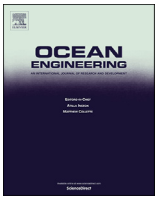
Ocean Engineering 155 (2018) 411–424

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Assessing the performance durability of elastomeric moorings: Assembly investigations enhanced by sub-component tests

T. Gordelier [a,*], D. Parish [a], P.R. Thies [a], S. Weller [a], P. Davies [b], P.Y. Le Gac [b], L. Johanning [a]

[a] *Renewable Energy Research Group, University of Exeter, Penryn Campus, Cornwall, UK*
[b] *IFREMER Marine Structures Laboratory, Centre de Brest, Plouzané, France*

ARTICLE INFO

Keywords:
Marine energy
Mooring
Elastomer
Durability
EPDM
Component testing

ABSTRACT

The growing marine renewable energy sector has led to a demand for increasingly compliant mooring systems. In response, several innovative mooring tethers have been proposed demonstrating potential customisation to the stiffness profile and reduced peak mooring loads. Many of these novel systems utilise materials in a unique application within the challenging marine environment and their long term durability remains to be proven.

This paper presents a multifaceted investigation into the durability of a novel polyester mooring tether with an elastomeric core. Laboratory based functionality tests are repeated on tether assemblies following a 6 month sea deployment. Results show a 45% average increase in dynamic axial stiffness. This is supported by high tension laboratory based fatigue endurance tests showing a peak increase in dynamic axial stiffness of 42%. Sub-component material tests on the core elastomer support the assembly tests, separately demonstrating that certain aspects of tether operation lead to increased material sample stiffness. The average increase in material radial compressive stiffness is 22% and 15% as a result of marine ageing and repeated mechanical compression respectively; these are the first results of this type to be published.

The performance durability characterisation of the tether establishes the mooring design envelope for long-term deployment. This characterisation is crucial to ensure reliable and effective integration of novel mooring systems into offshore engineering projects.

1. Introduction

The highly dynamic nature of many marine renewable energy devices places new demands on mooring system design in contrast to conventional oil and gas floating offshore systems. In addition to reliably maintaining the station keeping of a device, for many device designs the mooring system must also provide the compliance required to harvest energy from the marine environment. Synthetic mooring ropes are now commonly used in this application (Weller et al., 2015a; Davies et al., 2014; Ridge et al., 2010) having greater compliance than wire rope or chain alternatives. For conventional synthetic ropes the compliance is correlated to the specified minimum breaking load (MBL). Hence, the compliance of the mooring system is frequently compromised in order to achieve the required MBL to survive the loads expected during operation. Additional compliance can be introduced through system architecture, utilising floats and weights in catenary mooring systems (Weller et al., 2014a). However, this introduces complexity, increases the risk of entanglement and increases the mooring footprint when ambitions for industry offshore deployments are striving for increasingly compact mooring footprints in array configurations.

As a response to these new demands, several innovative mooring systems have been proposed to introduce greater compliance into the mooring system, and in some cases, provide customisation to the stiffness profile of the mooring (Parish and Johanning, 2012; McEvoy, 2012; Bengtsson and Ekström, 2010; Luxmoore et al., 2016). Studies have shown these systems have the potential to reduce peak loads observed in the mooring system (Thies et al., 2015; McEvoy, 2012; Parish et al., 2017; Luxmoore et al., 2016). Thies et al. (2015) demonstrate a maximum line tension reduction of 20% and a mean line tension reduction of 10%, while McEvoy (2012) shows an 80–90% load reduction in a storm scenario when substituting conventional mooring configurations for a novel elastomeric tether. It is anticipated that a reduction in mooring loads will allow the down rating of other mooring components leading to a downward spiral of reduced weight and further reduced loads, with the potential to reduce the structural requirements and mass of the floating body (Parish et al., 2017). Estimates suggest foundations and mooring

---

* Corresponding author.
E-mail address: T.J.Gordelier@exeter.ac.uk (T. Gordelier).

https://doi.org/10.1016/j.oceaneng.2018.02.014
Received 18 August 2017; Received in revised form 20 December 2017; Accepted 4 February 2018

Abbreviations

ACM	Axial Compression Modulus
DGPS	Differential Global Positioning System
DMaC	Dynamic Marine Component Test Facility
EPDM	Ethylene Propylene Diene Monomer
ETT	Exeter Tether Test series identifier
IFREMER	Institut Français de Recherché pour l'Exploitation de la Mer
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
MBL	Minimum Breaking Load
MTS	MTS Systems - manufacturer of testing equipment
NWBS	New Wet Breaking Strength
OCIMF	Oil Companies International Marine Forum
OPERA	Open Sea Operating Experience to Reduce Wave Energy Cost
RCS	Radial Compressive stiffness
SWMTF	South West Mooring Test Facility
TCLL	Thousand Cycle Load Limit

systems account for 10% of device costs (Low Carbon Innovation Coordination Group, 2012) and given the strong correlation between MBL and cost of mooring components (Harris et al., 2004), the potential savings through use of these novel systems are significant. Ultimately, the resulting mooring system will be lighter, cheaper and easier to deploy.

If these novel systems are to be successful, the long term performance must be proven and, given the harsh operating environment of marine renewable energy devices, this remains a key priority for these systems. The focus for the work presented here is a durability assessment of the Exeter Tether (Parish and Johanning, 2012), focusing on both the tether assembly and detailed material tests of the elastomeric core. The paper is organised into five parts. In this introduction the key features and operating principles of the tether are presented. Section 2, Methods, outlines the test facilities and techniques employed. Section 3, Results, presents key findings from the study followed by a Discussion in Section 4 which puts these results into the operating context of the tether and addresses the limitations of the work. Finally Section 5 details the conclusions and outlines next steps for this work.

1.1. *The Exeter Tether*

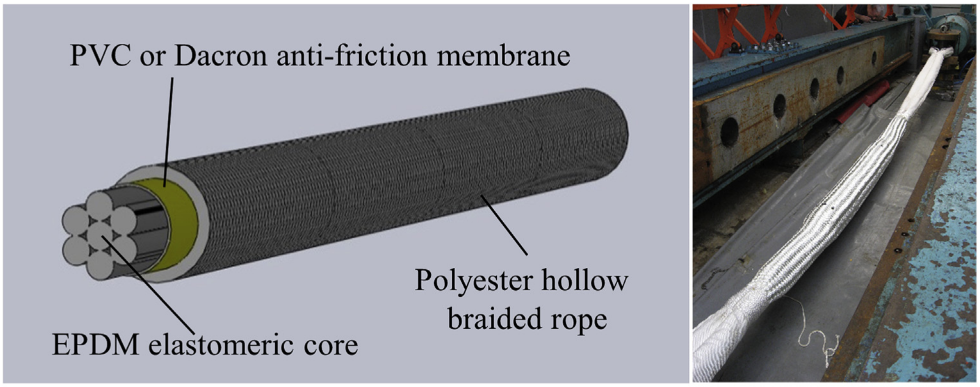
A detailed overview of the Exeter Tether and the P1 Prototype Series is presented in (Gordelier et al., 2015). A summary is provided here, based upon the specific prototype iteration utilising a core of seven solid elastomeric cords. The Exeter Tether comprises a hollow polyester rope braided around a core assembly of EPDM (Ethylene Propylene Diene Monomer) polymer strands wrapped in an anti-friction membrane as detailed in Fig. 1a. The polyester rope acts as the predominant load carrier and is terminated at either end with an eye splice.

The key principles of operation to appreciate are:

1. When under load, the tether extends along its length (axially) and simultaneously contracts across its diameter (diametrically), according to the helix angle of the braided rope.
2. As the rope diameter contracts, the elastomer core is compressed radially. The core resists this compression and thereby acts to resist the axial extension of the rope.
3. The compressibility of the elastomeric core dictates the resistance to diametric contraction, and in turn controls the axial extension. This compressibility is determined by both the cross-sectional form of the core and the material selection.
4. The helix angle of the braided rope dictates the ratio of the force vectors that act axially to extend the rope and circumferentially to compress the core. Typical helix angles for the P1 Prototype Series are detailed in (Gordelier et al., 2015).
5. Points (3) and (4) result in two distinct phases of tether extension as detailed in Fig. 2:
   (a) **Phase 1** - During the first phase of extension the elastomeric core strands are more easily deformed from seven individual round sections to eliminate the free space between the strands. At the same time, the helix angle is high, giving the braided rope considerable mechanical advantage in compressing the core. These factors combine to produce low axial stiffness during the first phase of extension.
   (b) **Phase 2** - As the free space in the core bundle tends towards zero, the resistance to further radial compression increases non-linearly. Simultaneously the extension of the tether also reduces the helix angle of the braid, thus reducing the rope's mechanical advantage over the core. These changes result in a second phase of extension which displays a marked increase in axial stiffness.

Critically, the choice of core geometry and material can be selected completely independently of the hollow rope. Thus, a series of tethers with the same MBL can be designed with a range of compliance values selected specifically for a device or location.

The working concept of the tether is presented in (Gordelier et al., 2015). This details the results from a *Proof of Concept* study with the P1 Series of 14 tether prototypes comprising a range of tether stiffness profiles achieved by varying the profile geometry and the Shore A hardness value of the elastomeric strands. The results presented in this paper focus on three of these tethers; the construction of these tethers is detailed in Table 1. It should be noted that the sheathing acts as an



(a) (b)

Fig. 1. The Exeter Tether. (a) Schematic detailing key components of P1 prototype series, replicated from (Gordelier et al., 2015); (b) full scale tether prototype from P4 series undergoing minimum breaking load testing at Lankhorst Ropes.