COMPRESSION-TENSION FATIGUE PROPERTIES OF FIBER CORDS/RUBBER COMPOSITES USED IN FLEXIBLE HOSES

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Abstract

The reinforcement of elastomers is usually made with cords of synthetic fiber, such as polyaramid, polyamide, polyester. These elastomers may be used in the production of, for instance, flexible hoses for oil offloading and these components may fail due to compression-tension fatigue of the cords after repetitive bending. Thus, this work presents the design & construction of an equipment for applying cyclic compressive/tensile strain in reinforced rubber belts. This machine allows for force, frequency and strain level monitoring/controlling and it was used to evaluate polyester and polyamide cords. The compressive/tensile strain levels used were -2.3/+0.5% and -6.9/+0.5%, for 10^4-10^6 cycles. The results indicate that fatigue strength decreases for higher compressive strain and a more sharp decrease in residual strength was observed after 10^5 cycles. The polyamide cord showed better performance than polyester and a decrease in residual strength was observed for higher tensile level.

1. Introduction

Flexible pipes are classified into bonded flexible pipe and unbonded flexible pipe. The difference between them lies in the fact that the reinforcement may either be embedded on a flexible polymer matrix (bonded), usually an elastomer, or be independent of the matrix (unbonded) [1] [2].

In the unbonded flexible pipe category, there are several types of flexible risers, where the different layers of steel that constitute the reinforcement move independently, sliding on anti-wear strips. The major difference between flexible risers and hoses is that the former is built to present great resistance to external pressure and compressive stress, while for the latter this property is not relevant [3].

The hoses belong to the group of bonded flexible pipes and the two main classes are the submarine and the floating hoses. Both are built around a guide roller cylinder that ensures an internal diameter. Two flanges are positioned at the end of the cylinder and, between them, layers of several materials (e.g. fibers, steel mesh, rubber) are deposited until the hose is completed, receiving later a protective cover [1] [4].

The liner, i.e. the inner most rubber layer of the hose, must display chemical strength to withstand chemical attack from the oil passing through the hose. The liner component can be manufactured using a variety of rubbers being primarily dependent upon the product which will be transported through the hose. The main plies provide good mechanical properties, such as tensile stress, adhesion strength, axial stiffness, among others, and can be manufactured with cords of different materials. The angle in which the reinforcement is oriented in each ply, the number of layers and the type of reinforcement are very important for the control of the mechanical properties of the hose [5].

To produce the cords, the polymer fibers are twisted in two stages: the fibers are first twisted to produce a yarn, and then the yarns are twisted to form the cord. The most common types of twist are the "S" and "Z" types, based on the direction of rotation [6] [7]. The cord twist favors elongation at rupture and fatigue strength, but with a detrimental effect on strength and modulus. The Twist Multiplier (TM) can be calculated according to Equation (1):

$$\text{TM} = 0{,}0137 \cdot \text{TPI} \cdot \sqrt{DL} \quad (1)$$

where: TPI is the number of cord twist, in turns per inch; DL is the linear density of the cord in denier (denier = grams of polymer in a 9000 m long cord [8].

In the literature, previous experiments have shown that, polyester cord has high modulus and low shrinkage characteristics in comparison to polyamide (nylon 6 an 66) and thus provides excellent dimensional stability during tyre making. Polyester also has better retention of relaxation modulus under constant strain exhibition higher elasticity at ambient temperature than polyamide. Nylon 66 has excellent fatigue resistance even at high strain deformation [9]. There is also an investigation about the strength to fatigue of polyaramid cords (Kevlar 29) with the Flex test (test device that provides compression in cords). Kevlar thus has flex fatigue properties, which while not as good at a given strain levels as those of more extensible and tough fibers like nylon and polyester, are nevertheless of the same general order of magnitude. With some care to avoid bending strains at as high a level as those adopted for test purposes, very long lives would be obtained [10]. In other paper, the tests with polyaramid cords were performed by a device called Roller fatigue testing. All results indicate that fatigue decreases with increasing twist. There was little strength decrease until 10^4 to 10^5 cycles. The smallest twist yields failure at 10^4 cycles. There was then a cycle range of rapidly decreasing strength. Unlike the Disc fatigue test, in which strength of cord gradually decreases, the Roller fatigue test only causes a decrease in initial strength near failure [11].

The aim of this study is to present the design & construction of an equipment for applying cyclic compressive/tensile strain in reinforced rubber belts and then use it to study the compressive fatigue life of polyester and polyamide cords. The investigation was carried out under distinct strain levels.

2. Methodology

2.1. Fatigue test Equipment

For the fatigue test, an equipment similar to a roller fatigue test was designed and built, as shown in Figure 1. The set-up includes: (1) Motor, (2) Travelling base, (3) Maniple, (4) Load cell, (5) Pulleys and (6) Control system. The cycles were monitored using an optical reflexive sensor coupled to a cycle counter Novus NC400. For comparison, this was also evaluated based on the data shown in Table 1. Parameters used for adjusting the fatigue test., which allowed estimation of the test period. A frequency inverter enabled control of the motor, which was adjusted to a rotation of 900 cycles/min (15 Hz).

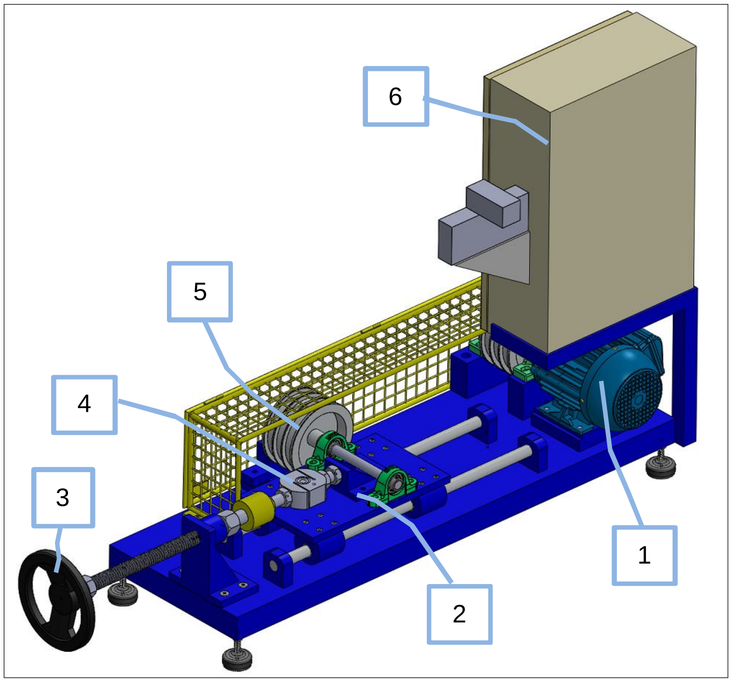

Figure 1. 3D Model of the cords compression fatigue test equipment: (1) Motor, (2) travelling base, (3) maniple, (4) load cell, (5) pulleys and (6) control system.

Parameter	*Value*	*Unit*
Load cell capacity	5000	kgf
Motor rotation	15	Hz
Belt length	1207	mm
Distance between pulleys	368	mm
Diameter and Perimeter of the pulley	150 and 471	mm

Table 1. Parameters used for adjusting the fatigue test.

During testing, monitoring of the tensile load was made using a load cell coupled to the pulley, and the travelling base was responsible for imposing the required tension on the belt. Figure 2 shows the image of the equipment during a fatigue test.

2.2. Preparation of samples and testing parameters

A belt of butadiene-acrylonitrile elastomer with two cord layers was coupled to a 16 in (406 mm) mandrel. The belts were produced with polyester cords (3000 to 5000 denier) or polyamide cords (10000 to 15000 denier). Two symmetrical layers of cords, in relation to the neutral plane, were tested by adjusting two rotating pulleys, being r the radial coordinate of the pulley (see Figure 3).

Figure 2. Photograph of the fatigue equipment during testing.

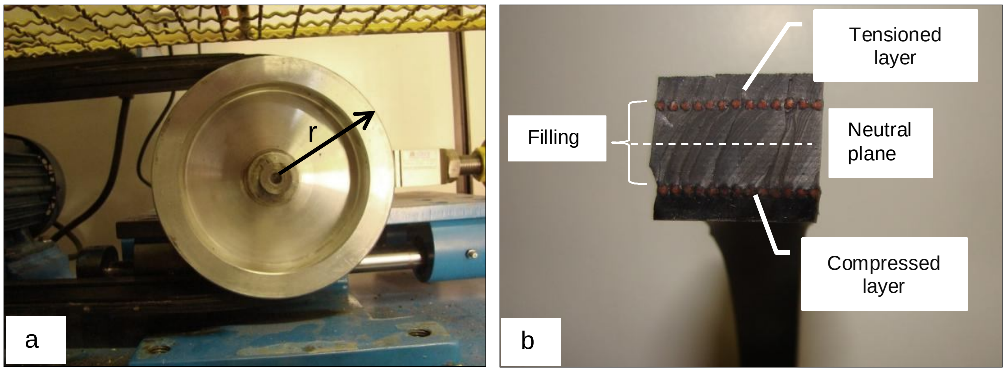

Figure 3. (a) Belt curved on the pulley and (b) cross section of the belt.

In all experiments, a tensile strain of 0.5% was applied to ensure proper dragging of the belt. For the samples with polyester cords, a constant load of 669 N was applied, whereas for the samples with polyamide cords, a constant load of 836 N was needed. To confirm that, two dots were drawn in the belt surface and the distance between them were measured before and after applying the load.

To estimate the compression level, measurements in the transversal section of the belt were made. In both the cases, the compression level of the cords ($\in_2$) was varied (-2.3 and 6.9%), as calculated by Equation (2):

$$\in_2 = \frac{(R_2 - R_{0f})}{R_{0f}} - \frac{(R_2 - R_3)}{R_3} \qquad (2)$$

Where: R_2 is the medium radius of the first layer of the cord; R_{0f} is the neutral radius after applying the tensile stress in the cord; R_3 is the medium radius of the second layer of the cord [11].

Table 2 shows the belt dimensions after vulcanization of the rubber and the test conditions (tensile and compression levels, number of cycles and testing period). Three to four tests were carried out in each case. After testing, the belt was pulled out of the equipment and a 300 mm long section was cut at the inner side, close to the threads, to facilitate extraction. The specimen was soaked in a solvent (Trichloroethylene, CCl_3CH_3) for 24 ± 4 h, and after that the cords were carefully pulled, one at a time, from the inner layer. Identification tags were attached and they were dried in an oven with air circulation (25ºC, for 24 h).

The fatigue behavior was addressed based on measurements of residual strength after cycling (10^4, 10^5 or 10^6 cycles). Tensile tests of the inner cords of the belt were carried out according to ASTM D885, and the residual strength (%) was obtained by comparison with the strength of the original (uncycled) cord.

<table>
<tr><th>Belt/Cord</th><th>a (mm)</th><th>b (mm)</th><th>Thickness of belt (mm)</th><th>Compression level (%)</th><th>Tensile level (%)</th><th>Number of cycles</th><th>Time (min)</th></tr>
<tr><td rowspan="6">Rubber+ Polyester

OR

Rubber+ Polyamide</td><td rowspan="6">3</td><td rowspan="3">2.3</td><td rowspan="3">9.9</td><td rowspan="3">-2.3</td><td rowspan="3">0.5</td><td>10^4</td><td>14.2</td></tr>
<tr><td>10^5</td><td>142.3</td></tr>
<tr><td>10^6</td><td>1423.2</td></tr>
<tr><td rowspan="3">12</td><td rowspan="3">19.6</td><td rowspan="3">-6.9</td><td rowspan="3">0.5</td><td>10^4</td><td>14.2</td></tr>
<tr><td>10^5</td><td>142.3</td></tr>
<tr><td>10^6</td><td>1423.2</td></tr>
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Table 2. Belt dimensions and fatigue test conditions.

3. Results and discussion

Before vulcanization of the rubber, the polyester and polyamide cords exhibited load at break of 214 N and 565 N, respectively. It can be seen in Table 3 that the values for the uncycled samples show just a slightly decrease after vulcanization, with 6.1% and 1.0% decrease, respectively.

Table 3 also shows the tensile properties of the cords after cycling, and it is possible to see that the load values are approximately unchanged up to the 10^4 cycles. The strain showed the same behavior than load. The same behavior could be observed for other properties (initial modulus, toughness and tenacity). In addition, the 6.9% compression level resulted in a greater decrease in strength as compared to the 2.3%. In most cases, the force control during testing caused in the initial modulus decreased with increasing number of cycles. For polyester cord with compression level 2.3%, the drop represented about 96% of the initial retained strength to 10^6 cycles. For polyester cords with compression level 6.9%, the prop was 95%. The contribution of decreased strength, initial modulus and strain caused a great loss of toughness, around 88% and 58% for compression levels 2.3% and 6.9%, respectively. Due to the tenacity to be related only to the force, the drop of this property matched the same drop of force. The polyamide showed a very similar behavior to that of polyester.

The plots of residual strength versus number of cycles for the polyester and polyamide cords are shown in Figure 4 and 5, respectively, for both compression levels. The polyamide sample began to lose strength after 10^4 cycles. For 2.3% compression level, polyester and polyamide cords exhibit excellent strength retention, about 95% and 97% of its initial strength, respectively. However, for higher compression, strength retention decreases to 78% and 79%, respectively. Although the polyamide and polyester to be similar, the retained strength of polyamide is better than polyester. Polyester may undergo degradation due to the ingredients (organic amine functionality) present in the rubber compound. Aminolysis of polyester is well known. In the case of polyester the properties are the worst. Naskar et al. reported that dynamics heat generation may affect the fiber molecular chains in a different way. Chances in microstructure of the fiber after fatigue. Apart from intrinsic cord/fiber characteristics, cord-matrix adhesion is also a probable influencing parameter in the fatigue resistance as a similar trend (as that of the fatigue resistance). In the literature, in a recent study, polyaramid 6 cords, polyamide 6.6 and polyester, with strain ±10% lost 19, 18 and 32% of its initial strength before cycling for 120 h. The polyester cord would be more susceptible to fatigue than the polyamide cord by presenting a higher modulus and lower elongation [9].

Sample/ Compression level	Cycles	Load (N)	Strain (%)	Initial modulus (mN/tex)	Toughness (J/g)	Tenacity (mN/tex)
Rubber + Polyester	Uncycled	204.1 ± 3.9	14.2 ± 0.8	4318 ± 139	183.4 ± 16.8	483.4 ± 9.2
Rubber + Polyester/ 2.3%	10^4	205.7 ± 3.4	14.4 ± 0.6	4295 ± 138	188.8 ± 11.4	487.3 ± 8.2
	10^5	200.3 ± 3.8	13.5 ± 0.5	4270 ± 115	172.7 ± 11.4	474.4 ± 9.0
	10^6	194.1 ± 8.0	13.1 ± 1,0	4155 ± 161	162,2 ± 19,1	459,7 ± 18,9
Rubber + Polyester/ 6.9%	10^4	205.1 ± 12.8	13.8 ± 1.0	4101 ± 107	134.2 ± 19.8	485.7 ± 30.3
	10^5	197.9 ± 13.3	13.2 ± 0.9	4242 ± 91.2	163.8 ± 24.3	468.7 ± 31.4
	10^6	160.3 ± 18.9	10.8 ± 1.0	4116 ± 174	107.7 ± 22	379.8 ± 44.8
Rubber + Polyamide	Uncycled	563.8 ± 13.5	24.3 ± 1.3	2682 ± 105	682.1 ± 37.3	462.1 ± 11.1
Rubber + Polyamide/ 2.3%	10^4	560.8 ± 8.2	28.8 ± 0.9	2933 ± 97	660.5 ± 48.2	472.7 ± 15.8
	10^5	554.0 ± 33.1	22.4 ± 1.8	2916 ± 191	622.5 ± 91.3	456.5 ± 27.3
	10^6	547.6 ± 24.4	22.0 ± 1.0	2745 ± 81	624.6 ± 67.3	450.1 ± 20.0
Rubber+ Polyamide/ 6.9%	10^4	556.4 ± 10.9	21.1 ± 0.5	2979 ± 81	601.8 ± 11.7	457.3 ± 9.0
	10^5	509.8 ± 1.9	23.0 ± 1.1	2979 ± 155	668.4 ± 32.9	478.8 ± 5.6
	10^6	447.6 ± 107.4	18.3 ± 3.1	2796 ± 384	428.6 ± 144.7	367.9 ± 88.3

Table 3. Tensile properties values of the cords after cycling process.

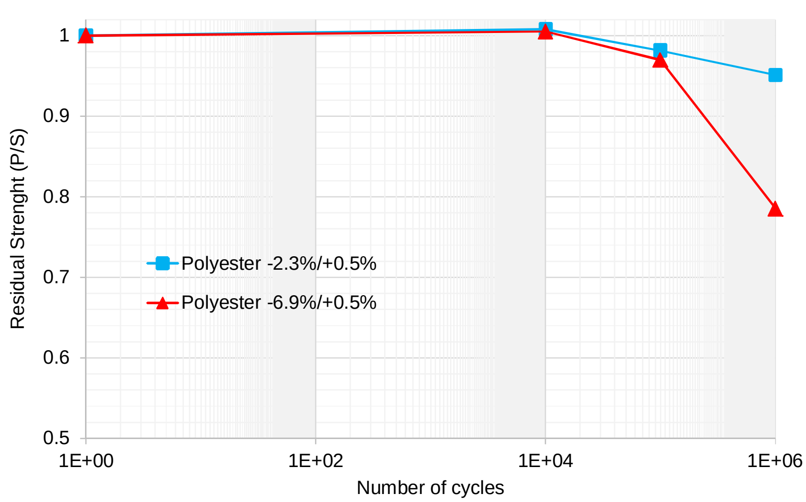

Figure 4. Residual strength vs number of cycles for polyester cords.

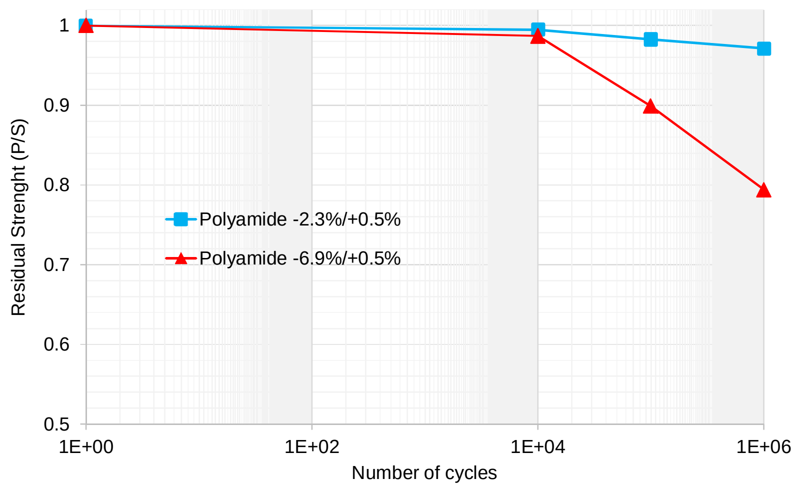

Figure 5. Residual strength vs number of cycles for polyamide cords.

Figure 6 shows images of the polyamide and polyester cords after tensile testing. There were no differences in the cords rupture regardless of the number of cycles. Both cords showed a uniform rupture, revealing simultaneous breaking of all yarns of the cord.

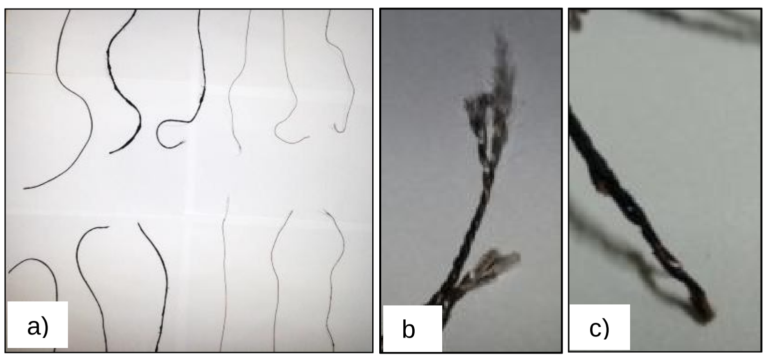

Figure 6. Image of the cords before (a) and after polyester (b) and polyamide (c) cords rupture.

4. Conclusions

The designed and built fatigue equipment showed excellent performance in the tests, and it was possible to provide an accurate tensile and compression forces in the cords. The results obtained in this study can be used as reference for designing flexible hoses or even other rubber equipment. The methodology employed can be used as an alternative to traditional methodologies such as the *Disc Fatigue test*. The rubber vulcanization process caused little effect in cord strength. The polyester and polyamide cords showed good fatigue properties and no significant strength loss was observed even after one million cycles for low compression level.

Acknowledgement

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