MECHANICAL BEHAVIOR ANALYSIS OF THE HIGH DENSITY POLYETHYLENE AFTER BEEN SUBMITTED TO CYCLIC LOADING

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Abstract. The aim of the present work is to evaluate the cyclic loading influence on the mechanical behavior of the polymeric external layer (HDPE) that conform the optical-power submarine cables, employed in offshore operations. First, in the laboratorial arrangement specially projected and constructed for the experimental work, it was tested a 13,5m long section of a cable with an external diameter of 108 mm, subjected to fatigue loading. After a pre-defined number of loading cycles, samples of the external layer were retired from loaded cable. Following the standard ASTM 638, tensile test specimens were machined from the obtained samples, as well as from unloaded samples. After the tensile test, the results analysis showed that the material had suffered changes in its mechanical behavior. It was observed an abrupt drop in the material tenacity caused by the cyclic loading. Finally, using the Finite Element Method (FEM), and with the help of the softwares LUSAS and ALGOR were developed physical-mathematical models with the purpose of evaluate large strains in these types of materials. The geometries used followed the patterns of the tensile test specimens.

Keywords. *High Density Polyethylene; Optical-Power Submarine Cables; Mechanical Behavior, Fatigue; Finite Element Method.*

1. Introduction

With the discovery of great basins petroliferous in deep waters in Brazil, a great effort has been developed in the country in the last decades in order to reach the self-sufficiency in the production of petroleum and its derivates. In this context, the need of the development of new techniques of engineering appeared to assist to the current demands in the operations of hydrocarbons prospecting in the sea bottom. These techniques involve the use of floating production system, constituted of production platforms, of converted ships and of the subsystems composed by them, such as, electro-optical submarine cables (umbilical cables), non-flexible and flexible production risers, anchorage lines, etc. It appears that there exist the need of great investments in research and development for part of the government and of great companies. The main focuses of the researches are the adaptation, innovation and search of new technologies to turn more productive and safe the oceanic operations.

The umbilical cables used in the floating production systems are submitted to the conditions of the sea atmosphere, in other words, waves and sea currents originating lateral displacements of the platforms and movement of the lines along the length of the cables, generating on the same ones a combination of traction, bending, torsion efforts and external pressure. Such efforts can cause structural failures like fracture of the metallic and polymeric parts, as well as the precocious aging of the polymeric parts. It should be emphasized that the failure of the umbilical cable results in a disastrous consequence under the economical point of view, due to the stoppage of production or perforation operations.

2. Structural and Functional Characteristics of the Umbilical Cables

The electro-optical submarine cables are utilized to transmit control signs and to supply with energy the valves systems installed in the heads of the petroliferous wells in the bottom of the sea. The typical structure of an umbilical cable, illustrated in the Fig. (1), is composed basically of an overlap of plastic and metallic layers of structural character, copper conductors, whose function is to drive electric power, and an optical fiber cable responsible for the transmission of signs. Its structure is composed by metallic and polymeric materials, that confer it support and flexibility, making possible its continuous production and use in facilities of long segments of cables. The main advantage is that they present larger tolerance to the lateral movement of the floating production system, and as disadvantage, the difficulty of production of the same ones involving different geometries and materials.

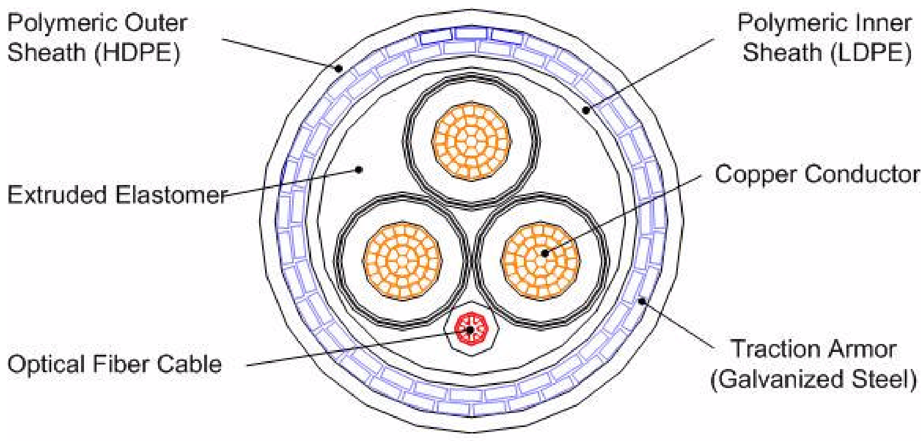


Figure 1. Typical structure of a Umbilical Cable (cross section).

For a good operation of the umbilical cable, the polymeric outer sheath, composed of polyethylene of high density (HDPE), usually extruded on the external traction armor carry out the fundamental functions of provide watertight to the cable, protecting the interns structure against corrosion, abrasion and impact damages, besides helping to maintain the wires of the traction armor in the correct position.

To prevent harmful effects, as illustrated in the Fig. (2), (Alves; Costa, 2001), (Quintela; Alves, 2002), the polymeric sheaths should have good properties in relation to the aging, resistance to the wear and tear, great elongation before reaching the rupture, and good flexibility, since the dynamic effect that the cable is submitted during its service life can provoke fissures and rupture for fatigue and aging of the polymeric materials that compose it.

Figure 2. Effect of the corrosion in the internal structure of a flexible line due to fissures in the polymeric outer sheath.

3. Fatigue Test in Umbilical Cable

This experiment was made to simulate the several and complex stresses that the umbilical cables are submitted during its installation and service in the offshore operations.

The bench, especially projected and built for the accomplishment of the tests, illustrated in the Fig. (3), was conceived starting from a wheel (it pulley) of 3,5 meters of diameter and a traction system capable of stretching the specimen (umbilical cable) with a load of 200 tf. As a reference guide, in the projection and construction of the bench was used the graph of the figure I-2 of Appendix I - it Fatigue Testing (API-17E), where it is shown the disposition of the cable around of an oscillating pulley.

The specimen was tested a 13,5m long section of a cable with an external diameter of 108 mm, instrumented with strain gage in 8 points in the external traction armor.

During the fatigue test, the specimen was submitted a traction load of 60 tf. Soon afterwards, staying that load, it was made the pulley to oscillate (external diameter of 3,5 m) with an alternative movement, being imposed curvature changes in the umbilical cable originating cyclical stress and cyclical strain in its different layers. The cable, in each cycle, inflected a length of 1,8 m. The duration of the test was of 30 000 cycles and the duration of each cycle was in the range of 5 and 10 seconds.

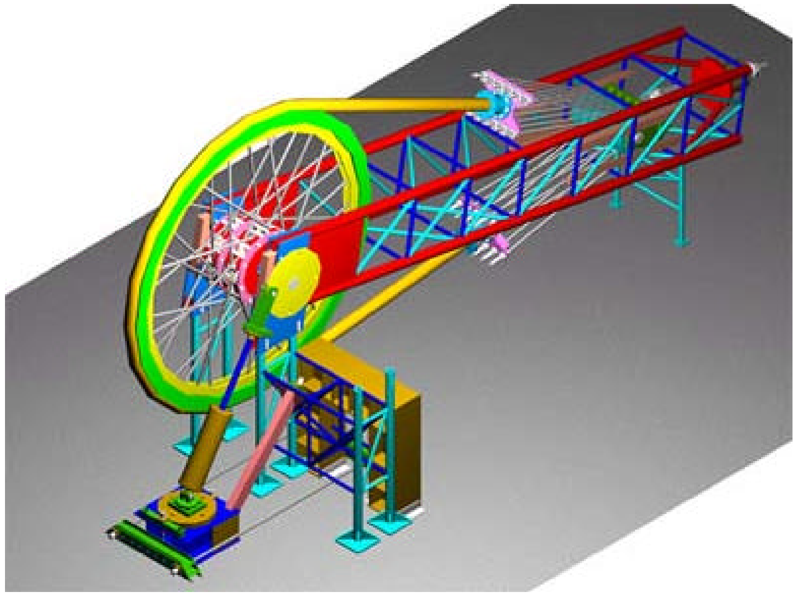


Figure 3. Draw of the bench for mechanical fatigue test in the umbilical cable.

During the fatigue test it was observed that the residual strain grew with the increase of the number of the cycles in the external traction armor of the cable. Before and after having concluded the test, measurements of the passage of electric current were made along the copper conductors and in the optical attenuation of the fibers, being observed a quick increase in the electric resistance of the conductors and any effect in the optical attenuation of the fibers.

4. Tensile Tests of Specimens of the Polymeric Layers

The tensile tests were based on the norm ASTM D 638, Standard Test Method for Tensile Properties of Plastics. This norm establishes, for application in this study type, the use of specimen type "Dumbbell-Shaped" of the type I, illustrated in the Fig. (4). This type of specimen was chosen for being the most appropriate for tests with polymeric that are included in the group of the semi-rigid plastics with thickness larger than 1 mm and smaller than 7 mm, as it is the case of the polyethylene of high density (HDPE).

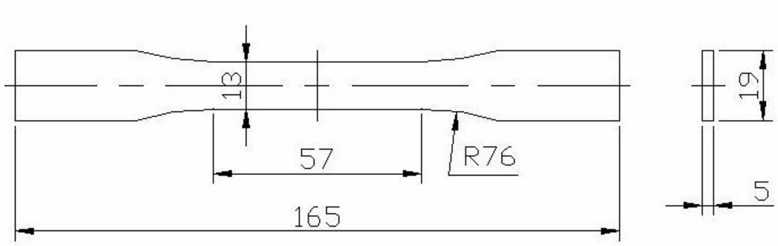


Figure 4. Specimen for tensile test with plastics according to the norm ASTM D 638.

To verify the variation of the mechanical properties of the cable tested and of one that hadn't suffered any loading, samples were removed from the area where the cable was submitted to cyclical loadings of traction and flexion previously of the fatigue test and of the polymeric of an umbilical that hadn't been submitted any loading.

Following the norm establishments, five specimens were made of each one of the samples of the materials; being tested two lots of five specimens for each one of the polymeric, totaling ten specimens.

According to the norm ASTM D 638, to accomplish tensile tests with polymers is advisable a room temperature of $23 \pm 2\ ^oC$ and a relative humidity of $50 \pm 5\%$ for no less than 40 hours before the test. The tensile tests were carried out in temperature of 24^oC and relative humidity of 52%, respecting the established for the norm. The speed used in the test was of 50 mm/min for being a medium speed among the three recommended by the norm. The test was conducted using an INSTRON TTL-DM-L screw-driven mechanical test system, with 10 tf of loading capacity.

The specimen was submitted to traction effort along his length, that tends to stretch, originating a strain of the material in the direction of the applied force. While load is applied, the strain grows continually until almost the end of the test. As much the strains as the efforts they were measured by devices coupled in the test machine.

5. Analyzes and Discussion of the Results of the Tensile Tests

The results showed clearly that the cyclical loads, that were submitted one of the sections of the electro-optical submarine cable, had great influence in the mechanical properties of the out sheath of the cable (HDPE). This was noticed after to analyze and to compare the results of the tensile tests of the specimen done with the samples of polymeric material, of the cable sections, from one that was submitted to cyclical loads previously and from another that hadn't suffered any loading.

Comparing the stress-strain curves obtained in the tensile tests of the extracted specimen of the two samples of material of the layer of the cable done of HDPE, it could be observed that the behavior for both is similar in the first part of the curve reaching the medium yield stress of 20,3 MPa with a medium strain of 22,3%.

However, when the material began to flow in the specimens done with the sample of polymeric that it hadn't been submitted to cyclical loads before the tensile test, the stress decreased abruptly until a medium value of 13,34 MPa and a medium strain of 57%. Since then an uniform necking he began in the area of work of the specimen originated by a reorientation in the polymeric chains and could be appreciated a plateau in the stress-strain curve, in other words, staying an almost constant stress in this part of the curve with tendency to a small increase, due to reorientation phenomenon mentioned previously, until the end of the test where the value of medium stress was of 13,57 MPa with a strain of 300%.

The behavior of the three specimens of the lot No.1 elaborated with the sample of material of the outer sheath, HDPE, of the cable that hadn't been submitted to any loading was very similar. In the Fig. (5) are shown the stress-strain curves for the three specimen of the lot No.1, ET 1.1; ET 1.2; ET 1.3, and in the Tab. (1) it can be observed significant values of the stress and strain of the three tests with the medium values of each one.

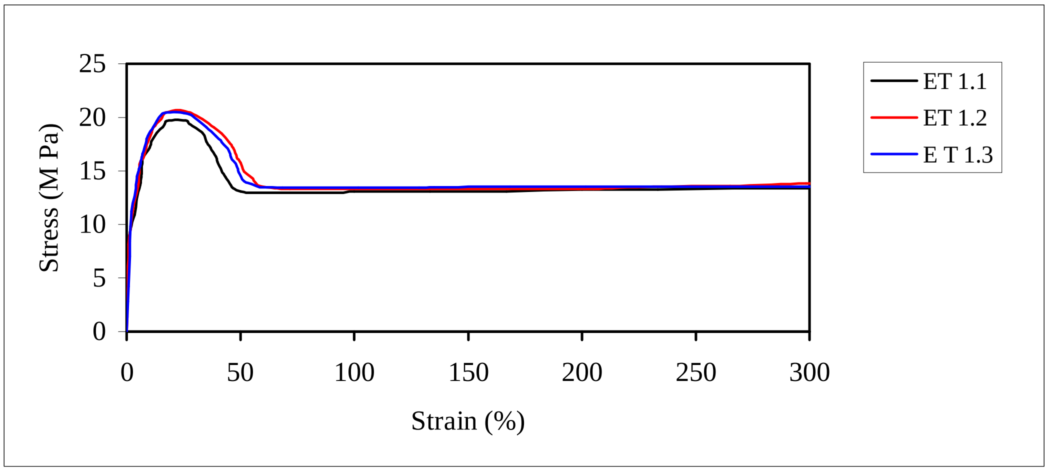


Figure 5. Stress-strain curve for the specimen of HDPE, material that the wasn't submitted any loading before of the tensile tests.

Table 1. Significant values of stress and strain of the tensile tests of the HDPE specimen, material that wasn't submitted any loading before the tensile test.

Mechanical Properties		ET 1.1	ET 1.2	ET 1.3	Average	Deviation
Yield Stress	(M Pa)	19,79	20,66	20,52	20,32	0,467
Yield Strain	(%)	22,50	22,50	21,70	22,20	0,461
Reorientation Stress	(M Pa)	12,96	13,59	13,46	13,34	0,332
Reorientation Strain	(%)	53,30	58,30	61,60	57,70	4,178
Ultimate Strength	(M Pa)	13,37	13,80	13,56	13,57	0,215
Ultimate Strain	(%)	300,00	300,00	300,00	300,00	0,000

For the specimen of the lot No. 2, made with HDPE and submitted to cyclical loads before being submitted to the tensile test, in the instant after having reached the yield stress, it is noticed an abrupt decrease of the stress and at the same time a no uniform necking of the work area of the specimen ill its rupture. That is due to a nucleation of defects and micro-pores that work as stress concentrators, reducing the tenacity of the material. The behavior of these specimens of the lot No.2, made with the material of the polymeric outer sheath, from the cable that had been submitted to cyclical loads, was very similar. In the Fig. (6) are shown the curves stress-strain for the three specimen of the lot No.2, ET 2.1; ET 2.2; ET 2.3, and in the Tab. (2) some of the significant values of stress and strain of the three tests can be observed with the medium values of each one of them.

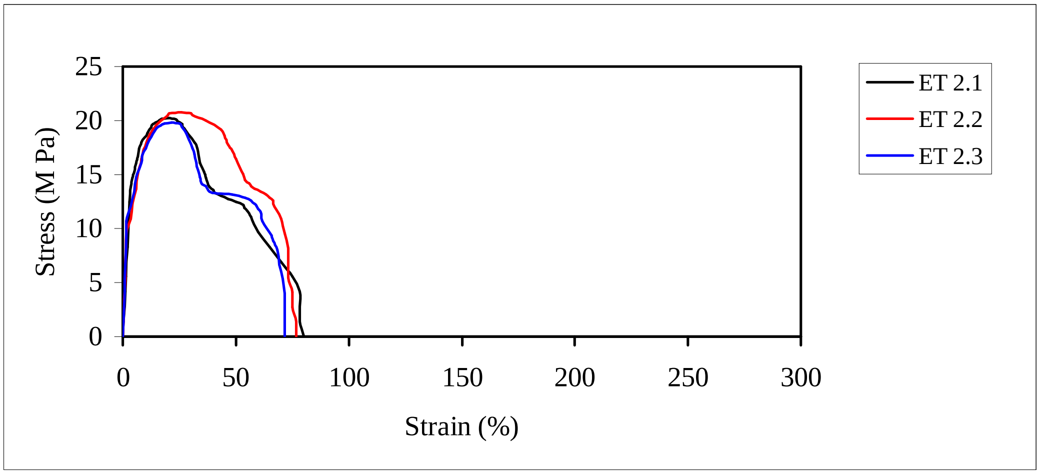


Figure 6. Stress-strain curve for the HDPE specimen, material submitted to cyclical loads before the tensile tests.

Table 2. Significant values of stress and strain of the tensile tests of the HDPE specimens, material that the wasn't submitted to any loading before the tensile test.

Mechanical Properties		ET 2.1	ET 2.2	ET 2.3	Average	Deviation
Yield Stress	(M Pa)	20,22	20,78	19,82	20,27	0,482
Yield Strain	(%)	20,00	25,80	21,70	22,50	2,981
Ultimate Strength	(M Pa)	11,91	12,31	12,06	12,10	0,202
Ultimate Strain	(%)	53,70	66,70	59,20	59,90	6,525

In the Tab. (3) is observed the magnitude of the variation in the range of the medium values of the stress and strains of the tensile tests, made with samples from materials of the outer sheath of the section of the umbilical cable that it hadn' t suffered any loading, (Lot No.1) and from the section of the cable that was submitted to cyclical loads previously (Lot No.2).

Table 3. Magnitude of the variation among the medium values of the stress and strains obtained in the tensile tests of the polymeric outer sheath of the cable.

Mechanical Properties		Lot Nº. 1	Lot Nº. 2	Variation (%)
Yield Stress	(M Pa)	20,32	20,27	0,25
Yield Strain	(%)	22,20	22,50	1,35
Reorientation Stress	(M Pa)	13,34	12,10	10,25
Reorientation Strain	(%)	57,70	59,90	3,81
Ultimate Strength	(M Pa)	13,57	12,10	12,15
Ultimate Strain	(%)	300,00	59,90	400,83

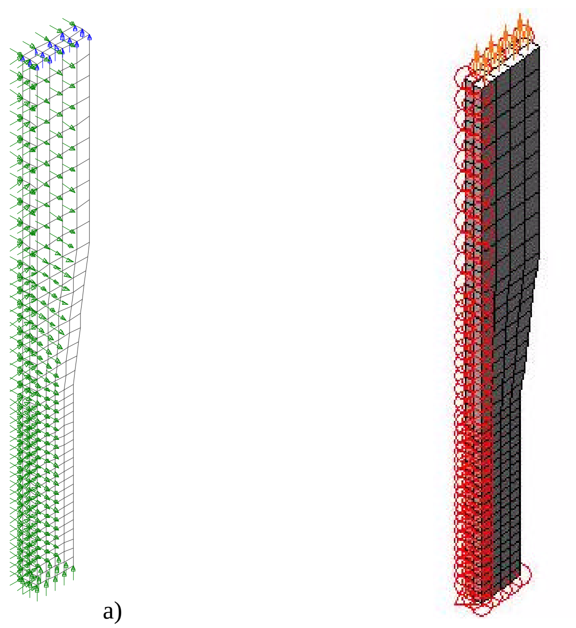
6. Numeric-Computational Evaluation

For the modeling of the specimen, were used the computational codes LUSAS [Theory manual. United Kingdom: FEA Ltd., 2000] and ALGOR [http://www.algor.com] to simulated the tensile tests. The modeling of this type of analysis was No Linear Static, due to the properties of the viscoelastic material and to the low speed with that were made the tests. As model of the material, was used Stress Potential type von Mises in the LUSAS software and von Mises curves with Isotropic Hardening in the software ALGOR, since it is know the stress-strain curve of the material, supplied by the manufacturer and from the bibliography. It was used in the elastic part of the curve a modulus of elasticity of 670 MPa and a yield stress of 21,00 MPa, while in the part no linear the modulus was of 3,71 MPa and ultimate strength was of 32,00 MPa.

Were used Hexahedral Solid Elements with 8 nodes, since the thickness of the bodies to be modeled were of 5 mm, quite considerable, taking into account that the specimens had width of 13 mm in the work area (neck) and length of 165 mm.

Taking advantage of the triple symmetry of the geometries of the specimens only, ¼ of the body was modeled. In the superior extremity of the model was applied the traction load, in the direction +Z, distributed in the superior surface to avoid undesirable stress concentrations in their vertexes. The applied loading was 520 N.

In the Fig. (9), are shown the meshes configured for the models with the boundary conditions and the imposed loading in the LUSAS and in the ALGOR softwares.



a) b)

Figure 9. Models of the specimens with the mesh, the boundary conditions and applied loading in the softwares: a) LUSAS and b) ALGOR.

After having analyzed the modeling results of the tensile test from the polymeric specimens, simulated by the Finite Element Method, with the computational codes LUSAS and ALGOR, it was observed that in the simulation of the test that the stress and strain values obtained with both softwares were satisfactory until the drawing process of the material, since they presented good agreement with the relative numbers to the mechanical properties given by the manufacturer of the cables and for the consulted bibliography.

Later, with the LUSAS program, good results were obtained along the whole stress-strain curve resulting from the simulation, being reached a strain of more than 300%. With the software ALGOR, after the materials reached the yield and when the strain reached 69,20%, practically all of the elements of the work area (neck) reached a state that the stress and strain values remained constant, disabling the accomplishment of the calculations of efforts and subsequent displacements for the softwares, besides, the values of last stress obtained for the modeling were larger than the one should be obtained as a result of the computational simulation.

The more significant results of stress and strains of von Mises obtained in the modeling with the computational codes LUSAS and ALGOR, as well as the variation of the results of the modeling with the data supplied by the manufacturer of the cable and of the consulted bibliography, are shown in the Tab. (7).

Table 7. The more significant values of stress and strains of von Mises obtained from the modeling with the LUSAS and ALGOR programs and compared with the data supplied by the manufacturer of the cable.

Mechanical Properties	Manufacturer	LUSAS	Variation (%)	ALGOR	Variation (%)
Yield Stress (M Pa)	21,00	21,00	-	21,00	-
Yield Strain (%)	3,13	8,27	164,21	7,45	138,02
Ultimate Strength (M Pa)	32,00	28,26	11,68	75,90	137,18
Ultimate Strain (%)	300,00	300,00	-	(*)	-

(*) In the program ALGOR it wasn't possible to reach 300% of strain; the calculations were interrupted with the strain of 69,20%.

7. Conclusions

After finished the study, it was arisen the following conclusions:

- The cyclical loadings that the submarine cable was submitted had a marked influence in the mechanical properties of the outer sheath of the cable, HDPE, provoking a great decrease of its tenacity. This was observed when the material began to flow. In the specimens made with the sample of polymeric that it hadn't been submitted to cyclical loads previously to the tensile test, it was noticed more than 300% of strain without reaching the rupture. The specimen submitted to cyclical loads before having tensile test, in the subsequent instant to the yield, it was noticed an abrupt decrease in the stress of the rupture of the specimens, being the medium strain in the moment of the rupture 59,9%;
- In the modeling of the specimens for the Method of the Finite Elements (MEF) using the LUSAS computational code was obtained good results, demonstrating the good acting of this software for the simulation of models that involve no linearity and large strains as in the case of the polymeric materials;
- In the case of the modeling of the specimens for the Method of the Finite Elements (MEF) using the ALGOR computational code the results obtained wasn't satisfactory, demonstrating that this software is not adequate for the simulation of models that involves no linearity and great deformations, larger than 69,20%.

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