Fibre rope selection for offshore renewable energy: Current status and future needs

Dr Sam Weller
Tension Technology International Ltd
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Primer

Tension Technology International (TTI) is a group of independent consultants who are experts in the **design, development, procurement, installation and testing** of mooring and anchoring systems for the offshore and renewable energy sectors.

With a technology-neutral ethos, TTI consultants have led key mooring projects since the 1980s.

**TTI Ltd (Eastbourne)** – Mooring component / system R&D and analysis.

**TTI Marine Renewables Ltd (Inverness)** – design services from conception through to detailed engineering of the mooring system and its components. Physical and numerical hydrodynamic testing and analysis.

**TTI Testing Ltd (Wallingford)** - R&D and forensic testing on a wide range of mooring components, electro-mechanical cables and pipes.
Mapping the landscape

TTI was recently commissioned by Wave Energy Scotland to investigate ways to reduce the LCoE of wave energy mooring and foundation systems.

- Landscaping
- Voice of Customer Survey
- TRIZ – Innovation
- Case Study Benchmarking

Pathways to reduce WEC LCoE

Cost Reduction in Supporting Infrastructure – Moorings and Foundations accessible from the Wave Energy Scotland knowledge library
https://library.waveenergyscotland.co.uk/
Fibre ropes
Extensive offshore use

Lankhorst Gama98®
## Steel vs. Synthetic

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Melting/charring point (°C)</th>
<th>Moisture (%)⁽¹⁾</th>
<th>Modulus (N/tex, GPa)</th>
<th>Tenacity (mN/tex)</th>
<th>Strength (MPa)</th>
<th>Break extension (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.85</td>
<td>1600</td>
<td>0</td>
<td>20, 160</td>
<td>330</td>
<td>2600</td>
<td>2⁽⁴⁾</td>
</tr>
<tr>
<td>HMPE</td>
<td>0.97</td>
<td>150</td>
<td>0</td>
<td>100, 100</td>
<td>3500</td>
<td>3400</td>
<td>3.5</td>
</tr>
<tr>
<td>Aramid</td>
<td>1.45</td>
<td>500</td>
<td>1-7</td>
<td>60, 90</td>
<td>2000</td>
<td>2900</td>
<td>3.5</td>
</tr>
<tr>
<td>PET</td>
<td>1.38</td>
<td>258</td>
<td>&lt;1</td>
<td>11, 15</td>
<td>820</td>
<td>1130</td>
<td>12</td>
</tr>
<tr>
<td>PP</td>
<td>0.91</td>
<td>165</td>
<td>0</td>
<td>7, 6</td>
<td>620</td>
<td>560</td>
<td>20</td>
</tr>
<tr>
<td>PA6⁽²⁾</td>
<td>1.14</td>
<td>218</td>
<td>5</td>
<td>7⁽³⁾, 8⁽³⁾</td>
<td>840⁽⁶⁾</td>
<td>960</td>
<td>20</td>
</tr>
</tbody>
</table>

**Synthetic**

- **Low density**
- **Low modulus**
- **High strength**
- **Compliant**

**Low cost and weight:** 146mm diameter parallel strand polyester rope (MBL: 6,000kN) versus 76mm R4 studlink chain (MBL: 6,001kN) => Cost of rope is 42.2% of chain, and 10.4% of linear mass⁽⁵⁾

⁽¹⁾ At 65% rh and 20 °C.
⁽²⁾ PA6.6 has a higher melting point (258 °C) than PA6.
⁽³⁾ The modulus and strength of nylon is approximately 15% lower when wet (McKenna et al.).
⁽⁴⁾ Yield point of steel.
⁽⁵⁾ Per 100m length. Rope cost includes end terminations and protection.

(values from McKenna et al. 2004)
Fibre type and rope construction

(from Dingenen, 2001)

Effect of construction on nylon ropes (OPTIMOOR, 2019)
Comparative fatigue performance

LR: Load range
BL: Break load

(from Ridge, Banfield et al. 2010)
Permanent mooring failures

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Girassol buoy</td>
<td>3 (+2) of 9 lines</td>
</tr>
<tr>
<td>2006</td>
<td>Liuhua</td>
<td>7 of 10 lines parted. vessel drift, riser broken</td>
</tr>
<tr>
<td>2009</td>
<td>Hai Yang Shi You</td>
<td>Entire system collapse, vessel drift, riser broken</td>
</tr>
<tr>
<td>2009</td>
<td>Nan Hai Fa Xian</td>
<td>4 of 8 lines parted, vessel drift, riser broken</td>
</tr>
<tr>
<td>2010</td>
<td>Jubarte</td>
<td>3 lines parted (2008-2010)</td>
</tr>
<tr>
<td>2011</td>
<td>Gryphon Alpha</td>
<td>4 of 8 lines parted, vessel drift, riser broken</td>
</tr>
<tr>
<td>2011</td>
<td>Volve</td>
<td>2 of 9 lines parted</td>
</tr>
<tr>
<td>2011</td>
<td>Banff</td>
<td>5 of 10 lines parted</td>
</tr>
</tbody>
</table>

Typical floating platform lifespan ~25 years -> there is greater than 60% chance of failure during lifetime

Ma, K-t et al. (2013)
Marine Renewables Commercialisation Fund (MRCF)
MRCF objectives

- To develop and qualify **enabling** technology and mooring products suitable for station-keeping of a wide range of floating wave and tidal array based technologies.
- To **build on** related mooring subsystem qualification programmes funded by Carbon Trust and TSB.
- To advance qualification of a **novel anchor bag** in accordance with DNV Recommended Practice for new technology (DNV-RP-A203)
- To advance **qualification of Nylon rope** in accordance with Lloyd’s Register Technology Pathway
- To develop **methodologies and guidance** for the design of Nylon based mooring systems
- To demonstrate **step changes in cost reduction** while increasing mooring array density.
- To demonstrate technology viability through open water testing
Situation:
Novel technologies or new applications may not be covered by existing rules and standards

TQ Aim:
To identify, create and review the evidence that technology will function reliably within specified limits

- Goals may related to: i) safety, ii) environmental, iii) functionality, iv) performance, v) reliability and vi) availability
- Process typically applied during the early stages of technology development
- Usually cost of assurance and development of qualified technology is high due to requirements for testing
TQ Stage 1

Stage 1: Goals

- Ensure mooring line integrity
- Characterizable performance throughout component lifetime
- Acceptable probability of failure
- Be inspectable
- Accommodate standardised end connections
- Not leach materials into the sea
- Block ingress of hard marine organisms into load bearing core
- Limit weight and drag increases due to marine growth
TQ Stage 1

Stage 1: System decomposition and technology maturity assessment

Process involves signposting to codes and standards for proven components.
Stage 1: Risk assessment

Potential failures identified using FMEA (i.e. design and operational risks and hazards)

<table>
<thead>
<tr>
<th>ID (Threat Number)</th>
<th>Component</th>
<th>Function</th>
<th>Failure mode</th>
<th>Failure mechanism or cause</th>
<th>Pre-MRCF Risk Ranking</th>
<th>Start/mid/end life</th>
<th>Comments</th>
<th>MRCF Project contribution</th>
<th>Recommended Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Main Line</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Load Transfer</td>
<td>Line Breaking</td>
<td>Excessive load applied</td>
<td>R3</td>
<td>P2</td>
<td>green</td>
<td>100% MBL/95%/90% which reduces safety factor, so initial SF must be higher to compensate</td>
<td>Change in Length Stiffness Tests, break load tests</td>
<td>Mooring design and tank testing to ensure loads within limits, sub- and rope breaks tests</td>
</tr>
<tr>
<td>3</td>
<td>Tension-tension fatigue</td>
<td></td>
<td></td>
<td>R3</td>
<td>P3</td>
<td>yellow</td>
<td>As so long small loss not effect</td>
<td>Excessively long life, not an issue (MOSAIC 10 Million cycle testing)</td>
<td>Ensure proper finish and sample test fatigue life</td>
</tr>
<tr>
<td>4</td>
<td>Abrasion due to small particle ingress</td>
<td></td>
<td></td>
<td>R3</td>
<td>P2</td>
<td>green</td>
<td>Increase strength loss at linear rate through life</td>
<td>Well tested and developed, filter keeps out all particles</td>
<td>Fit particle filter</td>
</tr>
<tr>
<td>5</td>
<td>Nylon 3 strand  subrope</td>
<td>Creep failure</td>
<td></td>
<td>R3</td>
<td>P3</td>
<td>yellow</td>
<td>Creep life excessively long, this is more for testing residual life for field specimens #Evidences is required to support statement # Evidence is two years and 20 million cycles fatigue testing at 30% mean load, that is equivalent to 100's years at typical pretension 10% See also section 6.3.3 of APN 25M and factor of safety applicable to Nylon Rope from LR OU rules</td>
<td>Creep testing</td>
<td>Check creep life on yarns and subrope</td>
</tr>
<tr>
<td>6</td>
<td>Axial compression</td>
<td></td>
<td></td>
<td>R3</td>
<td>P1</td>
<td>green</td>
<td>Not considered problem for nylon as API2SM states</td>
<td>Model number low tension cycles as check</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>External abrasion seabed</td>
<td></td>
<td></td>
<td>R3</td>
<td>P3</td>
<td>yellow</td>
<td>Any strength loss will be additive to other effects, this is considering proxy of the rope on seabed but not under tension</td>
<td>Apply extra coatings or buoyancy to keep line off seabed</td>
<td></td>
</tr>
</tbody>
</table>
Stage 2: TQ plan development

Novel components -> Determine why technology is immature/risks high -> Specify risk mitigation activities/methods -> Assess against acceptance criteria

<table>
<thead>
<tr>
<th>System</th>
<th>Description of failure mode</th>
<th>Failure causes</th>
<th>Results of initial screening (RIS)</th>
<th>Threat #</th>
<th>QA ID</th>
<th>Qualification activity</th>
<th>Mitigation / Qualification methods and activities</th>
<th>Acceptance criteria for each qualification activity</th>
<th>Track to goals</th>
<th>Test procedures and plans (Reference to detailed test plan document - document reference number)</th>
<th>Other Studies &amp; Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Line Breaking</td>
<td>1. Nylon 3 strand subrope</td>
<td>Tension - tensile fatigue</td>
<td>yellow</td>
<td>3</td>
<td>3</td>
<td>Fatigue tests</td>
<td>Ensure proper finish and sample test fatigue life</td>
<td>Conduct short and long term fatigue tests</td>
<td>Residual strength is high and S-N curve gives long fatigue life</td>
<td>Fatigue testing on nylon sub rope</td>
<td>Final Report for WST2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Abrasion due to small particle ingress</td>
<td>green</td>
<td>4</td>
<td>4</td>
<td>Particle test</td>
<td>Fit particle filter</td>
<td>Must keep out particles down to 5 micron</td>
<td>Block particles</td>
<td>API 25M and ISO</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Creep failure</td>
<td>yellow</td>
<td>5</td>
<td>5</td>
<td>Creep strain and stress relaxation test</td>
<td>Check creep life on yarns and subrope</td>
<td>Conduct creep tests to measure elongation</td>
<td>Predict creep performance</td>
<td>Creep not conducted in this or previous studies for nylon. Imploded short and long term fatigue tests, if creep rupture were an issue, failure would have occurred in the extreme high load tests</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Axial compression</td>
<td>green</td>
<td>6</td>
<td>6</td>
<td>Low minimum load Fatigue tests</td>
<td>Model number low tension cycles as check</td>
<td>Fatigue test to low minimum loads</td>
<td>No major degradation</td>
<td>Effect of mean load &amp; low min load on fatigue endurance of nylon trilobates WLI. Minimum 5 percent</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>External abrasive seabed</td>
<td>yellow</td>
<td>7</td>
<td>7</td>
<td>Abrasion tests, buoyancy design</td>
<td>Apply extra coatings or buoyancy to keep tensile off seabed</td>
<td>Wear not to go through protective cover and for sufficient buoyancy</td>
<td>Ensure mooring line integrity</td>
<td>Not conducted in this or previous studies for nylon</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hysteresis testing</td>
<td>green</td>
<td>8</td>
<td>8</td>
<td>Cyclic load test</td>
<td>Test load ranges and cycles and measure temperature</td>
<td>Temperature rise limited to material and strain range</td>
<td>Ensure mooring line integrity</td>
<td>Fatigue tests conducted at very high load range well beyond expected in any mooring and no heating found. TTI also has confidential data.</td>
<td></td>
</tr>
</tbody>
</table>
TQ Stage 3

Stage 3: Qualification activities

- QA3 Nylon 3 strand sub rope: Tension-tension fatigue
- QA5 Nylon 3 strand sub rope: Excessive creep
- QA7 Abrasion on sea-bed
- QA10 Rope yarn tension-tension fatigue
- QA15 Yarn imbalance
- QA16 Inter-strand abrasion
- QA17 Loss of marine finish due to sea water washing

Output: List of Recommendations for Certification
Wet nylon subropes subjected to 20,000,000 load cycles had a residual strength level of 108% (based on average new breaking strength).

- Rope supplied by Bridon for 20M fatigue tests
- Rope tubular sleeve “over braid” by Culzean
- Rope splices designed and splices made by TTI
- 8 break tests (5 Bridon 3 TTI)
- 1 x fatigue test
- Test completed March 2016 and witnessed by LR
Ideol Floatgen case study

(2014-2016) Testing, Qualification & Commercialisation of Synthetic Mooring System

FLOATGEN displacement ~6000T
Water depth = 32m
Extreme design Hs = 9m

Peak line tensions using nylon mooring limbs (~3500kN, 30% to 50% lower than other options considered).

Hardware cost which was 20% lower than the polyester solution and <50% lower than an all-chain system.

The installation time of synthetic semi-taut system was estimated to be 17% lower than for a chain system.
A high level view of synthetic rope modelling

Load [%MBL] vs. Strain [%] for different models:
- Linear, time-invariant stiffness
- Non-linear, time-invariant stiffness

Time-domain material-construction model (Tschoegl 1989)
Quasi-static material-construction model (Banfield et al. 2001)
Time-domain FEA (Davies et al. 2016)

Increasing model complexity
Rope modelling in the MRCF project

Focus on modelling nylon rope stiffness and developing guidelines
Marine Renewables Commercialisation Fund (MRCF) key outcomes

Key Outcomes

- Completed extensive rope testing programme for nylon. Key tests witnessed by Lloyd's Register
- Lloyd’s Register facilitated **FMEA approach to qualification of nylon** with input from all project stakeholders (High TRL)
- Lloyd’s Register Statement of Compliance Nylon Qualification
- Developed new technique **for modelling non-linear and hysteresis stiffness of nylon and guidelines**
- Completed **validation trials of Orcaflex** via tank tests of dummy buoy
- Completed **qualification plan for anchor bag design** (DNV-RP-203)
- Design & manufacture of 10 x 50T capacity gravity bags
- Deployment and recovery trials of single anchor bag
- Completed **cost benefit assessment of technology** for range of generic device sizes, environments and water depths, also partner devices
- Chain costs can be an order of magnitude bigger than nylon, as chain needs a bigger break load to satisfy Min FOS.
- Array densities in MW/km2 are significantly improved.
Other relevant projects
2013-2016
Synthetic Fibre Rope Polymer Line Fairleads
• Light weight, no heavy chain or handling equipment
• Reduced maintenance
• No fatigue issues, unlike many bending fatigue failures in chain
• Fast and easy hook-up/disconnect using light rope

Line bend testing (18° wrap angle)
Development and testing of fairleads and jackets
H2020 ERA-NET Cofund DemoWind

2016-2019
Simulate, implement and demonstrate the technical and economic viability of a twin-turbine floating solution by testing a 1:6 scale platform at a sea testing site (PLOCAN, Canary Islands) in order to achieve a TRL of 6.

- Development & correlation of hydrodynamic models with tank tests.
- Benchmarking conventional steel moorings with synthetic based moorings
- 6th scale mooring design & analysis to specify mooring
- Site selection at PLOCAN
- Procurement and supply of 6th scale mooring
- Commercial scale mooring FEED
- Market & Economic studies
To develop fit-for-purpose, standardized single point mooring subsystem which would cover the needs of most floating MRE converters and FWTs and their associated output power range.

- Experimental testing campaign at 1/10 scale
- Design of a single point mooring system for a multi MW device (based on the EOLINK prototype) and for a multi-kW device developed by GEPS TECHNO.
- Associated benchmarking on logistics, cost-benefits and environmental impact
Future Needs
Requirements

- No approved supplier of nylon yarn currently exists worldwide (for example approval to DNV TAP 322)

- Current guidance may not be the best fit, commercially or technically, for the ORE sector, for example, the scope and extent of the ‘3-T’ (tension, time and temperature) approach to testing

- Concern (from rope manufacturers and developers) about the costs associated with extensive testing and certification. These costs would be easily absorbed by rope orders for the first large commercial ORE farms.

- Larger scale commercial ORE systems are expected to require lines which have an MBL well in excess of 1000T. The impact of this on testing, qualification and certification requirements should be explored

- Robust modelling techniques are required to represent short- and long-term performance of fibre ropes in this application
Contact

Sam Weller
weller@tensiontech.com

Ben Yeats
yeats@tensiontech.com

Stephen Banfield
banfield@tensiontech.com

www.tensiontech.com