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EVALUATION OF RESIDUAL STRENGTH OF POLYMERIC YARNS SUBJECTED TO PREVIOUS IMPACT LOADS

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Abstract.

The discovery of oil fields in deep and ultra-deep waters provided an opportunity to evaluate the use of synthetic ropes, complementarily or alternatively to traditional steel-based mooring lines in offshore units, mainly because of the former's lower specific weight. Considering the series of complex dynamic-mechanical mainly axial loads to which these structures may be subjected, originated from different sources, such as wind, water current, tide, etc., there may be cases when at least one of these lines may possibly face an abrupt, shock-like axial load of considerably larger magnitude. The goal of the present study is to evaluate the residual tensile strength of three different synthetic yarns (polyester, and two grades of high modulus polyethylene) after exposure to such axial impact loads. It was observed that, for the tested materials, polyester is the one with the largest impact resistance to the conditions evaluated herein, mainly because of its comparatively greater energy absorption properties.

Keywords: Offshore mooring, ultra deep-water, impact load.

1. Introduction

Since the end of the World War II, there has been an increase in the application of synthetic materials, mainly because of the reduction of their production costs and their significantly advantageous mechanical properties [1]. As an example, one can mention the construction of polymeric ropes, which can be used in a wide range of sports and industrial applications, such as climbing, rescue operations, mooring of offshore structures, shipping operations, etc. [2].

During the 1990s, the offshore oil industry began to replace the traditional mooring system based on steel cables and chains by systems consisting mainly of polyester cables. The main motivation for this shift was the severe increase in the water depth in which these structures were now being anchored, requiring compliant ropes with low specific weight in order to reduce the overall weight of the floating system [3, 4]. Nowadays, as examples, one can mention the synthetic fibres typically used for mooring ropes manufacturing: polyester (PET), high modulus polyethylene (HMPE), polyamide (PA), liquid crystal polymer (LCP), aramid and polypropylene (PP).

Apart from the mechanical loads originating from the movement of the floating unit, such anchoring systems may be subjected to some degree of environmental damage caused, for example, by ultraviolet incidence and hydrolysis, depending on the fibre group [5, 6]. Yarn-on-yarn abrasion is another (now a mechanical) degradation mechanism, even more relevant than the previous ones, that can affect the material's mechanical behaviour [7]. For characterisation purposes considering mooring ropes applications, static and dynamic stiffness of polymeric multifilaments are typically assessed according to ISO 18692 [8] and ISO 14909 [9, 10].

Polyester yarns have a high mechanical resistance, good tenacity and abrasion resistance [7, 11, 12]. When exposed to the environment under typical mooring conditions, they do not degrade considerably and are resistant to hydrolysis and ultraviolet incidence [5, 13]. Polyester is also not biodegradable, has a negligible creep behaviour at room temperature and, when exposed to high temperatures, it contracts instead of expanding [14, 15].

High modulus polyethylene is produced from a gel spinning process, resulting in a highly crystalline structure, oriented and extended along the fibre axis, with many different grades available in the market with specific properties. In general, HMPE fibres present a lower-than-water density allowing its buoyancy in regular water, which makes it a very interesting choice for marine applications. As for its mechanical properties, the fibre has a high tenacity and stiffness as compared to similar materials. Also, the deformation of HMPE at rupture is very low, but it shows remarkable creep behaviour at lower temperatures [16, 17].

There is a lack of previous studies in the literature regarding the influence of severe and abrupt tensile loads on the mechanical properties of polymeric materials applied to mooring ropes. However, it represents a relevant topic in regards to synthetic fibres used for mooring and operation lines since during its lifetime, an anchoring or operation line might be exposed to such loads several times. One important factor that influences the capacity to support shock loads is the degree of crystallinity, which is inversely proportional to the resistance to high, instantaneous tensile forces [18, 19].

Considering the aforementioned, the main goal of this paper is to assess the residual tensile strength of polyester and high modulus polyethylene yarns exposed to a prior shock-like axial load.

2. Materials and methods

2.1. Materials

In the present work, one grade of PET and two different grades of HMPE are evaluated, referred to as PET, HMPE1 and HMPE2, respectively. The materials have titers of 3300 dtex, 1761 dtex, and 1759 dtex, respectively.

2.2. Methods

2.2.1. Environmental conditions during tests

All tests were performed with 500 mm long yarn specimens conditioned according to ISO 139:2014, which determines that the samples must stay for at least two hours in an environment at $20 \pm 2\,°C$ and a relative humidity of $65 \pm 4\,\%$ prior to any experimental procedure. The tests themselves must also be performed in such environmental conditions.

2.2.2. Tensile tests in reference unexposed samples

To determine the YBL reference values, for comparison purposes, unexposed fibres were tested according to ASTM D2256. 30 rupture tests were performed for 500 mm long yarn samples of PET, HMPE1 and HMPE2 at 250 mm/min. Prior to tensile testing, samples were twisted along their axes with 60rounds per meter. An EMIC DL2000 universal testing machine with a 1 kN load cell was used.

2.2.3. Impact tests

It is considered that there is a critical velocity, above which the material shows brittle behaviour. The British standard BS EN 892:2012 proposes impact tests in mountaineering ropes, which consists in the application of an instantaneous tensile force applied

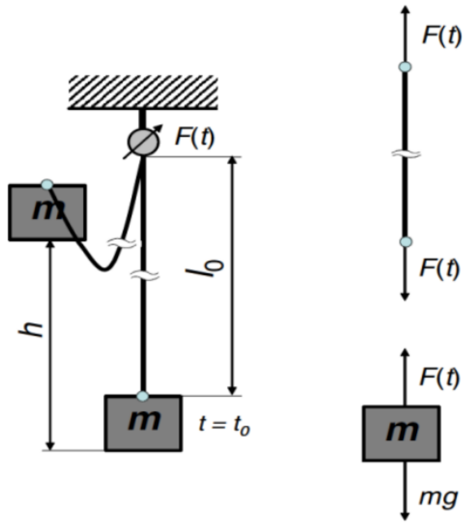

Figure 1. Free-fall diagram. Source [20].

by a free-falling mass (Figure 1) [20]. The input data to the experiment are the rope length, the free fall height, the mass of the falling object, and standard atmospheric conditions, such as temperature and relative humidity. BS EN 892:2012 brings different procedures depending on the investigated factors, such as stiffness, cycle number for impact load, transmitted force in the rope and maximum stretching.

Multifilaments used in the impact test are expected to present the capacity of dissipation and absorption of the potential energy. Specimens must be capable of preserving their original elastic behaviour, granting structural integrity and not compromising their mechanical properties. In the present paper, we apply such loads to the specimens and investigate eventual changes in their yarn break load (YBL) in the two distinct moments: immediately after the impact load, and 24 hours after the test. The YBL of the tested material is compared to that of an unexposed sample.

The application of the abrupt tensile forces was performed with increasingly heavier dead weights, typically from 1 % to 7 % YBL (and higher whenever applicable) increased by 2 % YBL steps. If samples did not fail when exposed to the chosen dead weight, residual strength was evaluated (as described in the next sections) and a new set of impact tests with increased dead weight was performed. In all tests, the dead weight was released from a 250 mm height, which corresponds to a half of the samples' length. A total of 30 untwisted samples were used for each of the investigated materials.

2.2.4. Residual strength tests

2.2.4.1. Residual strength of partially impacted samples

In order to evaluate the intermediate residual quasi-static tensile strength of the materials after the application of each of the impact loads steps detailed in Section 2.2.3, those samples that did not fail by

Material	YBL (N/tex)	Specific deformation at break (%)
PET	0.76 ± 0.01	10.90 ± 0.04
HMPE1	3.04 ± 0.15	3.30 ± 0.14
HMPE2	3.08 ± 0.10	3.20 ± 0.09

Table 1. Yarn break load of reference unexposed samples of PET, HMPE1 e HMPE2.

Material	Maximum impact load promoted by the 1 % YBL dead weight (N/tex)	YBL (N/tex) after impact	Specific deformation at break (%)
HMPE1	1.24 ± 0.03	3.25 ± 0.09	3.30 ± 0.12
HMPE2	1.33 ± 0.02	3.23 ± 0.10	3.20 ± 0.12

Table 2. Results of the tensile tests for residual strength evaluation immediately after the impact load of 1 % YBL.

Material	Maximum impact load promoted by the 3 % YBL dead weight (N/tex)	YBL (N/tex) after impact	Specific deformation at break (%)
PET	0.31 ± 0.01	0.76 ± 0.01	10.30 ± 0.40
HMPE1	2.14 ± 0.13	3.15 ± 0.17	3.20 ± 0.20
HMPE2	2.22 ± 0.10	3.11 ± 0.11	3.20 ± 0.11

Table 3. Results of the tensile tests for residual strength evaluation immediately after the impact load of 3 % YBL.

rupture were subjected to tensile tests using the procedure of Section 2.2.2. The time interval between both experiments was of 1 minute and 30 seconds, during which the samples were kept under the same controlled environmental conditions of Section 2.2.1. The same EMIC DL2000 machine was used.

2.2.4.2. Residual Strength of samples after resting time

A second round of tensile tests was performed in order to evaluate the influence of the resting time of the samples between the impact experiments and the residual tensile strength measurements. For that, instead of testing the samples for their residual YBL immediately after the shock-like events, they were first left to rest for 24 hours in a controlled environment (see Section 2.2.1). After this period, the tensile tests were performed according to the procedure detailed in Section 2.2.2.

3. Results and discussion

3.1. Yarn break load of reference (unexposed) samples

Table 1 shows the results for YBL of PET, HMPE1 e HMPE2, determined according to the experimental setup detailed in Section 2.2.2 considering 30 samples each. It can be seen that PET shows a lower YBL and a higher elongation at break when compared to both grades of HMPE, as expected.

3.2. Tensile tests immediately after the impact loads

As detailed in Section 2.2.3, each material was tested with abrupt tensile loads using an initial dead weight equivalent to 1 % YBL, which exposed the samples to a specific impact load. Due to technical difficulties in measuring the very small force during the tests for PET (approximately 2.5 N), this material was excluded from this first experimental batch.

After the tests with 1 % YBL, no visible damage was observed in any of the HMPE samples. Moreover, no sample has failed during the impact load. Immediately after the impact tests, tensile tests were performed in order to observe eventual changes in the materials' original YBL. Table 2 shows the results considering 30 samples each.

Although the impact forces applied to the samples were close to half of the materials' original YBL, both HMPE showed an apparent increase in their tensile strength: HMPE1 increased its YBL by about 7 % and HMPE2 by about 5 %, when compared to the materials' reference YBL (see Table 1). There was no significant change in the specific deformation at break. It was observed that the standard deviation of the HMPE1 samples decreased as compared to the results in the reference unexposed samples.

Then, additional impact tests were performed, increasing the dead weight to 3 % of the materials' original YBL, now including PET samples. Again, there was no visible damage in any of the samples after the application of the sudden axial loads. Table 3 shows

Material	Maximum impact load promoted by the 5 % YBL dead weight (N/tex)	Number of samples impact tested	Samples broken during impact	YBL (N/tex) after impact	Specific deformation at break (%)
PET	0.50 ± 0.02	30	0	0.77 ± 0.02	10.50 ± 0.40
HMPE1	2.86 ± 0.12	78	48	Not applicable	
HMPE2	2.98 ± 0.10	54	24	3.09 ± 0.12	3.20 ± 0.13

Table 4. Results of the tensile tests for residual strength evaluation immediately after the impact load of 5 % YBL.

Material	Maximum impact force caused by dead weight drop (N/tex)	Number of samples impact tested	Samples broken during impact	YBL (N/tex) after impact	Specific deformation at break (%)
PET 7 %	0.62 ± 0.02	30	10	0.77 ± 0.02	10.50 ± 0.35
PET 9 %	0.69 ± 0.01	47	17	0.77 ± 0.02	10.30 ± 0.41
PET 11 %	1.12 ± 0.02	58	28	Not applicable	
HMPE2 6 %	3.09 ± 0.09	52	22	Not applicable	

Table 5. Results of the tensile tests for residual strength evaluation immediately after impact load – higher dead weights.

the results of the tensile tests performed after the impacts considering 30 samples each.

Here, the axial load for the HMPE samples exceeds almost 70 % of the materials' original YBL, while for polyester, it was close to 50 % of its original YBL. The results for PET showed no significant difference when compared to the unexposed reference material (Table 1). Both HMPE samples showed, after impact, a higher YBL than that of the reference samples, but now only 3 % higher for HMPE1 and 1 % for HMPE2. Again there was no significant change in the specific deformation at the break. The high standard deviation of HMPE1 may be an indication of permanent damage caused to the multifilament structure during the impact tests even thoughthe quasi-static mechanical behaviour was not jeopardized.

Increasing the deadweight to 5 % YBL, more than 50 % of the HMPE1 samples failed by rupture during the impact test, which means that the impact strength of that material was reached. Less than half of HMPE2 samples showed failure by rupture. Some of the samples that did not break during the impact test showed visible, macroscopic damage in their structure, while all PET samples did not show any visible structural damage. Table 4 shows the residual tensile strength test results. Impact sampling was performed in order to always guarantee around 30 viable samples for the residual tensile strength tests afterwards.

Results show that, the higher the impact load, the higher the standard deviation and, in this case, it is reaching the limits of the impact tolerance for the HMPE fibres, with a significant amount of fibres already failing under impact. Again, PET showed a very small increase in its tensile strength, while the specific deformation at break remained almost unchanged.

The next set of tests was performed with a deadweight of 7 % YBL. As expected, all samples of HMPE2 have broken during impact, so, for that material, the load was decreased to 6 % YBL, in order to find its impact strength. Following the procedure of increasing the load by 2 % YBL, PET was further tested up to 11 % YBL, which was found to be beyond the material's impact strength. Table 5 shows these results.

3.3. Tensile tests 24 hours after the impact loads

In this section, the effect of the time interval between the impact test and subsequent tensile tests on the quasi-static residual strength of the fibres was observed, aiming to observe any potential microstructural accommodation. Therefore, because of the similar mechanical behaviour of HMPE1 and HMPE2, only PET and HMPE1 were chosen to undergo this new set of experiments.

Samples of PET were subjected to an impact load of 5 % YBL and HMPE1 to 3 % YBL. These values were chosen because they were found to be the highest impact loads (among the loads tested in the study) that do not cause macroscopic damage to the material (see Section 3.2). After the impact experiment, the samples were left to rest for 24 hours in a controlled environment as determined by ISO 139:2014. Table 6 shows the results.

In Table 3, it can be seen that PET has a tensile strength of 1.12 ± 0.02 N/tex when the tensile test is performed immediately after the impact test. When

Material	Number of samples	Maximum impact force (N/tex)	YBL (N/tex) after impact	Specific deformation at break (%)
PET 5 % YBL	30	0.50 ± 0.02	0.77 ± 0.02	11.20 ± 0.33
HMPE1 3 % YBL	30	2.14 ± 0.13	3.11 ± 0.01	3.20 ± 0.12

TABLE 6. Results of the tensile tests for residual strength evaluation 24 hours after impact load.

the tensile test was conducted 24 hours after the impact experiment, the YBL was measured as 1.13 ± 0.02 N/tex. For HMPE1, the equivalent results are of 3.15 ± 0.17 N/tex (immediately after impact) and 3.11 ± 0.01 N/tex (24 hours after impact). It was concluded that the materials tested do not restore their tensile strength after a considerable time interval of 24 hours after the impact test.

4. Conclusions

The main goal of this article is to evaluate an eventual loss in tensile strength of polyester and (two grades of) high modulus polyethylene yarns after an exposure to abrupt, axial impact loads (as a percentage of materials' original YBL). This is made by measuring the YBL of the unexposed reference material's YBL, and comparing it to the YBL of samples previously exposed to different levels of impact loads.

The obtained results suggest that, among the tested materials, PET is the one being less affected by a % YBL impact load, having shown impact strength to an axial load equivalent to about 9 % of its original YBL (see Table 5). Both evaluated grades of HMPE, HMPE1 and HMPE2, presented an impact strength equal to 5 % YBL and 6 % YBL, respectively (see Tables 4 and 5). A possible explanation is that PET's elongation at break (~10 %) is significantly larger than those of HMPE's (~3.3 %), which means that the former is more capable of absorbing strain energy than the latter.

Because of the absence of similar studies in the literature, this study is considered to be pioneer in terms of the assessment of the consequences of axial, abrupt loads for the posterior tensile strength of polymeric yarns. The methodology followed here is considered adequate to be applied when one intends to quantitatively compare the impact strength of different polymeric fibres. It should be noted that due to the difference between the axial stiffness of the different tested materials, naturally, the strain rate is expected not to be the same when this approach, based on deadweight release, is used. If one intends to apply exactly the same strain rate to the materials being compared, more sophisticated experimental apparatus must be employed. It is also important to note that the results regarding impact strength can be highly affected by the temperature during the experiments, so it is recommended to perform the shock-like experiments at the service temperature of the materials for more accurate comparisons.

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