

# Study of defects influence on chlorinated polyvinyl chloride pipes damage and analysis of their fracture

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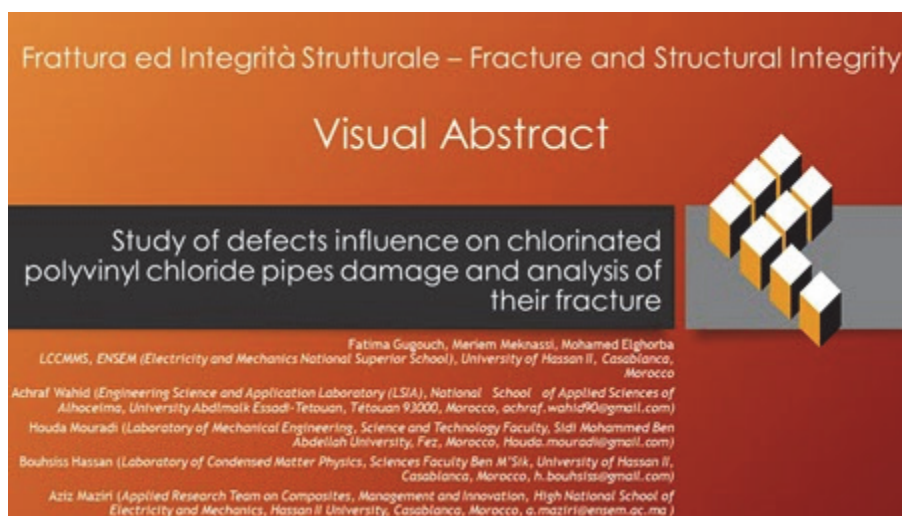
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**KEYWORDS:** CPVC pipes, Burst tests, Pressure, Unified theory, Fracture, Damage.



## INTRODUCTION

In industrial settings like water, gas, and sewage piping systems, selecting the right material is a crucial task that depends on a variety of criteria. Firstly, it related to the use conditions of each type of material. The material chosen features and the ability to identify the crack or failure, in order to prevent its occurrence, have an impact on the selection and, in the end, the mastery of the material's failure scenarios. Besides that, many specifications by codes such as ISO and ASTM have to be verified and respected during product process and supply chain of production. To deal with the rise in copper prices; one of the metals, widely used by humans in plumbing systems, the professionals have found a replacement. Furthermore, copper affects health of humans [1] and other material in the presence also of dirt and iron oxide [2] because it is released from corroded pipes [3]. Chlorinated poly (vinyl chloride) is produced through post-chlorination of the polyvinyl chloride (PVC). The main industrial applications for CPVC pipes include gas, water, and sewage piping systems, as well as other industrial uses including the transportation of minerals. The goal of additional chlorine to the molecule of Poly Vinyl Chloride is to raise the base resin Tg from a temperature of 95°C to a range between 115 and 135°C. Chlorine improves the physical and PVC mechanical properties [4]. Many investigations interested in studying the PVC and CPVC. Zekriti et al [5] studied the damage modeling of PVC by experiment and measurements of digital image correlation. Pal et al [6] studied the mechanical properties at room temperature of mixtures of polymers based on polyvinyl chloride intended for medical applications. They came up with an equation to determine the mechanical properties. The calculated values are quite close to the experimental values of the studied mixing system. Hitt et al [7] investigated the unplasticized PVC tensile properties at high temperatures (23 to 180°C). They get a gradual decrease in tensile strength as the test temperature increases. Merah et al [8] concluded that temperature decreases material's elastic modulus and yield strength linearly by the study the temperature influence on the CPVC mechanical properties. Al-Qahtani [9] studied the temperature effect and crosshead speed on the CPVC tensile properties. Previous experiments works have been performed for the mechanical characterization of different polymer tubes through static and burst tests [10, 11]. The results of the static tests performed on specimens extracted from an exploded tube showed that aging has the effect of reducing the elongation from 275 mm to 26 mm [12]. Majid et al [13] carried out a failure study and damage-reliability modeling of HDPE pipes. In addition, Ouardi et al [14] evaluated the severity of the defect on the Polypropylene Random (PPR) pipe failure. Comparison between two damage curves revealed that the circumferential notches are less severe than the axial notches. Safe et al [15] concluded that CPVC material embrittles with the pressure and temperature exposure owing to appearance of heterogeneous novel defects. Various hypotheses regarding material failure have been researched over the past years. Like metallic structures [16], thermoplastic ones, especially pipes were studied. The materials' faults reduce the reliability of the installations and shorten their lifespan [17]. While, the ASTM D 2837 [18] gives 11 years and the ISO 9080 [19] standard gives a stress-time extrapolation line of 50 years, failures can provide serious accidents in pressurized piping systems, as burst, leaks or ruptures. For this reason, we have to determine the pressure CPVC pipe probable damages. According to this study's ASTM D1599 code [20], we realized standard samples cut from a CPVC pipe. Then, using a fix step of 0.5 mm and depth levels ranging from 0 to 4 mm, we developed a semi-elliptic flaw to incorporate the fatigue test preloading. Through the use of experimental burst tests, in which prepared samples were subjected to internal pressure, we evaluated changes in burst pressure as a function of varying lifetime. Afterward, to assess the CPVC tube damage, we employed damage models. The resulting results from these models were graphically displayed to highlight how damage, in all of its manifestations, evolves over time. Additionally, it allowed us to calculate the critical lifetime that stands for the permitted maximum thickness drop. The main tool for distinguishing the stages of harm growth, from damage commencement through damage acceleration, is also this representation. As a result, we will be able to determine with accuracy when to maintain and replace the worn-out pipes.

## THEORY

### *Hypothesis*

We know that a tube in its original (virgin) state has a significant ultimate pressure. This pressure gradually decreases as the number of cyclic solicitations increases until rupture occurs. If the fatigue test is stopped before the final rupture, and the tube undergoes a burst test, the rupture occurs at a lower residual ultimate pressure,  $P_{ur}$ , situated between  $P_u$  and  $P_a$ , corresponding to the bursting pressure of the most stressed specimen

By analogy with cyclic behavior, considering a notch in a tube as a lifespan that consumes an equivalent number of cycles equal to  $N_i$ , we conducted burst tests on damaged specimens at various levels of artificial damage [21-26].



*Damage*

Damage of structure is a modification phenomenon of its geometry and mechanical characteristics, produced by chemical or physical attack, leading to reduced strength and, in turn, structural failure [27]. The theory of damage was initially proposed by Rabotnov and Kachanov [28]: they said, the material deterioration can be considered just by the variation of the material elastic characteristic description. Then the damage mechanic was developed mainly by Chaboche and Lemaitre [29] for ductile fracture and metallic materials. In literary works, for fatigue loads, there are theoretical models that are based solely on the mode of loading, loading conditions, and the mechanical features of the unbroken material [30], we will focus in this work only on Miner and unified theory models.

*Miner model*

The model of Miner is considered a pioneer damage model. Based on the stressed material's fluctuation in strain energy. Miner' model made for cyclic loading, founded on the hypothesis, witch total work absorption in fatigue [31] is the origin of the material failure. After applying ni similar cycles of fatigue, Miner developed a linear damage law where the life fraction, written below  $D_M$  like a percentage of the entire effort absorbed per material, is equal to the damage law : In Miner's writings, [32] damage is portrayed as being matched to lifetime, which is stated as follows:

$$D_M = \beta = \frac{n_i}{N_f} \tag{1}$$

$D_M$ : Damage

$n_i$  : Number of instantaneous cycles.

$N_f$  : Number of cycles to failure.

The results of this model are extremely approximate, because they do not take into account the progressive nature of the degradations and ignore the non-linearity of the material parameters.

The progressive nature of degradation is ignored by Miner's linear formulation of damage, and whatever the level of material degradation, the evolution of damage is identical, which raises concerns about the strategy in the event of genuine strains of a progressive character.

By similarity with the CPVC mechanical behavior which is submitted to cyclic loading, the ultimate pressure of the tubes is successively reduced due to the increase of notch depth, that is why we have adopted in this article a modified approach based on the law of mining, considering the fraction of life defined by: Thus, we have taken a revised coming based on the Miner's law, considering a lifetime defined as:

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

where:

e is the material thickness

a is the depth of defect.

*Unified theory*

Due to the non-linear nature of damage. Bui-Quoc created unified theory [32] combining works of Gatts, Valluri, and Shanley [33, 34]. It is based on the decrease of the residual stress in static tensile. He assumes that if a fatigue test is stopped and a static tensile test is then performed, the specimen will have a residual stress decreasing proportionally with the endurance limit.

This idea investigated how lowering the fatigue and endurance limits affected the material's ability to resist wear and tear. The damage relationship is given by:

$$D = \frac{1 - \gamma_e}{1 - \gamma_{ec}} \tag{3}$$

The damage final expression is provided as below:



$$D = \frac{\beta}{\beta + (1 - \beta) \left[ \frac{\gamma - \left( \frac{\gamma}{\gamma_u} \right)^m}{\gamma - 1} \right]} \quad (4)$$

with:

$$\beta = \frac{n}{N_f}; \quad \gamma = \frac{\sigma_{ur}}{\sigma_0} \quad \text{and} \quad \gamma_u = \frac{\sigma_u}{\sigma_0}$$

$\sigma_{ur}$ : Instantaneous value of static material tensile strength,

$\sigma_u$ : Maximum virgin material static tensile strength,

$\sigma_0$ : Undamaged material endurance limit

m: Material constant.

We adopted, In this study, a modified methodology built on unified theory, was built up by creating the artificial damages which are corresponding to the depth of the notches [35] instead of cyclic pre-loading and replacement of stresses by pressures. We replace the stresses in the Eqs. 3 And 4 by the pressures, The static damage that we acquire is stated as follows:

$$D = \frac{1 - \gamma_e}{1 - \gamma_{ec}} = \frac{1 - \frac{P_{ur}}{P_u}}{1 - \frac{P_a}{P_u}} \quad (5)$$

Therefore, the damage last expression is given as:

$$D = \frac{\beta}{\beta + (1 - \beta) \left[ \frac{\frac{P_{ur}}{P_0} - \left( \frac{P_{ur}}{P_u} \right)^m}{\frac{P_{ur}}{P_0} - 1}} \right]} \quad (6)$$

The parameter  $m=0.98$  for polymers [10].

## EXPERIMENTAL METHODOLOGY AND MATERIAL STUDIED

### *Investigated material*

We were choosing CPVC pipes by virtue of this material pressure-resistant characteristics and its behavior at high temperatures. Pressures withstanding CPVC tubes can equal to 1.40 MPa with regard to 0.95 MPa at 50°C for polyvinyl chloride [4]. Compared to other thermoplastics, CPVC is characterized by its suitability for use at high temperatures up to 90°C, the malfunction temperature is 95 °C according to standard ISO 15877. By combining these good characteristics with the technique of cold chemical welding and mechanical properties, CPVC piping is ideal for hot and cold-water networks, often as a replacement for copper [36]. The properties of CPVC material, which are produced our pipes by the company First Plastic, are summarized, Tab.1.

### *Experimental test procedures*

In order to calculate the CPVC pipe resistance using its burst pressure, we performed burst pressure experiments. The burst test is made possible by the experimental apparatus shown in Fig. 1. It has a hydraulic pump that pressurizes the tested

CPVC pipe together with a full water reservoir with controlled temperature. The maximum and instantaneous pressures obtained throughout the experiment are also displayed on the pump screen.

Proprieties	Unit	Values
Density	$g / cm^3$	1.56
Linear expansion coefficient	$Mm / m.^{\circ}C$	6- 8x10 <sup>-5</sup>
Thermal conductivity	W/mK	0.16
Water absorption (24 h at 100°C)	$mg / cm^2$	0,5
Softening temperature Vicat VST/B/50	$^{\circ}C$	> 110
Shock resistance	$kJ / m^2$	10
Hardness at ball penetration	$N / mm^2$	1400
Fire classification		M1

Table 1: Properties of CPVC.

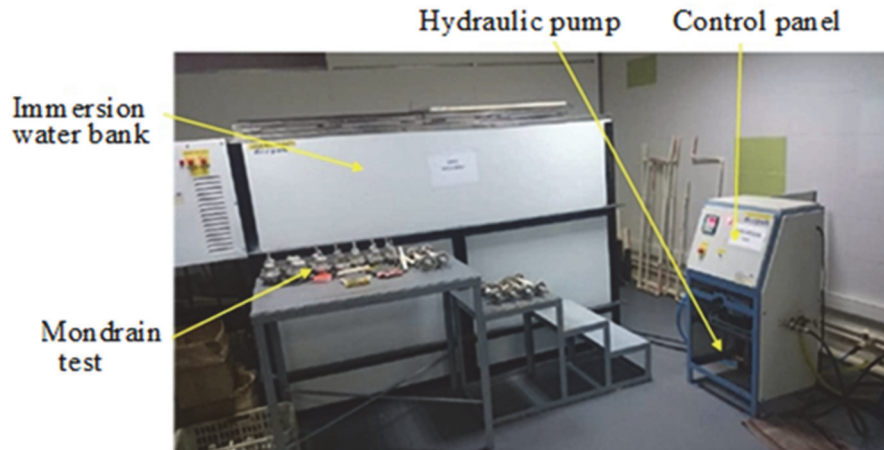


Figure 1: Experimental machine.

As a result, we began our initial testing with the bursting of three brand-new CPVC pipes in order to describe the CPVC material. The CPVC pipes under investigation will be damaged, and this will be determined by the tests that follow. To do that, we have been chosen the specimens according to ASTM D1599 standard test for short-term hydraulic pressure resistance of fittings, plastic pipes and hoses [17]; this code requires a known specimen with calculated length and known exterior diameter and thickness. We prepared 21-notched specimens. These samples are tubes with 4.5 mm thickness and 40 mm outside diameter, as exposed in Fig.2, notched in the middle of the wall with a defect depth varies from one millimeter to four millimeter with a 0.5 mm step. By milling machine, the defects were created as exposed in Fig.3.

CPVC tubes were prepared at the ambient temperature (23°C) and conditioned in this same condition proceeding to pressurization.

After preparation of specimens, we mounted them in the hydraulic tester machine end caps (Fig.4) closely clamped by bolts and we connected them to the pressurizing hose. After the air bubbles in the water tank were expelled, the CPVC pipes were submerged, and the burst pressure tests were then started (Figs. 4 and 5).

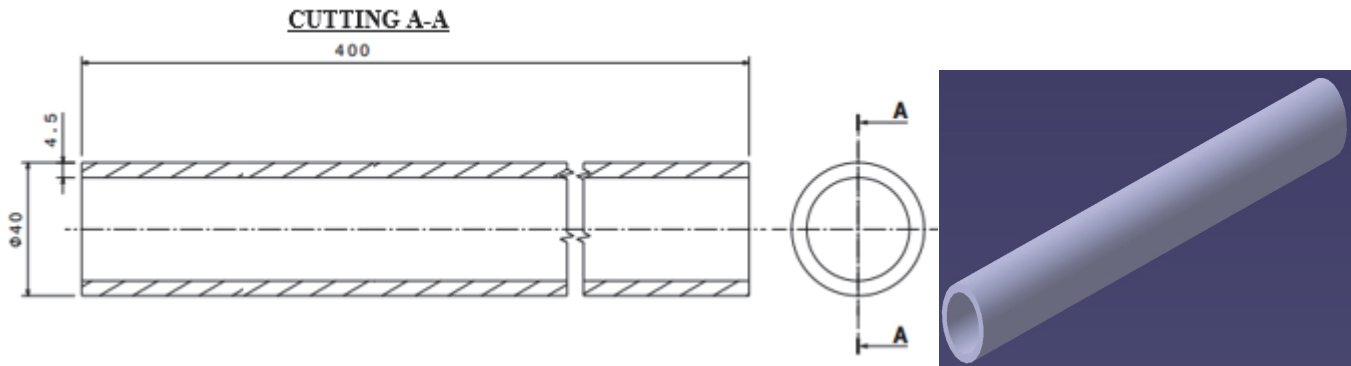


Figure 2: Specimen dimensions.

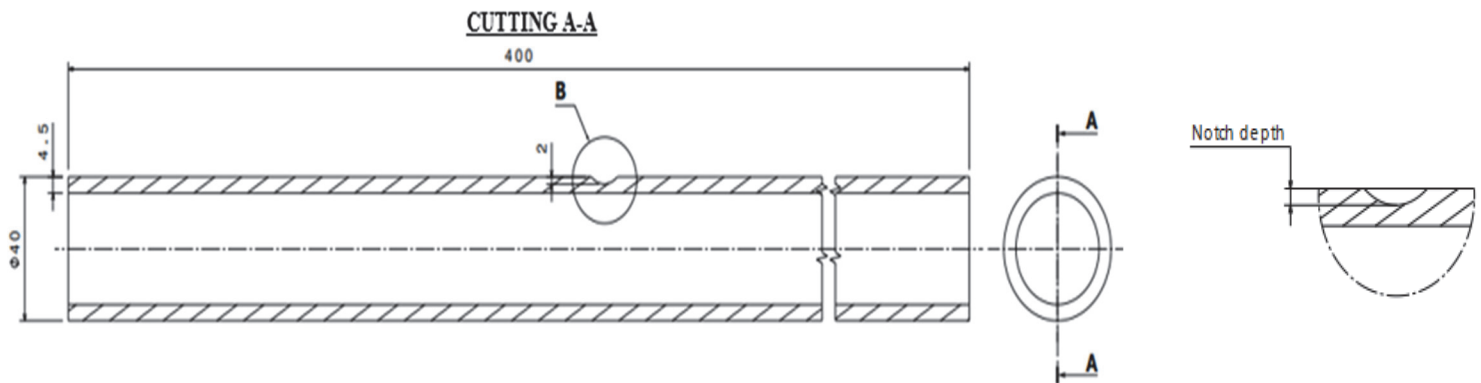


Figure 3: Creation of defects.

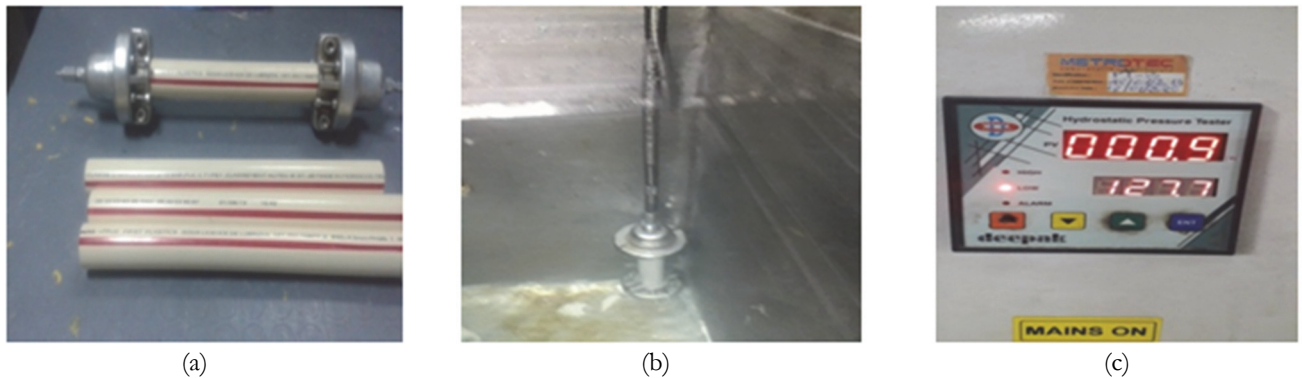


Figure 4: The employed equipment: (a) closed CPVC pipe end caps, (b) specimen immersed in tank full with water at 23°C and (c) pressure display screen.

## RESULTS

Undamaged CPVC pipes serve as the ultimate pressure in this study's subsequent steps, and damage models will be developed based on burst pressure determined during the initial testing. While burst pressures of studied pipes with notches represent the ultimate residual pressure.

During the experiment, the internal pressure rises continuously until the specimens rupture. As a function of time, we recorded the maximum pressure and its evolution using a digital system. Because of burst test, the CPVC specimens had two rupture form and nature as shown in Fig.6.

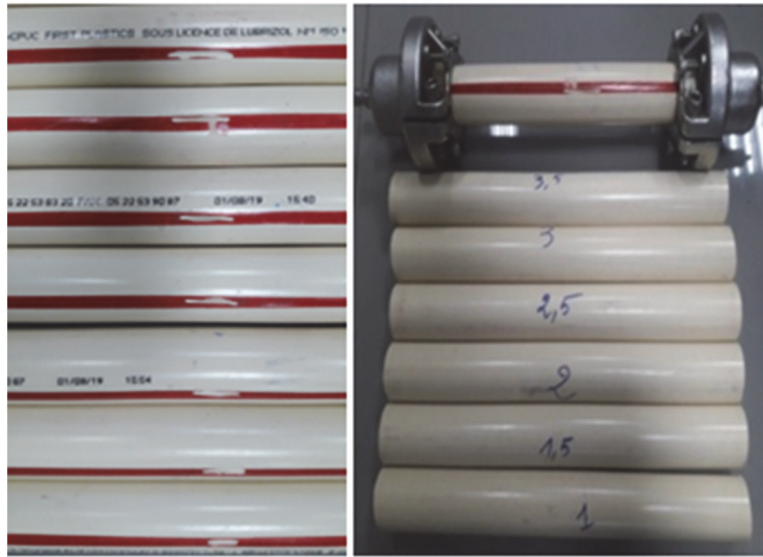


Figure 5: Models of notched CPVC specimens.



Figure 6: Breaking form of chlorinated PVC pipe.

In accordance with the codes, among the conditions of the test validation we notice absence of visible leakage on the CPVC pipes and a test time above 60 seconds.

Following are the stages that a CPVC pipe's pressure evolution goes through. The first one represents the pre-loading phase; it takes 35 seconds, corresponding to the pipe filling and the commencement of the specimens swelling. Then, the pressure accelerates suddenly until reaching the CPVC pipe elastic limit, which shows the elastic phase.

Subsequently, the increase in pressure accelerates after a relaxation, representing the plastic phase. Finally, the pressure drops after reaching the maximum pressure, which corresponds to the bursting of pipes.

However, it will be less than the first one until the fracture get. The fracture stage represented by this fourth stage represents Subsequently, all burst pressures for virgin and notched tubes were obtained, as shown in Fig. 8. The pressures obtained were represented as function of the lifetime.

From Fig.8, we conclude that the virgin pipe material behavior is different from that of the notched pipes. The times to fracture also decrease with increasing defect depth. In addition, the virgin tube has great burst pressure. During this time, the notched tubes show lower burst pressures, highlighting the harmfulness of the half-ellipse defect. The progression of the bursting pressure of experimental tubes serves as an example of their two pressures in the elastic and rupture phases.

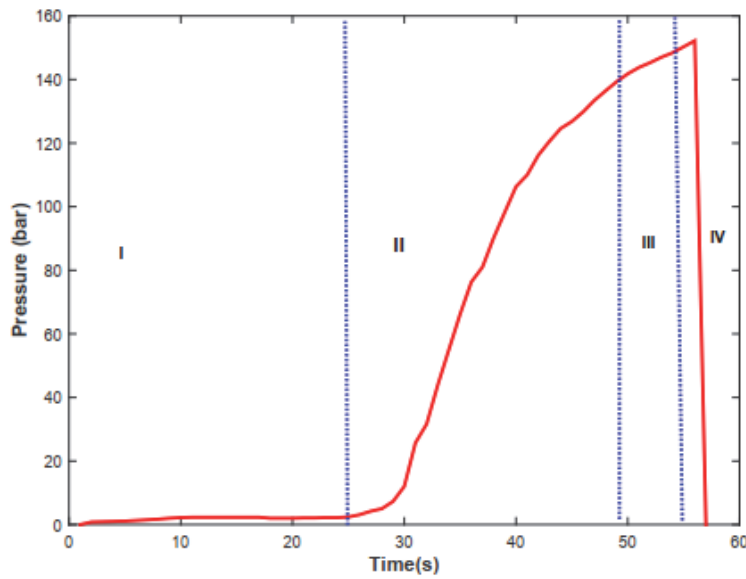


Figure 7: Internal pressure evolution according to the time of the virgin CPVC pipe

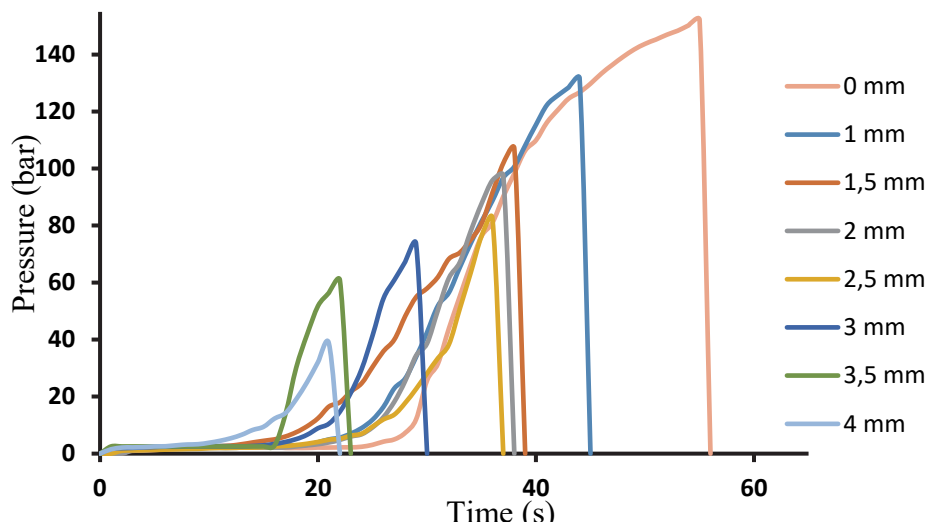


Figure 8: Change of burst pressure for virgin and notched CPVC specimens.

The static test curves performed on 24 machined semi-ellipse specimens are analyzed in function of the material life, which can be called fraction of life. Regardless of the author, the variable  $\beta$  is based on Miner's [37] notion, who described it as the report of the cycle's instantaneous number and the failure cycles number. By analogy to this approach, for a static loading (bursting of the tubes), the damage depends on the reduction in the thickness of the material. The thickness can therefore account for the level of damage causing the rupture of the material. The variable  $\beta$  can therefore be identified like the relationship between the notch depth and the virgin tube thickness, which assimilates the number of cycles of fatigue by a loss of the material of the tube, it is expressed by:

$$\beta = \frac{a}{e} \quad (7)$$

where:

a: Depth of the notch

e: Thickness of material.



The variable  $\beta$  represents a fraction of life in Eq.7. If it takes the value "0", means zero load and the value "1" indicates the level of stress causing complete failure of the material ( $0 \leq \beta \leq 1$ ). To identify the ultimate pressure, with undamaged specimens can tolerate, burst tests were performed on 40 mm outer diameters virgin CPVC pipes. In the aim to assess the severity of defects on the CPVC pipes burst pressure, many tests realized on a set of twenty-one pre-damaged pipes with semi-elliptical failures ranging from 1 mm to 4 mm in depth.

The burst pressure as well as the break time decreases with increasing notch depth. Fig. 9 shows the residual pressure variation curve inside artificially damaged pipes, according to lifetime  $\beta$ .

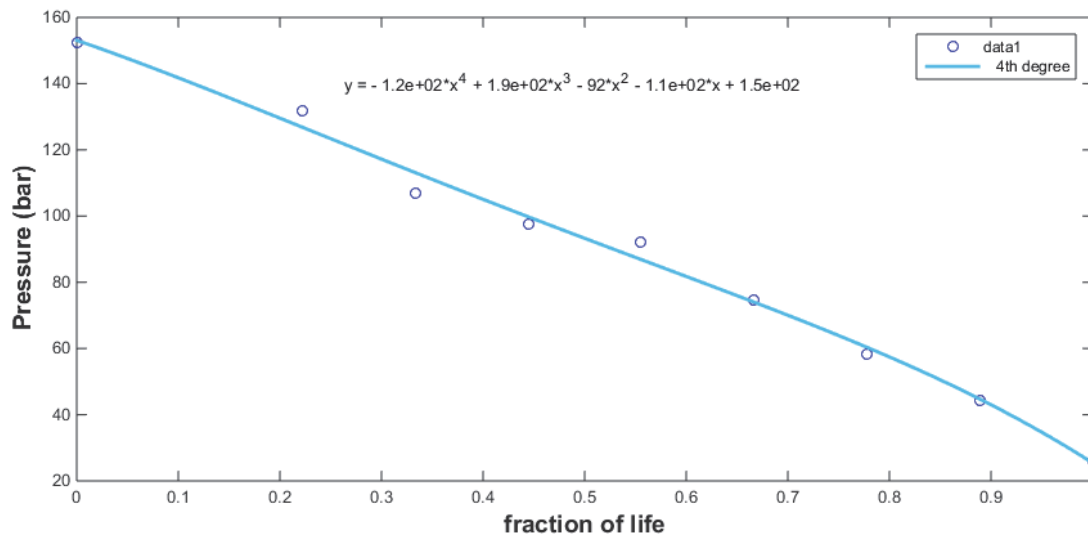


Figure 9: Bursting pressure change of CPVC specimens as function of lifetime

We notice from Fig.9 a gradual drop in the tubes burst pressure with the increase in the fraction of life which is a notch depth function. A slight change in behavior was observed during 55% of its lifetime, might be corresponding to the critical depth. Indeed, we observe a significant reduce in burst pressure at this point. When the damage stages are established, this criticality will be confirmed. Moreover, after the fraction of life reaches 77.5%, the pressure decreases with acceleration.

### Static damage

To study the damage assessment of our CPVC pipes, we applied the models presented above of this work. We based on the experiment result to get the damage curves as illustrated in the Figs. 10, 11 and 12.

Fig.10 gives the evolution of Miner damage and static damage given by Eq.5, according to the lifetime for pre-damaged CPVC pipes by semi-elliptic defects, from the virgin sample to the last pipe notched by a depth of 4 mm. The increasing of specimens' damage increases with increasing defect depth. The damage increasing indicates the loose of the sample strength during the burst testing. As shown in Fig.10, the evolution of damage can be defined in three stages.

According to Fig. 10, when a critical lifetime of 77% is attained, the static damage evolution alters curvature. Then, the damage accelerates. This curve indicates that the damage in notched CPVC tubes begins to be unsteady when the critical depth of the notch is reached. The first stage, which corresponds to fractions of life ( $0 \leq \beta \leq 0.22$ ), shows the damage initiation for CPVC pipes pre-damaged by semi-elliptic flaws. Starting at zero, the damage increases steadily to 0.16 with a  $\beta$  value of 0.22. Stage II, while range of  $\beta = [22\%, 77\%]$ , corresponds to progressive tubes damage. The notch depth approaches 77% of the entire thickness of the CPVC pipe as the damage increases from 0.16 at the beginning of the stage to 0.73; at this point, predictive maintenance is required of the industry to prevent major mishaps. The third stage, represents the insecure damage starts from the critical fraction of life (0.77), of the tube damage, which corresponds to a value of the notch depth equal to 3.46 mm. Henceforth, the damage will be even more severe, and the pipe can suddenly break..

### Unified theory damage

The unified theory damage calculated according to the Eq. 6 as a function of the lifetime  $\beta$  of the CPVC pipes damaged artificially for a notch in the shape of a half-ellipse, is carried by the curves of the figures below, each curve is associated with a particular loading level.

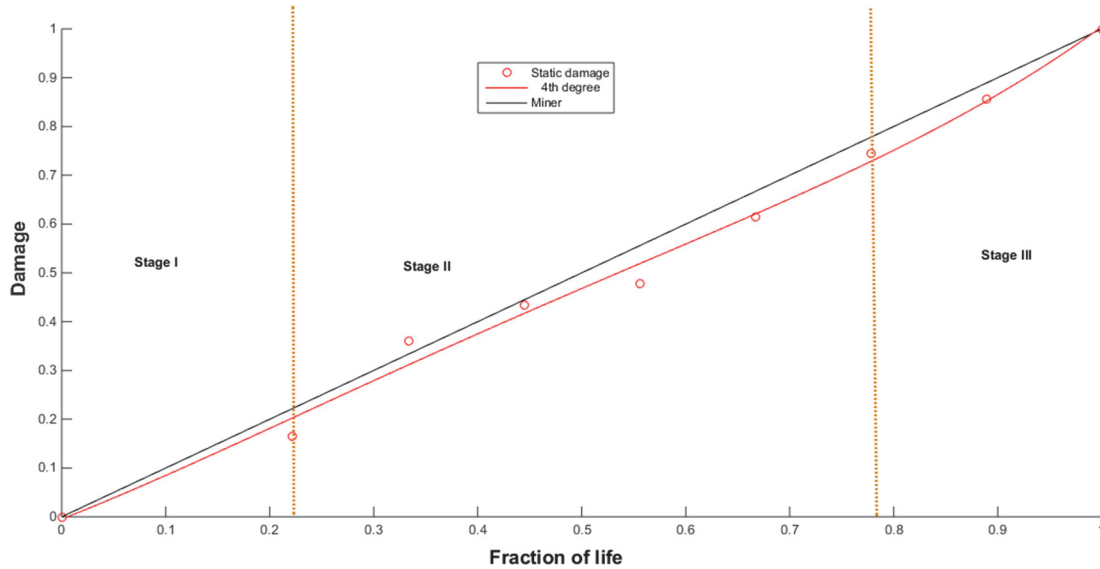


Figure 10: Curves evolution of Miner and static damages for pre-damaged pipes.

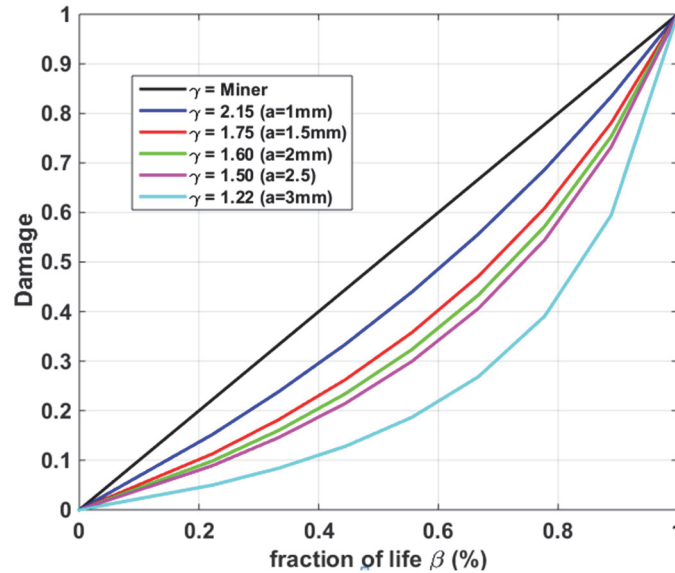


Figure 11: Unified theory damage evolution based according to the fraction of life.

We see in Fig.11, that the unified theory damage approaches sensibly the damage of Miner, when the level of loading increases, which is normal from a mechanical view, the fatigue tests with a loading high cyclic approximate the tensile test. We equated a defect depth with a loading level. To obtain the evolution of damage, according to the unified theory model, we have represented the allures for different values of  $\gamma$ . Each value reflects a level of loading, on which depends the behavior of the damage curves of this model. The curve concavity is maximum when the loading is low ( $\gamma = 1.22$ ). As we raise the load level, it largely conforms to Miner's linear model. This parameter takes an extremely low value for the greatest notch depth.

The critical lifetime  $\beta_c$ , is known to correspond to lifetime, where the smallest dimensionless curvature  $\gamma$  load is maximal, therefore, we plotted the curvature in accordance with the expression below:

$$C = \frac{\frac{d^2 D}{d\beta^2}}{\left(1 + \left(\frac{dD}{d\beta}\right)^2\right)^{3/2}} \quad (8)$$

The representation of the curvature is shown in Fig. 12, according to the Eq. 8, we can determine the critical lifetime graphically that matches to the abscissa of the maximum point that corresponds to curve of  $\gamma = 1.22$ .

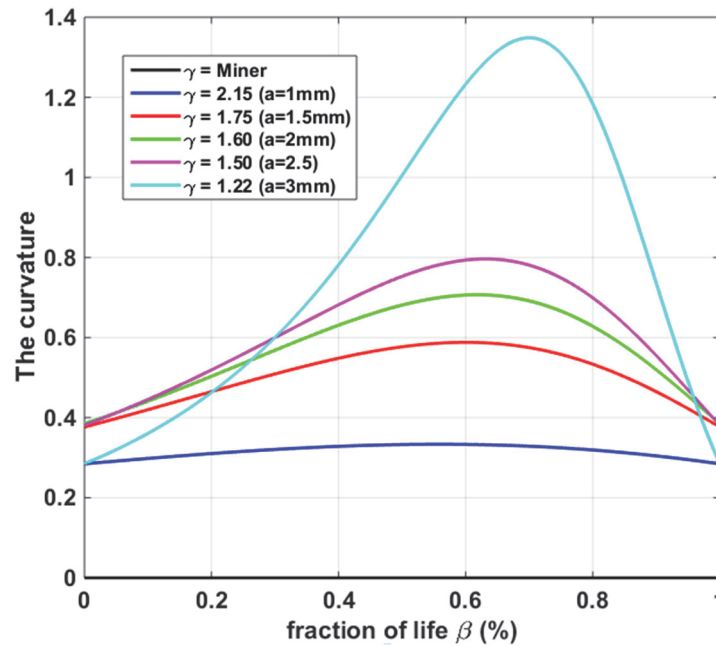


Figure 12: Change in curvature according to the lifetime.

We notice from previous figure that the critical lifetime corresponding to the change of curvature is extremely close to it, which determines by the static damage law what means that they are two different methods of evaluation of damage caused to the CPVC tube.

Thus, a comparison of the static and unified theory curves (Fig. 13), we can see that burst pressure evolution is comparable to these of the damage curve of the unified theory, which corresponds to a first-stage damage rate of  $\gamma=2.16$ .

In Fig.13, on all the curves of the static and theoretical damage, we note a fluctuation of the damage between stages corresponding to  $\gamma = 2.16$  and  $\gamma = 1.75$ , for the second stage. Although an acceleration of the damage follows just after. Then, toward the finish of the third stage the damage evolution coincides with that of loading level  $\gamma = 1.6$  this denotes a very good resistance before the initiation of the first crack. The damage curve by Miner's law is above that of the static damage and these of the theoretical curves one according to Bui Qouc.

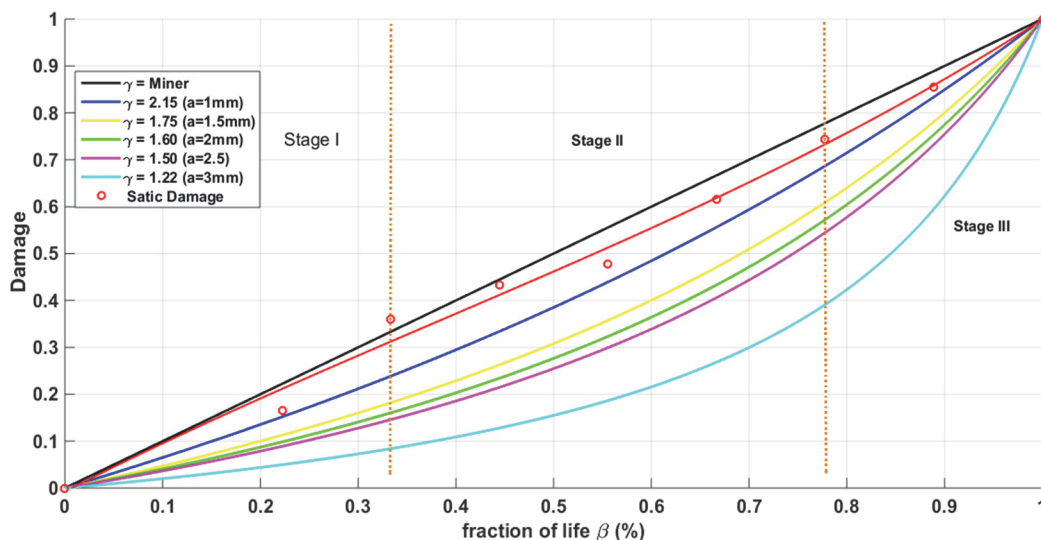


Figure 13: Curves of static damage, unified theory damage and Miner's damage, according to the lifetime.



## CONCLUSION

Analyzing and presenting the results of a study on the effect of semi-elliptical defects on the mechanical behavior of CPVC specimens is the most important objective of this work. To carry out this work, we used burst tests on intact and pre-damaged specimens, after they had been blown up to fracture under internal pressure. The comparison between virgin and notched results showed that defects reduced the tubes ultimate burst pressure. Moreover, we noted that a depth of defects increasing has caused a residual ultimate burst pressures decreasing of defected pipes. Using damage curves, we were able to determine three stages of use of CPVC pipes in industry, also the critical lifetime from which pipe equipment become unsafe. Furthermore, the second stage is considered a key decision-making tool for maintenance personnel to engage predictive maintenance, then avoid grave accident and reduce production losses, all that based just on burst static tests only without expensive and longer fatigue tests. Therefore, as further work in this article, we use similar principles to forecast the CPVC tubes cycle number, through static test and without the fatigue tests. Then, we will base on the results in particular burst time aim to premature pipe failure under a reduction of thickness and a semi-elliptic defect.

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