Visual Abstract

Fracture analysis of defect Chlorinated Poly Vinyl Chloride pipes based on burst pressure and prediction their fraction of life

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ABSTRACT. Most Chlorinated Poly Vinyl Chloride (CPVC) resins contain 63-69 % chlorine, particularly those used for the extrusion of plumbing tubes, due to this basic PVC chlorination, CPVC offers a mixture of corrosion resistance and low installation costs for its main applications requiring service in non-ambient conditions. CPVC substitutes copper owing to its economic gain and by virtue of its pressure resistance characteristics. In this article, we have been interested in fracture analysis and modeling of CPVC tube damage by CPVC samples subjected to burst pressure tests. We performed a serie of burst tests on virgin and artificially damaged CPVC pipe at different notch lengths, and then submitted the specimens to burst pressure tests, in addition to recording the pressure and time during these tests to be used in the completion of the study. The results of the bursting tests were exploited to estimate the damage and the reliability of the material, these two parameters enable us to follow the degradation of the pipes used; subsequently, we determined a new relationship between these two parameters through the fraction life. It is therefore possible to predict the moment of the acceleration of the damage acceleration and to intervene at the right time to engage predictive maintenance.

KEYWORDS. CPVC, Burst tests, Pressure, Fracture, Damage, Reliability.

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INTRODUCTION

Polymers are omnipresent in everyday life, their use has made it possible to achieve significant gains in construction time and installation costs thanks to the extreme variety of products that can be designed, to their continuous development and to the flexibility of their implementation techniques. Among these materials, there is Chlorinated Polyvinyl Chloride (Chlorinated PVC or CPVC) which is a thermoplastic polymer material belonging to the family of chloropolymers, resulting from the process of polyvinyl chloride chlorination. The history of the discovery of plastic materials began with the discovery of PVC in 1913, plexiglass in 1924, polystyrene in 1933, polyethylene in 1935, Teflon in 1938, ABS in 1946 arriving at polypropylene in 1954.

CPVC is a engineering material owing to its relatively ease of installation; through cold welding and low cost, CPVC resist to corrosion and scale [1-3] furthermore copper is dangerous to transport drinking water owing to human health infection [4,5]. CPVC polymer have better thermal insulation and phonic insulation, it is formed by addition more chlorine to PVC that's improve some properties of the material, his temperature of transition rise up to 135 ° C also he can support a higher pressure than PVC and it does not deform like PVC in boiling water; that's a quality which finds its use in the manufacture of domestic plumbing pipes. Sufficiently high temperature resistance is obtained for chlorine levels close to 65% (the PVC chlorine level is 56.5%) [6,7]. CPVC pipes are often used in domestic hot and cold water systems as a copper replacement, which is becoming increasingly expensive due to growing global demand. Additionally to these attractive properties, the Chlorinated PVC mechanical strength makes it a practical candidate for replacing many kinds of metal pipe under conditions where the metal's susceptibility to corrosion limits its use.

Indeed, in the water distribution industry, where CPVC pipes are frequently used, they have many advantages, thus manufacturers of CPVC pipes and design consultancies generally assess for these materials, predictive maintenance lifetimes of 50 years also have some drawbacks, since the conditions of complex stresses can cause them local deformation or degradation, as well as environment sensitivity. They are many causes of material damage and their rupture [8-11], micro defects can occur after leaving the factory, during the process of storage, installation, and even during operation. As a result, micro damage of various sizes exists in most structures, primarily from manufacturing defects, installation and thermal shock. Micro and macro cracks can be harmful at a certain (critical) size from which the propagation becomes brutal and unpredictable even under normal operating pressures. Thus, such a structure requires periodic and regular monitoring and control in order to be maintained and replaced in time, because the accidental rupture of these structures causes significant inconveniences in aspects as diverse as human and material losses.

For this reason, the concern that preoccupation of researchers and engineers in design offices is to provide CPVC tubes operators with solutions to estimate the resistance of a tube from its current state, therefore, analyze and model bursting phenomena from experimental results under controlled defects. Also evaluate the risk of rupture of this tube for an imposed level of stress in order to predict the evolution of the damage, knowing that the degradation will continue.

This present article is a contribution to the development of methods for expecting the behavior and service life of pipes. Use of material safely have to respect several specifications and rules belong to codes ISO, ASTM…, the industrial verifies these requirements during all stages of the life of the material beginning by production process while studying damage occurs in the injection and extrusion level [12,13], then production supply chain.

Significant efforts have been made in the literature for probabilistic pipeline analysis. Wang & al [14] developped the model for predicting the burst pressure of corrroded pipes through a regression analysis of finite element based experimental data and results. Rael & al [15] conducted an extensive comparison of the reliability of corroded pipe from available models of recognized academic literature and codes, and the susceptibility of each model to faulty corrosion was assessed. Simalarly, according to the bursting pressure formula proposed by Netto et al [16]. Mechab & al [17] presented an analysis of 3D finite element methode of semi-elliptic surface fissures in internally pressurized. According to the results obtained, it can be seen that the uncertainties related to the applied load and to the length of the crack lead to an increase in the probability of rupture of the pipe and to a reduction in the durability of the structure.

Moreover, several works on the mechanical reliability and behavior of polymers have been carried out [18-24] paying attention to rupture and failure of polymer structures to keep away from accidents causing production loose plus life damage of both human and material, besides saving money. Necar [25] studied the effect of temperatures ranging from –10 to 70 ° C on the mechanical properties of CPVC. They found that the yield strength and the elastic modulus decrease linearly according to temperature. A brittle fracture occurred below ambient temperature, while a ductile rupture occurred at ambiant temperature and at higher temperatures. They observed the minimum elongation at rupture at 10 ° C while the maximum at -70 ° C. They also observed a considerable necking at 50 ° C and 70 ° C.

In operation, the tubes are subject to several damage mechanisms which aggravate degradation under stress (temperature, erosion, corrosion, etc.). In this study, only the notch and the pressure are considered, disregarding other damage mechanisms, thus, it is important to appreciate the loss of resistance and the change in the behavior of matter over time under the combined pressure and notch action. In this article, the test specimens are prepared from CPVC tubes according to ASTM D 1599 [26], after that we have created a controlled defect in the form of a semi-ellipse 2 mm wide, in the wall middle of a CPVC PN25 tube with an outside diameter of 40 mm and a thickness of 4.5 mm that we will test under burst pressure (submit to burst tests.) at different notch depths. We were assimilated this pre-damaged to fatigue test preloading. Then the samples exposed to pressure until rupture.

Our main objective is to study pipes damage in order to predict the service life in favor of a strategy for optimizing the predictive maintenance of a hydraulic network built in CPVC and to find out the optimum moment to remove the structure without attending until fracture not changing the pipe healthy based only on simple tensile and burst tests, without resorting to expensive and time-consuming cyclic tests. While industrials estimate lifetime of polymer plastic pipes of 11 years in accordance with ASTM D2837 [27] and 50 years based on ISO 9080 [28].

The experimental methodology and the operating mode used are the subject of the experimental procedure part. After detailing the various test preparation processes according to specific standards, a range of experimental tests were carried out on the CPVC tubes. The third part is devoted to the results exploitation of the experimental bursting tests of the newly produced tubes, extracted directly from the output of the production line; virgin and artificially damaged by notching at different notch depths, where we analyzed the evolution of resistance and the behavior of the pipes which revealed a certain number of defects depending on the notch depth and the pressure. Then, based on the models using the physical parameters determined experimentally, in particular the rupture pressure, we carried out a study whose aim is to predict the damage of a CPVC structure under the effect of the notch and pressure, subsequently and with the establishment of the damage-reliability relationship, the reliability curve was established by exploiting the results collected from tests on CPVC specimens and it was possible to determine the critical fraction of life which allows to predict the instant of critical pipe damage and hence to intervene eventually for predictive maintenance of the structure. This work is based on an experimental part and on an analytical study, a graphical representation of reliability as a function of damage concludes this article.

EXPERIMENTAL PROCEDURE

The most important objective of subjected the CPVC pipe burst pressure tests is the ability to find out its resistance based on its rupture pressure.

Hence, we performed the burst test of three neat pipes in order to characterize the CPVC material. After that, we realized for each notch three specimens. A notch in the semi-ellipse form have been made through a vertical milling machine with a tool of 5 mm width Fig. 1, the depth of the notches vary from 1 mm to 4 mm with a step of 0.5 mm.

The goal of the second experiment is to evaluate the damage of the tested CPVC pipes.

For the choice of the specimens, we based on the international code ASTM D1599, that requires the geometric dimension of a specimen, identified by its thickness in this case 4.5 mm, its external diameter in this paper is equal to 40 mm and a length without exceeds five times the pipe diameter Fig. 3.

The CPVC specimens are performed and conditioned at the ambient temperature before pressurization.

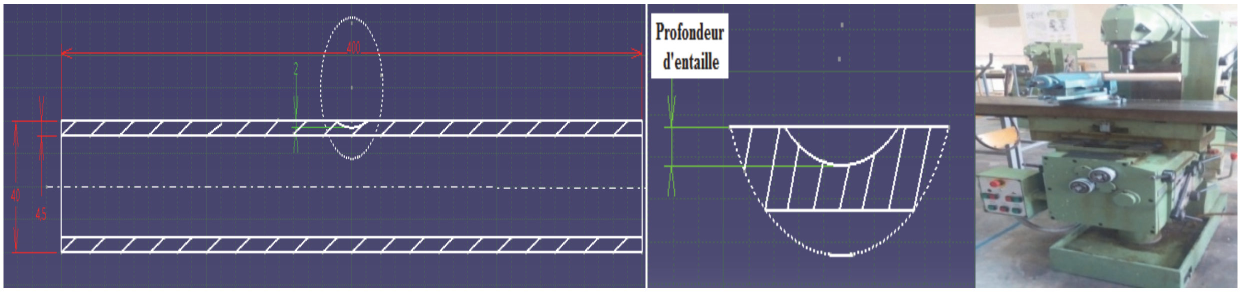

Figure 1: CPVC notched specimens

To do the burst test safely, to be able to bursting CPVC pipes, we used an apparatus of the hydrostatic tester. This machine is outfitted with a controlled of flow, feeding and pump with water. Subsequently, we mounted samples in the hydraulic last

part caps then we connected them to the hose of high pressure. Once purging the air, we put the mounted specimens inside of the burst test basin using water in the company of controlling temperature. The burst tests are started after that.
We used a hydrostatic test machine with automatic system of control containing two main parts. The first one is a control panel of burst pressure which allows controlling the internal pressure through regulation of the flow. The second and last part assembly an equipped electric for controlling the temperature of water basin and security mechanisms for the tester effectiveness Fig. 4.

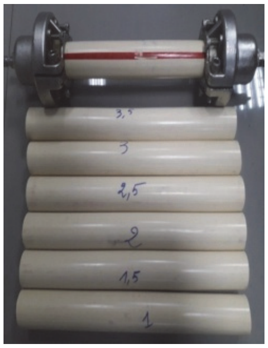

Figure 2: CPVC notched specimens at different depths.

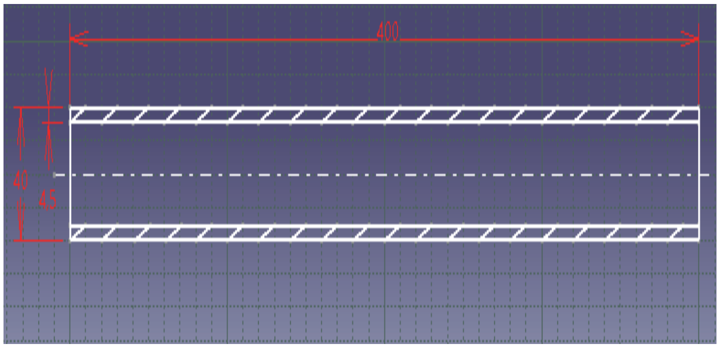

Figure 3: CPVC undamaged specimens.

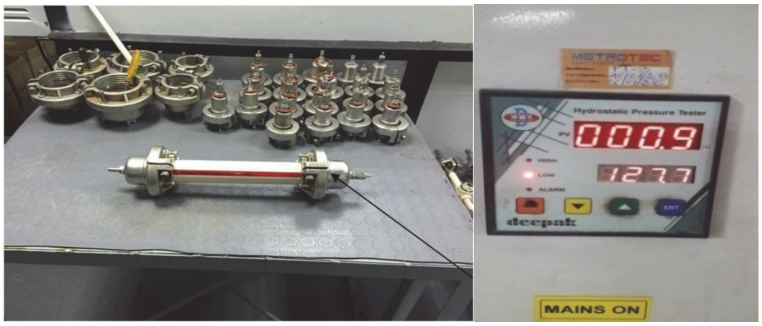

Figure 4: Equipment of the test.

The burst pressure obtained from the primary group of the test, undamaged CPVC pipes, is the ultimate pressure, it is the reference using in the next steps in this paper. Then, the indicate burst pressures recorded from the second test group, notched CPVC pipes, correspond to the ultimate residual pressure that consist the basic to be able to establish our models of damage.
The controlling principle is continuously increasing the pressure until we obtain a fix value accompanying with an exposed sound which mean specimen rupture. The maximum pressure and its evolution according to the time are registered. Finally, we obtain the time and the burst pressure of fracture. Following, we had finished the test of the burst; we will control both the rupture nature and its form as presented in the Fig. 5.

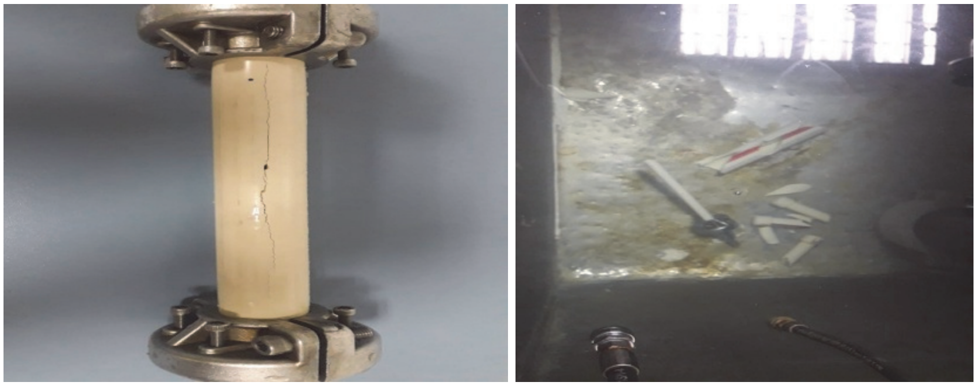

Figure 5: Rupture form of CPVC pipe.

To do this test valid according to the international codes, it's obligatory to avoid the following problems:
- Quick and instantaneous pressure dropping.
- Observable leaks on the CPVC pipe.
- Test time over to 60 seconds
- Pressure loss stopping his ascending increase.

RESULTS

Pressure decrease

To follow the evolution of the mechanical behavior of CPVC specimens, we have recorded the pressure evolution as a function of time of artificially damaged specimens at different notch lengths.

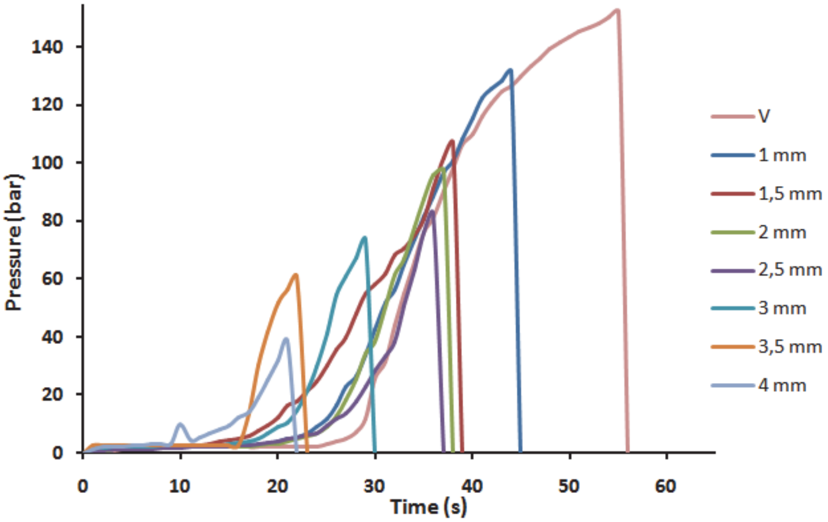

Figure 6: Evolution of the internal pressure according to time for virgin and notched CPVC pipes.

From the Fig. 6, we can see that the undamaged pipes, i.e. the virgin pipes can resist an ultimate pressure up to 152.2 bars. In addition, the notch caused a drop in the ultimate pressure of the notched pipes compared to the non-notched pipes. The increase in the depth of the notches leads to an exhaustion of the residual pressures of the notched CPVC pipes.

The decrease in the ultimate internal pressure during the increase in the notch depth, allows us to estimate a dimensionless pressure loss function Pur / Pu as a function of the life fraction β in this form:

$$\frac{P_{ur}}{P_u} = a_1 + a_2 e^{\beta^{a_3}} \tag{1}$$

Which β (%) is defined as follows:

$$\beta = \frac{\Delta e}{e} \tag{2}$$

where e is the material thickness and Δe is the notch depth.

We want to estimate the three unknown parameters of the Eqn. (1) a1, a2 and a3, then the problem is intrinsically nonlinear since we want to minimize.

The residual at each data point βi is:

$$E_i = \frac{P_{uri}}{P_u} - \left(a_1 + a_2 e^{\beta^{a_3}}\right) \tag{3}$$

The summation of the square of the residuals is:

$$f\left(a_1,a_2,a_3\right)=\sum_{i=1}^{n}E_i^2=\sum_{i=1}^{n}\left(\frac{P_{uri}}{P_u}-\left(a_1+a_2e^{\beta^{a_3}}\right)\right)^2 \tag{4}$$

We assume $a_3 \neq 0$ is fixed and we put $x_i = e^{(\beta^{a3})}$, we use the classical least squares for the linear model we find:

$$a_2=a_2\left(a_3\right)=\frac{n\sum_{i=1}^{n}\frac{P_{uri}}{P_u}x_i-(\sum_{i=1}^{n}\frac{p_{uri}}{P_u})(\sum_{i=1}^{n}x_i)}{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2} \tag{5}$$

$$a_1=a_1\left(a_3\right)=\frac{\sum_{i=1}^{n}\frac{P_{uri}}{P_u}\sum_{i=1}^{n}x_i^2-(\sum_{i=1}^{n}\frac{P_{uri}}{P_u}x_i)(\sum_{i=1}^{n}x_i)}{n\sum_{i=1}^{n}x_i^2-(\sum_{i=1}^{n}x_i)^2} \tag{6}$$

Then we set:

$$S\left(a_3\right)=f\left(a_1\left(a_3\right),a_2\left(a_3\right),a_3\right) \tag{7}$$

This means:

$$S(a_3)=\sum_{i=1}^{n}(\frac{P_{uri}}{Pu}-(\frac{\sum\limits_{i=1}^{n}\frac{P_{uri}}{Pu}\sum\limits_{i=1}^{n}x_i^2-(\sum\limits_{i=1}^{n}\frac{P_{uri}}{Pu}x_i)(\sum\limits_{i=1}^{n}x_i)}{n\sum\limits_{i=1}^{n}x_i^2-(\sum\limits_{i=1}^{n}x_i)^2}+\frac{n\sum\limits_{i=1}^{n}\frac{P_{uri}}{Pu}x_i-(\sum\limits_{i=1}^{n}\frac{P_{uri}}{Pu})(\sum\limits_{i=1}^{n}x_i)}{n\sum\limits_{i=1}^{n}x_i^2-(\sum\limits_{i=1}^{n}x_i)^2}x_i))^2 \tag{8}$$

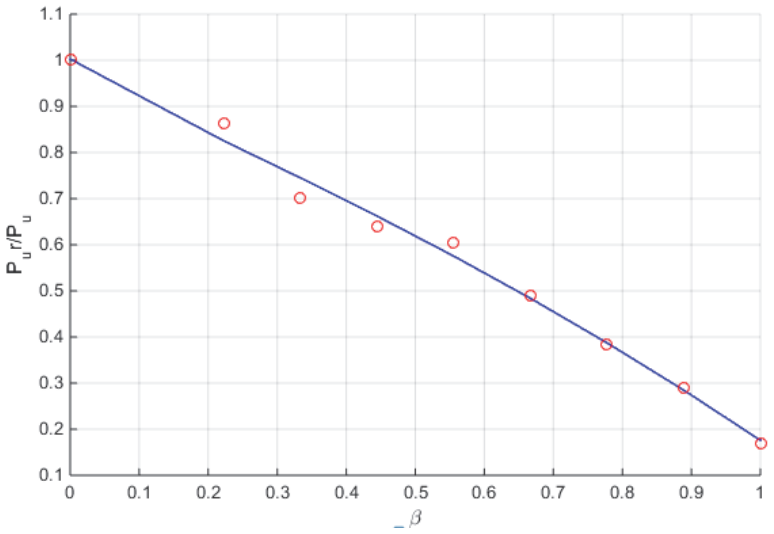

Figure 7: Dimensionless pressure loss as a function of fraction of life

The optimization problem is now reduced to finding the minimum of S(a3). This can be done either using the Newton method [29], this gives a3=0.7713, we substitute the value of a3 in the value of a2 and a3 we get: a1=1.4838; a2= -0.4812; which allows to obtain the final form of the additional pressure loss function.

$$\frac{P_{ur}}{P_u} = 1.4838 - 0.4812 e^{\beta^{0.7713}} \tag{9}$$

Fig. 7 shows the drop in dimensionless burst pressure according to the life fraction.
From Fig. 7, we see there is a progressive decrease in the burst pressure of the tubes as the critical life fraction increases.

Damage

The appearance of damage affects the physical and mechanical properties of the materials. Therefore, the damage theory aims to studying the evolution of the material behavior of the virgin state to the initiation of macroscopic cracks of the size of the representative volume element [30-31]. There are numerous types of laws in the literature that can model the damage from experimental results, but we limit ourselves here to the ERISMANN model [32].

ERISMANN postulates that at each moment in the life of a material, the damage is modeled as an entire configuration of certain significant physical parameters such as (load drop, hardness, strength... etc.). It is given by the following equation [33]:

$$D = \frac{\phi(x) - \phi(x_0)}{\phi(x_R) - \phi(x_0)} \tag{10}$$

ϕ(x): Well-defined monotonic function of x.
x: Property value of the damage.
O, R: index of beginning and end of life.

The function ϕ represents the variation of some parameters, for example (load drop, hardness, toughness, etc.). Our approach in this work is based on the artificial damage of tubes under pressure. As the notch depth increases; the ultimate pressure decreases. Therefore, by analogy with the law's ERISEMANN, we can consider that the variation of the residual ultimate pressure redresented by the function ϕ and X represents the fraction of life, i.e. ϕ (x) = Uur (β) from which the static damage by pressure is given by the following expression:

$$D = \frac{P_{ur}(\beta) - P_u(0)}{P_a(1) - P_u(0)} \tag{11}$$

Pu: the ultimate pressure of the tube when the material is virgin.
Pur: the material ultimate residual pressure when it is artificially damaged
Pa: the value of pressure just before rupture.
The damage evolution in function of the fraction of life is given in Fig. 8.

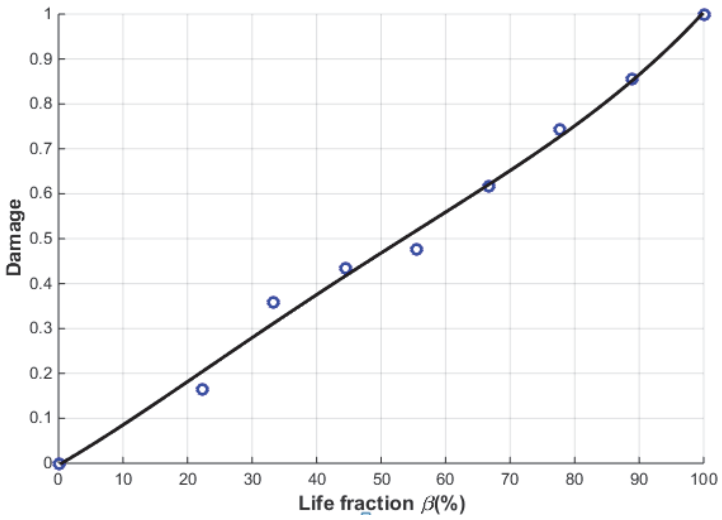

Figure 8: The static damage evolution based on the bursting pressures as a function of the fraction of life.

From Fig. 8, we notice that the damage is an increasing function according to the fraction of life, which means the growth of the loss in strength of the material during the burst test of the specimens. This loss evolves rapidly as the fraction of life takes a critical value (77%) up to the reduction rate of β=1 when the material becomes complement damaged.
We made comparison of our results with the results of reliable works in the literature. To allow us to evaluate the degradation and the harmfulness of severe geometrical defects, Safe & al [34] created artificial notches which have the shape of a groove with a depth variation of 1 to 5 mm, while we created semi-elliptical notches with a depth variation of 1 to 4 mm and the two nicked CPVC pipes were subjected to controlled internal pressure until they burst. Then, the static damage curves based on the burst pressure as a function of the fraction of life showed an increase of this damage as a function of the depth of the defect. Indeed, the defect seems to have a direct impact on the pipes used, for both forms. To make comparisons between the two defects possible, we determined the critical fraction of the lifetime of the static damage curves, then evaluated their behavior when they burst. In fact the critical life fractions are respectively 60% and 77% for the two grooves and semi-elliptical defects. Consequently, this affirms that the groove notch represents the most critical defect that reduces the service life of CPVC material.

Reliability

Reliability is a static parameter which can estimate the probability of survival of a material under specified operating conditions for a given operating time. To estimate the reliability, it is vital to choose a suitable statistical model. Here we chose the Weibull's law [35]:

$$R = \exp\left(-\left(\frac{t-\gamma}{\eta}\right)^{\lambda}\right) \tag{12}$$

with λ and γ are respectively the parameter of scale and shape.
The simplified expression of reliability in terms of fraction of life is provided by the relation follow [36]:

$$R(\beta) = \exp\left(-\beta^{\lambda}\right) \tag{13}$$

Fig. 9 illustrates the superposition of the two damage and reliability curves in function of the life fraction:

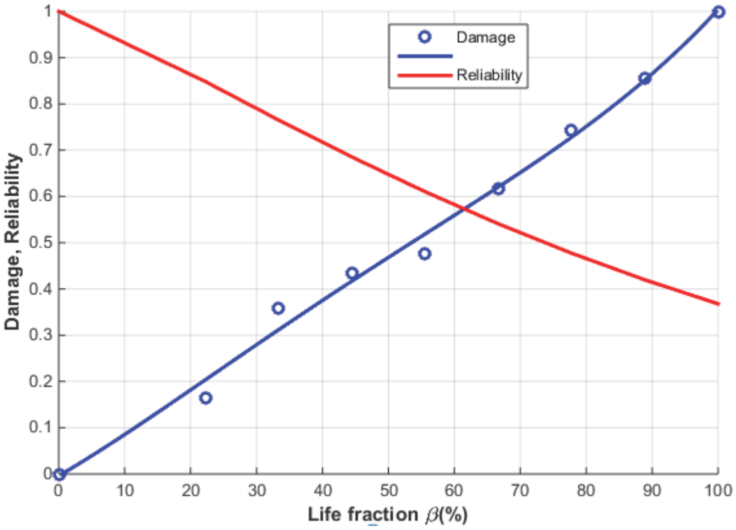

Figure 9: Damage-reliability curve as a function of life fraction

From Fig. 9, we notice that reliability varies in the opposite direction of damage, which means that there is a relationship connecting the two parameters that must be determined. We also note that the intersection point between these two parameters coincides with a reversal of the situation. Indeed, the reliability that initially exceeds the damage becomes lower beyond this point. This can have practical, very important consequences, with regard to predictive maintenance.

Damage-reliability relationship

To relate reliability to the damage parameter D through the fraction of life, any variable physical parameter must be expressed as a function of the fraction of life. Starting first with the Eqn. (11) which can be given bu the expression below:

$$D = \frac{1 - \frac{P_{ur}}{P_u}}{1 - \frac{P_a}{P_u}} \tag{14}$$

which give:

$$\frac{P_{ur}}{P_u} = 1 - D\left(1 - \frac{P_a}{P_u}\right) \tag{15}$$

We replace the Eqn. (1) in (15) we get:

$$a_1 + a_2 e^{\beta^{a_3}} = 1 - D\left(1 - \frac{P_a}{P_u}\right) \tag{16}$$

From Eqn. (16) we can extract the expression of the fraction of life in function of damage

$$\beta = \log\left(\frac{1}{a_2}\left(1 - D\alpha - a_1\right)\right)^{\frac{1}{a_3}} \tag{17}$$

This gives the expression of reliability in function of damage:

$$\mathrm{R} = e^{\left(-\log\left(\frac{1}{a_2}\left(1 - D\alpha - a_1\right)\right)^{\frac{1}{a_3}}\right)^{\lambda}} \tag{18}$$

The Fig. 10 shows the graphical illustration of reliability versus damage.

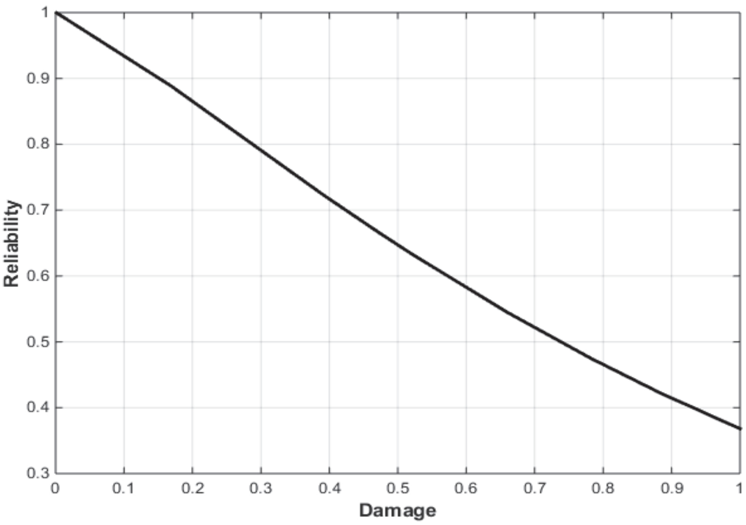

Figure 10: Graphic illustration of reliability versus damage.

The figure above aims to establish a link between reliability and damage. This link is used to associate each stage of damage with the corresponding reliability and vice versa. After a graphical reading of this curve, we notice that for damage equal to 1, the reliability is not equal zeros. Indeed, the damage theory considers that damage reaches its maximum value which equal one when there is the appearance of a macroscopic crack leading to rupture, but the material used retains a certain resistance which is reflected by no-zero reliability. This reliability becomes null when the material is completely broken.

CONCLUSION

In this paper, we have been interested in the fracture analysis and damage modeling of CPVC pipes, by conducting experimental and analytical studies, based on the test results, the curves showed that a drop in the burst pressure and burst time when incrementing the depth.

Firstly, we have developed a damage model based on the experimental results of the burst tests and on the modification of the concepts of ERISMANN's law using the residual lifetime. Subsequently, we estimated the reliability of the damaged tubes using Weibull's law. The intersection of the damage and reliability curves allowed us to derive a critical life fraction. Finally, we related reliability to damage through the life fraction. The determined relation allows us to associate each stage of damage with the corresponding reliability and vice versa. The results of this study are directly available for lifecycle monitoring of pipeline safely which is very useful for industrial and domestic use

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