CHARACTERIZATION OF THE MECHANICAL BEHAVIOR OF A THREE-LAYERED COMPOSITE APPLIED ON OIL PIPELINES THROUGH TENSILE TESTING AND FINITE ELEMENTS

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ABSTRACT

The oil & gas industry has to constantly face equipment corrosion challenges due to the chemical characteristic of the oil, gas and contaminants in the reservoirs. In 2010, a three-layered composite was developed, reinforced with glass fiber, for the terrestrial production pipelines as an alternative to Grade B API 5L steel, which was commonly used and more susceptible to corrosion. In this work, samples of pipes made of this composite were collected from two oil wells, which have been operating with this material for a few years. The samples were analyzed through tensile testing and compared with a new control sample. A finite element simulation was also performed in order to understand the mechanical behavior of this new material through modeling. The results pointed to a higher mechanical strength of the well samples and the finite element simulation revealed that the mechanical behavior of the composite is complex and multi-axial, with instrumented tensile tests with image correlation being more recommended to characterize this material.

Keywords: tensile test, finite elements, composite, petroleum piping.

INTRODUCTION

The oil exploration industry is hindered significantly by the corrosive process due to the complex characteristics and composition of the fluids in oil reservoirs. Mature onshore fields (old fields with declining production) have the characteristic of having a lot of water and other corrosive agents along with the oil, such as O_2, CO_2, H_2S and sulfate-reducing bacteria. These agents tend to attack the steel pipes internally, just as the soil and atmosphere tend to cause external corrosion in these types of equipment.

For some years already, composite materials have been consolidated as an alternative to be used in corrosive environments, replacing metal alloys because they combine more properties of more than one material **[1].** Their structural characteristics promote attractive property combinations, such as low density, high specific resistance, high modulus of elasticity, and high chemical resistance, which enable the manufacture of parts with complex geometries and high resistance to corrosion and degradation in various industrial environments **[2].**

Glassfiber reinforced polymer matrix composites (GFRP) are the most common in this category. The main advantages of these composites are their low cost, good tensile strength, good chemical resistance and excellent insulating properties. The disadvantages are their relatively low modulus of elasticity, high density (of the commercial fibers), sensitivity to abrasion during handling (which often reduces tensile strength), relatively low fatigue strength and high hardness (which causes excessive wear in molds and cutting tools) **[3].**

In general, several factors are of influence on the mechanical behavior of composites. These factors include the manufacturing process used, the manner in which the loads are applied, the developed damage mechanism, the presence of adverse humidity and temperature conditions, the respective volume fractions, the properties of the interface, the presence of voids, in addition to the properties of the constituent elements **[4].**

An important detail for composites engineering analysis is that unlike metals, which have properties that do not change with the loading directions (isotropic), composites may have different properties with the variation of the loading directions (anisotropic) because of their complex nature. For composite materials, these variations in properties generally occur in the directions of the main longitudinal and transverse stresses to the reinforcement of the material, which provides them a so-called orthotropic behavior (properties vary with these directions) **[5]**.

The objective of this work is to use tensile tests to understand the mechanical behavior a newly-developed, three-layered polymeric composite operating in mature oil fields. A finite element simulation was also performed, using software models for composite materials, in order to compare it with the tensile test result. This study may assist in the prevention of future failures of this new material due to harmful changes in its properties, avoiding future problems with operational, personal and environmental accidents.

EXPERIMENTAL

Materials

The composite under study was produced through the filament winding process, which is characterized by high dimensional control and mechanical strength **[6]**.

The material has an internal layer made of a glass fiber reinforced epoxy polymeric matrix, an intermediate layer of a glass fiber and silica reinforced polyester matrix and an outer layer coated with high density polyurethane. The material was specified for 3-inch pipes, a maximum operating pressure of up to 5.17 MPa (750 psi) and a design temperature of 95 °C **[6].**

The innermost epoxy layer with glass fiber is the most important layer of the material, since this is the layer that is in first contact with the pressure, temperature and characteristics of the fluid that flows through the pipeline and therefore needs to have the best properties. The intermediate polyester and silica layer is meant to improve the rigidity of the composite without the need to increase the thickness of the inner layer, saving on the final cost of the material **[6].** The outermost layer of high-density polyurethane, on the other hand, is meant to serve as an insulating, mechanical and corrosive protection against agents present in the soil or atmosphere **[7]**.

Samples of these types of composite pipelines were taken from two oil wells that have been operating with this material for eight years, and a sample was also taken from a control pipe that was never used. Table 1 shows the identification and year of start of operations of the samples.

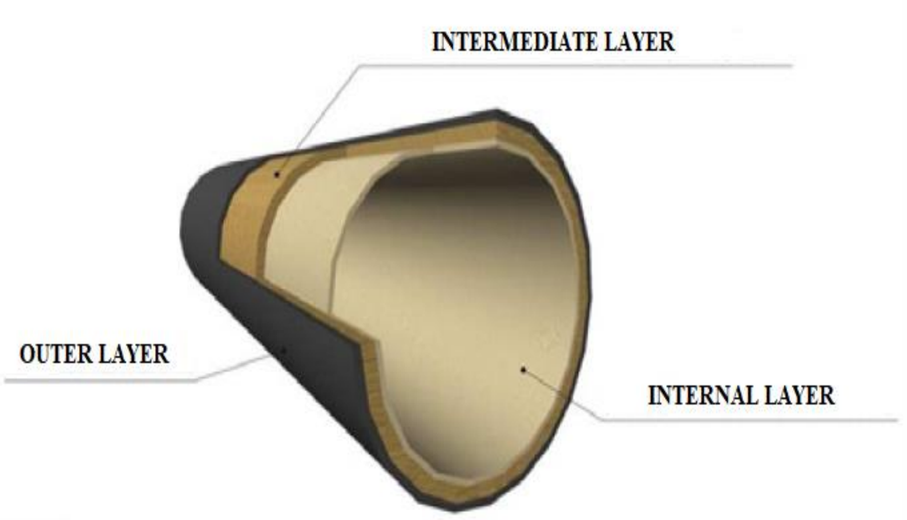

Figure 1. Three-layered polymeric composite **[6]**.

Table 1. Samples of composite production lines.

Sample Identification	Year of Operation
Control	-
RP-0147	2012
PL-0288	2012

Methodology

Tensile Testing

Three longitudinal specimens were removed from the central region of each of the three pipes, totaling nine tests (the specimens were not machined). The specimens had a strip shape according to the dimensions shown in Figure 2 (300 mm by 18 mm) and the tensile test procedure followed the NBR 15536 standard (Annex G) **[8]**. The device used in the tests was a Shimadzu universal testing machine model AG-I-250N.

Figure 2. Dimensions of the composite samples.

Simulation by Finite Elements

In order to simulate the mechanical behavior of the material in another tool, a finite element analysis was performed with the NX Nastran software. The software has mathematical models to analyze complex stresses and strains that could not be analyzed without computational assistance.

A simulation was made with a model with the same dimensions as the specimen for the tensile tests, but with the lower end fixed and the upper end receiving a uniaxial loading in the longitudinal direction of 10 kN in order to ensure a situation similar to the tensile test and to know if this test generates reliable results for this type of material. For simulation purposes, 7 slices of 300 μm from the internal layer (54.75º angle) and 7 slices of 300 μm from the intermediate 35 layer (83º angle), were considered. The outer layer is polyurethane (isotropic material) **[6]**. The values of the composite's properties (P) in the longitudinal and transversal directions returned by the simulation were calculated according to the Mixing Rule through Equations 1 and 2, using the volumetric fractions informed during the development of the material (*V*). The fiber and matrix properties are shown in Table 2 (E_1, E_2 and υ_{12}) **[5]**.

$$P1 = Pf * Vf + Pm + Vm \quad (1)$$

$$P2 = \frac{Pf * Pm}{Vf * Em + Vm * Pf} \quad (2)$$

Table 2 - Values of the layer properties according to the Mixing Rule.

Property	Internal Layer	Intermediate layer	Outer layer
E_1	63.84 GPa	60.7 GPa	0.70 GPa
E2	12.05 GPa	58.36 GPa	0.70 GPa
υ_{12}	0.33	0.26	0.4

RESULTS AND DISCUSSION

Tensile Tests

Figure 3 shows the stress-strain graph of the control sample. The sample had a mean of 13.60 MPa for the breaking strength, a modulus of elasticity of 147.59 MPa, and an average elongation of 2.19%, as can be seen in Table 3.

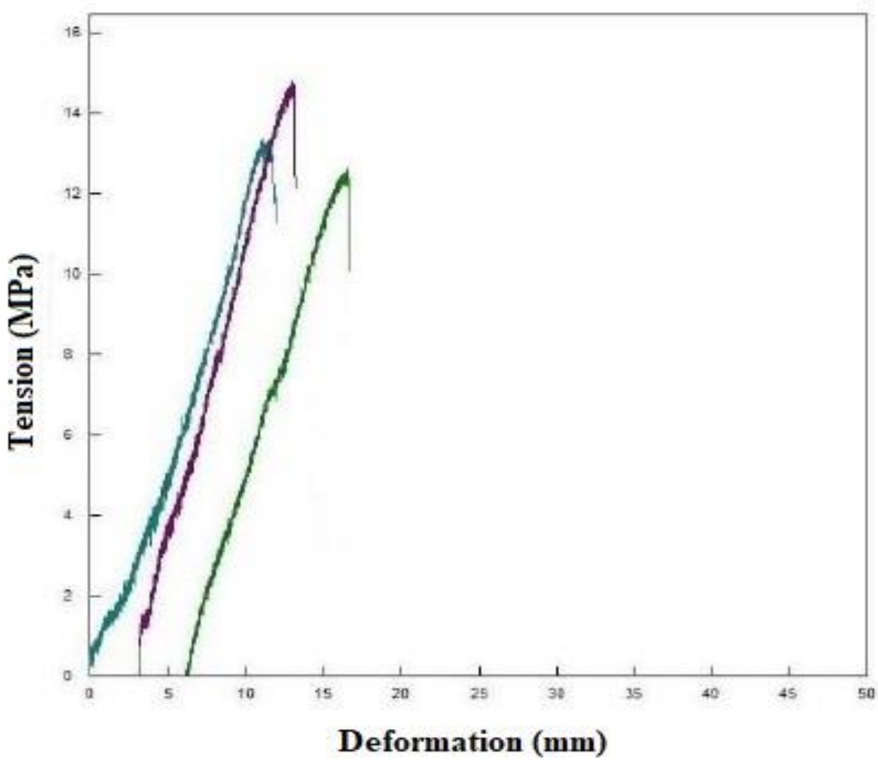

Figure 3. Stress-strain graph of the control sample.

Table 3. Tensile test values of the control sample.

Test specimen	Breaking Strength (MPa)	Deformation (%)	Modulus of Elasticity (MPa)
CP-C-01	13.37	2.5	147.38
CP-C-02	14.8	1.8	161.34
CP-C-03	12.61	2.3	134.59
Mean	13.60	2.19	147.59
Standard Deviation	1.11	0.36	13.64

Figure 4 shows the stress-strain graph of the RP-0147 sample. The sample of well RP-0147 had a mean of 14.65 MPa for the breaking strength, a modulus of elasticity of 182.83 MPa, and an average elongation of 0.57%, as can be seen in Table 4.

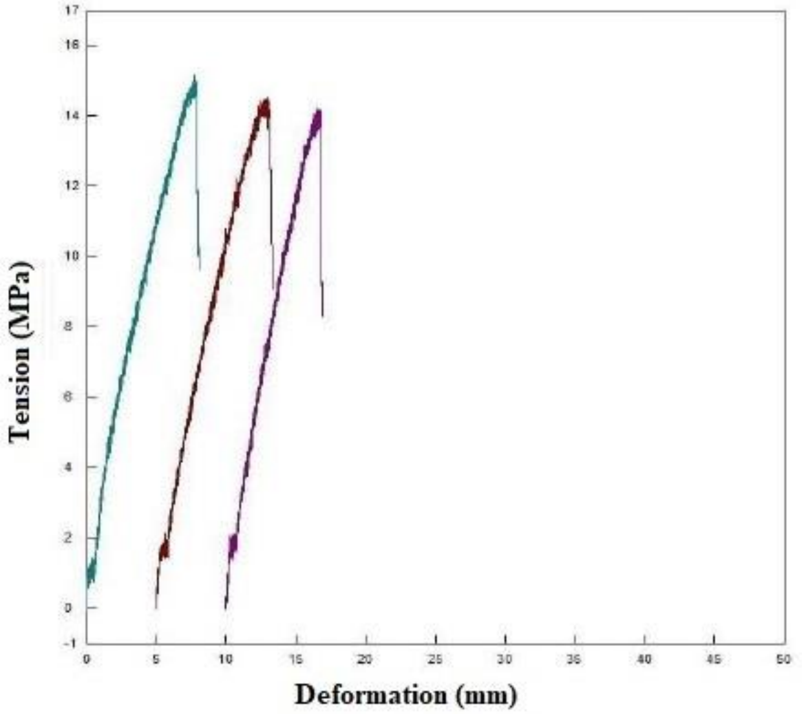

Figure 4. Stress-strain graph of the RP-0147 sample.

Table 4. Tensile test values of the RP-0147 sample.

Test specimen	Breaking Strength (MPa)	Deformation (%)	Modulus of Elasticity (MPa)
CP-RP-01	15.16	0.58	171.36
CP-RP-02	14.55	0.5	178.93
CP-RP-03	14.25	0.6	198.20
Mean	14.65	0.57	182.83
Standard Deviation	0.47	0.07	13.84

Figure 5 shows the stress-strain graph of the PL-0288 sample. The sample of the well had a mean of 20.05 MPa for the breaking strength, a modulus of elasticity of 231.16 MPa, and an average elongation of 0.60%, as can be seen in Table 5.

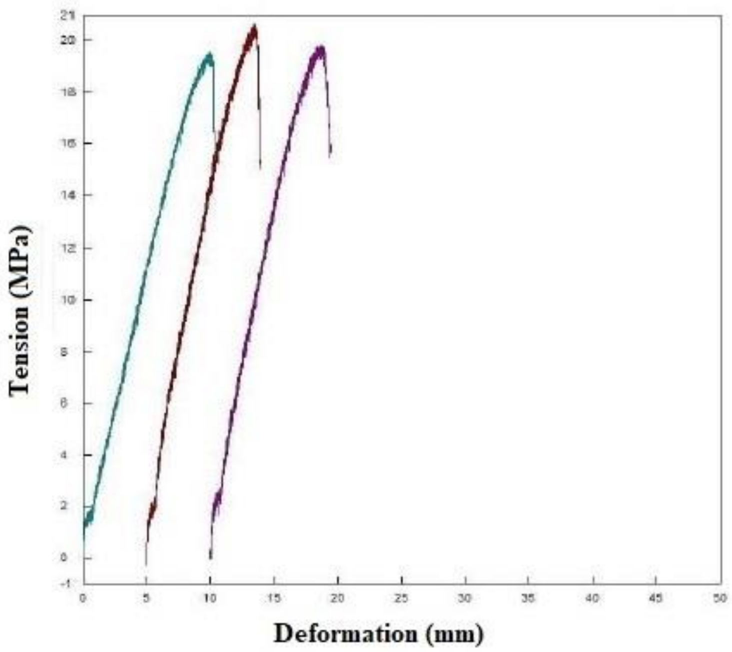

Figure 5. Stress-strain graph of the PL-0288 sample.

Table 5. Tensile test values of the PL-0288 sample.

Test specimen	Breaking Strength (MPa)	Deformation (%)	Modulus of Elasticity (MPa)
CP-PL-01	19.60	0.96	216.08
CP-PL-02	20.68	0.44	248.36
CP-PL-03	19.86	0.40	230.11
Mean	20.05	0.60	231.16
Standard Deviation	0.56	0.31	16.19

Simulation by Finite Elements

The finite element simulation showed that the specimen model rotates and flexes on different axes when subjected to uniaxial loading (mechanical behavior different from an isotropic material like steel). This is due to the complex nature (three layers) and orthotropic behavior of this composite material, where each layer has a different stiffness (different materials), which results in a multiaxial stress state, as can be seen in the model in Figure 6.

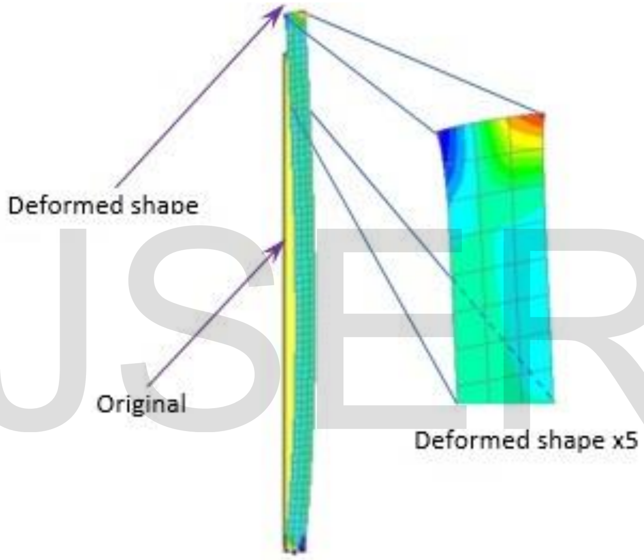

Figure 6 - Flexo-axial deformation of the specimen.

CONCLUSION

There were variations in the breaking strength of the samples, with the control sample having the lowest value of them all. In the elongation, there was also a greater discrepancy in the control sample, which had a value that was about three times greater than the mean of the well samples. Consequently, it has a lower modulus of elasticity. The PL-0288 well sample had the highest values in the mechanical properties of the samples. It is important to note that the material had a fragile behavior in the fractures and the samples in operation showed greater strength than the control sample. This fact can be explained by the compression of the polymeric matrix generated by the internal pressure and external restrictions caused by the soil.

Through the finite element simulation it was possible to conclude that the material behaves in a complex way mechanically, quite different from steel, and the standard tensile test is not the ideal technique to determine the mechanical properties of this material. It would be more interesting to perform instrumented tests with image correlation to obtain specific stress and strain information for this composite.

It is important to study the properties of new materials in real-life situations in the field to understand their behavior and prevent failures that may cause personal, environmental and operational damage (especially in the petroleum industry). These failures are often difficult to predict in the development stages of the material.

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