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Level of damage assessment of polypropylene pipes (PPR) subjected to burst pressure tests using static and unified damages and estimation of the remaining life

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ABSTRACT: The polypropylene copolymer (PPR) is a thermoplastic material widely used to transport hot and cold water under pressure. In operation, PPR pipes are sometimes subjected to accidental damages that may cause a reduction in residual resistance or even a complete fracture of the structure. Hence the need to characterize the behavior of virgin and defective PPR pipes under pressure to develop carefully a maintenance strategy to ensure a minimum cost with the maximum reliability. In this article and according to ASTM D1599, we conducted a set of real tests of bursting on virgin and notched pipes to assess the level of damage reaches mechanically and characterize the behavior pipes in PPR pipes. The experimental results allowed and identification of the three stages of development of damage namely: initiation, progression and sudden acceleration. The estimation of the damage degree by the model of static damage led to identify theoretically the three stages of the evolution of damage. Subsequently, a theoretical reassessment of the damage level was done through a judicious adaptation of the theoretical model proposed in unified theory of damage. Theoretical and experimental results showed a good agreement.

KEYWORDS: PPR pipes; mechanical characterization; burst test; static damage; unified damage.

1 INTRODUCTION

The use of plastics in the piping is well established because of low cost, light weight and excellent performance that can offer comparing to metallic pipes such as iron and copper. Have achieved a high level of penetration in different applications, ranging from water supply to gas distribution networks, from sanitary systems to sewage networks, the use of the plastic material does not cease to continue growing in a consistent manner with a rate of about 5-10% per year [1].

According to product specifications, PPR pipes can be used under a hydrostatic pressure of 20 bars and high temperatures up to 70 ° C continuously for 50 years [2]. Comparing with other polymers for the transport of hot and cold water under pressure, the PPR is the usually used polymer for hot and cold water for residential buildings, commercial complexes, offices and hotels due to its physical, chemical and mechanical performance and especially its low cost [3].

Several researchers have studied the behavior of PPR tubes. Litvinov Soliman and [2] have studied the failure modes and the effect of temperature on the time to failure of PPR pipes under hydrostatic pressure at different temperatures. Furthermore, authors did additional analyses to examine the influence of time and temperature of pressure tests on the intrinsic characteristics of PPR pipes such as crystallinity, melting temperature and the induction time of oxidation ILO) by several techniques, among others, the wide angle X-ray diffraction (WAXD) and differential scanning calorimetry (DSC). Zgoul et al [3] evaluated the convenience of two types of thermoplastic pipes to transport domestic hot water and industrial by a comparative study of tubes PPR and PEX in terms of the melting temperature and the mechanical strength (tensile and under pressure). To do this, the authors used the differential scanning calorimetry (DSC), uni-axial tensile tests and hydrostatic pressure. Geertz et al [4] have put under hydrostatic pressure pipes PPR for 3000 and 10000 hours, the goal was to study the influence of the internal pressure and temperature on the diffusion of the antioxidant (Irganox1010) by means of infrared spectroscopy (IR) and differential scanning calorimetry (DSC).

The damage can be defined as a deterioration of the mechanical and geometrical properties of structures subjected to physical and / or chemical stress. In order to quantify it, researchers have developed theoretical models. Miner [5] has proposed the first formulation of cumulative damage; it's a simple linear law according to the fraction of life. Later, Bui Quoc has developed the unified theory. Serving of assumptions of the loss of strength, he proposed a non-linear formulation of the damage called the unified damage [6].

2 MARTERIALS AND METHODS

2.1 GEOMETRY AND PIPES PREPARATION

Pipes made of PPR material with an external diameter of 90 mm and 15 mm of thickness were prepared according to ASTM D1599 [7]. Figure 1 shows pipe dimensions:

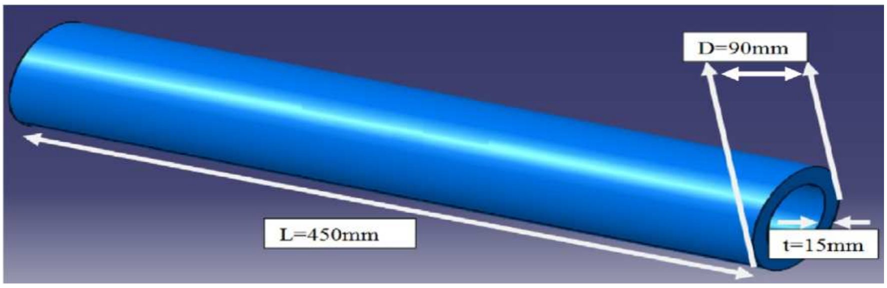

Fig. 1. Pipes dimensions

Eight pipes were notched using a universal milling machine with grooves of 6 mm width, lengths of 100 mm and depths ranging from 2.42 to 14.5 mm. The fraction of β life is defined as the ratio of the depth of the notch (a) to the total depth of the tube (t). The goal is to study the effect of the notch on the strength of PPR pipes under pressure. Figure 2 and Table 1 show the dimensions of the grooves performed.

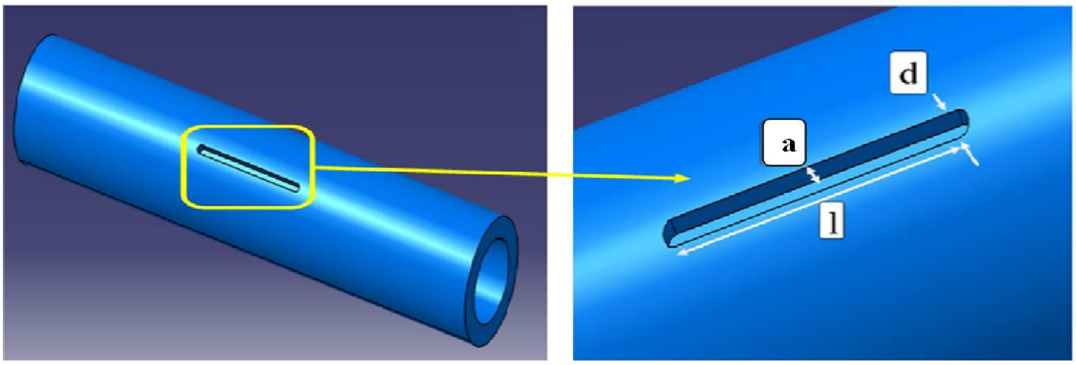

Fig. 2. Grooves dimensions

Table 1. Grooves performed dimensions

Number of pipe	d (mm)	l (mm)	β=a/t
Virgin	6	100	0
1	6	100	0,16
2	6	100	0,32
3	6	100	0,43
4	6	100	0,54
5	6	100	0,71
6	6	100	0,8
7	6	100	0,9
8	6	100	1

2.2 EQUIPMENTS AND EXPERIMENTAL PROTOCOL

2.2.1 EXPERIMENTAL DEVICE

The experimental device (Figure 3) consists of a tank filled with water to absorb damage of the burst, and a hydraulic pump for pressurizing and displaying the instantaneous pressure within the pipe.

Fig. 3. Experimental device

2.2.2 EXPERIMENTAL PROTOCOL

In order to prevent leakage giving bad results and to provide a pressure inside the tube, end-caps are attached to the ends of the pipes and strongly clamped by means of bolts; these ends are connected with the hydraulic pump through pressurizing pipes.

At room temperature, Pipes were immersed in the tank filled with water (Figure 4). Then, a pressure gradient is applied by the hydraulic pump up to burst. The purpose of this test is to determine the evolution of the residual ultimate pressure at failure according to the β fraction of life.

Fig. 4. Pipe immersed in the tank

2.3 RESULTS AND DISCUSSION

2.3.1 LOSS OF THE STRENGTH OF NOTCHED PPR PIPES UNDER PRESSURE

The variation of the ultimate pressure inside the pipes as a function of the fraction β of life is described in Figure 5.

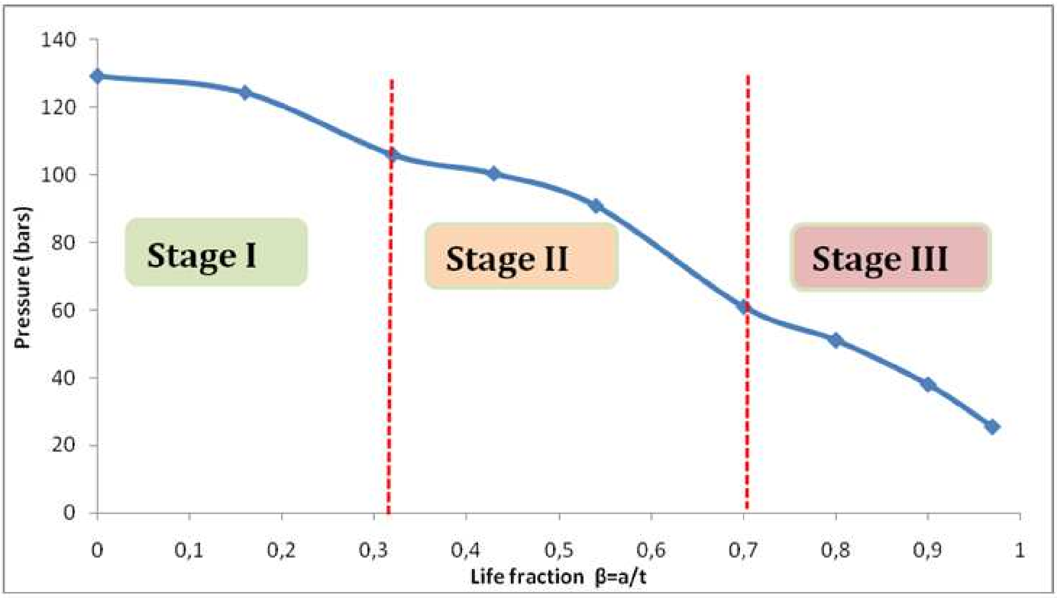

Fig. 5. Pressure evolution in function of the life fraction

Virgin tubes can withstand an ultimate pressure Pu=129,3bars. As much as the reduction of the thickness increases, residual ultimate pressures decrease in a gradual manner; this is explained by a loss of the strength of notched PPR pipes under pressure because of the increase in depth of the notch.

In addition, the curve shows the existence of three stages of the major variation in the residual pressures in function of the fraction of life of notched pipes, the first stage of initiation of damage corresponding to range of the reduction of thickness from 0 to 32%, the second stage dominates the range from 32 to 70% where the damage is increased. Beyond 70%

the curve reaches the third stage characterized by a sudden acceleration of the damage. The importance of these stages has resulted in the validation of the damage stages of development achieved by the static damage.

2.3.2 STATIC DAMAGE

Static damage Ds allows a quantification of the damage in function of the ultimate, critical residual forces [8]. By analogy, a static damage mathematical formulation based on pressure is given by the following equation:

$$D_s = \frac{1-\frac{P_{ur}}{P_u}}{1-\frac{P_a}{P_u}}$$

With:

Pu: Ultimate pressure at failure of the virgin pipe (P_u=129,3bars).
Pur: Residual pressure at failure of notched pipes.
Pa: Critical pressure (Pa=20 bars)

The curve 6 illustrates the variation of the static damage depending on the β fraction of life. We note that the damage D_s gradually increases with the decrease of the effective thickness of the pipe, this is explained by a loss of mechanical properties caused by an increase of the depth of the notch. In fact, the evolution of the damage is divided into three stages. In the first stage (0% <β<32%), the damage starts with zero and grows slowly(initiation of the damage). The second stage (32% <β<70%) is characterized by an increase of the damage with the increase of the notch depth, from β = 70% begins the third stage, whose damage accelerates to have a value of 1 for a fully damaged pipe.

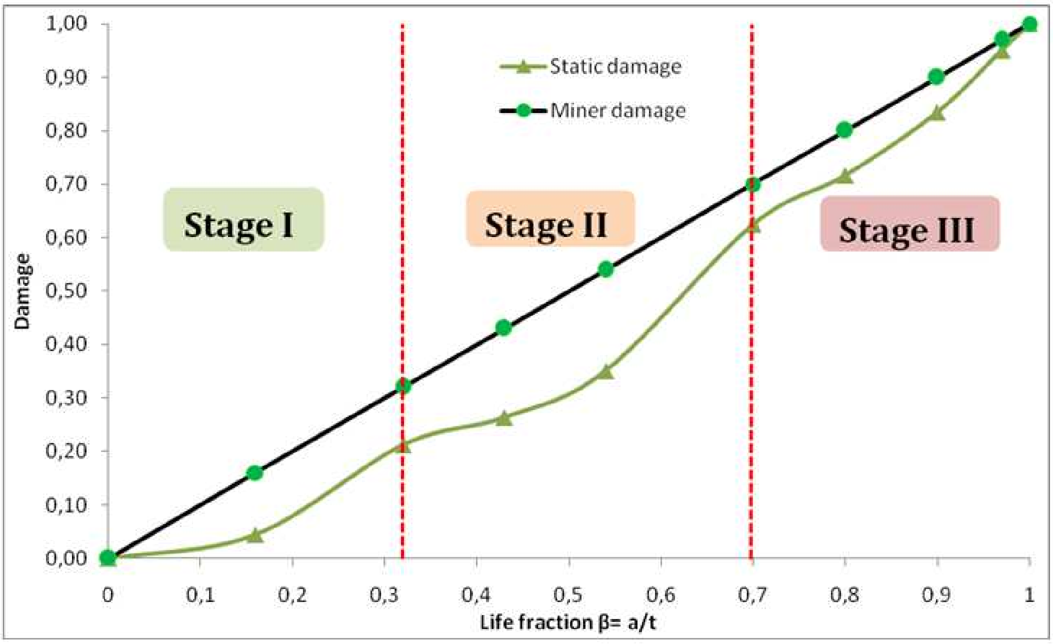

Fig. 6. Static damage variation in function of the life fraction

2.3.3 UNIFIED DAMAGE

By correlation to the expression of the unified damage proposed by Bui-Quoc, a relationship describing the evolution of the damage depending on the fraction of life and pressure is given by the next equation:

$$\mathrm{D_{unifid}} = \frac{\beta}{\beta + (1-\beta)\left[\frac{\gamma - (\frac{\gamma}{\gamma_u})^m}{\gamma - 1}\right]}$$

With:

β: Life fraction.
m: Empirical constant depending on material (m=1 for our case).
γu=Pu/Pa: Parameter reflecting the strength of the material in a virgin state.
γ=Pur/Pa: Parameter characterizing the effect of the damage on the mechanical characteristics of the material.

The variation of the unified damage in function of the fraction life β is given in the figure 7.

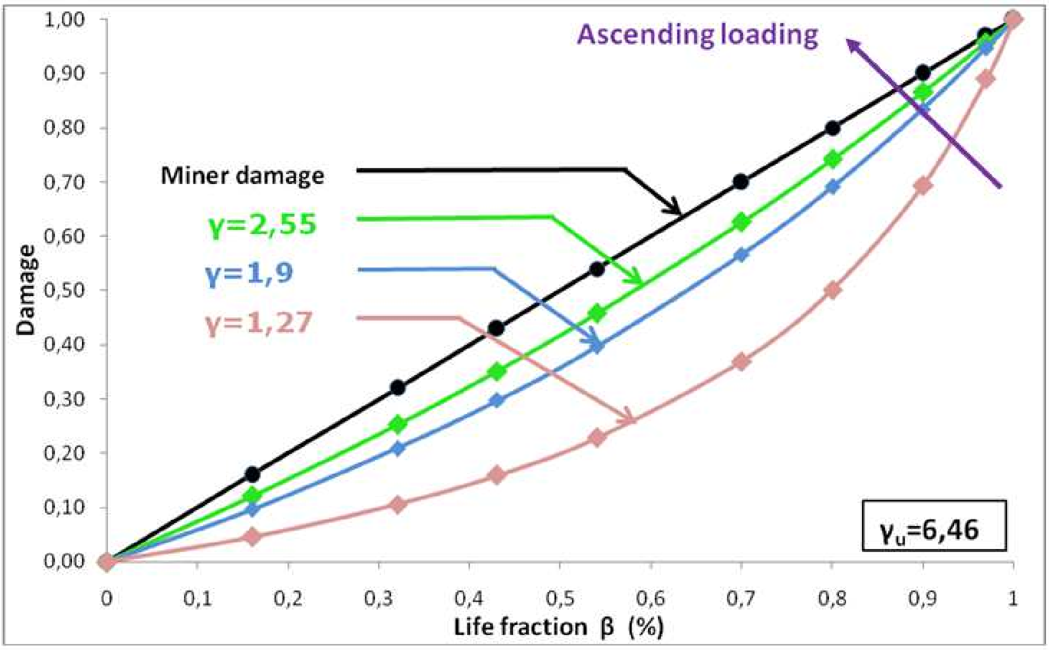

Fig. 7. Unified damage variation in function of the life fraction

The unified damage is indicated by a set of curves associated with a constant pressure ratio γu=Pu/Pa(Pu=129,3bars and Pa=20bars) and a variable parameter γ=Pur/Pa. Therefore, each curve is associated with a separate level of applied pressure. In the direction of increasing γ, the curves of the unified damage grow to linear tendency for high loading levels.

2.3.4 STATIC DAMAGE AND UNIFIED DAMAGE COMPARISON:

Static Figure 8 shows the variation of static and unified damages (γu = 6,46) and that proposed by Miner in function of the β fraction of life.

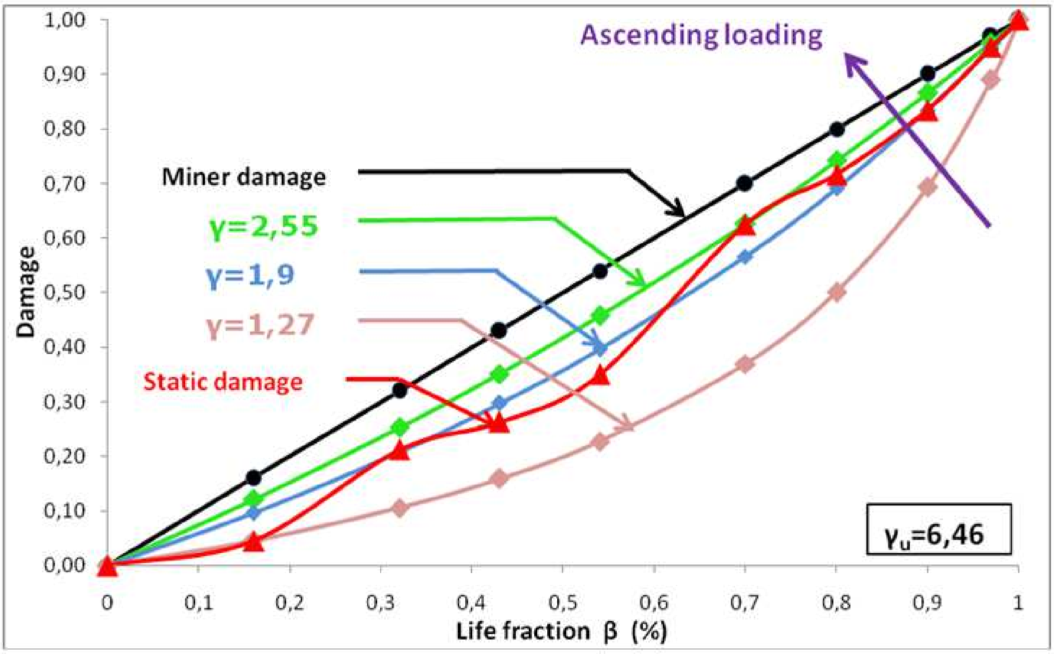

Fig. 8. Static, unified and Miner damages comparison

For low life fractions (0% <β<16%), static damage and unified damage at a loading level γ = 1.27 is similar. With the increase of the fraction β of life, the curve of static damage approaches to the unified damage corresponding to the loading level γ = 1.9 until they superimpose at the end of Stage I. Then, in the beginning of stage II and up to a fraction of life β equal to 60%, the static damage is below the theoretical damage corresponding to γ = 1.9. Then it exceeds the curve of this loading level and overlaps in this time with the curve of the unified damage at a loading level γ = 2.55 at the end of stage II. In stage III curves of static damage and unified damage for γ = 1.9 return back similar again. Both graphs of the two types of damage remain below the damage given by Miner.

3 CONCLUSION

F In this article, an investigation of the damage has been provided based on simple burst tests and easy to implement. This study provides both a mechanical characterization of virgin pipes of PPR material, and damage control of pipes made of the same material but with the type of notch as an external longitudinal grooves.

Results show that the notch caused a drop in residual bursting pressures of notched tubes comparing to those virgins. In addition, an increasing the depth of the notch leads to a drop in the residual pressure of notched pipes themselves.

The interest of using static damage is determining theoretically the three stages of development of damage (initiation, progression, and acceleration of the damage), these stages have shown good agreement with those obtained experimentally.

The comparison of the unified damages calculated for different load levels revealed that the loading level γ = 1.9 gives the best results with respect to the static damage, it seems most realistic to properly describe the progression of the damage of the tubes PPR with defects in the form of external longitudinal grooves.

For preventive maintenance, the quantification of the damage by static damage and unified damages helps maintenance department to implement a wise strategy to intervene at the right time in order to minimize the cost of interventions and maximize the reliability of the installation.

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