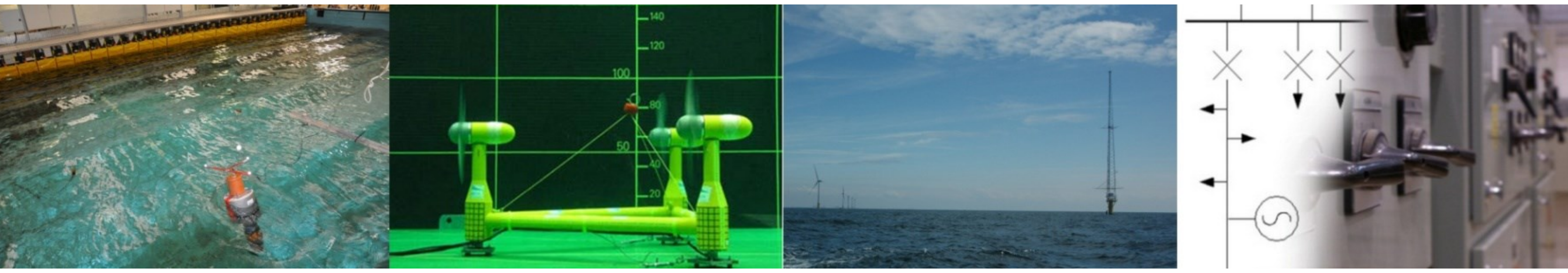
MARINET

Marine Renewables Infrastructure Network



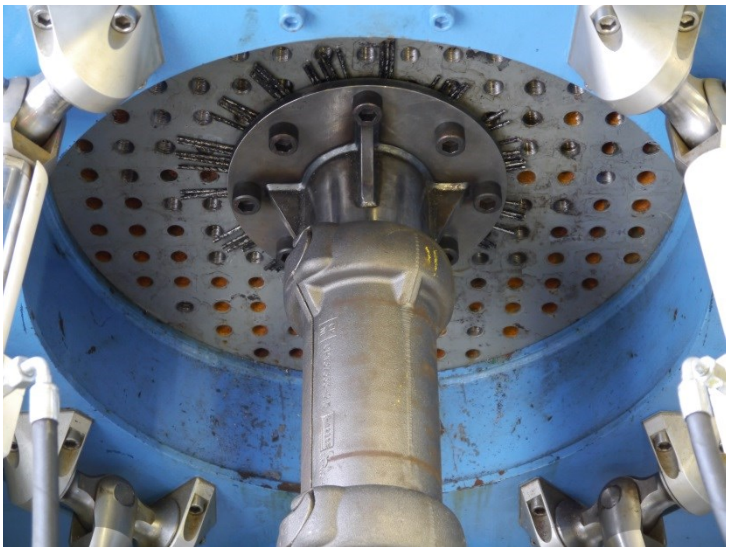
Infrastructure Access Report

Infrastructure: UNEXE Dynamic Marine Component Test Facility

***User-Project*: Bend restrictors**

Accelerated reliability testing of articulated cable bend restrictor for offshore wind applications

CPNL Engineering GmbH



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EC FP7 "Capacities" Specific Programme
Research Infrastructure Action

ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The aim of the initiative is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

Ireland
University College Cork, HMRC (UCC_HMRC)
Coordinator
Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
Aalborg Universitet (AAU)
Danmarks Tekniske Universitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
Institut Français de Recherche Pour l'Exploitation de la Mer (IFREMER)

United Kingdom
National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
University of Strathclyde (UNI_STRATH)
The University of Edinburgh (UEDIN)
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Spain
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Norway
Sintef Energi AS (SINTEF)
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About This Report

One of the requirements of the EC in enabling a user group to benefit from free-of-charge access to an infrastructure is that the user group must be entitled to disseminate the foreground (information and results) that they have generated under the project in order to progress the state-of-the-art of the sector. Notwithstanding this, the EC also state that dissemination activities shall be compatible with the protection of intellectual property rights, confidentiality obligations and the legitimate interests of the owner(s) of the foreground.

The aim of this report is therefore to meet the first requirement of publicly disseminating the knowledge generated through this MARINET infrastructure access project in an accessible format in order to:

- progress the state-of-the-art
- publicise resulting progress made for the technology/industry
- provide evidence of progress made along the Structured Development Plan
- provide due diligence material for potential future investment and financing
- share lessons learned
- avoid potential future replication by others
- provide opportunities for future collaboration
- etc.

In some cases, the user group may wish to protect some of this information which they deem commercially sensitive, and so may choose to present results in a normalised (non-dimensional) format or withhold certain design data – this is acceptable and allowed for in the second requirement outlined above.

Acknowledgement

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Legal Disclaimer

EXECUTIVE SUMMARY

Power cable failures for offshore marine energy applications are a growing concern since experience from offshore wind has shown repeated failures of inter-array and export cables. These failures may be mitigated by dedicated cable protection systems, such as bend restrictors. This study presents the rationale and the results for accelerated reliability tests of an articulated bend restrictor. The tests are a collaborative effort between the University of Exeter, CPNL Engineering and NSW, supported by the EU Marinet Programme.

The tests have been carried out at full-scale and exposed the static submarine power cable – bend restrictor specimen to mechanical load regimes exceeding the allowable design loads in order to provoke accelerated wear and component failures. The tested load cases combined cyclic bending motions with oscillating tensile forces.

A range of acceleration factors have been applied in respect to the 1:50 years load case, subjecting each of the three restrictor samples to 25,000 bending cycles (50,000 tensile cycles). The static power cable was also loaded beyond its intended use, testing the worst case scenario of repeated dynamic loading, purposely inflicting failure modes for investigation. Throughout the test the static submarine power cable sustained over 77,000 bending cycles (154,000 tensile cycles).

The test demonstrated the integrity of the cable protection system with quantified wear rates obtained through 3D scanning of the individual shells. The static power cable also showed a high reliability level. None of the failure modes, mainly fatigue cracks and fretting, identified by cable dissection would have caused direct loss of service.

The observed failure modes could also be predicted through numerical load analysis, giving confidence in the utilised mechanical modelling and cross-sectional analysis for dynamic applications. Overall the study shows how dedicated collaborative component testing can make an important contribution to quantify and validate component behaviour in challenging offshore operating environments.

CONTENTS

1 INTRODUCTION & BACKGROUND

1.1 INTRODUCTION

A recent industry estimate is that whilst only approximately 10% of the capital expenditure for offshore wind installations is associated with cable cost, 90% of reported insurance claims are attributed to cable failures. This rate is stable for more than 5 years in a row. It has become one of the emerging challenges to achieve high availability levels and this can be achieved by higher reliability of inter-array and export cables.

The root causes of cable failures are reported to be a combination of poor installation practice, inadequate design of the cable itself and related accessories as well as inadequate mechanical protection for the given environmental load conditions.

Mechanical protection, called cable protection systems (CPS), are commonly used in the oil and gas and offshore wind sector to prevent damage to all kinds of cables from overbending, which evidently leads to cable failure.

There are two types of CPS: bend restrictors and bend stiffeners. The focus is on the articulated pipe as a bend restrictor that is defined as a number of interlocking elements, which are compliant until a specified bend angle/bending radius, greater than the MBR (minimum bend radius) of the cable is reached. It is a commonly used product to avoid the submarine cables from overbending.

A product lifetime indication of the bend restrictor was not properly tested. An experimental setting was created with several load regimes, reaching above the allowable design loads for both cable protection system and submarine power cable, respectively 0.22 – 6.67 times the 1:50 years extreme load event for given offshore wind installations.

1.2 DEVELOPMENT SO FAR

The first articulated pipe, presented by CPNL Engineering in 2009, consisted of fastener holes and fasteners to assemble the product together. At time of presentation the only feedback given by crew members was: please exclude fasteners, as it will make our work easier. From that moment on CPNL developed a design without fasteners and optimised the design to an extent that the product could be used as a 180 degree bow and applied in multiple scenarios. Where other organisations tend to limit themselves in seeking security of intellectual property, CPNL searched its security in technical lead of the product group and try to find scientific support, as a differentiator. The product claims needed to be confirmed in order to stand out from other cable protection suppliers.

1.2.1 Stage Gate Progress

Previously completed: ✓
Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	
• Finite monochromatic waves to include higher order effects (25 –100 waves)	
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	
• Restricted degrees of freedom (DofF) if required by the early mathematical models	
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	✓
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	
• Real seaway productivity (scaled duration at 20-30 minutes)	
• Initially 2-D (flume) test programme	
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	

STAGE GATE CRITERIA	Status
• Evidence of the device seaworthiness	✓
• Initial indication of the full system load regimes	✓
Stage 2 – Design Validation	
• Accurately simulated PTO characteristics	
• Performance in real seaways (long and short crested)	
• Survival loading and extreme motion behaviour.	
• Active damping control (may be deferred to Stage 3)	
• Device design changes and modifications	
• Mooring arrangements and effects on motion	
• Data for proposed PTO design and bench testing (Stage 3)	
• Engineering Design (Prototype), feasibility and costing	
• Site Review for Stage 3 and Stage 4 deployments	
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	➲
• To employ a realistic/actual PTO and generating system & develop control strategies	➲
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	➲
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	
• Manufacturing, deployment, recovery and O&M (component reliability)	
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan For This Access

The reason for requesting access to the Dynamic Marine Component test rig (DMaC), was found in our aim to replicate marine environmental load conditions as closely as possible. The idea to approach the influence of tides on the cable and cable protection in terms of loads and the cause of wear and fatigue on the total system. Most experiments/tests are focused on static scenarios, while a subsea environment is highly dynamic. An experiment to approach the highly dynamic environment and its impact on the cable protector and cable was considered relevant for further verifications/comparisons, calculations and simulations to identify its relevance.

Initially, the request was made for tidal applications, but as CPNL's prospected partner withdrew itself from the test, the request was made for offshore wind applications due to availability of bend restrictors and submarine cable suitable for inter-array cabling.

Short term objectives:

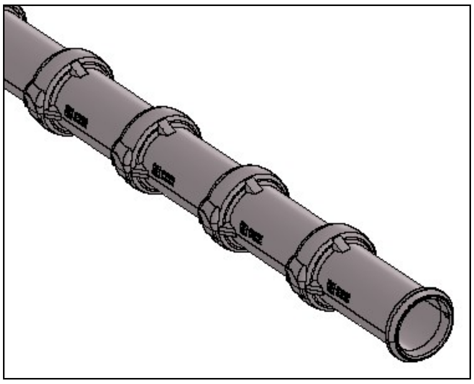
- establish fatigue behaviour
- analyse frictional wear between elements and the cable
- observe failure modes

Medium term objectives:

- analyse and present test data for the marine energy industry
- Reduce risks at component level to serve the industry
- Build confidence with the industry that these solutions have been tested

1.2.2.1 CPNL Bend restrictor

The CPNL bend restrictor solution is a string of elements that surround a cable. A single element can be seen in **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.**. Two of these elements fit together to form a pipe section which will interlock with other pipe sections forming the string. The detailed specifications of the shells are shown in **Fout! Verwijzingsbron niet gevonden.**. The material of the segments is cast iron EN-GJS 400/15 with a UTS of a segment 18% that of the material property. The test length of the sample will be 5.55m requiring a string of 30 elements.



1.2.2.2 Static load cable

The cable that the bend restrictors surrounded will be a 30kV power cable supplied by NSW. The cable construction and dimensions are detailed in Figure 1 as well as in Table 1 and Table 2.

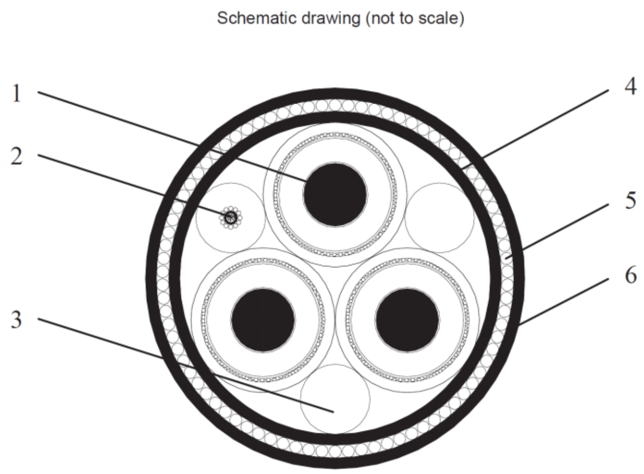


Figure 1: Schematic drawing of NSW submarine power cable (3x240mm2, 18/30 (36) kV, courtesy of NSW

Table 1: General Cable Characteristics, courtesy of NSW

1	Power cores 18/30(36) kV 240 mm² Copper Conductor XLPE Insulation Copper wire screen Composite layer sheath (aluminium/copolymer tape and PE jacket)
2	Fibre Optic Elements 48 SMF (4 x 12 SMF) in a copper tube with steel wire armouring and jacket
3	Filler (smaller fillers are not shown in the drawing)
4	Bedding layer
5	One layer of galvanized steel wires (nom. 58 x 5.5 mm)
6	Yarn Cladding

Table 2: Mechanical Cable Characteristics, courtesy of NSW

Property	Dimension	Unit
Nominal overall cable diameter	123	mm
Nominal cable mass	26400	Kg/km
Nominal cable weight in water	15900	daN/km
Max. recommended pulling force	60	kN
Recommended minimum bending radius	2.5	M
Recommended minimum bending radius in cage (coiled)	3.0	M

1.2.2.3 Fixtures

Fixing the sample in to the test rig required custom made attachment termination made by CPNL. The attachments pieces had to interface with the backing plate of the DMaC and the Zram attachment plate. The headstock attachment piece is a stainless steel adapter plate. At the end of the shank is a lip with will interlock with the bend restrictors. The headstock connection piece was attached to the rig with M24 bolts.

The Zram attachment comprises of an attachment face that bolts to the Zram attachment piece and a central shaft entering inside the bend restrictor string. The bend restrictors are then clamped to the piece using semi-circular clamping plates. There are 4 clamping plates making two layers of full circular clamps with opposing joins.

2 OUTLINE OF WORK CARRIED OUT

2.1 SETUP

Please find below the load scenarios executed at the DMaC facility with samples A, B and C using a different set of articulated pipes. The static load cable was used and reused in samples A to C.

	Axis	Max	Min	Total cycles
SAMPLE A (Shells 1-30)				
Load Case 1_1	Zram	80000 N	20000 N	2334
	Head stock y	28 degrees	-28 degrees	1167
Shell 29 & 30 failed and were replaced with 31 & 32				
SAMPLE A+ (Shells 1-28, 31, 32)				
Load Case 1_2	Zram	15000	10000 N	45028
	Head stock y	14 degrees	-14 degrees	25014
SAMPLE B (Shells B1-B30)				
Load Case 2	Zram	20000 N	15000 N	49980
	Head stock y	14 degrees	-14 degrees	24990
SAMPLE (Shells C1-C30)				
Load Case 3	Zram	20000 N	15000 N	49980
	Head stock y	7 degrees	-7 degrees	24990

Table 2.1 load scenarios

2.2 TESTS

2.2.1 Load Case 1-1 Sample A

Load case 1-1 was prescribed by CPNL requiring both manipulation of the sample in bending and axial loading. The conditions of the test are summarised in Table and Table , detailing a short test for trial purposes (Table) (with 2 cycles at the headstocks) and a longer test with 833 cycles at the headstock (Table), see also Figure .
The tensile load varied between 80kN and 20kN, with bending angle (y-axis) of ±28°.
The phase relationship between the Zram and the head stock is such that the maximum axial tension occurs at zero bending of the headstock and the minimum axial load occurs and maximum and minimum bend angle of the headstock.

Table Load Case 1-1 (Short) – Sample A

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	80000 N	20000 N	4.32 s	4	2x	8
Head stock x	0	0	0	0		0
Head stock y	28 degrees	-28 degrees	8.64 s	2		4

Table Load Case 1-1 (Long) – Sample A

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	80000 N	20000 N	4.32 s	1666	2x	2326
Head stock x	0	0	0	0		0
Head stock y	28 degrees	-28 degrees	8.64 s	833		1163

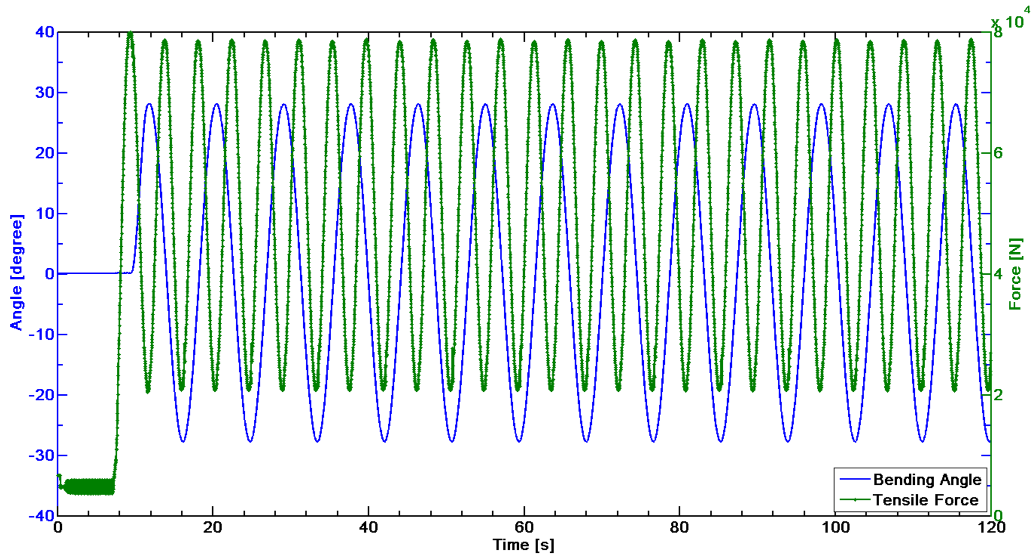


Figure Load case 1-1 – Extract of recorded time series

2.2.2 Load case 1-2 – Sample A

Load case 1-2 was again prescribed by CPNL and tested the sample at a reduced load and bend angle that would be more comparable to the conditions experienced by a cable and bend restrictor assemble during operation. It is a reduced load regime compared to load case 1-1. The conditions of the test are summarised in Table and Table . The tensile load varied between 15kN and 10kN, with bending angles (y-axis) of ±14°.
The phase relationship between the Zram and the head stock is such that the maximum axial tension occurs at zero bending of the headstock and the minimum axial load occurs and maximum and minimum bend angle of the headstock.

Table Load Case 1-2 (Short) – Sample A

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	15000 N	10000 N	4.32 s	6	8x	48
Head stock x	0	0	0	0		0
Head stock y	14 degrees	-14 degrees	8.64 s	3		24

Table Load Case 1-2 (Long) – Sample A

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	15000 N	10000 N	4.32 s	1666	30	49980
Head stock x	0	0	0	0		0
Head stock y	14 degrees	-14 degrees	8.64 s	833		24990

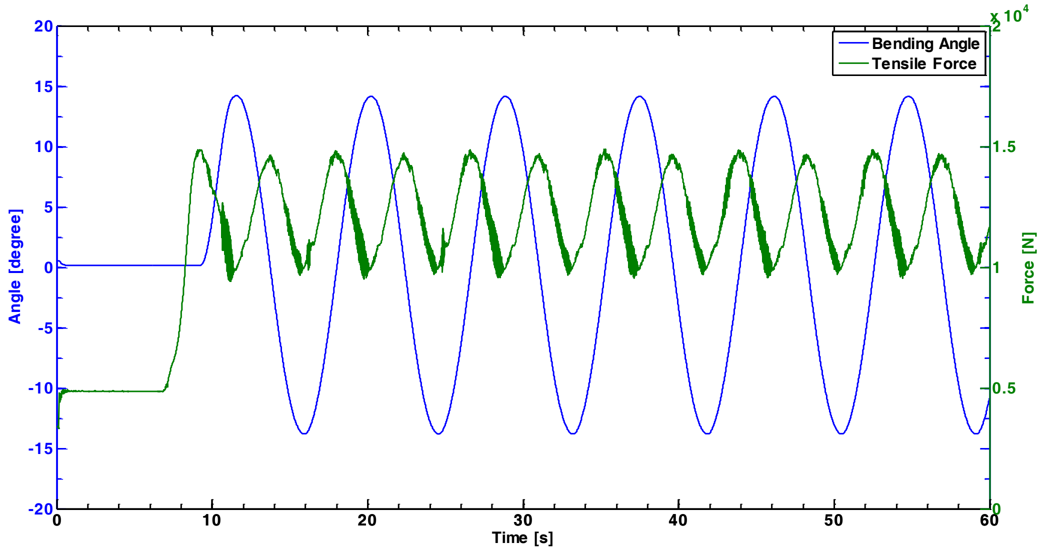


Figure Load case 1-2 – Extract of recorded time series

2.2.3 Load case 2 – Sample B

Load case 2 was agreed with CPNL and tested sample B at increased tensile load and similar angles compared to load case 1_2. The conditions of the test are summarised in Table and Table . The test was started (3 test runs) with the cycle periods stated in Table . Due to the smaller bending angles, the period was reduced by 1/3rd in order to speed up testing. The load replication was not influenced by this change. The associated time series is plotted in Figure .

Table Load Case 2 – Sample B

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	20000 N	15000 N	4.32 s	1666	3	4998
Head stock x	0	0	0	0		0
Head stock y	14 degrees	-14 degrees	8.64 s	833		2499

Table Load Case 2 (Shorter Period) – Sample B

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles
Zram	20000 N	15000 N	2.88 s	1666	27	44982
Head stock x	0	0	0	0		0
Head stock y	14 degrees	-14 degrees	5.76 s	833		22491

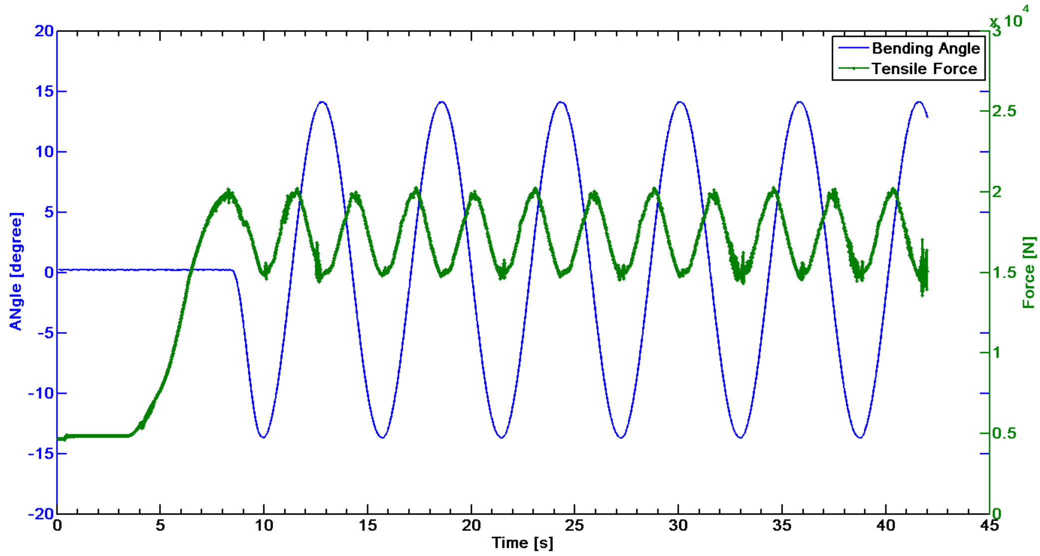


Figure Load case 2 – Extract of recorded time series

2.2.4 Load case 3. – Sample C

Load case 3 was agreed with CPNL and tested sample C at the same tensile force, but lower bend angles compared to load case 2. The conditions of the test are summarised in Table and an extract of the recorded time series is shown in Figure .

Table Load Case 3 (Shorter Period) – Sample C

Axis	Max	Min	Period	No of cycles	Repetition	Total cycles

Zram	15000 N	20000 N	2.88 s	1666	30	49980
Head stock x	0	0	0	0		0
Head stock y	7 degrees	-7 degrees	5.76 s	833		24990

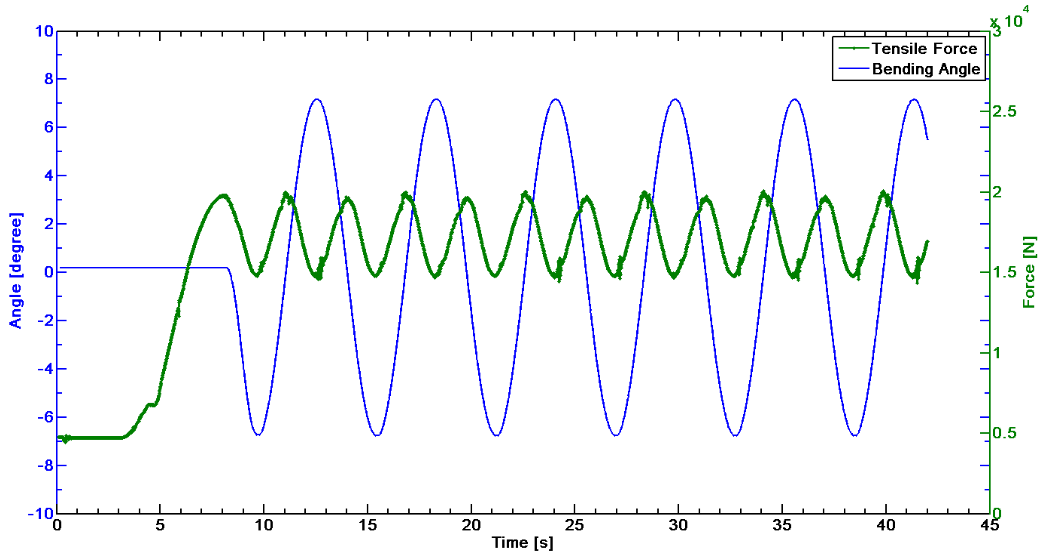
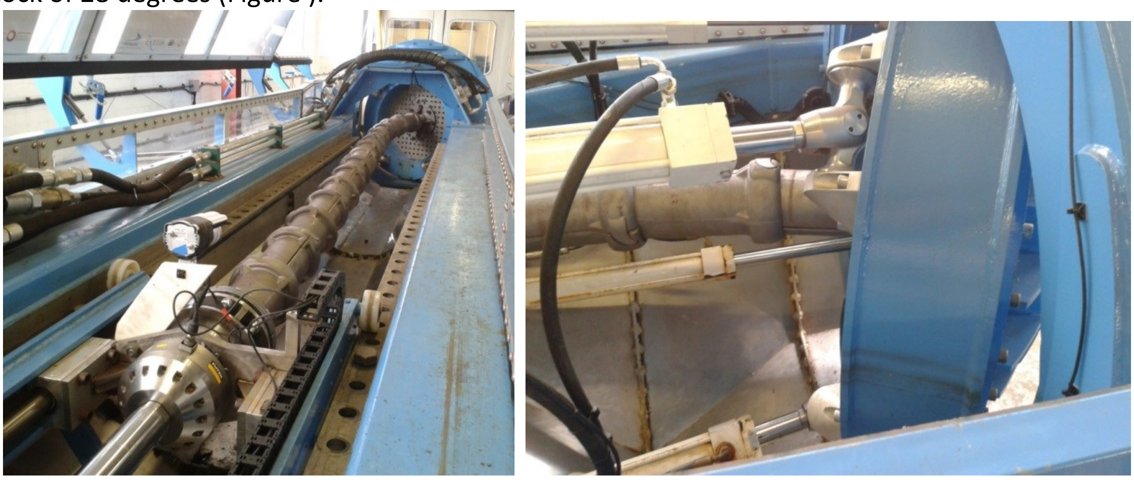


Figure Load case 3 – Extract of recorded time series

2.3 Results

2.4 System Documentation testing

Initial testing is undertaken to establish the limits of the machine-sample combination. In this case it was important to ensure that the DMaC head stock could manipulate the cable to large enough extents whilst under axial load. For this test the load on the Zram was maintained at 20kN manually and the machine jogged to incur an off axis angle on the head stock of 28 degrees (Figure).



(a) **(b)**

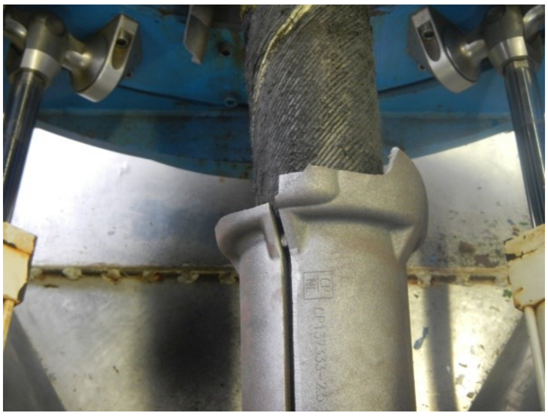
Figure Test operation, Load case 1 showing overview (a) and headstock angle (b)

2.4.1 Load case 1-1

The sample was tested under the conditions outlined in load case 1-1 and the machine was run using two hour continuous testing scripts. This exposed the sample to 833 cycles in bending and 1666 cycles of axial loading every two hours. The data logged by the test rig included the Zram displacement and load measured at the Zram and the angle about the x and y axis of the headstock.

The sample was tested for 3 hours before a failure of the bend restrictor occurred. The shells that broke were located at the end sections connecting the sample string to the headstock. The failure was on the lip of the shells that locks over the lip on the stainless steel attachment piece; see Figure and Figure .

The failure event at occurred during the second test (failed specimen 29 & 30) – elapsed test time 2856s. This equates to 330 bending cycles at the headstock and 660 tensile cycles at the tailstock.



(a)

(b)

(c)

Figure Failure event, Sample A (Shell 29, 30), showing failure location (a), fracture surface and abrasion (b) and close-up of connection lip.

(a) **(b)**

Figure Failure event, Sample A (Shell 29, 30), showing broken pieces from shell 29 (a) and 30 (b)

After this failure the pieces were removed from the test rig and photographed and labelled. The pictures are shown in Figure . The cause of this failure attributed to the stainless steel-cast iron contact of the shell-headstock interface connection. The two shells (29 and 30) were exposed to considerable wear and abrasion (visible abrasion residue). Following this failure event, the load case specifications were reviewed and adjusted to make a more representative test case. The broken shell specimens were replaced, and the refitted sample A was subsequently exposed to Load case 1_2.

2.4.2 Load case 1-2

Load case 1-2 was completed without failure. Some wear and abrasion was visible near the headstock.

2.4.3 Load case 2

Load case 2 was completed without failure. Some wear and abrasion was visible near the headstock.

2.4.4 Load case 3

Load case 3 was completed without failure. Some wear and abrasion was visible near the headstock.

2.5 Analysis & Conclusions

The first outcome, of the test scenario A, with specimen failure, was something we expected to happen. The product CP137-333 has shown in a static experimental setting to cope with loads up to XXX kN. With dynamic loads and extreme bending at the headstock, it was likely to experience tear, as the tension and friction was at its highest point.

However, the other bend restrictor parts were reused for scenario A+, resulting in low wear and fatigue indications. Initially, our expectance was that this would be higher in comparison to the other specimen used in the load case scenarios B and C.

Furthermore, we were surprised by the outcome that the cable was still functional – able to supply power. This was opposed to our expectations, as we considered that the cable would suffer serious damage due to the extreme load case A.

The outcomes taught us that the bend restrictor is significantly stronger than other bend restrictor designs containing fasteners. It was found that the fasteners weaken the construction due to the creation of holes in the design.

3 MAIN LEARNING OUTCOMES

3.1 Progress Made

This test was a starting point for further calculations and Orkaflex simulations. The results were used for elaborative comparison in terms of cross referencing with environmental data of several offshore wind farm locations. The worst case scenarios of these offshore wind farm locations were used to calculate in accordance with the following DNV-GL standards and/or codes and simulate in Orkaflex the behaviour of the bend restrictors in terms of pull-in loads analysis, scour development, in-hydrodynamic analyses and structural integrity of the bend restrictors as part of a cable protection system. This also indicated that the load scenario A was not representative for offshore, as these loads were highly extreme. Load scenarios A+, B and C were more representative in terms of approaching environmental loads, as cross referenced in a later stage.

The cross reference was necessary to identify if the calculations and simulations were in line with previously achieved test results, and consider these outcomes as representative for offshore environment.
DNV-GL reviewed all outcomes in line with their codes and standards, resulting in a design certificate. CPNL Engineering is now among a selective group of suppliers to provide this specific certificate with its two cable protection systems.

3.1.1 Progress Made: For This User-Group or Technology

For this user-group or technology the progress is made in terms of product integrity. This experimental study has revealed that the product is robust and suitable for an offshore environment. The progress after completing this study was steep, with a rapid follow up of elaborate studies in terms of adequacy for offshore use.
It is a start for articulated bend restrictor developers to standardise test procedures in product development and indicate towards potential customers the product integrity.

3.1.1.1 Next Steps for Research or Staged Development Plan – Exit/Change & Retest/Proceed?

The next steps for research would be in general to retest at a test rig/test site with seawater and sediment. We have noticed that a dry test is not the same as a wet test, which influences the outcomes in a positive sense. Seawater chemically responds to nodular cast iron parts with iron oxidation and in case of pollution material response can be given in terms of corrosion.

Sediment is able to calcify over time and interfere the bending of a system in the dynamic parts, but also the capability to transfer heat.

3.1.2 Progress Made: For Marine Renewable Energy Industry

The test setup can be reused by other marine renewable energy industry members, especially for articulated bend restrictors in order to determine the adequacy of product design and the product integrity. This test can be reproduced to increase reliability of the load scenarios. Other members of the industry can easily copy the load scenarios, supply their articulated bend restrictors, and create the necessary fixations for the head stock part and the Zram part in order to obtain their own results. It is a starting point to standardise in the field of marine renewable energy industry and identify similarities and differences between different suppliers, which also contribute to a better assessment of what product is suitable and/or adequate for a certain offshore project.

3.2 Key Lessons Learned

- First scientific collaborative study regarding mechanical cable protection and submarine cable
- The importance of product verification, as it will also help increase product integrity
- The potential to standardise test methodology for marine renewable energy applications

4 FURTHER INFORMATION

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- Been in contact with International Journal of Marine Energy, but the work is not published

4.2 Website & Social Media

Website: www.cpnl.eu
YouTube Link(s): www.youtube.com/CPNLMarloes
LinkedIn/Twitter/Facebook Links: www.linkedin.com/cpnl-engineering

5 REFERENCES

6 APPENDICES

6.1 STAGE DEVELOPMENT SUMMARY TABLE

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.

DEVELOPMENT PROTOCOL	*STAGE 1* *CONCEPT VALIDATION*			*STAGE 2* *DESIGN VALIDATION*	*STAGE 3* *SYSTEMS VALIDATION*		*STAGE 4* *DEVICE VALIDATION*		*STAGE 5* *ECONOMICS VALIDATION*
	TRL 1: **Confirmation of Operation**	**TRL 2:** **Performance Convergence**	**TRL 3:** **Device Optimisation**	**TRL 4:** **Sub-Systems Assessment**	**TRL5:** **Sub-Assembly Bench Tests**	**TRL 6:** **Full System Sea Trials**	**TRL 7:** **Solo, Sheltered, Grid Emulator**	**TRL 8:** **Solo, Exposed, Grid Connected**	**TRL 9:** **Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power *v* Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfrm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1:25 - 100$ ($\therefore \lambda_e = 1:5 - 10$)			$\lambda = 1:10 - 25$	$\lambda = 1:2 - 10$		$\lambda = 1:1 - 2$		$\lambda = 1:1$, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration –*inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production Pre-Commercial		Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δ*f*) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed Power [kW]									
Converted Power [kW]									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

SEVENTH FRAMEWORK PROGRAMME

6.2 ANY OTHER APPENDICES