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Critical lifetime of HDPE pipes through damage and reliability models

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ABSTRACT

Damage models are not directly applicable on high-density polyethylene (HDPE) pipes. In this paper, static and strain-unified theory damage models are adapted to fit the HDPE case by substituting the dynamic tests' endurance limits by preloading simulation through notch and stiffness evaluation. Then, tensile and burst tests are following up to evaluate the specimens' residual life. Compared to virgin specimens, the rupture limit of old HDPE pipes' specimens had dropped significantly and their elongation decreased from 275 mm to about 26 mm. The degradation of the seven categories of specimens are different. Indeed, the degradation is too noticeable, disappearance of the plastic phase, for the categories 6 and 7, which are in the bottom of the pipe. Then, a reduced plastic phase on the lateral categories 4 and 5 showing an important impact of degradations. Finally, a larger plastic phase for the categories 1 and 2 taken from the top of the pipe, showing a medium impact of degradation. Thus, the use of the stiffness factor, reflecting the variability of degradation of the different categories of specimens, and the thickness reduction as life fractions for both aged and neat HDPE specimens was possible. The developed strains damage model compared to static burst pressures' one confirmed the damage stages and the critical life fraction of HDPE pipes. By comparing these models, the drastic change of HDPE pipes' behavior, from a ductile to a brittle one, have been proved. These findings allowed us to find out the critical life fraction of neat and old HDPE pipes, which has been confirmed by comparing the burst pressure curves of a notched and an old pipe. The presented approach is cost effective allowing a deep analysis of HDPE pipes failure and damage quantification through simply made models based on static tensile and burst test instead of tedious and very costly dynamic ones.

Keywords: Life fraction; tensile test; burst test; strain damage and reliability; burst pressure static damage; HDPE pipes.

INTRODUCTION

The production of polyethylene pipes began in the mid-1950s. Their use has increased enormously because of its flexibility and the advantages it offers compared to steel and concrete pipes. These pipes have known an evolution from PE40 product ranges to PE100. This evolution is not perfect and incidents/accidents on the produced tubes appear from time to time[1–4].

In fact, the intensive use of HDPE materials pushed many industrial to be suspicious of its quality. Thus, many improvements have been done through the years to reach the best mechanical characteristics for the produced material. This concern is a good motivation for many researchers to conduct mechanical characterization and damage evaluation, through the necessary tests, to predict the residual lifetime of the used material and improve the characteristics for the newly produced pipe [5,6,1,7].

The ageing effect is a slow and irreversible evolution of one or more properties of the HDPE material, the different mechanisms responsible for ageing of HDPE materials can be classified into physical or chemical categories. This effect is essentially caused by high temperature, high pressure and the nature and concentration of the chemical agents. Other aspect have been inspected in the literature such as the exterior climate effect, the effect of the environmental conditions and the speed of solicitation of the material on the ductile or brittle behavior of the ruptures. The majority of studies have been interested in accelerating the ageing based on total immersion tests in aggressive environments of different site conditions and temperatures. For that reason, the use of real samples from the industrial field remain very important to understand the ageing mechanisms involved and thus correlate them to those obtained in laboratory accelerated ageing [12–16].

Fatigue tests are among the most costly tests and are hard to ensure. These tests are carried out in dynamic mode and require the intervention of approved organisms. In this context, a simplification of the test procedures is necessary by opting for static tests instead of dynamic ones, which are costly and difficult. The static damage of the unified theory has the advantage of ensuring a very good evaluation of the damage without the need for dynamic tests[17–19].

In this paper, aged HDPE pipes have been investigated. Indeed, a characterization of the HDPE pipes' material have been done through tensile and burst test. Furthermore, new damage models based on the strain compared to the burst pressure one have been developed. In fact, a comparison between the natural ageing of aged HDPE pipes and the notch level effect of newly produced ones have been analyzed.

EXPERIMENTAL SET UP

An experimental study of HDPE pipes which have been working in a buried drinking water's piping network under an operating pressure of 3 to 6 bars has been conducted. The HDPE pipe, PE100, have a diameter of 63 mm, a thickness of 5.8 mm and a nominal pressure of PN16. In order to characterize the studied material and define the nature of its mechanical behavior, tensile test over 24 specimens taken from three different places of the aged specimen of 5 meters length and over 6 neat specimens have been carried out. The three part, taken from the aged pipe, have been cut the same way and they have been marked according to the position of the specimen in order to analyze the found results and gather them in homogeneous categories. In fact, it has been noticed that the tensile test results are not identical for all the specimens. This finding have been noticed for the three places of the aged pipe. Thus, the tensile curves for seven categories of specimens, which have the same trends of (σ-ε) curves, have been drawn. Indeed, it has been found that the strain is changing according to the place of the taken specimen. Afterwards, tensile tests have been conducted on standard specimens by using a tensile test machine, which can handle a force of 5 KN and a moving speed of 100 m/s, working under the EN12201 code, Figure 1. To ensure a complete comprehension of the degradation phenomena, pipe specimens, of 400 mm length, have been extracted for burst test purpose in a bursting hydraulic tester. The tester increases the internal pressure until reaching the rupture, Figure 2. The tensile curves (σ-ε) and the internal pressure (P, time) ones have been registered for analysis.

Figure 1. Machine and standard specimen for tensile test

Figure 2. Machine and standard specimen for burst test.

MATHEMATICAL MODELLING

Thermoplastic piping systems are often subjected to cyclic loads due to pressure fluctuations. These pressure variations are fatigue sources of material, sometimes accelerated by the presence of environmental harmfulness.

This situation causes a reduction in the expected lifetime of the damaged material requiring re-estimation of its remaining life in the presence of defects.

In the literature, the various theoretical approaches developed by different authors have addressed this phenomenon of accelerated degradation by putting different hypotheses such as the linearity of the damage proposed by Miner [20] and the accumulative one proposed by Gatts and Valuri [21,22].

Based on the previous models, Bui Quoc [23] developed a damage model called the unified theory, which is considered as the best tool for this study by introducing the beta-fraction parameter and the residual resistance loss.

In this paper, damage modeling of HDPE pipes has been led to quantify the failure of aged HDPE pipes validated through a pressure damage model. For this, measurable parameters, such as rupture strain, have been defined. These parameters are maximal for the virgin category and take residual values for the other categories according to the level of degradation.

The static damage model, to evaluate the cumulative damage of aged HDPE pipes, has been used. For that reason, a modification of the static damage using the endurance limits [23] has been led. For all models, the limit conditions supposed to be true are D = 0, if the specimen has not been subjected to any preliminary damage and D = 1, if the specimen has failed. The developed model definition is based on logical and measurable properties.

Linear Damage Rule

The linear damage rule of Miner is one of the most used methods in the codes and in the literature. According to this rule, the damage is directly proportional to the life fraction.

$$D = \beta = n/N_f \tag{1}$$

Life Fraction

While talking about brittle rupture, the strain at the limit of elasticity, corresponding to the necking of the tensile curve, is equal to the strain at the rupture whatever the loading conditions ($\varepsilon_{neck}/\varepsilon_r = 1$). For ductile materials, this situation represent the highest limit of the stiffness index and give an information about the ultimate level of degradation. Meanwhile, this ratio takes values inferior to the unity (<1) to show the residual life of the specimen. The distance between the necking strain and the rupture strain is inversely proportional to the degradation level. The ratio is considered in this article as the life fraction of the aged HDPE pipes.

$$\beta = \varepsilon_{neck}/\varepsilon_r \tag{2}$$

Where $\beta = 1$ for completely damaged HDPE pipe and $\beta = 0$ for neat one.

Damage Based on Strain

For cyclic loadings with a controlled strain, an approach have been developed considering that the material loses its ductility because of the cumulative damage [24]. As for fatigue, it is considered that the resistance of a material associated with a residual ultimate strain decreases from an initial value for low degradations to a critical value for high degradations through the wall of the pipeline. The damage D of the strain controlled unified theory as a function of β (β = n / N) is given by:

$$D=\ln(\varepsilon_e/\varepsilon_{eo})/\ln(\varepsilon_{ec}/\varepsilon_{eo}) \quad (3)$$

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

Where: $\lambda = 1 + \ln(\varepsilon/\varepsilon_{eo})$ and $\lambda_f = 1 + \ln(\varepsilon_f/\varepsilon_{eo})$ (5)

In this paper, a modified version of the equation (4) have been proposed by representing the coefficients λ and λ_f according to the measurable values of the strain through tensile tests εu, εur and ε_0. λf is a constant equal to 2.2.

Where: m= 1; $\lambda = 1 + \ln(\varepsilon_{ur}/\varepsilon_o)$ and $\lambda_f = 1 + \ln(\varepsilon_u/\varepsilon_o)$ (6)

From the equation (4), a new equation is deduced, representing the damage in function of the life fraction and a coefficient α witch takes values between 0 and 1 and give information about the damage stages which are initiation, propagation and acceleration. The coefficient α is replacing the expression of strain parameters λ and λf.

$$D=\frac{\beta}{\beta+(1-\beta)*\alpha} \quad (7)$$

For α = 20%, the evolution of D in function of the life fraction β represent the stage I's limit of damage. For α = 52%, the evolution of D in function of the life fraction β represent the critical life limit of damage. For α = 75%, the evolution of D in function of the life fraction β represent the stage II's limit of damage.

Burst Pressure Model

The presented damage models will be compared to a damage model based on the burst pressure which was established for the notched pipes.

The expression of the pressure damage model is given below

$$D=(1-P_{ur}/P_u)/(1-P_a/P_u) \quad (8)$$

This model is a modified approach of static cumulative damage developed by replacement of cyclic preloading by creating an artificial damage through different level of groove notches on HDPE pipes 'specimens, equation (3). For this case, we adopted a life fraction defined by $\beta = \Delta e / e$.

RESULTS AND DISCUSSION

Tensile Test Results

The aged HDPE pipes' specimens show a significant variability in the degree of degradation according to the elongation at rupture, Figure 4. Thus, tensile curves have shown that the virgin HDPE specimens, category 1, have larger strains than the aged ones characterized by the length of the plastic phase which goes from larger one for categories 2 and 3, too reduced one for 4 and 5 and disappearance of them for 6 and 7. It has been shown that the rupture limit of aged HDPE pipe specimens is smaller than the neat one. Therefore, the influence of the ageing on the mechanical behavior of HDPE results in a stiffening of the same material up to its embrittlement. In fact, a general change in the mechanical behavior from a ductile to a brittle one is noticeable. The Figure 3 shows an example of failed specimens.

Figure 3. Example of broken specimens after the tensile test.

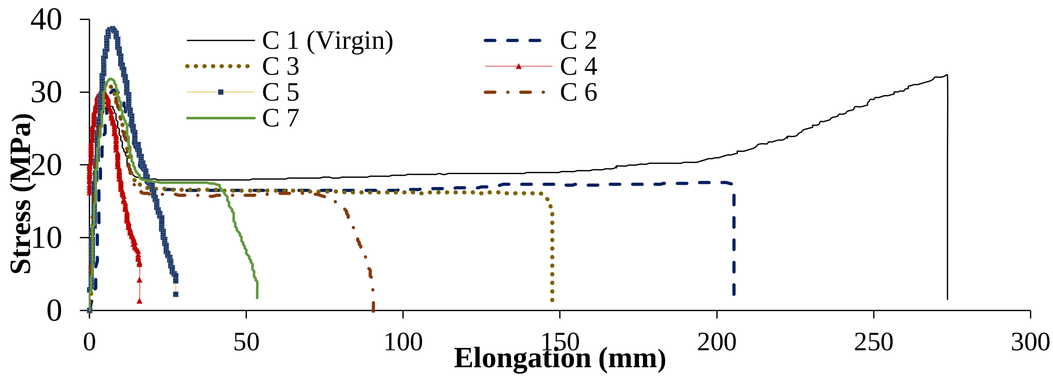

Figure 4. Example of stress-elongation curves of aged specimens through a wall of an aged HDPE pipe and an undammaged specimen (virgin).

Table 1. Experimental average values of strain obtained from tensile tests.

Specimen category	ε_r	$\beta = \varepsilon_{neck}/\varepsilon_r$	Std. Dev. ε_r
Category 1 (Virgin)	8,10	1	0,7 %
Category 2	10,94	0,54	0,5 %
Category 3	5,20	0,52	0,6 %
Category 4	3,29	0,49	0,2 %
Category 5	1,64	0,36	0,8 %
Category 6	1,08	0,32	0,3 %
Category 7	0,25	0,19	0,5 %

The Figure 4 shows that the rupture stress is decreasing significantly. Therefore, the aged HDPE pipe's degradations have an effect over the mechanical characteristics, which leads to the embrittlement of the material.

The ductility of HDPE material, which have a lower rigidity and a higher nominal strain at rupture, is characterized by the presence of larges strains representing a localized necking, which stabilizes just before spreading to reach the specimen rupture on the stress-strain curves. When the material shifts to brittle state, characterizing a fragile material with a big rigidity and a limited nominal strain at rupture, the absence of larges strains is associated with a sudden break of the specimen before getting to its necking. Taking into consideration this change of behavior, a life fraction have been defined as the ratio between the strain at the maximum point, corresponding to the neck of the stress-strain curve, and the strain at the rupture $\varepsilon neck/\varepsilon r$, Table 1.

Burst Test Results

In order to characterize the effect of ageing over the aged HDPE pipes, burst tests were led, Figure 5. The comparison of the obtained internal pressure-time curves to the one obtained from neat HDPE pipes has been done.

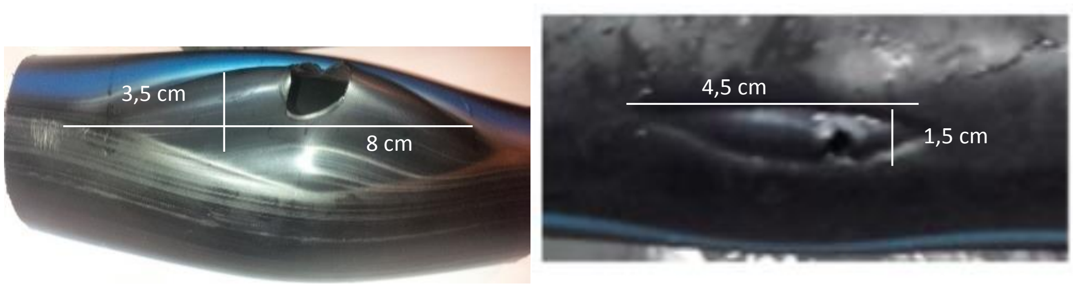

Figure 5. Burst test of Neat pipe at the left and an aged pipe at the right.

From the figure 6, a significant change in the mechanical behavior of the HDPE material has been registered. In fact, a reverse behavior of the internal pressure has occurred. The maximum pressure at the elastic stage has been reduced from 63.2 bars to 36.7 bars, which represent 42% of decreasing. At the plastic phase, the size of the burst neck of aged pipe, figure 5, has become smaller than the neat HDPE one, which explain behavior of the curve at this phase. Finally, at the rupture phase, we notice a reverse behavior of the rupture pressure. It has been increased from 49.8 to 69.7 bars, which represents 40% of increasing. Furthermore, the total time for burst rupture have been reduced significantly from 49 s to 28 s. All these results confirm the tensile test ones. They are showing that the degradations effect over aged HDPE pipes are characterized by modifying their mechanical behavior, by shifting from ductile to brittle one. The effect is not distributed the same way all over the wall of the aged HDPE pipe compared to neat one.

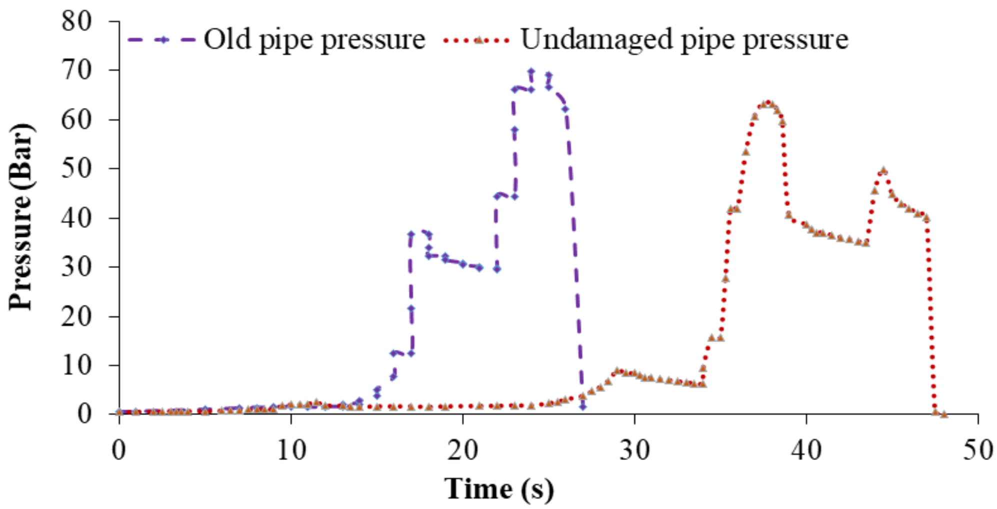

Figure 6. Internal pressure evolution in function of time for an aged and an undamaged HDPE pipes.

Figure 6 shows that the internal pressure for the burst of aged HDPE pipes has the same time to failure as a notched pipe at 52% of the thickness reduction. Therefore, the critical life fraction is equal to 52 % corresponding to 3 mm of thickness loss. The discrepancies between the reached maximum pressure show that the aged and the notched HDPE pipes' degradations are not having the same impact. Indeed, the reduction of the thickness has a more significant impact than the natural degradation. HDPE pipes' behavior due to thickness loss, groove creation, is changing completely toward brittle one characterized by the disappearance of the plastic phase and the limitation of the elastic phase at the same level as the elastic phase of the aged one. Meanwhile, the natural degradation is characterized by a reduction in the resistance of the completely aged pipe by the loss of 42 % of the elastic resistance and the increasing of the plastic phase before rupture. The Figure 7 shows also photos for the different ruptures showing the disappearance of the rupture neck for the notched pipes and its reduction compared to neat one as shown by Figure 5.

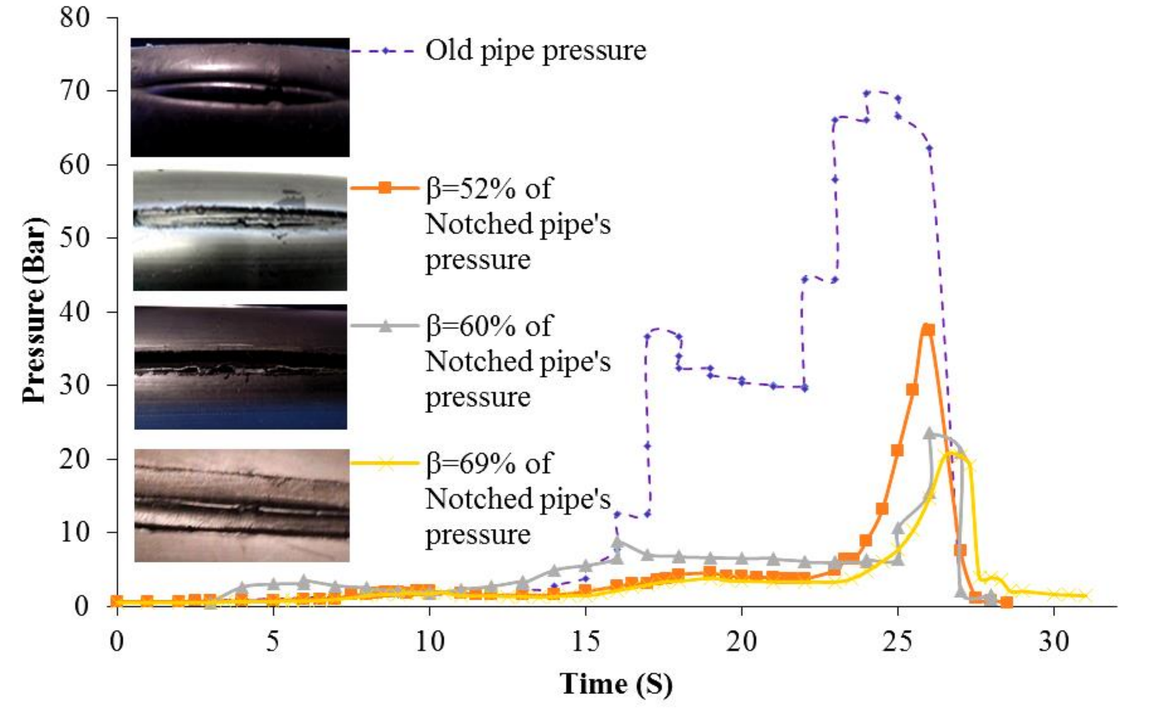

Figure 7. Comparaison of aged HDPE pipe's internal pressure curve to notched pipes' curves (3 mm, 3.5 mm and 4 mm of notch depth)

Damage Evaluation

To evaluate the damage of the aged HDPE pipes, a comparison of the damage resulting from the aged HDPE pipes, based on the tensile test strains, Equation (4), to the one obtained through the bursting of artificially notched pipes has been done, Equation (8). The strain damage model, obtained through a modified version of the strain controlled unified theory formulas, have been shown in Figure 7(a). The curves for different values of λ, corresponding to a level of loading of aged HDPE pipes have been represented. The damage curves of the strain models have different trends according to λ values going from a maximum concavity for ($\lambda = 1.46$) to an almost linear behavior for ($\lambda = 1.9$).The damage limits, obtained through the equation (7) have been presented in Figure 7(b). All the damage curves, corresponding to different values of λ, are represented in the third stage of damage as shown in the Figure 7(c) above the critical life damage limit.. Therefore, 52% is representing also a critical life fraction for the aged pipes. In fact, the studied aged pipes have defects beyond the critical life fraction, which have obliged their replacement. They presents irregular and fluctuating values of damage through their wall.In the first stage, the burst pressure damage correspond to the strain damage curves of ($\lambda = 1.46$). Then, in the second stage, it goes through the curves of ($\lambda = 1.9$).

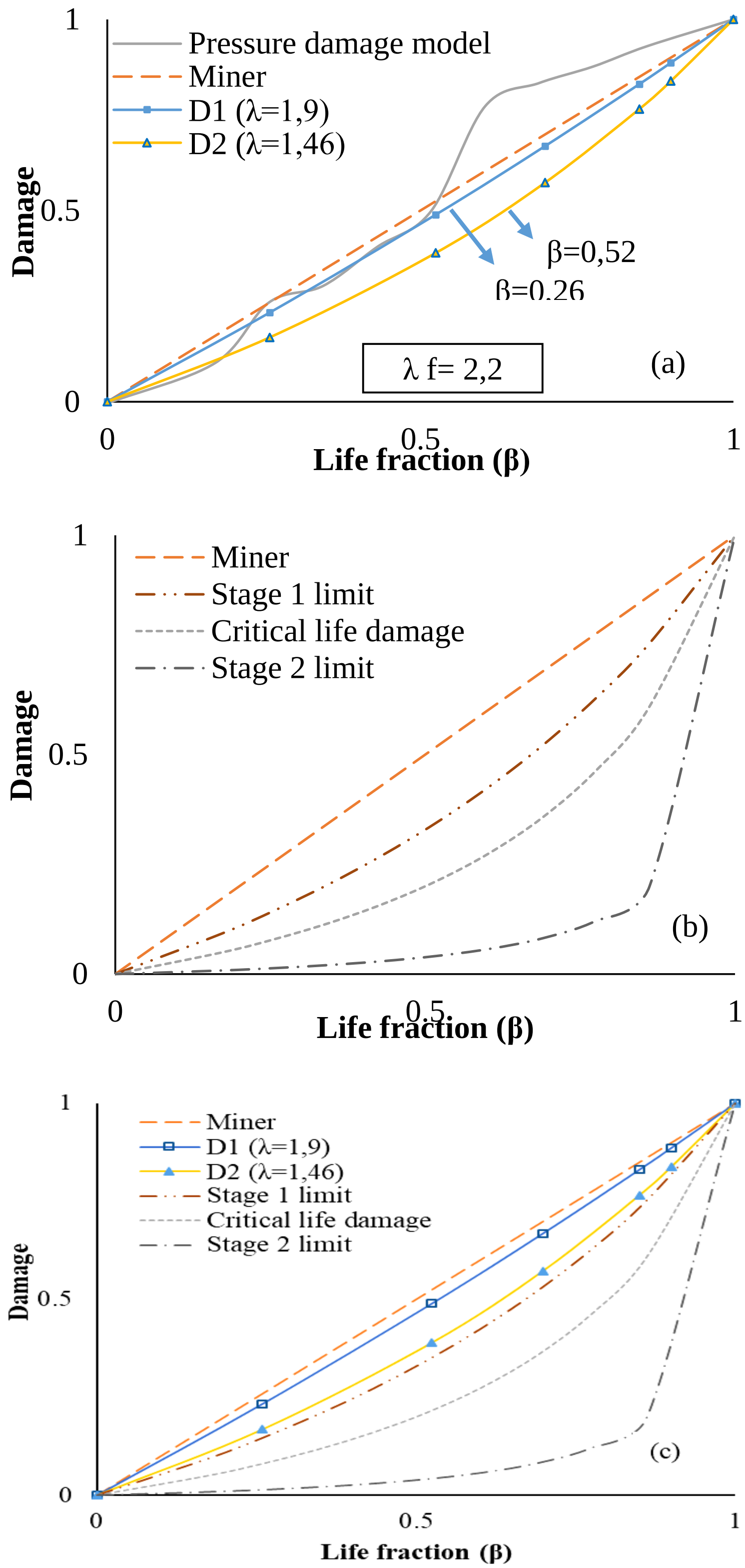

Figure 8. (a) Strain and burst pressure damage curves evolution (b) damage stages and critical life damage (c) Comparison of strain damage to the damage stages.

Damage and Reliability Analysis

Generally, reliability can be defined [25,26] as the probability that a device or system will perform a required function at a given point in time, when operated under specific conditions. In other words, reliability is a quantitative measure of non-failure operation over an operational time interval. The static reliability is deduced from damage calculations through the formula (9):

$$\text{Reliability} = 1\text{-Damage} \tag{9}$$

In this paper, we evaluated the damage of the studied HDPE pipes according to strain model and burst pressure one, figure (8-a). The discrepancies between them show that the material behavior is not the same for the main used parameters. The strain damage curves are behaving differently according to the loading level from a maximum concavity for weak loading level until almost linear curves for high loading; figure (8-b). The burst pressure model's curve has an evolution that fits the strain damage curves, according to the damage stages, until getting to the critical life fraction. Beyond this, the damage is dominant and has an accelerated evolution toward the unity.

For the studied case, the superposition of the damage and reliability curves of the model based on pressures has an intersection at the life fraction βc1 of 52%, figure (8-a). The intersection point is showing a reversal situation in which the damage, which have been lower than the reliability, becomes more important and the critical life fraction is reached. After that, a maintenance decision must be taken to prevent the related risks.

Moreover, the superposition of damage and reliability of the strain damage model, the curves corresponding to the highest value of loading, (λ = 1.9), is having an intersection at the value of βc2 = $\beta c1$. By decreasing the loading level from 1.9 to 1.46, the critical life fraction is allowing more time for the use of HDPE pipes until reaching a critical life fraction $\beta c3$, Figure (8-b).

The damage evolution has three stages. The first one, initiation phase, corresponds to an interval of β between 0 and 20%. Then, the second one, propagation phase, corresponds to a value of β between 20% and 75%. Finally, the last stage, acceleration phase, is considered for a life fraction more than 75%.

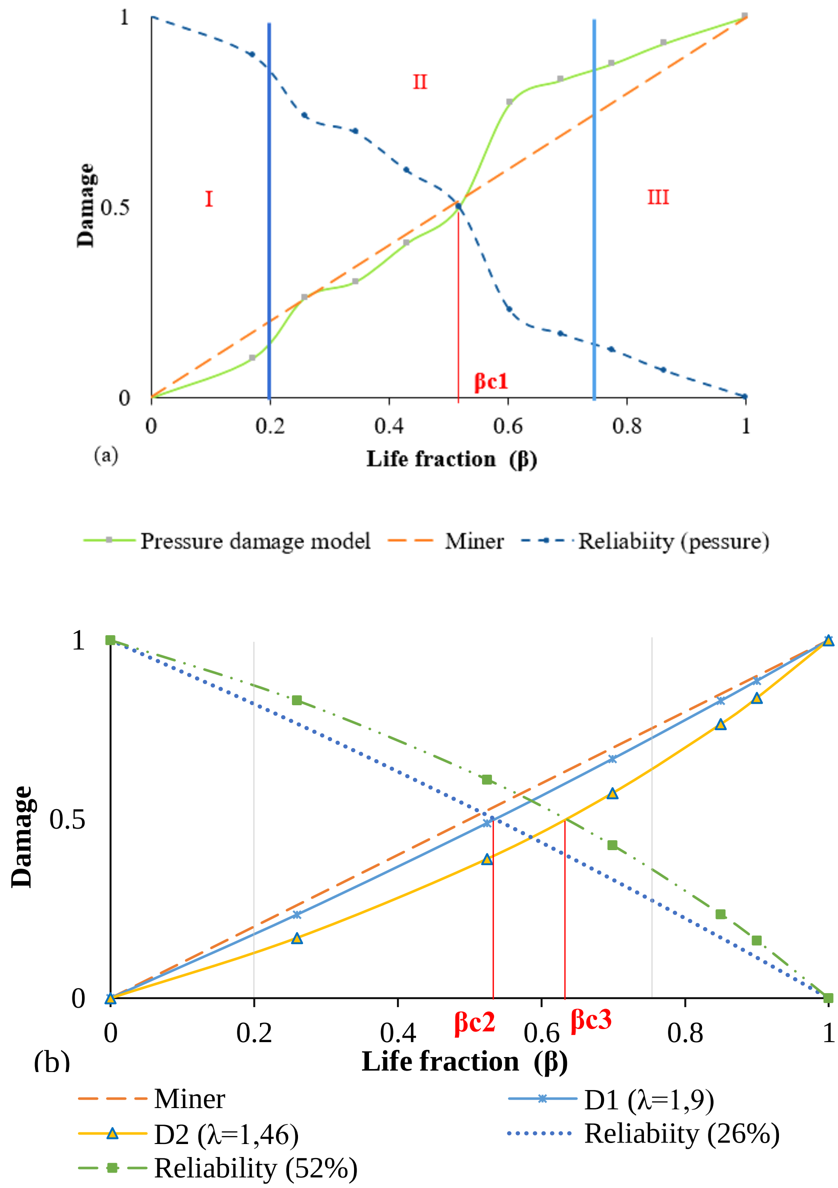

Figure 9. Damage and reliability evolution for (a) burst pressure (b) strains

Table 2. Values of the critical life fractions.

Life fraction	Value
βc1	0.517
βc2	0.524
βc3	0.698

CONCLUSION

This paper's aim is to assess the damage and reliability of high-density polyethylene pipes (HDPE) and find out the critical life fraction of this material to help industrials and researchers to deal with HDPE pipes networks and proceed to their removal or repair in the right moment in a safe, cost effective and sure way. Thus, aged and neat specimens have been prepared for both tensile and burst test according to ASTM codes. For that reason, tensile test and burst test machines have been used to get the different results. Through the obtained curves, new life fraction were determined to allow damage and reliability quantification of both of the pipes. Then, strains unified theory damage model and static damage burst pressure one were compared to come out with many conclusions concerning the damage stages and the critical life fraction. Indeed, 52% of life fraction were confirmed as a critical one. The evaluation of the spent life of aged pipes showed that the critical life fraction is already reached and the aged pipes must be removed, confirming that these pies were subjected to severe use conditions in the buried drinking water piping network. Through the results' interpretation of the curves compared to the damage stages, the shifting of HDPE pipes' behavior from ductile to brittle have been significant when higher life fractions are reached. All these finding could lead to master the use of HDPE pipes in industrial installation and avoid the risks related to sudden degradation and burst of pipes through simple tests over a part of the repaired parts or samples taken from the real field without spending a lot of money over dynamic and costly tests. As a future work for the present paper, Wholer curves and maintenance strategy choice of both neat and aged HDPE pipes can be done.

REFERENCES

[1] Zhang Y, Ben Jar PY. Comparison of Mechanical Properties Between PE80 and PE100 Pipe Materials. Journal of Materials Engineering and Performance. 2016;25:4326–32.

[2] Christensen RM, Perspective on Materials Failure Theory and Applications, Journal of Applied Mechanics. 2016;83:111001-06.

[3] Alvarado-Contreras Ja, Polak Ma, Penlidis A. Constitutive Modeling of Damage Evolution in Semicrystalline Polyethylene. Journal of Engineering Materials and Technology.2010;132:41009-21.

[4] Barker MB, Bowman J, Bevis M. The performance and causes of failure of polyethylene pipes subjected to constant and fluctuating internal pressure loadings. Journal of Materials Science. 1983;18:1095–1118.

[5] Choi BH, Chudnovsky A, Paradkar R, Michie W, Zhou Z, Cham PM. Experimental and theoretical investigation of stress corrosion crack (SCC) growth of polyethylene pipes. Polymer Degradation and Stability. 2009;94:859–67.

[6] Duan HF, Ghidaoui MS,. Tung YK. Energy Analysis of Viscoelasticity Effect in Pipe Fluid Transients. Journal of Applied Mechanics. 2010;77:44503-07.

[7] Bozorg-Haddad A, Iskander M. Comparison of accelerated compressive creep behavior of virgin HDPE using thermal and energy approaches. Journal of Materials Engineering and Performance. 2011;20:1219–29.

[8] Adib A, Domínguez C, García RA, Garrido MA, Rodríguez J. Influence of specimen geometry on the slow crack growth testing of HDPE for pipe applications. Polymer Testing. 2015;48:104–10.

[9] Alzerreca M, Paris M, Boyron O, Orditz D, Louarn G, Correc O. Mechanical properties and molecular structures of virgin and recycled HDPE polymers used in gravity sewer systems, Polymer Testing. 2015;46:1–8.

[10] Grigoriadou I, Paraskevopoulos KM, Chrissafis K, Pavlidou E, Stamkopoulos TG, Bikiaris D. Effect of different nanoparticles on HDPE UV stability. Polymer Degradation and Stability. 2011;96:151–63.

[11] Hoàng EM, Lowe D. Lifetime prediction of a blue PE100 water pipe. Polymer Degradation and Stability. 2008;93:1496–503.

[12] Devilliers C, Laiarinandrasana L, Fayolle B, Gaudichet-Maurin E. Characterisation of aged HDPE pipes from drinking water distribution : investigation of crack depth by Nol ring tests under creep loading. Fracture of materials and structures from micro to macro scale - ECF 18 Germany. 2010: 8 p.

[13] Douminge L. Etude du comportement du polyéthylène haute densité sous irradiation ultraviolette ou sollicitation mécanique par spectroscopie de fluorescence. Thesis of université de la rochelle. 2010.

[14] Fayolle B, Audouin L, Verdu J. Oxidation induced embrittlement in polypropylene - a tensile testing study. Polymer Degradation and Stability. 2000; 70:333–40.

[15] Lemaitre J. A Continuous Damage Mechanics Model for Ductile Fracture. Journal of Engineering Materials and Technology. 1985;107:83–89.

[16] Cárdenas NO, Machado IF, Gonçalves E. Cyclic loading and marine environment effects on the properties of HDPE umbilical cables. Journal of Materials Science. 2007;42:6935–41.

[17] Thang BQ, Dubuc J, Bazergui A, Biron A. Cumulative fatigue damage under strain-controlled conditions. Journal of Materials. 1971;6: 718–37.

[18] Lemaitre.J, Desmorat R. Engineering Damage Mechanics. Book. 2005.

[19] Besson J. Continuum Models of Ductile Fracture: A Review. International Journal of Damage Mechanics. 2010;19:3-52

[20] Miner M. Cumulative damage in fatigue. Journal of Applied Mechanics.1945;12;159-64.

[21] Gatts R. Application of a cumulative damage concept to fatigue. Journal of basic Engineering.1961;83:529-34.

[22] Manson SS. Interpretive report on cumulative fatigue damage in the low cycle range. Welding Journal Research Supplement.1964:9 p.

[23] Bui-Quoc T, Dubuc J, Bazergui A, Biron A. Cumulative fatigue damage under stress-controlled conditions. Journal of basic Engineering. 1971;93:691–98.

[24] Bathias C, Pineau A. Fatigue of Materials and Structures. Book. 2013.

[25] Marshall J. An Introduction to Reliability and Life Distributions Module. Product Excellence using 6 Sigma Module, Reliability and Life distributions. 2012:1–38.

[26] O. Cronvall, Structural lifetime, reliability and risk analysis approaches for power plant components and systems. Book. 2011.