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# Synthetic rope responses in the context of load history: The influence of aging

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ABSTRACT

In order to design marine renewable energy mooring systems which are both economical and durable it is necessary to establish the lifecycle performance of individual components. In parallel with numerical tool development, physical component testing utilising realistic load cases is pivotal in achieving a greater understanding of performance variations including the contribution of degradation mechanisms. Building upon previous experimental tests conducted by the authors, tension–tension tests were conducted on a sample used in first part of the study and samples extracted from a mooring line which was deployed for 18 months with the South West Mooring Test Facility. In agreement with the first part of the study it was found that sample axial stiffness and damping are influenced by load history and instantaneous strain. The increased compliance, lower load bearing capacity and reduced tension–tension fatigue performance of aged specimens are symptomatic of fibre-on-fibre abrasion damage sustained in service. Visual inspections of the rope and yarns including scanning electron microscope analysis of fibres revealed that abrasion wear was accelerated by debris found within the rope structure, highlighting the importance of preventing particle ingress. Datasets are provided to facilitate the development of rope and mooring system simulation tools.



## 1. Introduction

### 1.1. Synthetic mooring ropes for marine renewable energy (MRE) mooring systems

The Carbon Trust *Technology Innovation Needs Assessment* (*TINA*): *Marine Energy Summary Report* (Low Carbon Innovation Coordination Group, 2012) reported that the cost of energy of moorings and foundations for wave and tidal energy devices is approximately 10%. Paredes et al. (2013) highlighted the disparity between the cost of mooring systems for floating oil and gas platforms and MRE devices with respect to the total expenditure of the system and profit obtained from the sale of the product. This is in part due to the current necessity of MRE mooring designs to adhere to existing offshore guidelines and component testing procedures (e.g. Cordage Institute, 2001b; Det Norske Veritas, 2010, 2013; Bureau Veritas, 2007) which have questionable relevance for MRE devices. To facilitate the design of economical mooring systems, more relevant design standards such as the forthcoming IEC TC114 guidelines (IEC, 2015) are in development. The utilisation of synthetic ropes instead of mooring chains has been identified as one way of reducing the capital cost of MRE mooring systems (e.g. Carbon Trust and Black & Veatch, 2011) due to their comparatively low unit cost, as quantified by Ridge et al. (2010). In addition, the low weight per unit length of these components and inherent ability to absorb tensile energy (and hence reduce peak loads) enable lower capacity connecting hardware and more efficient device structures to be specified. Over the past two decades these advantages have driven a transition towards polyester, nylon, HMPE and aramid mooring ropes to be utilised for the station-keeping of offshore equipment. This shift has initiated large scale research and development (R&D) programs including physical testing and the development of numerical codes to model rope behaviour (da Costas Mattos and Chimisso, 2011; François et al., 2010; Chailleux and Davies, 2003; Leech et al., 2003; Overington and Leech, 1997; Oil Companies International Marine Forum, 2000). Significant progress has been made in understanding the operational and long-term performance of these components in the context of the loads experienced by offshore equipment mooring lines. One such material, polyamide (nylon), has been favoured for demanding applications (e.g. SPM hawsers, François et al., 2010) and its compliance, low

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unit cost and weight mean that it is a feasible contender for MRE mooring systems (Ridge et al., 2010).

### 1.2. Aging mechanisms

Real-world insight into the causes of failure of mooring components has been provided by long-term studies such as the *Floating production system JIP FPS mooring integrity* conducted by Noble Denton Europe Limited (2006). Due to their prevalent use in the offshore industry the damage mechanisms which reduce the load carrying capacity of synthetic ropes have been well studied (Bitting, 1980; Backer et al., 1981; Flory et al., 2005; Kenny et al., 1985; Ridge et al., 2010; McKenna et al., 2004) including, but not limited to creep, ultraviolet (UV) exposure, tension and compression fatigue (through load cycling), external abrasion, wet-dry cycling, hysteresis heating and snatch loading.

Synthetic ropes gradually extend or creep under the application of continuous tensile loading (Davies et al., 2003) and considerable effort has been put into improving the creep characteristics of materials which are susceptible to this phenomenon (Vlasblom et al., 2012). For large platforms such as those used in the oil and gas sector, mooring lines are usually retensioned in order to retain the stiffness of the mooring system (Noble Denton Europe Limited, 2006). Ropes constructed from polyolefin materials (i.e. polyethylene and polypropylene) are particularly susceptible to degradation through exposure to UV light. In the context of operational conditions experienced by mooring ropes, fatigue induced by load cycling occurs in two modes: (i) tension–tension and (ii) compression loading. Tension–tension fatigue is mainly caused by wear occurring due to friction between moving fibres or yarns which are in contact (Flory et al., 2005). This wear can be accelerated by the ingress of debris such as grit or marine species into the rope structure (Ayres, 2001). Compression fatigue occurs when fibres of stiff materials (i.e. aramid) buckle and fatigue concentrations or 'hinges' are formed through repeated loading (McKenna et al., 2004). External abrasion of the outer elements of the rope may also occur. It is possible for salt crystals to form during wetting and drying cycles if the rope is partially submerged and this could form an abrasive medium contributing to wear between contacting fibres (Backer et al., 1981). The hysteretic response of viscoelastic materials in combination with slip occurring between fibres will cause localised heating of the rope. Research has demonstrated that in extreme cases (such as large diameter polyester ropes subjected to large strain ranges) heating can cause peeling and melting of the fibre surfaces (Flory et al., 2005; Overington and Leech, 1997). The snatch loading of ropes attached to a highly dynamic MRE device may also cause localised heating. However the snatch loading of synthetic materials has been well studied for other applications (e.g. aircraft arresting systems, Mason, 1999) and provided that the load capacity of the rope is not exceeded and the dissipation of heat to the exterior of the rope is sufficient, occasional snatch loading should not result in damage. Offshore experience and laboratory testing has led to the development of friction reducing fibre coatings (known as 'marine finishes') to improve yarn-on-yarn abrasion performance and micron-level particle filtration screens to prevent the ingress of potentially abrasive debris (International Standards Organisation, 2007). Braided jackets surrounding the load bearing elements of the rope are also used to prevent degradation through external abrasion or UV exposure. These three developments have contributed to significant increases in the fatigue performance of synthetic ropes (Ridge et al., 2010; Otten and Leite, 2013).

### 1.3. Component testing

Despite the accumulated knowledge of the offshore sector the performance and long-term durability of these materials is not fully understood for MRE applications, which are likely to include highly variable loading conditions. In addition the need to achieve a Levelized Cost of Energy which is competitive with other forms of electricity generation may require the adoption of a less conservative approach to mooring system design. Carbon Trust-funded studies focusing on MRE devices such as Ridge et al. (2010) and Tension Technology International Ltd (2013) have paved the way to the development of a knowledge base. However further detailed component testing and the continued development of performance and reliability tools are required to inform the design, operation, maintenance and retirement of economical and durable MRE mooring systems.

In an earlier performance assessment conducted by the authors (Weller et al., 2014) as part of the MERiFIC (Marine Energy in Far Peripheral and Island Communities) consortium, three dry, new, parallel-stranded nylon 6 rope samples were subjected to loading conditions that are potentially relevant to those experienced by buoy-like MRE devices or other small offshore equipment. By varying the initial loading conditions (through different levels of 'bedding-in' cycling) both non-linear and time-dependent behaviour were demonstrated; more specifically the instantaneous level of strain had a direct influence on the subsequent axial stiffness and damping of each sample. This trend was also observed after the application of a load set comprising a mixture of harmonic and irregular loading intervals, with the irregular time-series based on axial mooring tension measurements recorded by the University of Exeter's South West Mooring Test Facility (SWMTF: Johanning et al., 2011). Utilising the measurements obtained in the first part of this study, it is the intention of the second part to gain insight into the effect of rope saturation, by retesting Sample 2 from the previous study (NS2) after prolonged submersion in tap water. Comparisons are also made between the load-to-failure strain behaviour of two new samples (NS5 and NS6) after submersion in tap and sea water and a dry sample (NS4). This analysis is extended further to investigate the effects of aging with comparisons made between the performance of rope sample NS2 and the one extracted from the SWMTF mooring rope after its first deployment at sea (AS1). In addition, investigations are made into the performance of aged and new yarn assemblies subjected to scaled (by tenacity, units: N/Tex) harmonic loading, as well as the tension–tension fatigue performance of new and aged yarns.

In the next section the experimental equipment used in this study is outlined. The loading regimes applied to the rope samples are then defined in the context of mooring tension measurements recorded by the SWMTF. The experimental method and analysis techniques adopted are then summarised. In Section 3 results are presented from load tests involving new and aged rope and yarn assemblies (including yarn assemblies loaded until failure). In Section 4 tests involving harmonic, irregular and failure loading of rope samples in dry and wet states are presented. In Section 5 possible damage mechanisms are assessed utilising visual inspection tests as well as yarn-on-yarn abrasion tests to determine the fatigue performance of new and aged yarns.

## 2. Experimental approach

In this section the experimental equipment and analysis method adopted are summarised. For further details the reader is referred to a more detailed description in the first part of the study (Weller et al., 2014).

### 2.1. Rope and yarn samples and the South West Mooring Test Facility (SWMTF)

The ropes tested in this study comprise multi-filament nylon 6 fibres organised in hierarchical levels of yarns, yarn assemblies, strands and seven parallel-stranded subropes covered by a