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An experimental investigation on fatigue behaviors of HMPE ropes

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ABSTRACT

With offshore oil and gas exploration moving into deeper waters, HMPE (high modulus polyethylene) ropes have been widely investigated. However, the tension-tension fatigue behavior of HMPE ropes, especially the effect of mean load on the fatigue life of HMPE ropes, is still lack of sufficient and quantitative understanding. Therefore, to capture the fatigue behavior of HMPE ropes, fatigue tests of HMPE ropes are systematically performed in the present work utilizing a specially designed experimental system. An experimental procedure is proposed and test results show the whole fatigue process of HMPE ropes including tension-time, strain-time and tension-strain curves. The dynamic stiffness of HMPE ropes is also investigated, which shows that it increases with increasing mean load, while decreases with increasing loading amplitude. An empirical expression that accounts for the relationship of the mean load, loading amplitude and fatigue life is proposed to describe the damage evolution of HMPE ropes under long-term cyclic loading. The present work is beneficial to understanding the fatigue resistance ability of HMPE ropes and to application of HMPE ropes in deepwater moorings.

1. Introduction

Synthetic fiber ropes were first proposed as mooring lines in the 1960s (Banfield and Casey, 1998), and since then lots of studies have been performed. In 1992, experimental researches on the mechanical behavior of polyester ropes were first systematically investigated by Del Vecchio (1992). These experimental results including dynamic stiffness, creep and fatigue behaviors of polyester ropes made a significant contribution to the application of polyester ropes in deepwater moorings. In 1997, Petrobras installed the first polyester mooring system in the Campos Basin, offshore Brazil (Petruska et al., 2010). After that polyester ropes have become the preferred option for depths down to 1500 m. However, with numerous discoveries of natural resources in deeper waters, the question of whether polyester ropes can be utilized and provide enough stiffness to maintain acceptable platform offsets at all depths has been raised (Davies et al., 2002; Chi et al., 2009; Vlasblom et al., 2012). As the offshore oil and gas explorations move to ultra-deep waters, two challenges have to be faced in terms of polyester ropes for moorings. One is that the size and weight of large long polyester ropes may exceed the storage capacity of anchor handling vessels and then cause installation difficulties (Davies et al., 2002; Chimisso, 2009). The other is that the high stretch of long polyester ropes can lead to larger horizontal offsets which may exceed the limits of risers beyond 2000 m water depth (Chi et al., 2009; Vlasblom et al., 2012). It is noted that, on the condition of equivalent minimum breaking load, HMPE ropes show lighter, smaller diameter and higher modulus than polyester ropes. This makes HMPE ropes provide both technical and operational advantages over traditional polyester ropes for ultra-deep moorings (Davies et al., 2002; Chi et al., 2009). Therefore, various hybrid rope configurations have been proposed (Garrity and Fronzaglia, 2008; Leite and Boesten, 2011; Vlasblom et al., 2012; Lian et al., 2015a), in which stiffer HMPE ropes are used in cooler water closer to the seabed and polyester ropes are used in warmer water closer to the vessel or platform. Hybrid mooring lines can provide the stiffness needed to handle maximum loads during station-keeping in storm, while ensuring sufficient elasticity to damp peak loads induced by waves.

Obviously, to correctly understand dynamic response of taut-wire mooring systems, it is necessary to capture mechanical properties of synthetic fiber ropes due to the fact that mechanical behaviors of fiber ropes will directly affect the mooring response (Weller et al., 2014). Mechanical properties of synthetic fiber ropes including residual strength, creep and creep-rupture, dynamic stiffness, as well as fatigue resistance performance have been investigated to reduce the uncertainties of application of fiber ropes.

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In the aspect of residual strength, Berryman et al. (2002) conducted laboratory study of HMPE ropes which had been placed into the MODU mooring lines about 110 days, finding that these ropes were still in good condition compared to new ones. Williams et al. (2002) described small-scale static tension tests of polyester elements and sub-rope components to investigate the behavior of ropes with damage. Ward et al. (2006) performed full-scale tests of polyester ropes to obtain the effect of damage on the residual strength of mooring ropes and developed guidelines for the damage tolerance of polyester ropes. Flory (2008) made the artificial quantifiable damage of rope specimens including nylon, polyester and HMPE ropes and performed tensile breaking tests with these specimens to assess the strength loss of damaged fiber ropes. In 2008, numerical analysis of MODU mooring system which was engineered by HMPE ropes was performed and the results show that HMPE ropes can improve the survivability of the mooring system (Garrity and Fronzaglia, 2008). Besides, Pasternak et al. (2011) conducted residual strength tests of HMPE "mud ropes" which were once connected to the gravity-installed anchor in the mud about 544 days and found that these ropes showed no abnormal reduction in breaking strength compared to a new one. It should be noted that in the aspect of numerical approaches, Beltran and Vargas (2012) investigated the effects of broken rope components on rope failure strain, failure load and rope stiffness originally utilizing 3D finite element analyses which has capability to predict damaged rope response. Beltran and De Vico (2015) proposed a mechanical model to estimate the static response of a polyester rope asymmetrically damaged and the accuracy of this approach was proved by comparing the numerical results with the results of static tension tests.

As to creep, it is not a typical design issue for polyester and aramid ropes at loads normally experienced in mooring applications (Petruska et al., 2010; API, 2015). However, creep is of concern for HMPE ropes. Jacobs (1999) and Smeets et al. (2001) performed numerous creep tests of HMPE yarns and developed a two-process creep rate model to describe the primary and secondary creep. Based on Jacobs' work, Vlasblom and Bosman (2006) presented an updated model seeking to accurately predict the creep rate. Chimisso (2009) conducted creep experiments of HMPE multifilament and revealed that HMPE has a better mechanical behavior in low temperature. Caldeira et al. (2010) performed creep experiments of HMPE yarns and the results showed that the creep rate increases with increasing loading level and temperature. Regarding the creep-rupture behavior, da Costa Mattos and Chimisso (2011) first proposed a mathematical model to quantitatively describe the creep tests of HMPE fiber yarns based on the thermodynamic framework and their experimental results showed that the creep life and failure strain decreases with increasing loading level. After that, creep and creep-rupture tests of HMPE strands at different loading levels were performed and a creep-rupture model which can describe the entire creep process of synthetic fiber components was proposed by Lian et al. (2015b).

With respect to dynamic stiffness, Davies et al. (2002) performed short-term cyclic experiments of polyester, aramid and HMPE ropes and first proposed an empirical equation of dynamic stiffness which considers the effect of mean load. They also highlighted the need for improving knowledge of HMPE fatigue behavior. Davies et al. (2011) performed dynamic stiffness experiments of HMPE and aramid ropes to serve deep sea handling operation. Liu et al. (2014) performed experiments of aramid, polyester and HMPE ropes on dynamic stiffness behavior and proposed an empirical equation including the effects of loading cycles, strain amplitude and mean load.

In respect of fatigue behavior of fiber ropes, it is worthwhile to be investigated due to that fatigue resistance ability of fiber ropes is a key factor that affects the safe operation of taut-wire mooring systems under long-term environmental loads (Huang et al., 2011). Del Vecchio (1992) conducted fatigue experiments of polyester ropes and thought that polyester rope is suitable to apply in deepwater moorings. Banfield and Casey (1998) performed long-term cyclic tests of polyester and HMPE ropes under the condition of fixed mean load and found that the effect of mean load on fatigue life of fiber ropes is still uncertain. National Engineering Laboratory (1999) of UK stated that polyester ropes which show good fatigue resistance behavior are suitable to apply in deepwater moorings, while aramid and HMPE ropes which show higher stiffness are more suitable to apply in ultra-deepwater moorings. Casey et al. (2000) proposed an empirical equation reflecting the influence of load amplitude on fatigue life and suggested to further study the influence of mean load on fatigue life. Banfield et al. (2000) proposed a new empirical expression of fatigue life for polyester ropes based on the test data of polyester ropes in reviewed literatures. By performing fatigue tests of 10, 150 and 250 t polyester ropes, Banfield et al. (2005) proposed an empirical expression considering the effect of mean load on the fatigue life of polyester ropes and found that there is no size effect on fatigue life. Flory and Banfield (2006) concluded that internal abrasion may cause the fatigue failure of polyester ropes and creep-rupture may lead to cyclic failure of HMPE ropes. It should be noted that T-N curves of polyester ropes are advised by different guidance notes of fiber ropes (BV, 2007; DNV, 2008; ABS, 2011; API, 2015). However, T-N curves of HMPE ropes are currently not available from guidance notes and fatigue data of HMPE ropes are rather limited (Davies et al., 2002). It is noted that DSM Dyneema (2009) provided the fatigue life of a type of HMPE ropes under the condition of fixed mean load in the technical brochure which shows that HMPE ropes has better ability of fatigue resistance than polyester ones.

Based on above survey of current researches, it is clear that the tension-tension fatigue behavior of HMPE ropes still requires quantitative understanding and further investigation is needed. Especially, the following aspects are necessary to be captured, including the entire fatigue process of HMPE ropes under long-term cyclic loading, the effect of mean load on fatigue life of HMPE ropes, and the quantitative relationship of fatigue life of HMPE ropes with cyclic loading levels. Therefore, to enhance the knowledge of the fatigue behavior of HMPE ropes, an experimental system that can approximately simulate the practical working condition of mooring ropes is developed. By utilizing this specially designed experimental equipment, the detailed fatigue test procedure and cases for HMPE ropes are proposed. Based on the fatigue tests, the mechanical behavior of HMPE ropes under long-term cyclic loading is revealed. A quantitative equation of fatigue life for HMPE ropes is then proposed to take account of the combined effects of the mean load and loading amplitude. The present work is beneficial to understanding the fatigue resistance ability of HMPE ropes and to application of HMPE ropes in deepwater moorings.

2. Experimental system and specimens

2.1. Experimental system for synthetic fiber ropes

As well known, the engineering application state of the taut-wire mooring system is that the pre-tension is exerted and a complicated cyclic motion of the floating platform causes complicated tension response of the mooring lines. Therefore, in order to simulate the real state of mooring ropes, a special experimental system is designed utilizing mechanical and electrical technologies. This experimental system is made up of four parts, including the loading element, the water cycling system, the rope measurement system and the equipment foundation (Liu et al., 2015), as illustrated in Fig. 1. The loading element includes the dynamic loading element and the static loading element. The dynamic loading component provides the cyclic loading. It is created according to the mechanical principle of utilizing the centric slider-crank mechanism as the driving source, converting the rotary motion of the eccentric wheel to the reciprocating motion of the big sliding block. This sliding block has a termination which is utilized to install rope samples. The mechanical schematic diagram is shown in Fig. 2. The displacement of the sliding block can be calculated as