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# Residual life prediction of defected Polypropylene Random copolymer pipes (PPR)

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**ABSTRACT.** The polypropylene random copolymer (PPR) is a thermoplastic material generally used for the transport of water under pressure, especially hot water. PPR pipes are exposed to severe conditions in terms of pressure and temperature, hence the need to characterize their fracture behavior in order to avoid the design risks. Sudden overpressure is one of the most common problems in piping. It can affect the security of goods and the safety of people. In this context, we have performed tests of overpressures at the laboratory scale according to ASTM D1599 standard, on virgin and notched pipes, to characterize mechanically the fracture behavior of PPR pipes. Afterwards, we identify experimentally the evolution of their damage. The calculation of the damage, by experimental damage models, have led to determine the three stages of evolution of the damage, which are the initiation, the progression and the acceleration of it. Therefore, the concept of reliability is used to specify the critical life fraction relative to the notch depth (βc) of a defect modeled as an external longitudinal groove on the PPR pipe. A comparison of PPR and HDPE pipes damage and reliability has been done. Moreover, a theoretical reassessment of the damage level was done through a judicious adaptation of the theoretical model proposed by the unified theory. From the latter, we proved that theoretical and experimental results show good agreement and correlations.

**KEYWORDS.** Mechanical characterization; PPR themoplastic pipes; damage; reliability; burst pressure.

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## INTRODUCTION

The polypropylene random copolymer (PPR) is a thermoplastic material made by copolymerizing propylene and small quantity of ethylene (usually less than 7 %). In fact, the role of ethylene co-monomer is to disrupt the crystallization of the main chain of propylene by introducing irregularities leading to a decrease of the crystallinity, rigidity, melting point and glass-transition temperature [1-2]. Thanks to their good physical, chemical and mechanical characteristics along with the low cost of the installation and maintenance, PPR pipes becomes quickly one of the most used polymers in the market. Their application merged from transport of hot and cold water, to system of air-conditioned, and various industrial and medical applications. A complete range of fittings that can be welded to create well tight systems, even under most severe conditions [3], improved PPR pipes system.

Several researchers have studied the behavior of PPR pipes. Zgoul et al [3] evaluated the convenience of two types of thermoplastic pipes to transport industrial and domestic hot water by a comparative study of Polypropylene random copolymer (PPR) and Cross-Linked Polyethylene (PEX) pipes in terms of melting temperature and mechanical strength. Authors used differential scanning calorimetry (DSC), uniaxial tensile tests and hydrostatic pressure. Poduska et al were interested in the determination of residual stresses, and the fusion temperature of PPR pipes [4]. Geertz et al have put PPR pipes under hydrostatic pressure for a long time, which the purpose was to analyze an antioxidant diffusion named Irganox1010 (phenolic stabilizer) using infrared microscopy technique [5]. Litvinov and Soliman reported the effect of storage under hydrostatic pressure and high temperature on morphology, molecular mobility and behavior at the fracture of PPR tubes using the differential analyses of X-Ray Diffraction (XRD) and Differential Scanning Calorimetry (DSC) [6].
In the framework of damage mechanics, researchers developed theoretical expressions of damage like Miner, Starkey and Shanly. Bui-Quoc has developed the unified theory of metal fatigue and suggested expressions of damage that allows a quantification of the damage according to the initial and present fatigue limits [7]. In order to use this model for polymers' characterize, through static tests, needs a judicious adaptation taking into account different parameters. However, Makadir et al [8] used the normalized damage to characterize an Acrylonitrile-butadiene styrene (ABS) polymer plate under uniaxial loading. To highlight the influence of the notch on the behavior of Polyvinyl chloride (PVC) pipes, Arid et al [9] used normalized damage formulation on notched plat specimens. In this paper, we have used the normalized damage to define the different stages of the damage development within defected PPR pipes subjected to burst pressure tests. Furthermore, the calculation of the reliability allows the determination of the critical depth (βc) of a defect modeled as an external longitudinal groove on the PPR pipe.

## METHOD AND MATERIAL

The chosen pipes for the study are manufactured by extrusion from PPR material. They were prepared according to the ASTM D1599 standard [10], which requires samples of 450 mm length. The Fig. 1 shows dimensions of the used pipes in this work. In order to study the notch effect on the strength of the PPR pipes under pressure, eight pipes were notched using a universal milling machine with grooves of 6 mm width, 100 mm length and a depth from 2.42 mm to 14.5 mm. The life fraction β is defined as the ratio between the notch depth (a) and the total thickness of the pipe (t). Fig. 2 and Tab. 1 show the notched samples dimensions.
The experimental test bench is constituted of a tank filled with water and a hydraulic pump for the pressurization. The pump is equipped with a screen to display the pressure inside the pipe. In order to prevent any leakage, caps were fixed at the ends of pipes and strongly tightened through bolts; those caps are connected to a hydraulic pump through a pressurizing hose.
After fixing the caps, pipes were immersed in the tank filled with water. Then, the hydraulic pump applies a gradient of pressure until their burst. The goal of this test is the determination of the residual ultimate pressures according to each life fraction β.

**Diameter: 90 mm**
**Length: 450 mm**
**Thickness: 15 mm**

Figure 1: Specimen dimensions.

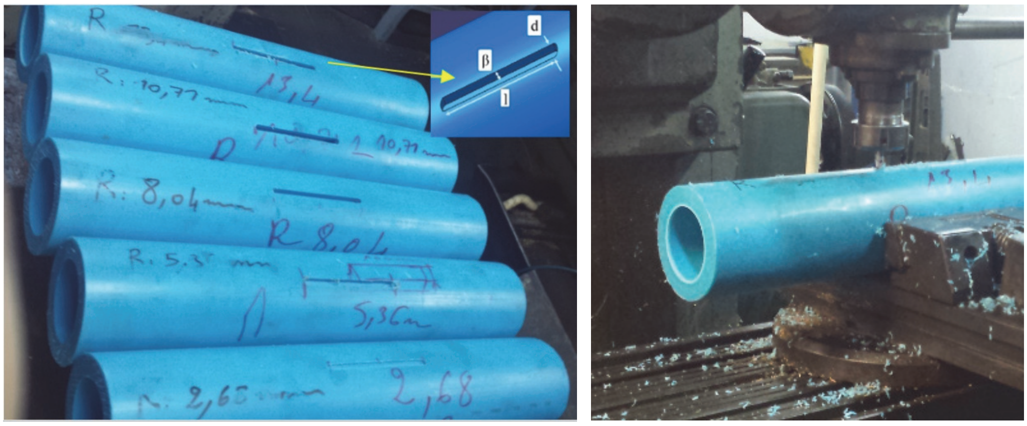

Figure 2: Groove Notch preparation and dimensions.

| Number of specimens | d (mm) | l (mm) | β = a/t |
|---|---|---|---|
| Neat | 6 | 100 | 0 |
| 1 | 6 | 100 | 0.16 |
| 2 | 6 | 100 | 0.32 |
| 3 | 6 | 100 | 0.43 |
| 4 | 6 | 100 | 0.54 |
| 5 | 6 | 100 | 0.71 |
| 6 | 6 | 100 | 0.80 |
| 7 | 6 | 100 | 0.90 |
| 8 | 6 | 100 | 0.97 |

Table 1: Burst pressure evolution in function of the life fraction.

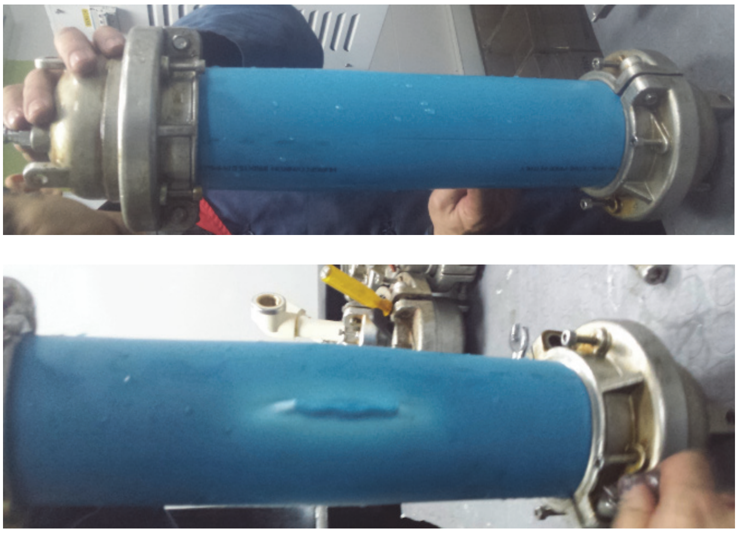

Figure 3: Rupture of PPR pipes.

## THEORY

### *Damage theories*

In this paper, we led burst tests over notched pipes for both HDPE and PPR materials. Thus, we prepared standard specimens according the ASTM 1599. Then, we created multi-level grooves in the produced specimens. After that, we exposed neat and notched pipes to an increasing internal pressure until the rupture through a hydrostatic burst tester. The studied specimens of HDPE and PPR have seemingly the same dimensions.

Moreover, the internal pressure evolution according to time have been registered for the neat pipe and the notched ones. Besides, the burst pressure and the time of burst have been also got from the hydrostatic tester display. These pressures are considered as the main parameters used in this paper to quantify the damage evolution. On the one hand, we interpreted the internal pressure evolution and the way it is representing the ductile behavior of the thermoplastic materials. On the other hand, the representation of the burst pressure according to the life fraction, which have been chosen as the ratio of the thickness and its fluctuation, have been detailed. The static damage of the unified theory based on the burst pressures has been developed to predict the damage evolution and the artificial preloading impact, which is represented by the notch depth [14, 15].

### *Static damage*

The static damage model is presented in the Eq. (1). This model is justified by the proportionality between the stress and the rupture pressure.

$$D = \frac{1 - \frac{p_{ur}}{P_u}}{1 - \frac{p_a}{P_u}} \tag{1}$$

### *Unified theory damage*

By correlation to the expression of the unified theory damage developed by Bui-Quoc, a relationship describing the evolution of the damage depending on the life fraction and pressure is given by Eq. (2):

$$D = \frac{\beta}{\beta + (1-\beta) \cdot \left( \frac{\gamma - \left( \frac{\gamma}{\gamma_u} \right)^m}{\gamma - 1} \right)} \tag{2}$$

with:

β: Life fraction.
m: Empirical constant depending on material (m=1 for our case).
$\gamma_u = P_u / P_a$ : Parameter reflecting the strength of the material in a virgin state.
$\gamma = P_{ur} / P_a$ : Parameter characterizing the effect of the damage on the mechanical characteristics of the material.

### *Reliability estimation*

Reliability analysis is an essential part of any safety study. Originally, reliability was related to high-tech systems (nuclear power plants, aerospace). Today, reliability has become a key parameter of quality and decision-making in the study of most components, products and processes for transport, energy, buildings, electronic components and mechanical components. Many industrialists are working to evaluate and improve the reliability of their products during their life cycle, from design to operation in order to develop their knowledge of the report Cost / Reliability and control failure causes [11].

In fact, reliability is defined as the probability of survival of systems during their operation at a given time. This parameter may be considered as the compliment to 1 of the damage. The relation between these two parameters is given by Eq. (3) [12]:

$$R(\beta)+D(\beta)=1 \tag{3}$$

By using this equation, the evolution of these two quantities can be studied at the same time as shown in Fig. 6.

## RESULTS AND DISCUSSIONS

### *Residual burst pressures*

The variation of the ultimate internal pressure of the pipes in function of the life fraction β is presented by the Fig. 4 and Fig. 5. Undamaged pipes can withstand an ultimate pressure of about 129 bars. In addition, the notch had caused a drop of the ultimate pressure of the notched pipes compared to neat one. The increase in depth of the notches leads to a depletion of residual ultimate pressures of notched PPR pipes.

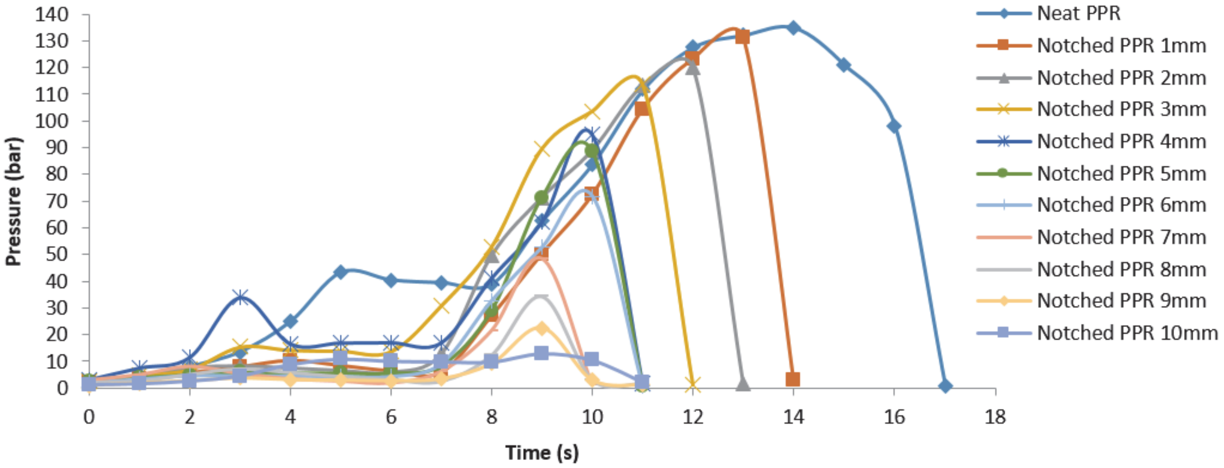

Figure 4: Internal pressure evolution for neat and notched PPR pipes.

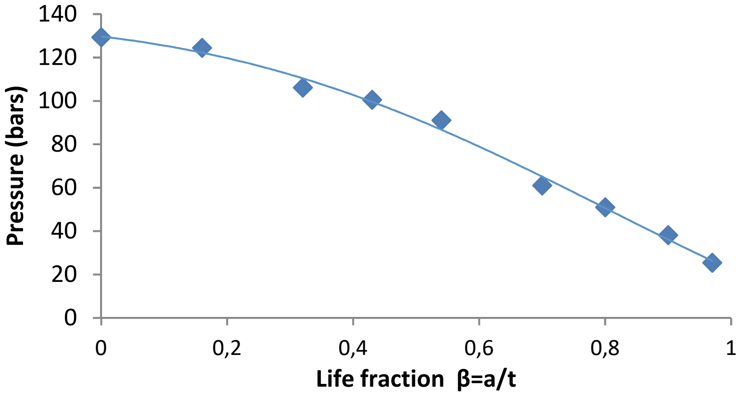

Figure 5: Ultimate pressure evolution in function of life fraction β

### *Static damage*

The HDPE and PPR polymers are relatively different materials. In this paper, we led a study of their performances by focusing over their mechanical behavior under an internal pressure until rupture. However, we were able to compare the internal pressure evolution and the way it is representing ductility of these materials. We showed that the impact of the internal pressure depends on the necessary time for burst and the duration of each stage (preloading, elastic, plastic and rupture). Moreover, the damage-reliability curves, Fig. 6, allowed us to define precisely the critical life fraction for both of them. Indeed, the critical life fractions are 52% and 58% for both HDPE and PPR respectively. The damage stages of them are different. Therefore, the first stage limit is 20% and 38%, the second one 75% and 78% and third over the last values for HDPE and PPR respectively. The performance of HDPE and PPR have a similar performance regarding the damage behavior and the criticism of thickness reduction. However, the two materials are very different considering the elastic and the rupture limits and the time to failure. In fact, the neat PPR reaches the burst pressure of 135 bars in 14 s. Meanwhile, the HDPE reaches the burst pressure of 69.5 bars at 49 s. The range of each pipe can explain the discrepancies of these values, the PPR pipes are PN20 and those of HDPE are PN16, and the thickness differences. In fact, we used the existing pipes in the market. Furthermore, we were able to validate previous researches done over HDPE, by comparing the HDPE and PPR performances and developing the modified version of the static damage model based on the burst pressures instead of the stresses as published in the literature [7,14]. Unlike the damage, reliability begins with the value of one, corresponding to the absence of damage, and decreases gradually as the notch depth increases; the total failure of the material is indicated by the zero value. The superposition of damage and reliability curves defines the life fraction at 52% and 58% of reliability for HDPE and PPR respectively. This point is located at the end of stage II and allows the maintenance department to decide on the time of reparation or even the change of the defected pipe.

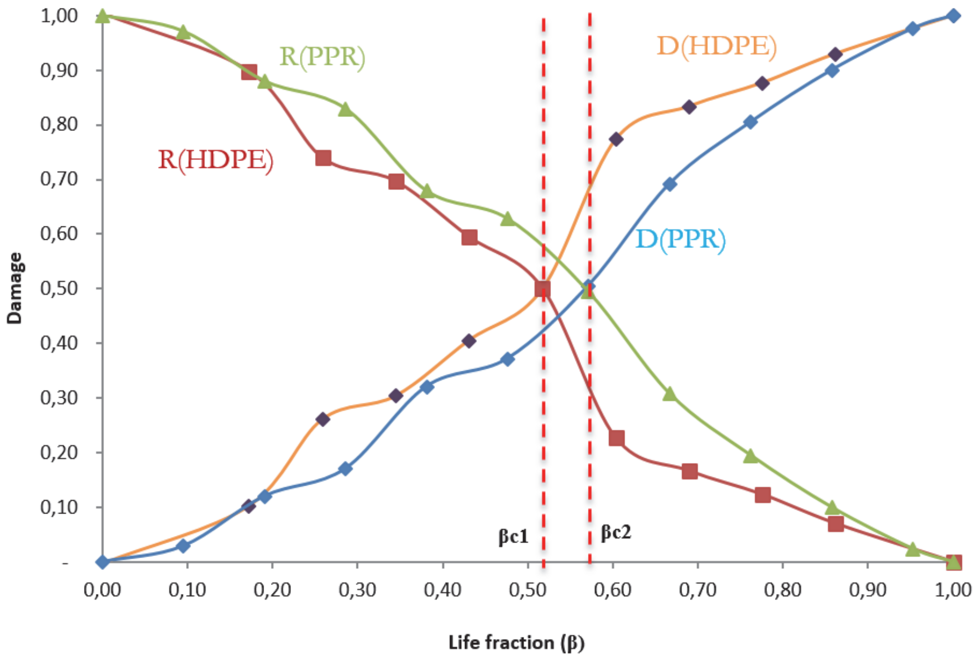

Figure 6: PPR and HDPE's damage-reliability evolution in function of the life fraction.

### *Unified theory damage*

The variation of the unified theory damage in function of the fraction life $\beta$ is given in the Fig. 7. The unified damage is indicated by a set of curves associated with a constant pressure ratio $\gamma_u = P_u / P_a$ ($P_u$=129.3bars and $P_a$=20bars) and variable parameter $\gamma = P_{ur} / P_a$. Therefore, each curve is associated with a separate level of applied pressure. In the direction of increasing of γ, the curves of the unified theory damage grow to reach the linear tendency for high loading levels.

### *Comparison of static and unified theory damages*

Fig. 8 shows the variation of experimental and unified theory damages ($\gamma_u = 6.46$) and that proposed by Miner in function of the β the life fraction.

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

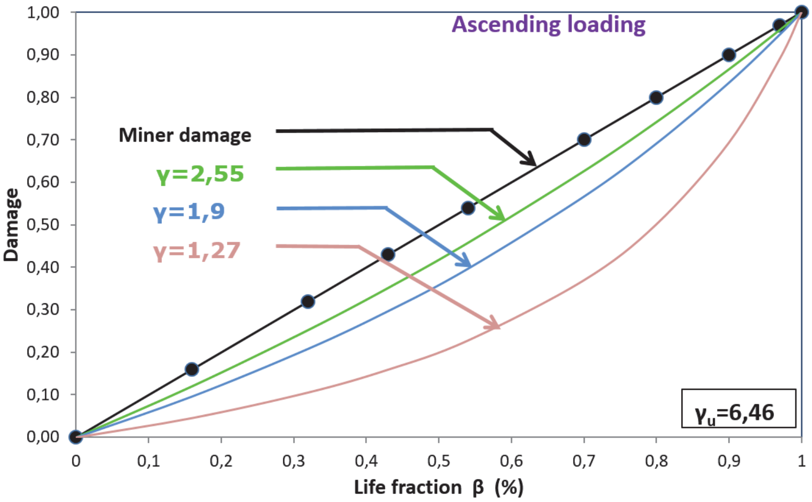

Figure 7: Unified theory damage variation in function of the life fraction β.

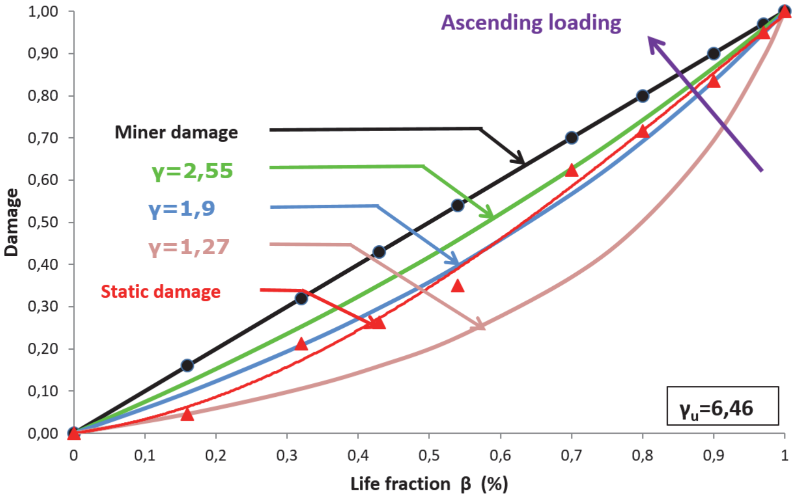

Figure 8: Experimental, unified and Miner damages comparaison.

## CONCLUSION

The polypropylene random copolymer (PPR) is a thermoplastic material used for the transport of under pressure water, especially hot waters. In the industrial conditions, PPR pipes are exposed to severe conditions in terms of pressure and temperature. In order to characterize the behavior of the PPR at failure we have performed tests of overpressures at the laboratory scale according to ASTM D1599 standard, on virgin and notched pipes. According experimental and theoretical results. Many results have been found:

- The notch had caused a drop of the ultimate pressure of the notched pipes compared to the undamaged ones. The increase in depth of the notch leads to a depletion of residual ultimate pressures of PPR notched pipes.
- The calculation of the damage, by the experimental damage formulation, have led to determine the three stages of evolution of the damage initiation, progression and acceleration of damage.

- The use of experimental damage ensures an optimization of maintenance costs for defective pipes by predicting low values of damage in comparison with that one gives by Miner's model.
- The calculation of the reliability allows the defining the depth β=a/t of external longitudinal groove in a PPR pipe that corresponding to 50% of reliability.
- In the framework of the preventive maintenance, at a value of 70% of the total depth of a longitudinal external groove, it is recommended to repair or change the defective pipe before that defect becomes unstable and causes costly fractures.
- The comparison of the unified theory damages calculated for different load levels revealed that the loading level γ = 1.9 gives the best results with respect to the static damage, it seems most realistic to properly describe the progression of the damage of the tubes PPR with defects in the form of external longitudinal grooves.

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## NOMENCLATURE

| | |
|---|---|
| $\gamma$ | $P_{ur} / P_a$ Parameter characterizing the effect of the damage on the mechanical characteristics of the material. |
| $\gamma_u$ | $P_u / P_a$ Parameter reflecting the strength of the material in a virgin state. |
| n | is the instantaneous number of cycles under an applied stress. |
| $N_f$ | is the total number of cycles at the rupture. |

| | |
|---|---|
| $P_{ur}$ | is the ultimate residual pressure. |
| $P_u$ | is the ultimate pressure corresponding to an undamaged HDPE specimen. |
| $P_a$ | is the pressure just before the rupture. |
| $P_0$ | is the endurance limit's corresponding pressure. |
| $\sigma_\theta$ | is the circumferential stress. |
| R | is the radius of the pipe specimen. |
| t | is the thickness of the pipe specimen. |
| a | is the notch depth |
| D | is the damage ($D = 0$ for neat material, $D = 1$ for completely damaged material). |
| $\beta$ | $(a/t) = (n/N_f)$ is the life fraction |