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The effects of mechanical degradation on the quasi static and dynamic stiffness of polyester yarns

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ABSTRACT

Polyester fibers are the most used in the manufacture of ropes for mooring systems and offshore operation, thus being constantly subjected to different situations. Such requests are implicated in a variety of load conditions, and their effects must be studied. This work presents data referring to an experimental study on the behavior of the quasi-static and dynamic stiffness of polyester yarns considering different mechanical levels of degradation and use. The study is performed with five different types of multifilament samples, these were extracted from a virgin spool and sub-ropes tested for tension and fatigue. The experimental procedure is carried out through an initial characterization where the linear density, the Yarn Break Load - YBL and the linear tenacity of the samples are determined. Continuing with the experimental tests, a procedure standardized by ISO 18962-2 is then carried out, consisting of three quasi-static stages and three dynamic stages, where the data acquired in the tests allow the determination of a dimensionless stiffness value. The results showed an increase in the quasi-static stiffness, tending to a plateau, and a linear increase in the dynamic stiffness, but with somewhat similar behavior between the samples. The results related to the total quasi-static stiffness also show that the specimens extracted from sub-ropes that underwent fatigue present greater total non-dimensionalized stiffness, this is indicative of the mechanical fatigue procedure as an improvement of the specimens, giving them greater stiffness, and consequently greater stresses rupture, a behavior that should be explored in future studies.

1. Introduction

In the early 1990s, Del Vecchio (1992) proposed mooring systems made entirely of polymeric fibers. In addition to replacing steel with synthetic fibers, it also represented a change in technique, moving away from steel catenaries and towards Taut-Leg systems. Over time, and advances in the offshore area, polymeric fibers are no longer an alternative material, and have become a consecrated material for such uses. Consequently these materials are widely studied, both in analytical, numerical and experimental approaches.

Synthetic ropes are used for offshore anchoring, mooring, and other marine applications (De Pellegrin, 1999; Rossi et al., 2010; Bastos & Silva, 2020). It was applied to offshore structures in Brazil by Del Vecchio (1992), and is now being used in West Africa, the Gulf of Mexico, and on almost every oil rig. Usually, they manufacture polyester (Flory et al., 2007; Bastos et al., 2017; Louzada et al., 2017; Melito et al., 2019), high modulus polyethylene (HMPE) (Vlasblom et al., 2012; Stumpf et al., 2016; Cofferri et al., 2017; Belloni et al., 2021) and polyamide (Humeau et al., 2018; Nadalin et al., 2019; da Cruz et al., 2020; Civier et al., 2022). Polyester ropes still dominate the market. They are used due to their low cost, simple processability, easy blending with other fibers, and recyclability (Louzada et al., 2017; Duarte et al., 2019; Melito et al., 2019; Jaffe et al., 2020; Khalid et al., 2020; Zorzanelli et al., 2023). It has good performance when submitted to cyclic loads, and its fatigue life

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increases as the amplitude decreases (Louzada et al., 2017). However, if the traction load in the polyester yarn is high, the fatigue life of the yarn is reduced (Louzada et al., 2017).

Moreover, its fatigue life in low load traction is not affected by the submersion in sea water (Louzada et al., 2017; Duarte et al., 2019), which is great for the mooring application. However, it was observed that when immersed in water at a temperature above 80º C, polyester undergoes hydrolysis that leads to chain splits in the amorphous phase, changing the material characteristics. This phenomenon causes a change in mechanical proprietie and, besides that, degradation can cause ocean pollution by microplastics (Arhant et al., 2019). Therefore, knowing the material in different applications is important because any change in load and environmental conditions can cause a change in its properties.

When designing a rope for stationkeeping, knowing only the yarn breaking load is not sufficient. Generally, parameters such as fatigue, creep, and stiffness should also be used in the material's characterization and monitoring (De Pellegrin, 1999; Stumpf et al., 2016; Louzada et al., 2017; Cofferri et al., 2017; Duarte et al., 2019; Melito et al., 2019; Belloni et al., 2021; da Cruz et al., 2022b). Stiffness is a fundamental parameter because it describes the load-elongation behavior. However, stiffness does not behave linearly on polymeric yarns, and it cannot be determined in a simple tensile test because the behaviour of synthetic material is not linear and verified in the data obtained. So, it was necessary to develop empirical-logarithmic equations to predict said behavior (Del Vecchio, 1992). Later on, these equations were used to determine the materials' stiffness modulus, at which time they were usually dimensioned in GPa and N/tex. Currently, stiffness modulus is non-dimensional according to the technical standard, which has specific criteria for stiffness determination (ISO, 2019).

Polymeric yarns stiffness primary data (load and elongation) should be measured in two different situations portrayed in reality (Stumpf et al., 2016). The first is quasi-static, representing a mooring condition, and the second is dynamic, representing a storm or a condition of severe wave frequency (Del Vecchio, 1992; Casey & Banfield, 2002; Liu et al., 2014). In 1999, a characterization of the polyester stiffness using mean load, load amplitude and frequency was developed. In the present study was demonstrated that the mean load is the main parameter determining the dynamic modulus (Bosman & Hooker, 1999). In the same year, another study about polyester stiffness using elasticity modulus, cross section area and length was published showing that an increase in load on the dynamic stiffness hardened the material (Fernandes et al., 1999). Also, a series of real-scale tests and experimental studies in the laboratory were carried out to obtain the approval and certification of the ropes and the behavior of the fibers that compose them.

With the standardized stiffness tests (ISO, 2019), several other studies began to emerge. The first research concluded that polyester yarns had an increase in dynamic stiffness with an increase in mean load (François & Davies, 2008). One second study compared polyester (PET) to polyethylene naphthalate (PEN) in stiffness and tenacity of fiber, stating that PEN can also be used instead of PET (Davies et al., 2008). Third, for the dynamic condition, stochastic loadings were used, and longer steps were used for the quasi-static condition, resulting in an increase in dynamic stiffness with increasing load in polyamide fibers (François et al., 2010). HMPE showed stable results by using the same methodology. The first phase tests for quasi-static and dynamic stiffness presented the lowest results, followed by a considerable increase in the second phase test, and finally, a smaller increase was found in the last test (Stumpf et al., 2016). Another study quantified the mean and time-varying axial stiffness properties of a polyamide mooring rope using similar stiffness standards, noting that the load history on the rope significantly influences its performance (Weller et al., 2014). Therefore, quasi-static and dynamic stiffness can become a way to monitor synthetic rope applied to mooring and other offshore applications.

Observing the highlighted studies, and the state-of-the-art as a whole, there is a scarcity of works focused on comparing quasi-static and dynamic stiffness at different levels of mechanical use. Therefore, the objective of this work is to compare quasi-static and dynamic stiffness of polyester yarns at different load levels or mechanical degradation. Having as material the polyester of different parts of tested sub-ropes, and applying for the experimental procedure the technical standard ISO 18692-2: Fiber ropes for maintenance of the offshore station-Technical standard of polyester.

2. Materials and Methods

In this investigation, PET samples were extracted from a virgin spool and also from sub-ropes. The mechanical tests carried out on the sub-ropes from which the samples were extracted were in uniaxial tension until failure and it was also tested only in fatigue. Thus, five different specimens of PET wires were used for stiffness testing. The first was a virgin wire (extracted from the coil), and the other four specimens were taken from the understring test, adding the five different samples. The four samples were taken from the sub-rope in regions selected to theoretically show damage. These chosen regions were the center and splicing hands.Such samples were chosen because they emulated various levels of mechanical usage of a rope applied to a mooring operation. The tensile tested as a comparison to a rope prior to breaking, and the fatigued as a rope with a normal usage. And by taking samples not only from the body but from the eye splice it is also possible to emulate a bending condition.

First, a mechanical characterization was necessary to compare the different wires. For this purpose, tensile tests were performed to determine their rupture or Yarn Break Load - YBL (ASTM, 2014). The tests were carried out on an Instron 3365 (Fig. 2B), with a load cell capacity of 5 kN and equipped with a rope and wire gripper, with a capacity of 2 kN, initial length between fixation of 500 mm and speed of 250 mm/min. Before the test, the specimens (Fig. 1A) were stretched out on a table, secured with a glued joint at both ends, followed by sixty (60) twists per meter around its axis, as it is recommended by the standard (ASTM, 2014), and a twist value that, according to the literature, homogenizes and optimizes the breaking value of polyester yarns (da Cruz et al., 2022a). Thirty (30) specimens were tested for each YBL determination, thus reducing the standard deviation.

Fig. 1. (A) Specimens ready to be twisted; (B) Sample ready for QSS and DS test.

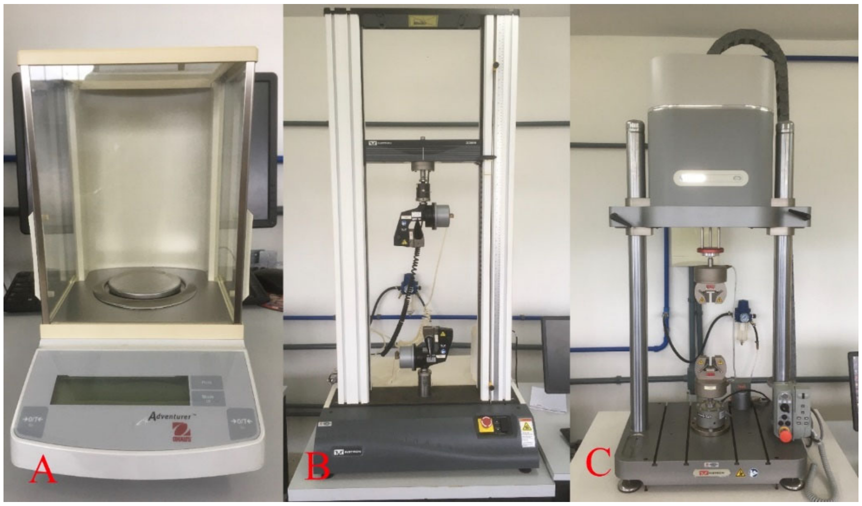

Fig. 2. (A) OHAUS Adventurer scale; (B) Instron 3365. (C) Instron ElectroPuls E3000.

Later on, the fibers' linear density was determinated according standard 2060: Textiles –Yarn from Packages- Determination of linear density (mass per unit length) by the skein method (Weller et al., 2014). Samples were one meter long and ten specimens per material were weighted on the precision scale (Fig. 2A) during a stabilization time of 5 minutes. After the YBL (in Newtons) and Linear Density (in tex – tex is g/km) are determined, it is possible to find the Linear Tenacity in Newtons per tex.

To determine the Quasi Static and Dynamic Stiffness (QSS and DS, respectively) the tests are not so straightforward, various controlled forces have to be applied throughout specific time periods. In order to achieve that an Instron ElectroPuls E3000 testing machine (Fig. 2C) with a 5 kN load cell and a 1 kN wedge action grip was used. Three samples per type of yarn were tested, they had 250 mm in length and were secured on both ends with a sandwich type bond (Fig. 1B).

The test routine, based on the ISO 18692-2 standard: Fiber Ropes for Offshore Station Maintenance, consists of 21 different steps (Fig. 3). It is divided into two sections: the first section is quasi-static and the second is dynamic. The routine is described in Table 1 and represented in Fig. 3.

Table 1. Test routine for quasi-static and dynamic stiffness (ISO 18692-2)

		Step	Description
Pre-Test		R1	Ramp to 10% YBL in 1 minute
		H1	Hold of 10% YBL for 1 minute (this represents the process called “bedding in” the modification of the mechanical properties in the first loading, as stated by Lian et al. (2018))
Quasi-Static	QSS 1	R2	Ramp to 30% YBL in 2 minutes
		H2	Hold at 30% YBL for 30 minutes
		R3	Ramp to 10% YBL in 2 minutes
		H3	Hold at 10% YBL for 30 minutes
	QSS 2	R4	Ramp to 30% YBL in 2 minutes
		H4	Hold at 30% YBL for 30 minutes
		R5	Ramp to 10% YBL in 2 minutes
		H5	Hold at 10% YBL for 30 minutes
	QSS 3	R6	Ramp to 30% YBL in 2 minutes
		H6	Hold at 30% YBL for 30 minutes
		R7	Ramp to 10% YBL in 2 minutes
		H7	Hold at 10% YBL for 30 minutes
Preparation		R8	Ramp to 30% YBL in 2 minutes
Dynamic	DS 1	C1	Cyclic load between 30-40% YBL Frequency of 0.1 Hz, 100 cycles (16.67 minutes)
		R9	Ramp to 40% YBL in 1 minutes
	DS 2	C2	Cyclic load between 40-50% YBL Frequency of 0.1 Hz, 100 cycles (16.67 minutes)
		R10	Ramp to 50% YBL in 1 minutes
	DS 3	C3	Cyclic load between 50-60% YBL Frequency of 0.1 Hz, 100 cycles (16.67 minutes)
Unloading		R11	Ramp to 0% YBL in 5 minutes
Total time=253 minutes (15180 seconds)			

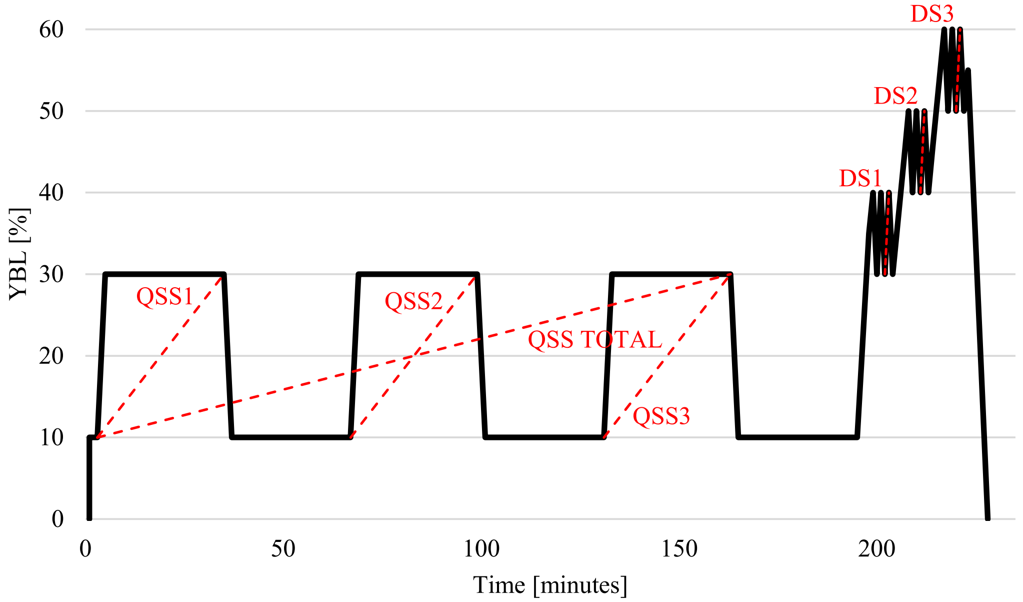

Fig. 3. Test routine based on ISO 18692: Fiber ropes for offshore stationkeeping.

To determine the Quasi Static and Dynamic Stiffness the data was to be put on an Eq. (1), which needs six different parameters: The Yarn Breaking Load (YBL) (in N), the initial length of the sample (L_0) (in mm), the load applied at the beginning of the step being tested (F_1) (in N), the variation in the length of the sample then (L_1) (in mm), the load applied at the end of the step being tested (F_2) (in N) and the variation in length of the sample then (L_2) (in mm). This equation delivers a non-dimensional stiffness, which can be found in more recent papers, as (Casey & Banfield, 2002; François & Davies, 2008; Davies et al., 2008; Weller et al., 2014), in comparison to other equations that deliver a modulus in N/tex or other dimensions (Liu et al., 2014; Bosman & Hooker, 1999). These moduli were also described by Del Vecchio (1992) and in the compilation done by De Pellegrin (1999).

$$QSS, DS = \frac{\left[\frac{(F_2-F_1)}{YBL}\right]}{\left[\frac{(L_2-L_1)}{(L_0-L_2)}\right]} \qquad (1)$$

3. Results and Discussions

Table 2 presents the initial data regarding the mechanical characterization of the PET samples tested here. It can be seen from the mechanical characterization that YBL, Linear Density and Linear Tenacity did not change much among the five samples. But it is possible to observe a decrease in Linear Density in all samples except the spool samples, which is expected, and another slight decrease in YBL in the samples tested in tension. In Table 2, in addition to the failure force values, the values in terms of stress in MPa are also presented. In fact, the mathematical definition of force over area is difficult to apply, due to the lack of accuracy in determining the area of a set of wires. Thus, a mathematical device is used for this determination, where the stress calculation is based on the rupture force (F), on the linear density (ρ_L) and on the specific gravity (ρ) of the material, Eq. (2). In this case, for polyester, its specific gravity corresponds to 1.38 g/cm3, and the other data are corresponding to each group.

$$\sigma[MPa] = \frac{F[N] \cdot \rho[g/cm^3]}{\rho_L[g/m]} \tag{2}$$

Table 2. Samples' Mechanical Characterization

Sample	Spool (Virgin)	Eye Splice Sample Tensile Tested	Body Sample Tensile Tested	Eye Splice Sample Fatigued	Body Sample Fatigued
YBL [N]	174.4 ± 3.2	167.4 ± 4.3	168.9 ± 5.0	172.7 ± 4.2	174.0 ± 4.2
Linear Density [tex]	233.8 ± 0.8	225.3 ± 1.3	224.6 ± 1.1	227.2 ± 1.3	225.3 ± 1.8
Tension [MPa]	1029,39	1025,35	1037,76	1048,97	1065,78
Linear Tenacity [N/tex]	0,746 ± 0,016	0,743 ± 0,024	0,752 ± 0,026	0,760 ± 0,023	0,772 ± 0,025

For each of the five types of samples, three specimens were tested following the test routine indicated in Table 1, and in Fig. 3. The data acquired during the test are applied in Equation 1 to determine the quasi-static stiffnesses: QSS 1 , QSS 2, QSS 3 and QSS Total, and also the dynamic stiffnesses: DS 1, DS 2 and DS 3. Table 3 shows the mean and standard deviation for all five sample types across all seven stiffnesses. The data are plotted in four different graphs, the QSS for the tensile tested samples, the QSS for the fatigued samples, the DS for the tensile tested samples and the DS for the fatigue tested samples, all compared with the virgin samples. Shown here in Fig. 4, Fig. 5, Fig. 6 and Fig. 7, respectively.

Table 3. Quasi-Static and Dynamic Stiffness.

Sample	Spool (Virgin)	Eye Splice Tensile Tested	Body Tensile Tested	Eye Splice Fatigued	Body Fatigued
QSS 1	4,26 ± 0,09	4,36 ± 0,12	3,61 ± 0,07	5,05 ± 0,17	4,78 ± 0,14
QSS 2	14,80 ± 0,09	14,66 ± 0,12	14,86 ± 0,16	14,48 ± 0,17	14,85 ± 0,12
QSS 3	15,61 ± 0,05	15,21 ± 0,10	15,36 ± 0,22	15,02 ± 0,11	15,25 ± 0,12
QSS Total	4,20 ± 0,11	4,32 ± 0,05	3,60 ± 0,06	5,02 ± 0,18	4,78 ± 0,13
DS 1	23,58 ± 0,11	23,20 ± 0,16	23,53 ± 0,41	22,91 ± 0,18	23,19 ± 0,13
DS 2	25,91 ± 0,05	25,63 ± 0,13	26,13 ± 0,39	25,28 ± 0,14	25,58 ± 0,13
DS 3	28,63 ± 0,15	28,16 ± 0,17	28,76 ± 0,56	27,83 ± 0,21	28,09 ± 0,16

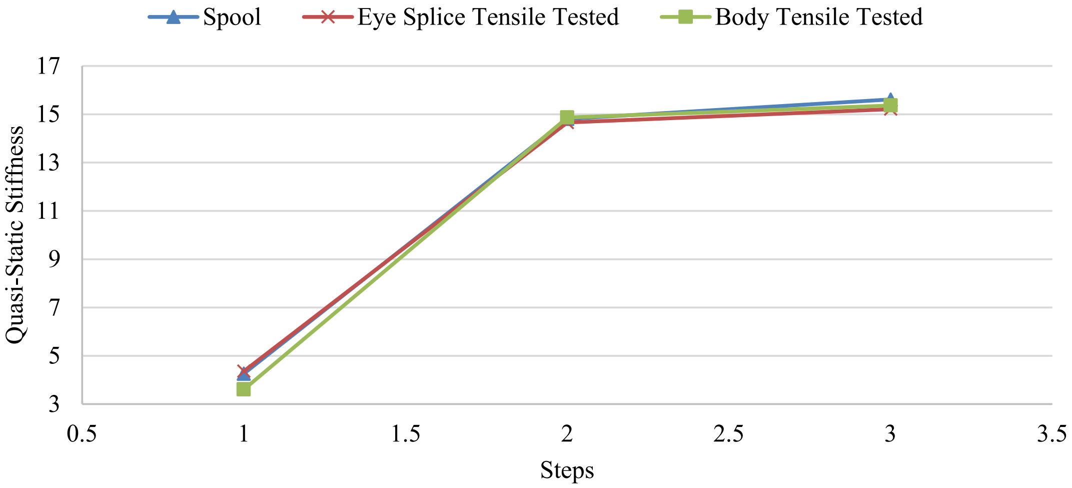

Fig. 4. Quasi Static Stiffness for the Tensile Tested samples.

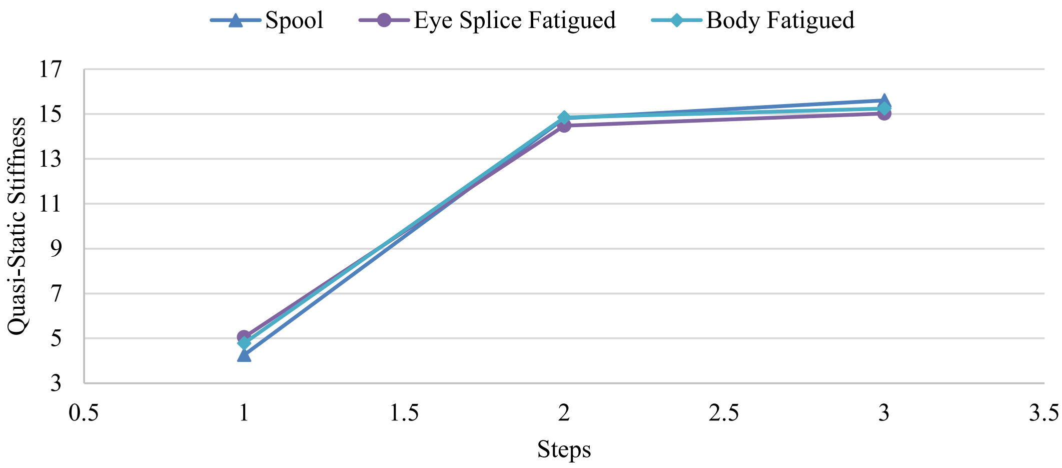

Fig. 5. Quasi Static Stiffness for the Fatigued samples.

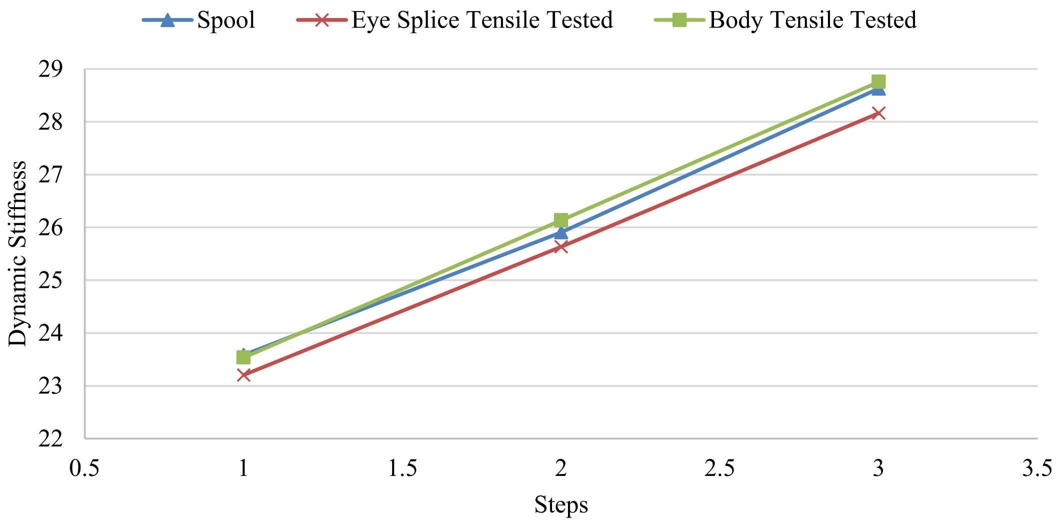

Fig. 6. Dynamic Stiffness for the Tensile Tested samples.

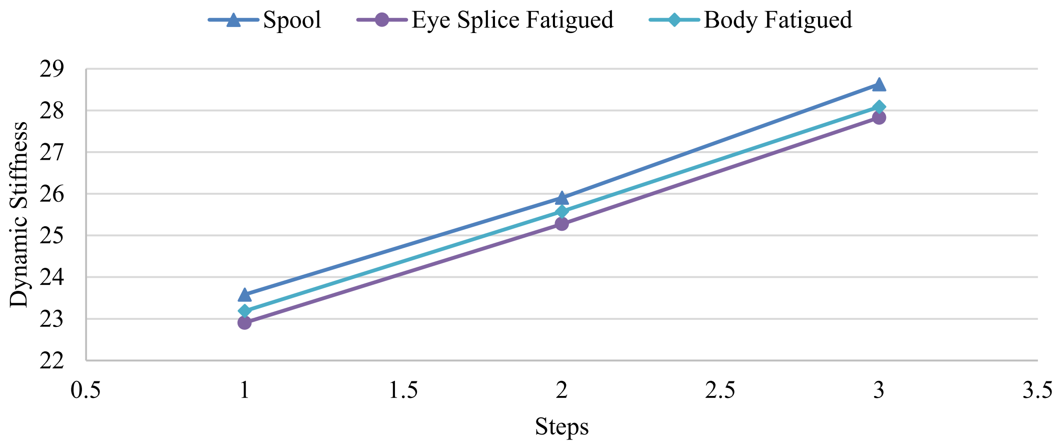

Fig. 7. Dynamic Stiffness for the Fatigued samples.

One can also compile the graphs into two general graphs, one for the dimensionless quasi-static stiffness values, and another for the dimensionless dynamic stiffness values. Although it is about 5 curves, and sometimes difficult to interpret, this graph allows comparing the dimensionless values between the samples of the sub-rope broken by traction, and the samples of the fatigued sub-rope. Fig. 8 shows the curves for dimensionless quase static stiffness, and Fig. 9 shows the curves for dimensionless dynamic stiffness.

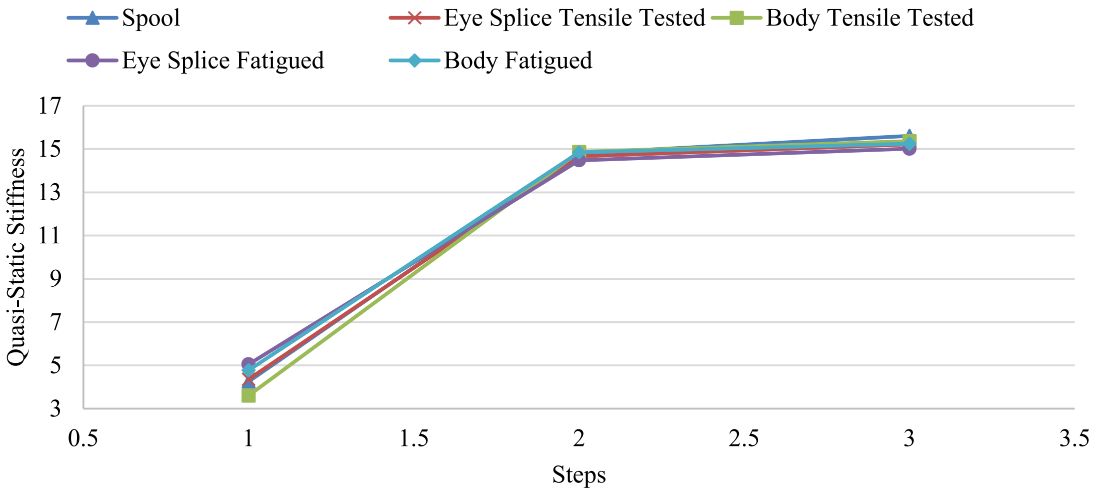

Fig. 8. Quasi Static Stiffness for all samples type.

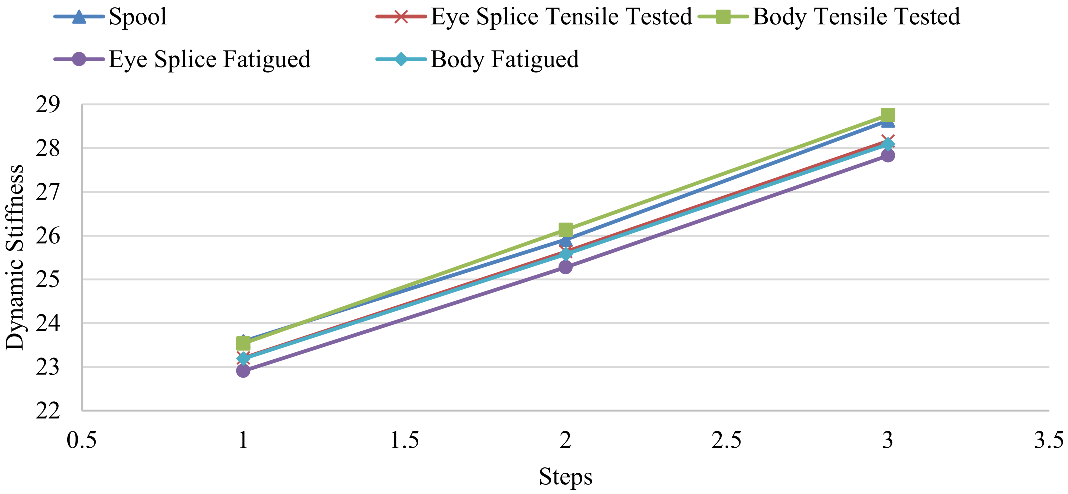

Fig. 9. Dynamic Stiffness for all samples type.

Other investigations reached similar results for the dynamic stiffness but instead of using an amplitude of 10% YBL, they used 0,6% at 40% (Casey & Banfield, 2002). Moreover, Davies et al. (2008) found lower results for DS, around 18 instead of a value between 23 and 28, but at a stochastic not synodical loading. And showed a very similar result for QSS Total. François & Davies (2008) did a somewhat similar test for QSS and reached a similar value when using sub-ropes and full-size ropes which concludes that a study on yarns characterizes the behavior of a sub-rope and rope. There is a clear increase in stiffness on the overall Quasi Static and the Dynamic tests, for all materials. Which indicates that upon usage a multi-filament tends to get stiffer. In the QSS the results tend to stagnate towards QSS 3, which could indicate that the stiffness reached a "plateau". The same behavior can be seen in other materials as the High Modulus Polyethylene (HMPE) in (Stumpf et al., 2016), further studies should increase the number of QSS cycles. A somewhat different procedure was conducted in (Liu et al., 2014) and showed that stiffness tends to plateau with the increase in number of cycles. Even though the Dynamic stiffness on the Fatigued samples are lower than the Spool samples, and in the QSS Total for the Body Tensile Tested and the Eye Splice

Fatigued are the ones most variant in comparison to the Spool, lower and higher, respectively. It is possible to see that the overall behavior is very similar throughout all the different samples. Which indicates that although the samples have been used and treated in different ways, their stiffness has not changed significantly. Addressing specifically the QSS Total that can be calculated by assigning the data in Eq. (1) that encompasses all three quasi-static steps, one can compare the dimensionless values for each of the 5 types of samples. Fig. 10 shows this data, which are the values for QSS Total shown in Table 3.

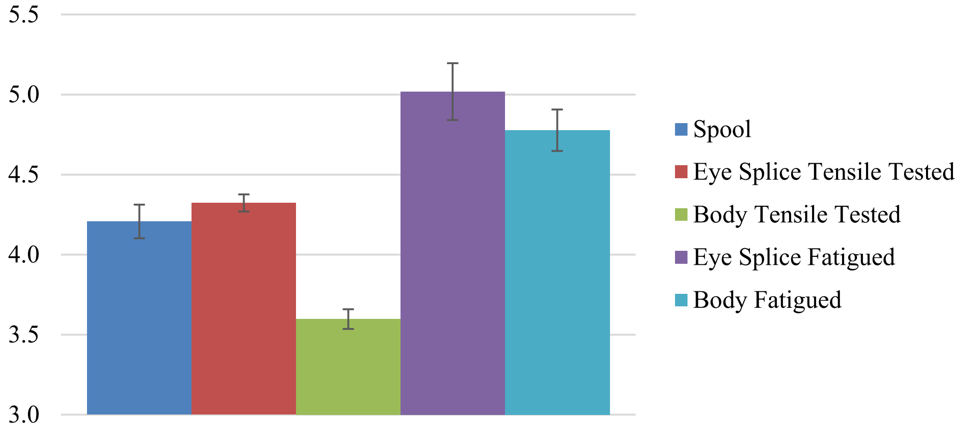

Fig. 10. Quasi Static Stiffness Total for all samples type.

From the behavior and values presented, it should be highlighted the low value of QSS Total for the sample extracted from the body region of the sub-rope tested under tension. This may be due to the fact that in the sub-rope test, the abrupt stretching of the chains confers greater stiffness to the multifilament extracted from this part, thus, the elongation evolution in the three static steps performed in the routine does not represent an increase in total quasi-static stiffness as significant as for the others, works in the literature can be referenced that show the mechanical degradation that rupture tests or other mechanical procedures can have on specimens (Dobah et al., 2016; Gagel et al., 2006; Shah, 2016; Khoddami et al., 2009). Still on the QSS Total, it should be noted that the highest dimensionless stiffness values are for the specimens extracted from the sub-rope subjected to fatigue. This is due to a mechanical improvement, there is the formation of an amorphous phase within the material that confers greater stiffness (Santos, 2002). The dynamic load makes this ordering better elaborated, in the same way that low impact loads in a controlled way can allow this mechanical improvement (Sry et al, 2017; Cruz et al., 2023), fatigue loads can have the same effect of conferring greater stiffness (da Cruz et al., 2023; Tate et al., 2018; Baley, 2002; Capela et al., 2019), it can also be inferred by intuition that this mechanical improvement can be improved as smaller fatigue amplitudes are made but with longer durations as long as the integrity of the wires is still maintained. Making parallels with what happens in steels, one can relate a cold work, a work hardening that mechanically improves the material.

4. Conclusions

Complementing the literature on the subject of Quasi Static and Dynamic Stiffness on synthetic materials, this work comes as a study of the effects of mechanical degradation on PET's Stiffness values, based on the technical standard. Polyester being the most used for a variety of marine applications. After analyzing the data, the Quasi Static and Dynamic Stiffness for the different samples tested herein did not vary significantly. Even though it is possible to see slight changes in their value, specially for the Dynamic Stiffness for Fatigued and Tensile Tested samples, it would be frivolous to say that such small variations should be considered a completely different behavior. Another important conclusion found is that the bedding-in process is necessary. The Quasi Static stiffness increases with the number of cycles, until it reaches a plateau. This means that without the bedding-in the QSS 1 result would have been wrong, because it would have contained the mechanical properties "plastic" variation. What can also be concluded by comparing the results shown herein with the overall results in other papers is that the stiffness behavior expressed by a yarn can characterize the behavior of a rope and sub-rope, since they were very similar. The results presented here, show the overall behavior of PET samples as for their Quasi Static and Dynamic Stiffness. The data for a material's stiffness, and how it varies, is of the utmost importance for the design of a rope for offshore anchoring, mooring or other marine applications. An essential part of the results is related to the QSS Total. Understanding the abrupt stretching of a specimen taken from a portion of a sub-rope that underwent rupture as a limiting factor for stiffness gain in the procedure, while the sample extracted from a sub-rope that underwent a fatigue process presents the greatest QSS Total values, where fatigue works as stiffness gain and mechanical improvement. This result itself should be explored in future studies, understanding how dynamic loads (fatigue and impact) can provide such improvement, and even if it can be achieved through a static load such as creep, for example.

Still along the same lines, the combination of these mechanical tests to determine maximum stiffness can be explored, a possible example is the performance of a controlled impact for the main stretching of the chains, followed by a fatigue cycle at low load and low amplitude but for long times, and by end as a "refinement" of the mechanical improvement a creep procedure with low load that still guarantees the integrity of the sample.

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