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Research article

Evaluation of damage and failure analysis of CPVC pipes

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ABSTRACT

In this paper, the work we have carried out has focused on the failure analysis of CPVC (chlorinated polyvinyl chloride) pipes. We stimulated the damage by notch effect and evaluated its properties using models available in the literature, specifically, the linear damage of Miner, the normalized damage and the unified theory. Burst tests allowed us to obtain ultimate pressure and time parameters for the virgin specimens and the residual parameters for the damaged ones. Then, we analyzed the effect of defect on the mechanical behavior of the studied structures; we found that the mechanical properties of the material were lost as defects increased. An observation and analysis of the pressure drop and thereafter the residual ultimate resistance brings out acceleration from it around the critical depth. Then, an evaluation of the static damage of the studied CPVC pipes was made according to model based on the experimental results of the burst tests and on the modification of the unified theory concepts and the static damage. Indeed, we evaluated the static damage of blank and notched tubes using mainly burst pressure parameters.

1. Introduction

Considering the rising price of copper, one of the metals most commonly used by humans in plumbing networks, experts have found a replacement, which is Chlorinated polyvinyl chloride (CPVC) due to its characteristics of resistance to pressure and its behaviour at high temperature. In addition, compared to other thermoplastics, CPVC is characterized by its suitability for use at high temperatures of up to 90 °C, the malfunction temperature is 95 °C according to EN ISO 15877 [1]. These excellent properties combined with chemical cold welding technology and mechanical properties make CPVC pipes ideal for transporting cold and hot liquids such as water.

The effect of temperature on the fatigue crack propagation (FCP) rate of several polymers has been widely studied [2–13]. Irfan and Merah [14] studied the effect of temperature on the fatigue cracking resistance of CPVC over a temperature range of −10 to 70 °C. The loading frequency used in most of these studies was 1 Hz. They reported that strength decreased with increasing temperature and demonstrated that cracking is the dominant failure mechanism at high temperature while shear is dominant at low temperature. In a recent study by Merah et al. [7], fatigue crack propagation in CPVC was observed at various frequencies and temperature ranges. As a result, we found that the crack growth rate increased with increasing temperature, regardless of the frequency level.

Polymers are sensitive to climatic conditions. The effects of the outdoor environment in Saudi Arabia on the tensile strength, fracture toughness, and colorimetric properties of CPVC extruded pipe materials over time were studied by N. Merah et al. [15], among

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the most affected tensile properties is tensile elongation, a decrease of about 20% during the first month was noted. Also, the description of the mechanical characteristics of thermoplastics used in pipes has been widely treated in the literature [16,17]. Many studies have been dedicated to the characterization of the uniaxial tensile curve and the detailed clarification of its different characteristics [18], the criticality and the influence of the direction of damage in Polypropylene Random Tubes (PPR) on the mechanical behavior of the material were evaluated by Ouardi et al. [19], they carried out tensile tests on sound dumbbell specimens and others artificially damaged by notches from the outside of the tube to the inside (external cut) and cuts from the inside to the outside (internal cut). The comparison of the two damage curves revealed that the internal faults in the PPR pipes are more severe than the external ones [20].

Unlike metals, polymers are sensitive to hydrostatic pressure. Similar to increasing temperature, decreasing hydrostatic pressure promotes molecular mobility, thus decreasing the stress and the strain thresholds values as well as the tangent modulus.

Different states of hydrostatic pressure can be imposed by means of a hermetic pressurized enclosure [21], or according to the type of test itself [22]. In the latter case, the pressure value is a direct result of the stress field suitable for testing, hence the need to study the damage of these polymer materials, especially thermoplastics.

The damage theory was at first proposed by RABOTNOV and KACHANOV [23]. From the physical point of view, the authors considered the initiation of the damage as an internal phenomenon of progressive damage of the material resulting in the presence of cavities and microcracks under the effect of the repetition of the load, causing the reduction from the surface of the straight section [24]. Subsequently, damage mechanics was developed especially by Chaboche [25] and Lemaitre [26] for metallic materials and ductile fracture, who proposed a law of damage by fatigue with nonlinear evolution.

Several studies in the literature have shown the importance of burst testing as a material characterization tool and as a lever for fracture mechanics [19,20,27]. In fact, they are the subject of means of choice for monitoring cracks from initiation, through propagation, to the acceleration of cracks and damage in general [28,29].

Composite pipes are becoming increasingly attractive, and their corrosion resistance, durability, and high strength-to-weight ratio are making them increasingly used in various industries such as marine, chemical processing automobiles and pressure vessels [30]. However, these materials are susceptible to degradation in mechanical performance, resulting in loss of structural integrity and fluid spillage following accidental impact during use or handling. Therefore, some studies stated the damage modes of fiber-reinforced composites [31–35]. Kara et al. [36] studied the effect of her MWCNT reinforcement on the low-energy impact behavior of carbon fiber-epoxy composite tubes. They found that the addition of MWCNTs significantly improved the impact strength of the composites and reduced damage progression. Taşyürek and Kara [37] investigated the impact behavior of MWCNTs reinforced epoxy resin composite pipe with an internal pressure of 32 bar at different energy levels. In addition, a new hybrid system was proposed, consisting of a carbon fiber reinforced polymer (CFRP) and CPVC hybrid confinement and an inner ECC layer [38]. Jiyeon Kim & al investigated Development of low cost carbon fibers based on chlorinated polyvinyl chloride (CPVC) for automotive applications [39].

The main novelty of our study is the characterization and prediction of damage in CPVC material, which is known to be sensitive to environmental conditions and constraints. Specifically, in this study, we focused on pressure, time, and notches, considering that pipes often operate under complex and long-term conditions. Subsequently, we identified different stages of damage to predict the occurrence of critical damage and enable timely intervention for predictive maintenance. The approach adopted in this paper represents a simplified method for assessing CPVC damage solely through static tests, without the need for dynamic tests.

This approach presents several advantages for manufacturers, including time and cost savings. It enables efficient and streamlined processes, allowing for quicker checks and facilitating quality control audits specifically for wire rope inspections.

2. Preparation of test specimens

Hydraulic rupture tests were performed on test specimens in the form of a tube prepared from extruded CPVC tubes. Based on the results of the uniaxial tensile tests carried out on CPVC dumbbell specimens according to ASTM D 638 standard [1], Table 1 provides the average values of the mechanical properties.

The main mechanical and physico-chemical characteristics of commercial tubes in CPVC, are regrouped summarized in Table 2.

Specimens were selected according to ASTM code D 1599 [40] which requires a sample, known for its thickness and outside diameter, of a length not to exceed five times the diameter of the tube, Table 3. The samples are prepared and conditioned at ambient temperature (23 °C) before pressurization.

The specimens used were prepared according to standard EN ISO 15877: plastic piping systems for cold and hot water installations – polyvinyl chloride on chlorinated (PVC–C) [1].

The purpose of a burst tests is to determine the strength of a thermoplastic tube based on burst pressure. Burst tests were carried out on two parts. Indeed, we carried out characterization tests on three virgin pipes in CPVC material and burst tests on artificially notched damaged pipes, through semi-elliptical defects ranging from 1 mm to 4 mm in depth with a step of 0.5 mm, thickness 4.5 mm and length 400 mm. It is a number of 21 specimens with defects at different depths. Specimens with notch depth are shown in Fig. 1.

Table 1
Mechanical characteristics of this material CPVC.

Young's modulus (GPa)	Elasticity limit (MPa)	Tensile Strength (MPa)	Elongation at break in %
2889	52	54	9,4

Table 2
Properties of CPVC.

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

Table 3
Dimensional characteristics of specimens of blank tubes according to the pressure test standard ASTM D 1599.

Number	Outside diameter	Inside diameter	Thickness	Length
3	40 mm	31 mm	4,5 mm	400 mm

3. Description of the test bench and performance of the bursting tests

Burst tests were carried out using a hydraulic test bench, Fig. 2.

The burst pressure control is ensured by the control panel, allowing flow adjustment to monitor internal pressure. The hydrostatic machine used contains a pneumatically controlled volumetric diaphragm test pump operating under a compressed air pressure of 7 bars, connected to the specimen by high pressure hoses and connecting mandrels. Two displays are available on the control table of the device to read the instantaneous pressure and the bursting pressure.

The specimens used for testing were immersed in a tank filled with water controlled at a temperature of 23 °C; using a thermal conditioning box. It was an enclosure replete with water whose temperature was maintained constant, to within 0.5 °C, by means of a thermoregulator and at ambient pressure to ensure safety users against accidents at the time of bursting. Indeed, the energy developed by the rupture of the tubes is absorbed by the fluidity of the water.

The tests were launched; the specimens were pressurized with a given constant loading speed. Simultaneously, we recorded the evolution of the internal hydraulic pressure and the time from the pressure control panel until the burst of the tubes Fig. 3.

A ruptured specimen after burst test is shown in Fig. 4 with a magnification of 1015X

4. Study of the behavior of a tube artificially damaged by notching

To evaluate the harmfulness of a rupture by bursting pressure according to the depth of the notch, we based ourselves on the experimental results of this work, in particular on the critical depth of the defects in the form of a half-ellipse parallel to the axes of CPVC pipes.

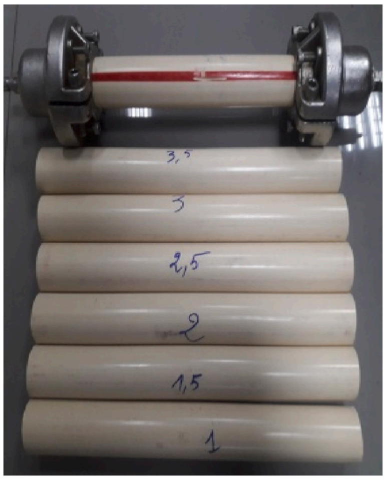

Fig. 1. Notched tubes for burst test.

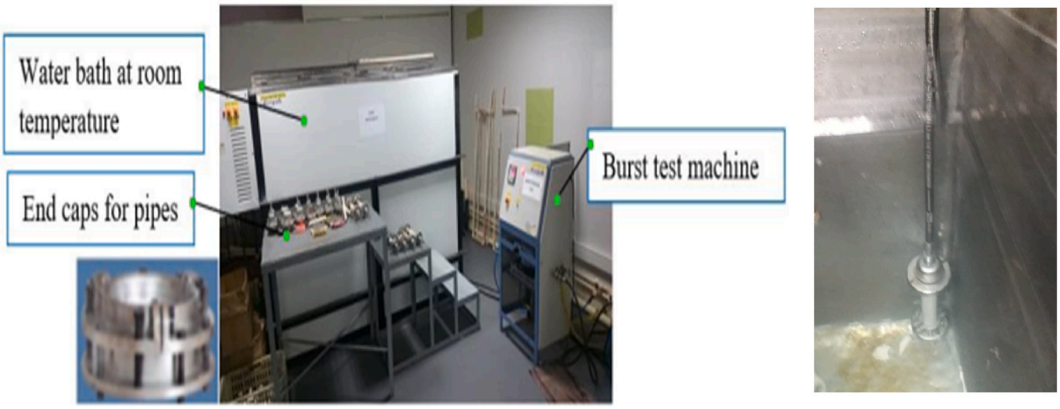

Fig. 2. Hydrostatic testing machine.

Fig. 3. Fracture shapes of CPVC specimens after bursting test.

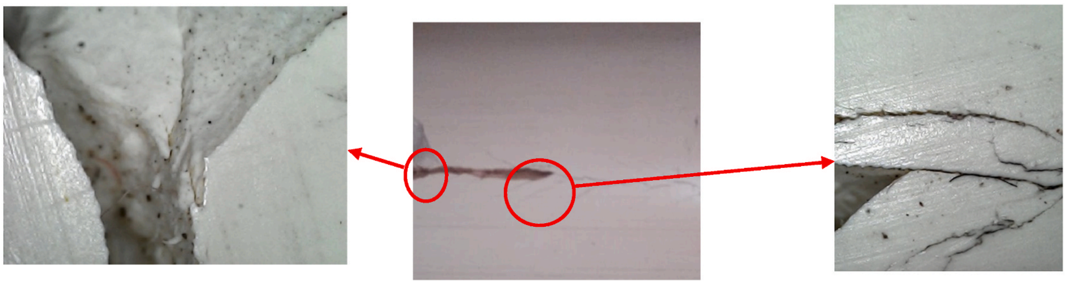

Fig. 4. CPVC specimen after rupture at magnification 1015X

5. Determination of damage model parameters

In this work, tests were performed that led to the characterization and damage assessment of CPVC pipes. To characterize these tubes, we recorded the evolution of the pressure as a function of time, Fig. 5. After that, we analyzed the behavior of the internal pressure.

We notice on the curve, Fig. 5, that the evolution of the pressure of a virgin CPVC tube has a four-phase behavior. During the first 25 s, we observe the filling of the tube; this is the preloading phase (phase I). Immediately afterwards, sudden acceleration of the pressure until reaching the limit of elasticity (phase II). There is then a phase of weak relaxation showing the plastic behavior of the CPVC tube (phase III) with a new rise in pressure until rupture is obtained (phase IV).

Subsequently, we obtained all the burst pressures for the virgin and notched tubes as shown in Fig. 5. The pressures obtained were plotted against the fraction of life.

Failure of thermoplastics can occur in a ductile or brittle manner. The type of failure depends on the physico-chemistry of the material, i.e. the composition, the weight of the macromolecular chain, the degree of imperfection and mechanics, such as the loading

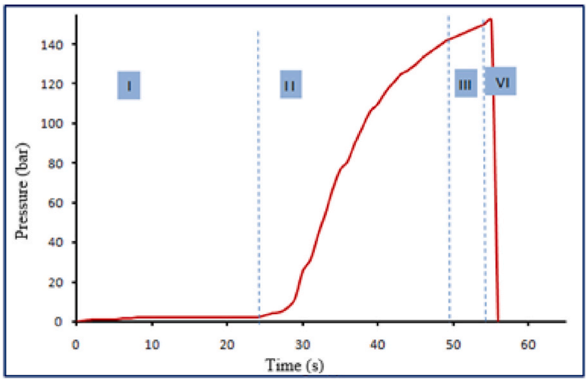

Fig. 5. Evolution of burst pressure of undamaged CPVC pipes.

conditions or the history thermomechanical. At low temperatures, CPVC is brittle [1,41]. Indeed, the molecular chains are fixed and no deformation process can accommodate stress singularities at the bottom of the cracks. At high temperature, this material has a ductile behavior [1,41]. In general, polymers fail by cracking or shearing. Within the experimental conditions, one mechanism is preferred to the other [42].

Pipe burst test carried on until specimens were broken. Each experiment was repeated three times and an average value was obtained. The relationship between pressure and rupture time is exposed schematically in Fig. 6 which illustrates the predominant mode of failure in CPVC pipe (ductile ruptures). The ductile failure of tubes is due to the fact that the plastic deformation which blunts the crack tip reduces the stress concentration, which slows the propagation of the crack. The plastic phase is quite narrow as shown in Fig. 6, because we conducted the tests at 23 °C, far from the transition temperature of the 135 °C [4].

From the curves above, we notice that the behavior of virgin pipes is different from notched pipes. Rupture times also decrease with increasing defect depth. In addition, the blank tube has a large burst pressure. Meanwhile, notched tubes exhibit lower burst pressures which highlight the harmfulness of the defect, in the shape of a half-ellipse. Thus, the evolution of the curves for the tubes presents two main pressures, one for the elastic phase and the other for the rupture phase. Experimental results were summarized in Table 4.

The tests results of a series of tests carried out on twenty-one machined semi-ellipse specimens are analyzed according to the lifespan of the material, which can be called the fraction of life, which is expressed by:

$$\beta = \frac{a}{e} \tag{1}$$

Where "**e**" is the thickness of the material and "**a**" is the depth of the notch.

The variable β represents a fraction of life in equation (1). If it takes the value "0″, means zero load and the value "1″ indicates the level of stress causing complete failure of the material ($0 \leq \beta \leq 1$).

The variable β regardless of the author is based on the concept of Miner, who defines it as the report of the number of instantaneous

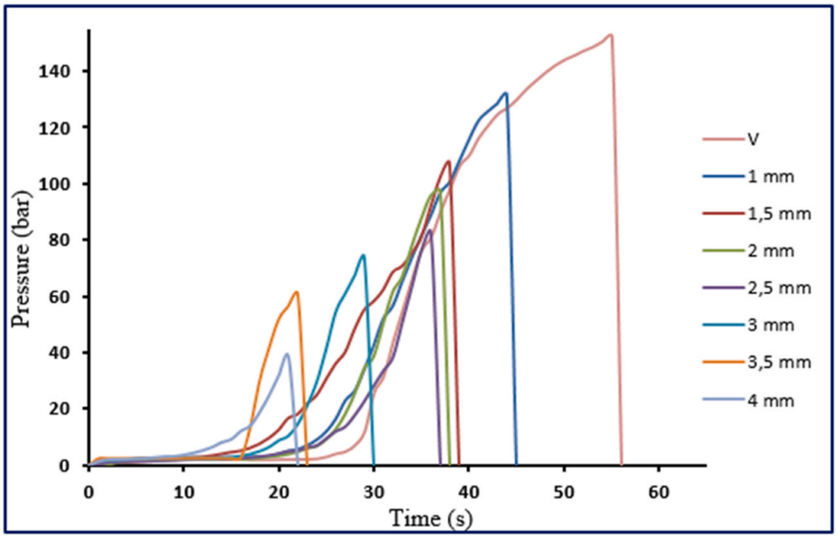

Fig. 6. The internal pressure curve according to time for virgin tubes and other notched ones.

Table 4
Burst pressure of CPVC pipes at different defect depths.

Defect depth (mm)	Tests	Burst pressures (bar)	Relative error
0	1	151,70	0,0052
	2	152,51	0,0001
	3	153,29	0,0052
	Average	152,50	
	Standard Deviation	0,795	
1	1	130,84	0,0065
	2	131,76	0,0005
	3	132,50	0,0061
	Average	131,70	
	Standard Deviation	0,832	
1,5	1	106,55	0,0046
	2	107,04	0,0001
	3	107,55	0,0047
	Average	107,05	
	Standard Deviation	0,500	
2	1	96,79	0,0063
	2	97,71	0,0031
	3	97,71	0,0031
	Average	97,40	
	Standard Deviation	0,531	
2,5	1	91,6	0,0054
	2	92,09	0,0001
	3	92,6	0,0055
	Average	92,10	
	Standard Deviation	0,500	
3	1	74,62	0,0004
	2	75,25	0,0081
	3	74,07	0,0077
	Average	74,65	
	Standard Deviation	0,590	
3,5	1	57,6	0,0137
	2	58,41	0,0002
	3	59,19	0,0135
	Average	58,40	
	Standard Deviation	0,795	
4	1	43,39	0,0194
	2	44,3	0,0012
	3	45,05	0,0182
	Average	44,25	
	Standard Deviation	0,831	

cycles and the cycle's number at failure. By analogy to this approach, in the case from a static loading (bursting of the tubes), the damage depends on the reduction of the material thickness, therefore the thickness has the possibility of taking into account the level of damage causing the rupture of the material be defined as the ratio of the notch depth to the thickness of the blank tube which equates the fatigue cycles number by artificial damage which consumes a certain initial cycle Ni of the tube.

Burst pressure and burst time decrease with increasing notch depth.

6. Application of cumulative damage models to CPVC

For polymers and in particular unfilled thermoplastics, work is more recent. The increasing use of plastic materials, especially "engineering thermoplastics", in moving parts and mechanical components, such as tubes [43,44], etc., has generated a demand for data necessary for design calculations (engineering) and the prediction of lifetimes, information unfortunately very little available in the technical literature.

To address the issue of damage, several models of damage have been created to show the non-linear nature of damage. In this perspective, Bui-Quoc [45] synthesized the results of the works of Shanley, Valluri and Gatts to invent the unified theory. This theory was interested in the study of the reduction of the limit of endurance, the limit of fatigue and its effect on the loss of the resistance of the material.

This concept of cumulative fatigue damage by means of test results gotten under axial load is adapted to the case of CPVC pipes, using the physical parameters obtained by burst tests.

Under axial load is adapted to the case of Chlorinated PVC pipes, using the physical parameters obtained by bursting tests.

To assess the damage to the CPVC pipes studied, we used two models, namely: the first is the damage by burst pressures (Model 1) it is a static model using burst pressures at place of constraints. This model yielded us the damage evolution according to the fraction of life and permitted us to make the dynamic damage approximation obtained from the fatigue test. Thus, the principle is to make assimilation of the artificial geometric defects to a fatigue preloading also to the bursting test as a needed step to find out the pipes residual life. Consequently, this approach offered a good approximation of cumulative CPVC pipe damage. The second model is that of the unified theory based [46] on the ultimate residual pressures (Model 2) it is a modified version of the unified theory with controlled stresses using the rupture pressures. This model measures the damage for each notch depth, by the report of the residual pressure and the pressure corresponding to the endurance limit of the material as explained by the unified theory of stresses.

The modified damage approach that we have proposed in this work has the advantage of directly using the results of the burst pressure tests of the blank and notched tubes instead of the stresses. The static damage using the stresses is expressed as follows:

$$D = \frac{1-\gamma_e}{1-\gamma_{ec}} \tag{2}$$

Where:

σ_u: Is the value of the ultimate stress in the initial state for the undamaged sample.

σ_{ur}: The value of the ultimate residual stress for the damaged sample.

σ_a: Is the stress just before failure.

7. Residual ultimate pressure model

To simplify this damage model, we based our study on rupture pressures obtained from experimental burst tests and theoretical calculations. This equality is possible due to the proportionality of the pressure and stress ratios in a cylinder. The damage model combining the static damage (Equation (2)), and the rupture pressure is expressed as follows (Equation (3)):

$$D = \frac{1-\gamma_e}{1-\gamma_{ec}} = \frac{1-\frac{P_{ur}}{P_u}}{1-\frac{P_a}{P_u}} \tag{3}$$

P_{ur} is the residual pressure for the damaged sample, P_u is the pipe ultimate pressure for the undamaged sample and P_a is the pressure registered just before failure.

From Fig. 7, we notice that the static damage evolution changes the curvature when we reach a critical life fraction of $\beta c1''$ of 77%. After this life fraction, the damage accelerates. This observation shows that the damage of the notched CPVC pipe becomes unstable when we reach the critical depth of the notch.

8. The unified theory model using residual ultimate pressures

Models of static load damage are generally different from models used to describe fatigue load [46]. The expression of the Bui-Quoc model of damage is performed in the framework of a cyclical demand. Its application to the calculation of static bursting pressure damage will necessitate an adaptation of the parameters appearing in the equations, (life fraction β", a load level γ and a mechanical characteristic of virgin material that must be correctly reformulated), make sure that the original idea of the model is retained [47].

By analogy with the behaviour of the material subjected to cyclical loads, the tubes have an extreme pressure in case of bursting test when the material is virgin; this pressure drops considerably when there is artificial damage that increases with time. That is why we have treated a modified unified theory approach; by replacing cyclical preloading with artificial damage and by replacing the constraints by the ultimate pressure, and by substituting only the stresses in the expression of γ_u and γ by the pressures one obtains the expression of the damage shown below (Equation (4)):

$$D = \frac{\boldsymbol{\beta}}{\boldsymbol{\beta} + (\mathbf{1}-\boldsymbol{\beta})\left[\frac{\frac{P_a}{P_0} - \left(\frac{P_a}{P_u}\right)^m}{\frac{P_a}{P_0} - 1}\right]} \tag{4}$$

The parameter $m = 0,98$ for the case of polymers [41].

Or $\gamma = \frac{P_a}{P_0}$ and $\gamma_u = \frac{P_u}{P_0}$.

($P_0 = \alpha * P_u$; With $\alpha = \frac{1}{Coéfficient \quad de \quad sécurité} = \frac{1}{2,5}$ for experienced CPVC pipes [1]).

P_u: Ultimate pressure of the blank tube;

P_a: Pressure just before rupture;

P_0: The endurance limit for pressure.

The unified theory damage calculated according to the relation (5) according to fraction of life β of CPVC pipes damaged artificially by a notch in the form of a half-ellipse, is carried by the curves of the figures below, each curve is associated with a particular loading level.

We see in Fig. 8 that the damage by the unified theory approaches substantially the linear damage of Miner when the pressure level increases, which is normal from a mechanical point of view, the fatigue tests with a loading very high cyclic are close to burst tests.

In our study, we assimilated a notch depth to a loading level. To obtain the evolution of the damage according to the second model, we represented the curves for different values of γ. Each value gives back a load level, on which the behavior of the Unified Theory damage curves depends. When we have a low level of loading ($\gamma = 1.22$), the curve concavity is maximum. But it tends to follow

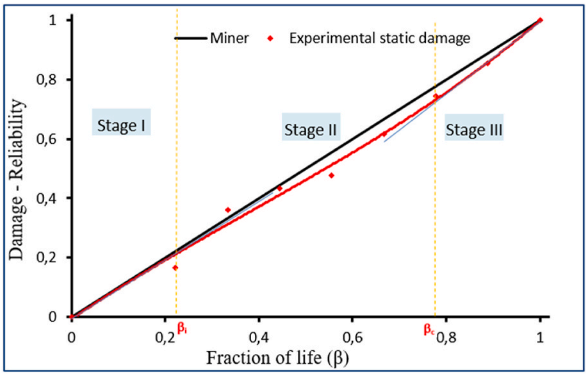

Fig. 7. Evolution of static damage based on burst pressures as a function of fraction of life.

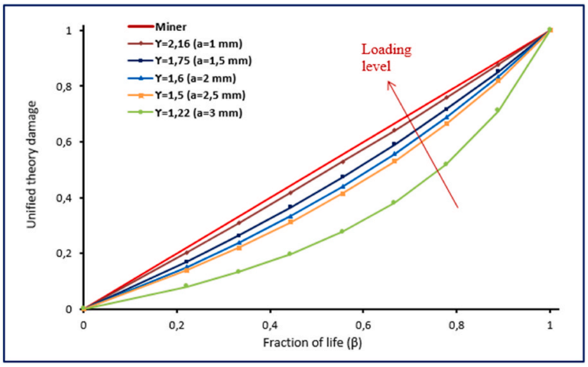

Fig. 8. Unified theory damage evolution based on burst pressures as a function of life fraction.

Miner's linear model as we increase the load level. This parameter takes a very low value for the greatest notch depth, which has been shown in Fig. 8.

Thus, by comparing the curves of the first model with the curves of the second in Fig. 9, we notice that the model of the burst pressure has the same evolution as that of the damage curve of the unified theory corresponding to $\gamma = 2.16$ for the first stage of damage.

In Fig. 9, we can see that for all the static and theoretical damage curves, the damage varies between load levels corresponding to $\gamma = 2.16$ and $\gamma = 1.75$ in the second stage. On the other hand, towards the end of the third stage, the damage evolution at load level $\gamma = 1.6$ (a = 2 mm). This indicates a very good resistance before the first crack initiation, but an acceleration of the damage just follows after. The damage curve by Miner's law is above the static damage and the theoretical one according to Bui-Quoc.

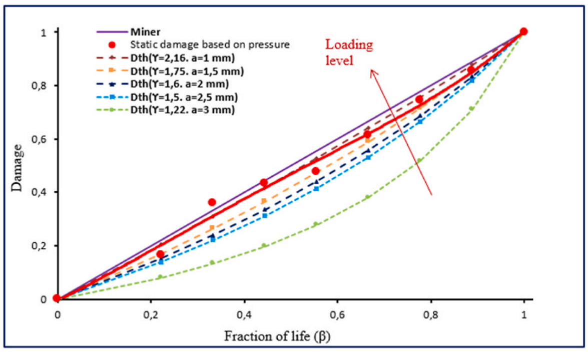

Fig. 9. Curves representing the static damage, according to the unified and Miner theory of half-elliptical notched tubes as a function of the fraction of life (β").

9. Conclusion

The results obtained from the exposure of the studied tubes to an internal pressure until the burst, allowed us to present the curves of damage according to the fraction of life chosen and to define for the model, Our tubes three stages of use: the first corresponds to the initiation of the damage, the second stage, corresponds to the progressive damage, considered as the precursor for the maintenance personnel to engage in predictive maintenance to avoid serious accidents and large production losses. At the ending of this stage, the damage reaches a critical value of defect length ($ac = 3.46$ mm) corresponding to a fraction of critical lifetime equal to 77%. The third stage corresponds to the brutal damage in which a low energy is able to break the specimen. During this analysis, it is also observed that as the step of the notch depth very small, the quantity of tests conducted also increases, resulting in a higher number of data points and consequently improving the quality of the experiment. In further works, we will establish the finite element model of the CPVC pipes to see the influences of the depth of notch on the stress concentration zones that can lead to premature failure; and we will compare these experimental results with the numerical result.

Data availability statement

All research data associated with our study is mentioned in this paper.

CRediT authorship contribution statement

Fatima Gugouch: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Aziz Maziri:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Mohamed Elghorba:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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