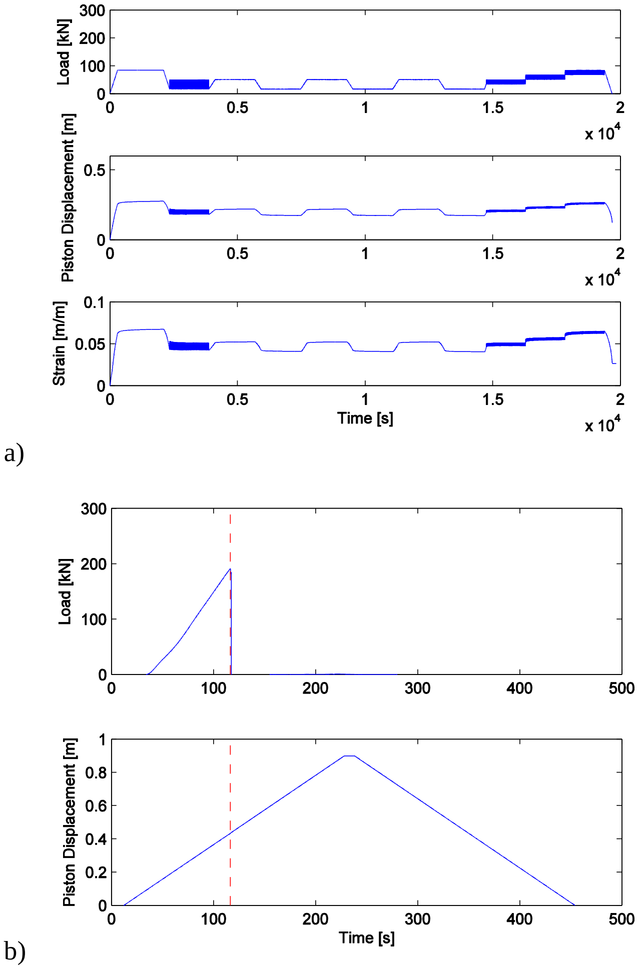

Figure 5: Examples of measured time-series for the PET-SSR sample during ISO 18692:2007(E): a) bedding in, quasi-static and dynamic loading and b) load-to-failure test.

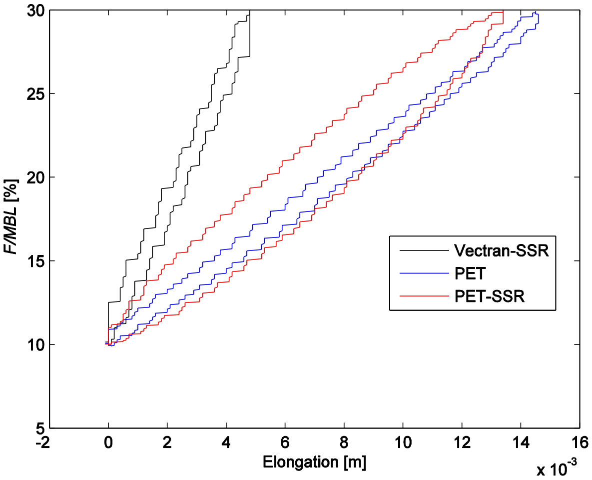

Figure 6: Example of measured load-elongation plots for the 100th cycle (and final) dynamic cycle during ISO 18692:2007(E) testing for the PET, PET-SSR and Vectran-SSR samples. Note: to enable comparisons to be made, sample elongation has been zeroed using the minimum measured elongation.

Figure 7: *(top)* PET and *(bottom)* PET-SSR samples after load-to-failure ISO 18692:2007(E) tests.

Similarly to the ISO 2307:2010(E) tests, the maximum loads achieved during the polyester load-to-failure tests were higher than those specified by the manufacturer (PET: MBL_m = 1.34MBL_s; PET-SSR: MBL_m = 1.13MBL_s). From visual inspection the PET sample failed at the end of the splice nearest the DMaC's headstock with failure of the PET-SSR occurring mid-way along the eye nearest the DMaC headstock (Figure 7). Minor abrasion damage was also noted near the centre of the PET-SSR sample.

ISO/TS 19336:2015(E) results

Time-series of the axial compression fatigue and cyclic loading endurance tests are plotted in Figure 8 and Figure 9 respectively, with initial gauge length values listed in Table 4. The load time-series applied to the two samples (denoted here as A and B) can be viewed as a preconditioning stage before the samples were loaded-to-failure (as reported in the next section). The strain time-series shown in Figure 8 and Figure 9 demonstrate strain stabilization behavior with repeated cyclical loading which has been well-studied for polyester [15] as well as other synthetic materials, including nylon [11].

Sample	Test	l_2 [mm]	F_{max} [%MBL]
A	Axial compression fatigue	1488.0	46.8
B	Cyclic loading endurance	1497.0	47.4

Table 4: Measured parameters from the Vectran-SSR ISO/TS 19336:2015(E) tests.

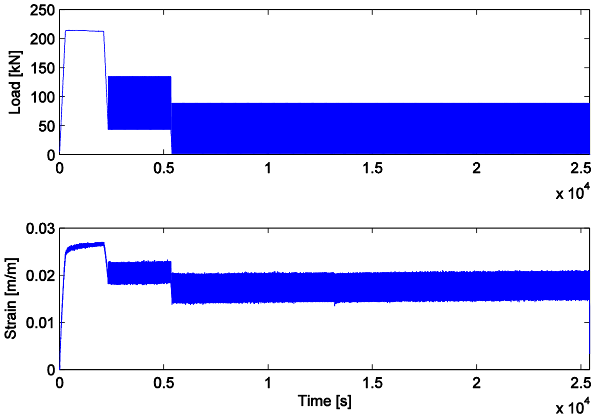

Figure 8: Measured axial compression fatigue test time-series for sample A.

During the axial compression fatigue test a power cut occurred at the DMaC facility which interrupted the test during the 1-20% MBL cycling interval after 13188s. The dynamic cycling interval of the test was quickly restarted and subsequently completed. Transducer measurements indicate that the sample did not significantly recover during the period of interruption, with a strain difference of less than 1% calculated using strain minima before interruption and upon the test being restarted. After the test was completed it was found the S-beam load cell used for calibration of the DMaC load cell had an erroneous offset of 2.638kN. The loads seen by this sample were therefore lower than specified. This is small in comparison to the MBL of the rope (<0.6%). The results plotted in this report include the measured load offset.

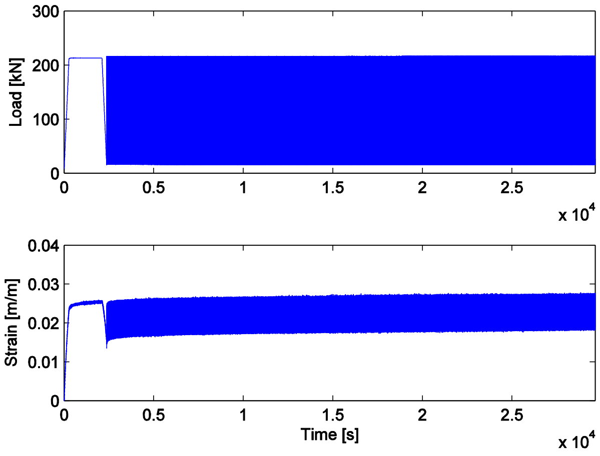

Figure 9: Measured cyclic loading endurance test time-series for sample B.

Additional load-to-failure tests

A summary of the additional load-to-failure tests carried out on Vectran-SSR samples by Ashimori Industry Co. Ltd can be found in Table 5. Percentage utilisation rates are based on the tensile strength of the Vectran fibers (1,164kN). For all of the samples tested it can be seen that the measured minimum break load greatly exceeds what was specified by the manufacturer, up to $MBL_m = 1.55 MBL_s$. In Figure 10 it appears that failure of the two samples occurred in between the splices; this being evidence of well-made splices.

Previous test	MBL_m [kN]	Utilisation rate [%]
ISO 2307:2010(E)	712.0	61.2
ISO 18692:2007(E)	670.0	57.6
ISO/TS 19336:2015(E)	702.0	60.3
	669.0	57.5

Table 5: Measured and calculated parameters from the additional load-to-failure tests.

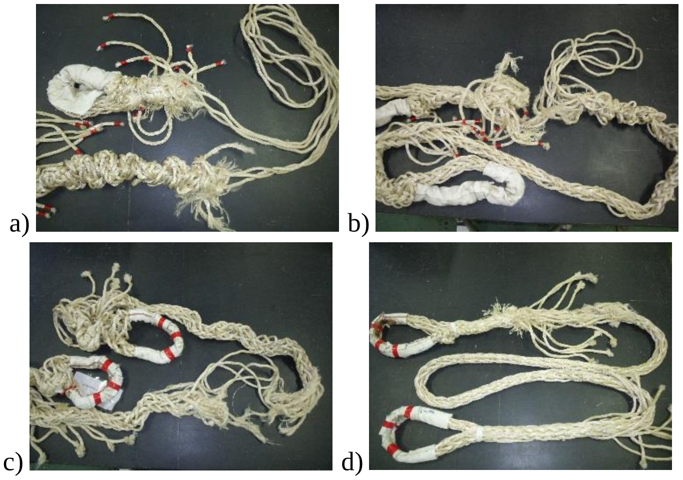

Figure 10: Load-to-failure tests carried out on Vectran-SSR samples previously tested to: a) ISO 2307:2010(E), b) ISO 18692:2007(E), c) ISO/TS19336:2015(E) axial compression fatigue properties test d) and ISO/TS19336:2015(E) cyclic loading endurance test.

CONCLUSIONS

A series of tests were conducted using tension-tension testing equipment at the University of Exeter's DMaC facility and at Ashimori Industry Co. Ltd to determine several performance metrics including ultimate load capacity and stiffness after several loading intervals. The polyester and Vectran samples were tested in dry and saturated conditions.

The results presented in this paper demonstrate that all of the rope samples which were tested until failure exceeded the MBL specified by the manufacturer. Some of the failures occurred around the splice or eye, however, because the measured loads were above those specified by the manufacturer this is deemed as being acceptable according to the ISO 2307:2010(E) and ISO 18692:2007(E) standards.

The results obtained allow comparisons to be made between performance and suitability of two different rope materials and constructions of the same outside diameter. More specifically:

1. Comparison of the polyester sample results has demonstrated that the SSR design has a higher minimum break load whilst retaining similar stiffness performance to the non-SSR variant.

2. As expected the Vectran-SSR samples exhibited considerably larger minimum break load and stiffness values than the PET-SSR samples.

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ANNEX A

TENSION-TENSION TEST SCHEDULES

ISO 2307:2010(E) test procedure

The ISO 2307:2010(E) tests included the following stages:

1. Bedding-in
    a. Hold for 10 s at 2% MBL.
    b. Ramp from 2-50% MBL at a load rate of 0.4 kN/s.
    c. Ramp from 50-2% MBL at a load rate of 0.4 kN/s.
    d. Repeat steps 1b and 1c two further times.
    e. Hold for 10 s at 2% MBL.
2. Load-to-failure
    a. Hold for 10 s at current position.
    b. Ramp up to breaking load at a displacement rate of 0.24 m/min.

ISO 18692:2007(E) test procedure

The ISO 18692:2007(E) tests included the following stages:

1. Bedding-in and dynamic stiffness
    a. Hold for 10 s at 2% MBL.
    b. Ramp from 2-50% MBL at a load rate of 10% MBL/min.
    c. Hold for 1800 s at 50% MBL.
    d. Ramp from 50-10% MBL at a load rate of 10% MBL/min.
    e. Cycle between 10-30% MBL for 100 cycles at 15.4 s period.
2. Quasi-static
    a. Ramp from 10-30% MBL for 240 s.
    b. Hold for 1560 s at 30% MBL.
    c. Ramp from 30-10% MBL for 240 s.
    d. Hold for 1560 s at 30% MBL.
    e. Repeat steps 2a – 2d two further times.
3. Dynamic
    c. Ramp from 10-30% MBL at a load rate of 10% MBL/min.
    a. Cycle between 20-30% MBL for 100 cycles at 15.4 s period.
    b. Cycle between 30-40% MBL for 100 cycles at 15.4 s period.
    c. Cycle between 40-50% MBL for 100 cycles at 15.4 s period.
    d. Ramp from 50 MBL to zero load at a load rate of 10% MBL/min.
    e. Hold for 10 s at zero load.
4. Load-to-failure
    a. Hold for 10 s at current position.
    b. Ramp up to breaking load at a displacement rate of 0.25 m/min.

ISO/TS 19336:2015(E) B.5 Cyclic loading endurance test procedure

1. Bedding-in
    a. Hold for 10 s at 2% MBL.
    b. Ramp from 2-50% MBL at a load rate of 10% MBL/min.
    c. Hold for 1800 s at 50% MBL.
    d. Ramp from 50-3.38% MBL at a load rate of 10% MBL/min.
    e. Hold for 2 s at 3.38% MBL.
2. Dynamic
    a. Cycle between 3.38-53.4% MBL for 6000 cycles at 5 s period.
3. Load-to-failure
    a. Hold for 2 s at current position.
    b. Ramp up to breaking load at a load rate of 10% MBL/min.

ISO/TS 19336:2015(E) Axial compression fatigue properties test procedure

1. Bedding-in
    a. Hold for 10 s at 2% MBL.
    b. Ramp from 2-50% MBL at a load rate of 10% MBL/min.
    c. Hold for 1800 s at 50% MBL.
    d. Ramp from 50-10% MBL at a load rate of 10% MBL/min.
2. Dynamic
    a. Cycle between 10-30% MBL for 300 cycles at 10 s period.

   b. Ramp from 10-1% MBL at a load rate of 10% MBL/min.
   c. Cycle between 1-20% MBL for 2000 cycles at 10 s period.
   d. Ramp from 1% MBL to zero load at a load rate of 10% MBL/min.
   e. Hold for 2.5 s at zero load.
3. Load-to-failure
   a. Hold for 2.5 s at current position.
   b. Ramp up to breaking load at a load rate of 20% MBL/min.