Uniaxial Fatigue of HDPE-100 Pipe

Experimental analysis

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Abstract— **In this paper, an experimental analysis for determining the fatigue strength of PE-100, one of the most used High Density Polyethylene (HDPE) materials for pipes, under cyclic axial loadings is presented. HDPE is a thermoplastic material used for piping systems, such as natural gas distribution systems, sewer systems and cold water systems, which provides a good alternative to metals such as cast iron or carbon steel. One of the causes for failures of HDPE pipes is fatigue which is the result of pipes being subjected to cyclic loading, such as internal pressure, weight loads or external loadings on buried pipes, which generate stress in different directions: circumferential, longitudinal and radial. HDPE pipes are fabricated using an extrusion process, which generates anisotropic properties. By testing in the Laboratory a series of identical specimens obtained directly from PE-100 HDPE pipes in longitudinal directions, the relationships between amplitude stress and number of cycles (S-N curve) test frequency 2 Hz and stress ratio R = 0.0 are established.**

Keywords- polyethylen; pipe; semi-cristalline; fatigue; damage

I. INTRODUCTION

The behavior of polymers gains more and more relevance in the study of materials, due to the growing utilization of polymers in complex applications, as a consequence of their technical advantages and lower cost [1]. The High Density Polyethylene (HDPE) is one of the most used polymers in the industry due to the diversity of its applications and to the multiple advantages that it has over more conventional materials. HDPE is extensively used in water and natural gas distribution system. However, a piping system is subjected to internal pressure or external loads varying in magnitude and frequency, generating different responses from the material [2]. Such cyclic loads cause cumulative damage and cracking that could produce a piping system failure [3]. It is important to emphasize that this presents a problem that should be especially considered, since a stress value lower than yield strength can produce a pipe failure in a relative short period of operation if the pressure is cyclic [4].

In general, during their life, the materials can undergo a progressive damage under the effect of the mechanical, thermal or chemical stresses requests to which they are subjected. Some aspects of Fatigue Crack Propagation (FCP) and fracture are often discussed as they relate to specific cumulative damage theories and lifetime prediction methods. Earlier reviews in polymer fatigue and FCP can be found in [5–11].

It is probable that the problems in materials subjected to cyclic pressure are generated by intrinsic defects during the manufacture process, which could generate failures in the pipe, causing great economic loss and operational damage in the piping systems [12]. At present, many companies test HDPE piping systems only hydrostatically, which allows the determination of pipe strength to monotonic loads but does not test the behavior of the material for alternating stresses, which are generally smaller than design stresses [13, 14]. Life prediction and reliability evaluation is still a challenging problem despite the extensive progress made in the past decades. A comprehensive review of early developments can be found in [15].

The aim of this work is to obtain the fatigue strength and fatigue lifetime of HDPE pipes, specifically PE-100, one of the most widely used materials in the fabrication of polymers pipes.

II. MATERIAL AND EXPERIMENTAL PROCEDURE

In this work, pipes of 200 mm outside diameter, nominal wall thickness range between 11.4 and12.7 mm and 12 m length made of HDPE grade PE-100 are used. Pipes were supplied by STPM CHIALI, an Algerian company who produces PE-100 pipes for natural gas systems according to EN 1555-1à 7 and ISO 4437 [16]. The scope of this study includes tensile tests and axial fatigue tests. Tensile testing is used for determining the monotonic mechanical properties of HDPE pipes, which are the bases for establishing several stress amplitude levels for fatigue testing.

Due to ground interaction and intern pressure, the axial stress can be relevant and even be greater than hoop stress. For this reason, it is necessary to evaluate the mechanical behavior of pipes in the axial direction. The specimens for both tensile tests and axial fatigue tests were cut directly from a HDPE grade PE-100 pipe, following the longitudinal direction, as shown in Figure 1. Cylinder sections were cut by a guillotine cutter used in the plastics pipes axially and transversally, to obtain curved plates, as shown in Figure 2. A total of 160 specimens were fabricated in a CNC Mechanized Center model Mill 55 with GE Fanuc (EMCO- Concept Mill), using the geometrical specifications shown in Figure 3.

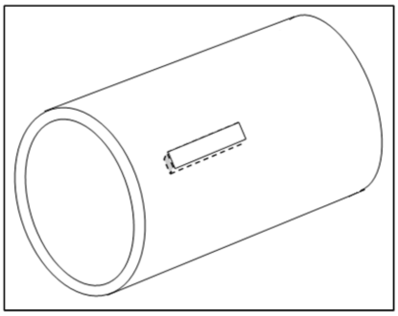

Fig. 1. Longitudinal specimen direction for mechanical testing.

Fig. 2. Cutting sections of cylinder

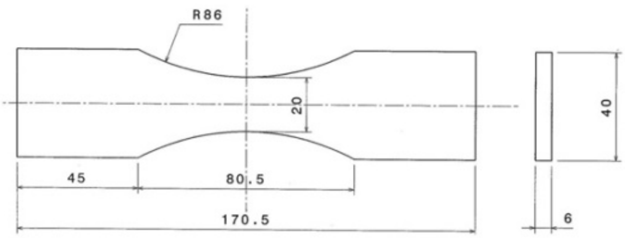

Fig. 3. Tensile Specimen according to ASTM D-638- Type I (dimensions in mm).

A Zwik, Z 100 uni-axial tension Testing Machine (shown in Figure 4), was used to monotonic tensile testing, according to ASTM-D638 Standards [17]. Tensile tests to 2 specimens for each strain rate of 0.1 and 0.01 s^{-1}, were carried out. The uni-axial fatigue was conducted made on the multi-axial test platform of the Mechanics Laboratory of Lille (LML), as shown in Figure 5.

Fig. 4. Zwik, Z 100 uni-axial tension Testing Machine

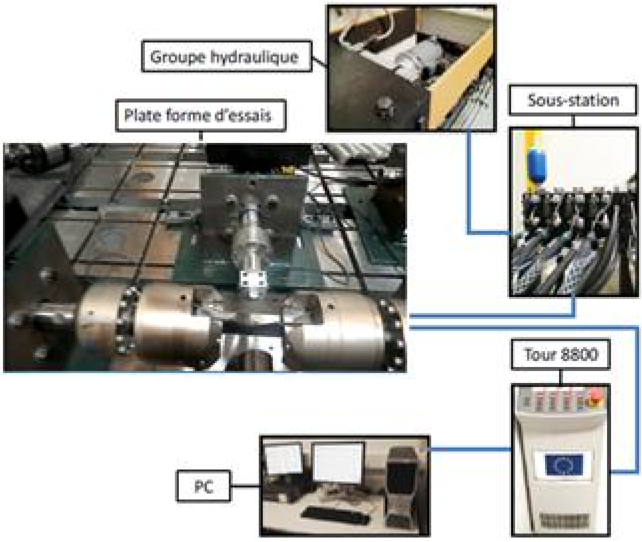

Fig. 5. Overview of the fatigue machine and its accessories

The main experimental means were:

- a platform made of a metal marble 3 m × 5 m in dimension, equipped with mesh rails, which allowed the alignment of cylinders, the fixing of the flanges and the adjustment of structure components.
- a servo-hydraulic cylinder (of a set of four available) of total travel of ± 25 mm and maximum capacity of 100 kN, operable at high frequency (150 Hz according to the amplitudes of the displacements of the actuator).
- a control system to control the cylinder implemented by a console and an Instron 8800 digital controller.
- the RS software package Labsite IST (Instron Structural Testing Systems) loaded onto a PC for the generation of instructions, data acquisition and processing

The cylinder can be controlled by force, displacement or deformation, Figure 5 shows an overview of the platform in biaxial and accessories. The Fatigue experiments were carried out under uniaxiale constant amplitudes to determinate the Wöhler curves. An equation for the S–N curve for the material was determined from a prior investigation according to ASTM standards [18]. The minimum number of specimens to obtain a reliable sample size in fatigue testing is determined using the ASTM E 739 standard [18], with a sample size of 3 for each value of stress amplitude level.

Table I shows the values of the test parameters considered in fatigue testing: load frequencies, stress ratios (R) and maximum stress levels. Maximum Stress Levels are computed as a function of yield strength obtained from tensile tests.

TABLE I. FATIGUE TESTING PARAMETERS:

Load Frequency (Hz)	Stress Ratio	Maximum Stress Levels (MPa)
2	0.0	15-16-17-18-19-20-22-24-26

The typical scatter in the number of cycles obtained from fatigue tests makes it necessary to process the fatigue failure data using statistical techniques. Due to the sample size, the mean square method is used to generate the Stress–Number of Cycles diagrams (S-N) required for studying the fatigue behavior of the HDPE grade PE-100 pipe. Each S-N diagram includes two sets of 50% constant probability and power law fitted from least squares) of survival data obtained by processing fatigue data using the normal distribution. Then statistical data is adjusted using the least-squares method for obtaining three S-N-P curves (Ps=50%).

Stress amplitude, Sa, is computed by:

$$S_a = \frac{S_{\max} - S_{\min}}{2} \qquad (1)$$

Stress ratio is computed as follow

$$R = \frac{S_{\min}}{S_{\max}} \qquad (2)$$

S-N data have usually power-law dependence [3]. For each set of statistical data (Ps=50% and least-squares), the following power-law equation (Basquin's equation) is fitted to obtain a mathematical representation of each curve:

$$S_{\max} = A.N^b \qquad (3)$$

where the maximum Stress ($S_{\max}$) is obtained as a function of A, a coefficient that represents the value of $S_{\max}$ at one cycle, and b, an exponent that depends of material and its characteristics.

III. RESULTS AND DISCUSSION

A. *Mechanical Properties*

The mechanical properties for HDPE grade PE-100 pipes based on Stress–Strain diagrams (Figure 6) obtained from tensional testing in longitudinal pipe direction, for 0.1 and 0.01 s^{-1} are shown in Table II.

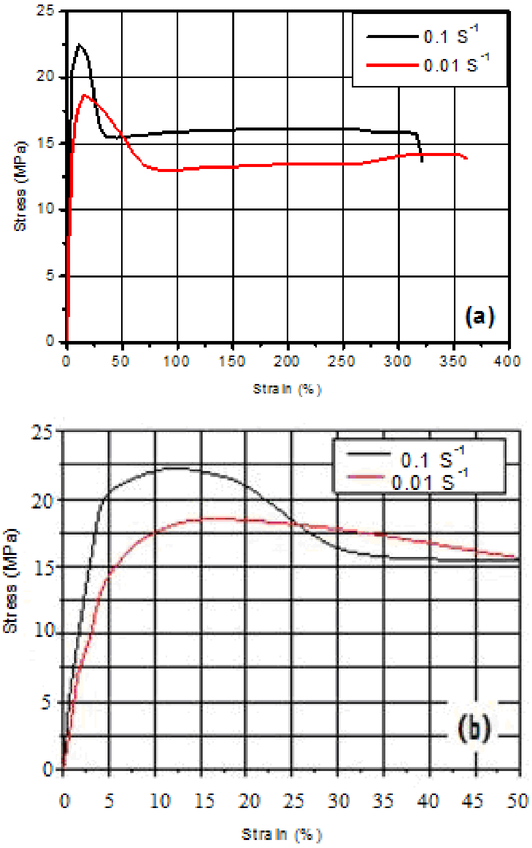

Fig. 6. Stress-strain curves for both strain rates, (a) global, (b) Small deformation zoom.

TABLE II. PE-100 PIPE´S MONOTONIC MECHANICAL PROPERTIES

Strain rate $\dot{\varepsilon}$ (s^{-1})	Yield stress σ_y (MPa)	Strain at Yield ε_y (%)	Elastic Modulus (MPa)
10^{-1}	22.5	12.36	990
10^{-2}	18.5	15.46	750

The curves are typical for semi-crystalline polymers. Figure 6 shows the curves obtained for the two strain rates. The difference in the mechanical properties for both strain rates of testing is relevant; however the viscoelastic nature of our HDPE-100 is clearly manifested by the dependence of the strain rate. To examine the response of our HDPE, it is necessary to determine the contribution of viscosity in its behavior through the influence of strain rate on the mechanical properties. As seen in Figure 5, the behavior of our HDPE for both strain rates is nonlinear and depends largely on strain rates. That said, it is of great interest for further study, to carefully consider such findings. Constant maximum stress levels for fatigue testing were established using the yield strength reported in Table 2, obtaining the following values: 24, 22, 20, 19, 18, 17, 16 and 15 MPa.

B. *Elongation change during fatigue tests*

Figure 7 shows the amplitude of specimen elongation measured during fatigue tests for, S_{max}=16 MPa and S_{max}=17 MPa. As shown, an increment of specimen elongation with increment of number of cycles can be observed. It is also shown that elongation changes are greater for 17 MPa than for 16 MPa. It is possible to correlate the elongation change with the cumulative damage phenomenon. These behaviors are expected due to the viscous nature of polymers and the magnitude of damage accumulation induced by cyclic loading, (so they depend widely on stress amplitude).

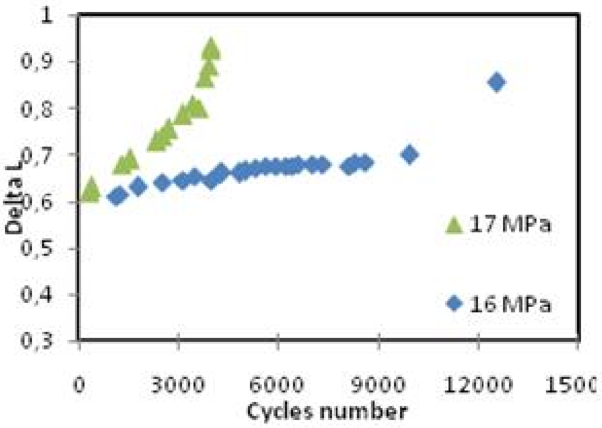

Fig. 7. Elongation changes during fatigue testing - Longitudinal direction for two levels of maximum stress 16 an 17 MPa.

C. *S-N Curves*

In Figure 8, S-N-50 % curves obtained from pipe fatigue tests in longitudinal direction for a load frequency of 2 Hz and R=0.0 are shown. In this case, stress level of 26 MPa was plotted in order to include the specimens' low fatigue life time, and this to verify a consistence of Basquin's Parameters, especially (A) which designates the maximum stress for one cycle.

Basquin's equation for a survival probability of 50% data (Ps=50%) is:

$$S_{\max} = 32.46 \cdot N^{-0.067} \qquad (4)$$

In Figure 9, experimental values curves obtained from pipe fatigue tests in longitudinal direction are plotted and the S-N curve is obtained directly by a least-squares method.

Basquin's equation for a survival probability obtained from the scatter of data is:

$$S_{\max} = 32.24 \cdot N^{-0.068} \qquad (5)$$

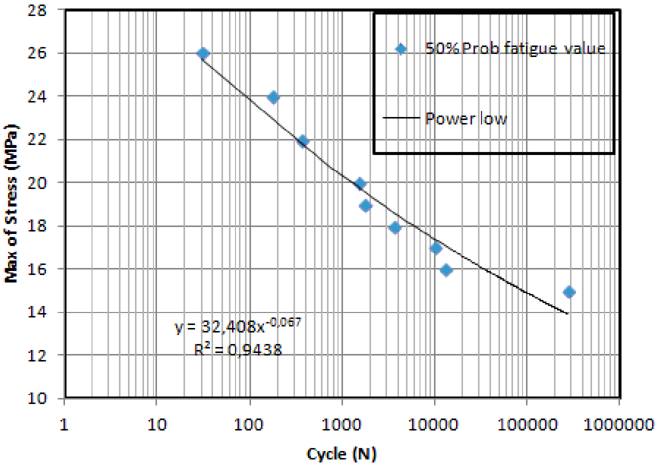

Fig. 8. Modeling the Wöhler 50% failure probability.

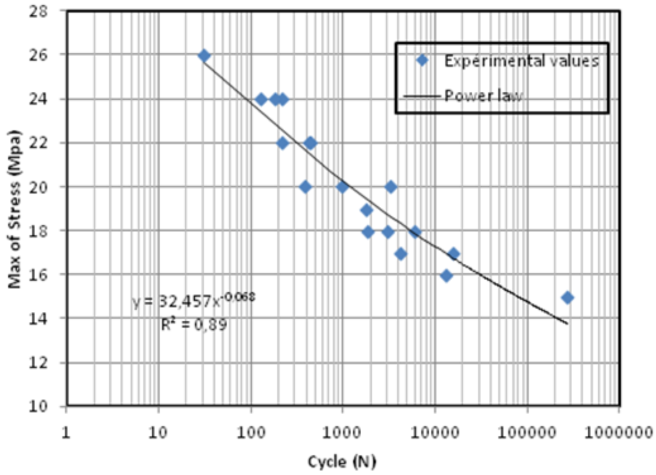

Fig. 9. Modeling the Wöhler curve by the least-squares method.

It is clear from the two figures above that the two methods give approximately the same results. Table III summarizes the parameters of Basquin's model for the two probabilistic methods used for establishing the Wöhler curve.

TABLE III. PARAMETERS FOR BASQUIN MODEL FOR THE WÖHLER CURVE

Least squares method on the scatter points			**Method of least squares on the midpoints (50%)**		
A (MPa)	**c**	**R2**	**A (MPa)**	**c**	**R2**
32.24	0.068	0.866	32.46	0.067	0.9484

IV. CONCLUSION

In this work, an experimental fatigue study was carried out that showed that the fatigue strength of HDPE grade PE-100 pipes depends on the pipe stress. It is shown that the monotonic behavior of HDPE-100 is widely time dependent, because of the dependence on strain rate. Subjected to cyclic loading, our HDPE exhibits a softening behavior detected by the increase of maximum elongation under maximum constant stress. Fatigue lives of HDPE are widely stochastic and a scatter in the number of cycles to rupture is observed for the same stress level. The explanation of the difference could be related to factors related to the manufacturing process of HDPE grade PE-100 pipes; when a spider header is used for the pipe extrusion, weld lines are generated in the pipe which could cause weakening in circumferential specimens, if these zones are coincident to test zone. This behavior is not convenient for pipes subjected to internal pressure, which is the case for the majority of HDPE pipe applications, due to the greatest principal stress (hoop stress) which is coincident to the circumferential direction and its value can duplicate the longitudinal stress. The results obtained are in good agreement with literature results.

ACKNOWLEDGMENTS

Authors would like to acknowledge to STPM CHIALI for the donation of PE-100 pipes and for allowing monotonic testing, and to LML (Laboratory of Mechanics of Lille) for allowing fatigue testing and to Mascara University for financial support.

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