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Damage Characterization of a Thin Plate Made Of ABS under Uniaxial Solicitation

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Abstract: *There is an important soaring in theuse of polymers in many industrial fields. Although they are abundantly used both in ordinary and high performance products, their versatility makesthem highly needed for newer applications; and thisrequires a detailed knowledge of their physical, chemical, rheological and mechanical properties. The determination of mechanical behavior of those materials becomes very necessary either during processing or under operation. In this work, we are interested in characterizing a notched polymeric ABS flat plate under uniaxial solicitation. TheUnified Damage Theory for characterizing and quantifying the damage is used. Our crucial aim, being thestudy of the stress concentration factor,and a contribution to the determination of the damage degree of notched structures.*

Key words: *Damage mechanics, Damage theory, Uniaxial characterization, Softened polymer, ABS.*

I. INTRODUCTION

Many engineering studies show that whatever the material (metal, polymers, composites, or wood),in spite of their various microstructures and physical properties, the qualitative mechanical behavior they exhibit is substantially identical. These include an elastic behavior, a yield stress, certain plasticity or irreversible deformation, more or less important deformation anisotropy, a hysteresis ring with damage by monotonic or cyclic loading, and a crack initiation under static or dynamic loading [1].Additionally, they exhibit many levels of imperfections, due to processing, post processing handling such as transportation and storage. Such imperfections include knit lines, flaws, vacuum or inclusions which make polymer-based structures heterogeneous to a certain degree.

The consequences of the presence of knit lines for example in such materials on the mechanical properties are discussed by Criens and Moslé [2]. Due to the presence of crazes, scratches, cracksand other imperfections, the mechanical properties of realpolymeric materials are not as good as they theoretically could be [3].Damage mechanics aimsat modeling these phenomena at the level of structures calculations. The purpose of this approach being to build behavior models which once included in a calculation code,could simulate the fracture and, more generally, to estimate the state of damagesin a structure according to one or many ultimate states [4].Modeling the structural behavior of polymers has been the subject of a range of researches. In this regard, several authors have addressed the problem of rheological behavior [5], formingand processing modeling [6], and the behavior during the failure process [7].This work is a contribution to the study of the failure mechanism of a flat plate made by ABS (Acrylonitrile-Butadiene-Styrene). Initially, the structural behavior of a smooth plate has been studied, in aim to study and reveal the mechanical characteristic under uniaxial solicitation tensile test, followed by a series of tests conducted on notched flat plates, the notch effect will be discussed and highlighted through experimental results. Finally, through the application of the stress concentration factor criteria [8], and the Unified Damage Theory [9], the damage evolution in the ABS material is investigated.

II. THEORY

Generally, damage decreases the stiffness and resistance of materials. For a given stress state, the deformations are all larger than the damage is high. Hence the importance of coupled calculations, which calculates simultaneously stress, strain and damage in mechanical properties evolution problems.The main aim of damage theories is to define a Damage parameter which translates the damage state of the structure. However, it remainsa delicate problem since nothing (or almost nothing!) distinguishes a damaged volume element of a virgin (blank)volume element macroscopically. It is then necessary to imagine an internal variable representing the state of deterioration of the material.

Several modelsare proposed for damage modeling in structural calculation.The most responded modelis the Minner model of damage [10], [11], however it remains limited in its linear method of description of the cumulative damage progress, which does not accurately reflect the state of the deterioration of the structure. Other proposed approaches have tried to adjust this model to a more adequate damage presentation;they include the models of Miller [12] and Chaboche [13]…

In order to address the various points omitted by the theoretical damage models, Bui-Quoc[9] proposed a model that involves several loading parameters. The Unified Theory hasthus been developed in this context, to define damageparameter which is the internal variable that describe the damage state of the structure in terms of the a life fraction$D = f(\beta)$, the fraction of life depends on solicitation conditions (for example the number of cycle for dynamics loading, notch dimension for static tensile loading, temperature conditioning…).In this respect, the endurance limit is defined as the stress level below which there is no damage, the part supports an infinite number of cycles in fatigue tests for example, or its resistance reach the highest level for a notched static test specimen. The rate of reduction of the endurance limitto the number of applied fatigue cyclesfor a dynamic solicitation test was suggested as follows:

$$\frac{d\gamma_e}{dn} = -\frac{1}{K}\gamma^b(\gamma - \gamma_{er})^2 \tag{1}$$

Wherethe various terms are successively:

$\gamma_e = \sigma_e/\sigma_0$	Non-dimensionalendurencelimit
$\gamma = \sigma/\sigma_0$	Non-dimensionalcyclic stress
$\gamma_{er} = \sigma_{er}/\sigma_0$	Instantaneous non-dimensional endurance limit
σ_0	Endurance limit of the virgin material
σ	Applied stress level
K and b	Material constants
n	Number of applied fatigue cycles

With boundary conditions:

i. $n = 0$ $\quad\gamma_{er} = 1$

ii. $n = N_f$ $\quad\gamma_{er} = (\sigma/\sigma_u)^m$

Where N_f is the number of cycles to failure for a fatigue test; for our study, it represents the critical diameter of the hole, m is an empirical material constant superior to one.

$$N_f = \frac{K}{\gamma^b}\left[\frac{1}{\gamma - 1} - \frac{1}{\gamma - (\gamma/\gamma_u)^m}\right] \tag{2}$$

With

$$\gamma_u = \sigma_u/\sigma_0$$

This equation determines the relationship between stress and applied number of cycles. The normalized damage is defined by:

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

With

$$\gamma_e = \sigma_e/\sigma_0$$

By setting ~~posing~~ $\beta = n/N_f$ this theory leads to the following equation:

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

For the damage quantification in the material, we used the damage variable for each life fraction, so by analogy with theory shown above, the life fraction of our study representsthe relationship between the hole diameter progressionand its critical value, which is the value of the larger hole diameter. Based on the earlier presented theories, we chose the law of damages given by the unified theory. The mean advantage of this theory relative to other approaches is to directly link the damage progressof the material to the variation of the ultimate residual limit, thus directly connecting the material’s damage to its characteristics.

Thedamage variable can thusbe defined as:

$$D = \frac{1 - \frac{\sigma_{ur}}{\sigma_u}}{1 - \frac{\sigma_l}{\sigma_u}} \qquad (5)$$

Where

σ_{ur} is theultimate residual stress

σ_u is the ultimate limit,

σ_l is the stress limit

III. Experimental

A series of tests was carried on forthe characterization of material damage, on two series ofrectangular specimensofABS (Acrylonitrile-Butadiene-Styrene), based on theguidelines prescribed by the ASTM D 882-02 [14] and ASTM D5766M [15]. Thefirst series consisted ofrectangular smooth specimens (without hole) to characterize the materialand the second series consisted of rectangular specimens with holes of 1 mm to 7mmdiameters. The first series was used as the reference, and the second to monitorandhighlight the influence of the hole size on the specimenbehavior. All the experimental series was conducted under controlled displacement. Elongations were determined using the displacement sensor crosshead incorporated in the machine. Figure 1 below shows the set-up for the tensile test.

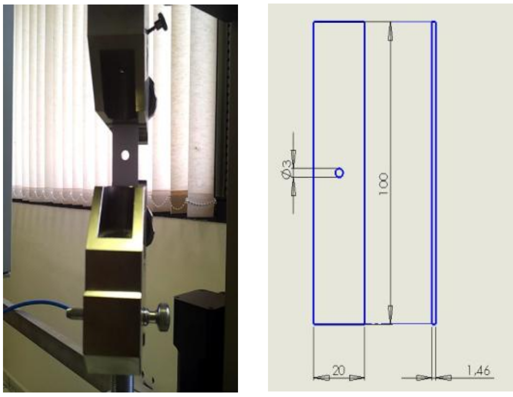

Figure 1. Experimental set-up:A test specimen held by the sample holder of the tensile testing machine (left), anddimensions of the test specimen (right).

IV. RESULTS

In the notched specimen, a stress concentration phenomenon near the hole takes place, and the response of the structure to the applied effort is affecteddepending on the hole diameter, we talk here on a notch effect.

Figure 2 shows the stress versus strain curves for the specimens with holes.As the tests proceed, these curves show a strikingdecreasing pace, and the gap between the values.

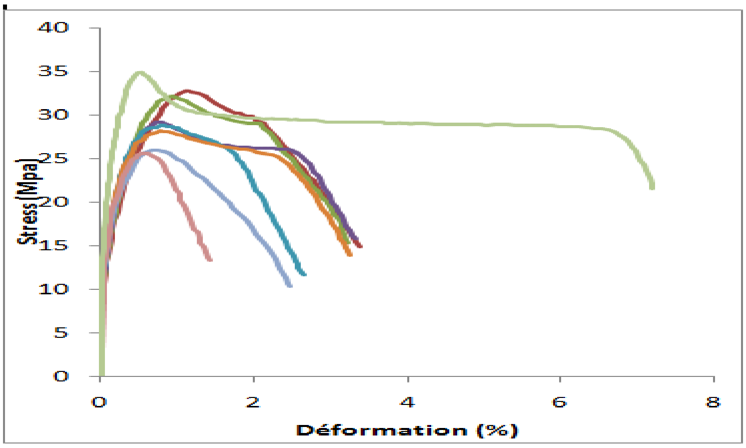

Figure 2. Evolution of the stress-strain curves foruniaxial tensile tests on rectangular test specimens with 1mm to 7mm hole diameters, according to ASTM D 882-02 two and ASTM D5766M

In fact, these curves showa remarkable degradation of the mechanical properties of the material with an increase in hole diameter; these properties include the elastic stress, ultimate stress, the failure stress and the elongation.We observe an area of stress stabilization, and a high elongation (maximum elongation). Additionally, rupture is often preceded by local yielding followed byanabrupt failure.The mechanical characteristics are affected due to the notch effect; the characteristics decrease as long as the notch diameter increases. Figures 3 showsthe evolution of the ultimate stress thewithhole diameter:

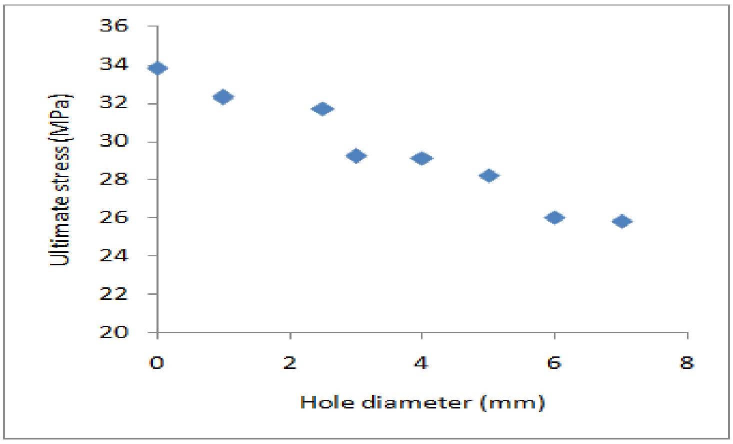

Figure 3. Ultimate stress evolution withhole diameters

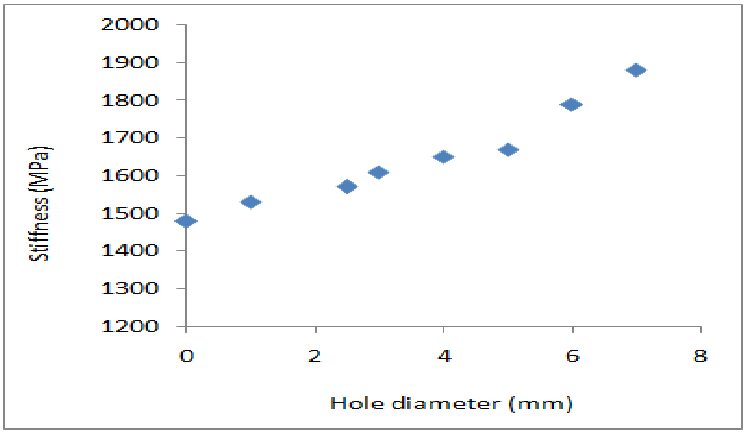

Figure 4. Stiffness evolutionwithhole diameters

As already mentioned above, a decrease in the ultimate stress (maximum stress value reached in the tensile test) with hole diameters was observed.The right branchof the stress-strain curve present the elastic response of the specimen, this branch allows the calculation of the *Young Modulus*. However, with the existence of the hole, we talk more about *Stiffness*for notched specimens'more than *Young modulus* for smooth specimens. The stiffness determines then the elastic response limits for notched structures. Figure 4 shows a significant rise in stiffness until values closer to those given by smooth specimens which represent the Young's modulus.As discussed above, the existence of notch affect the mechanical characteristics of the material, the evolution of its size has also remarkable influence on those properties. Figure 5 shows aschematicalevolution of the ultimate nondimensional stress versus nondimensional hole diameter.The ultimate nondimensional stress was obtained by nondimensionalization of the ultimate residual stress (the residual ultimate stress is given as the ultimate value of stress reached by a sane specimen in a simple tensile test, for our study, its value is $\sigma_{ur} = 34\ MPa$) by the ultimate stress level obtained for each hole diameter.The same for the nondimensional hole diameter which was obtained by nondimensionalization of the hole diameter by the critical hole diameter (the larger value of the hole diameter above which the structure no longer support any effort).

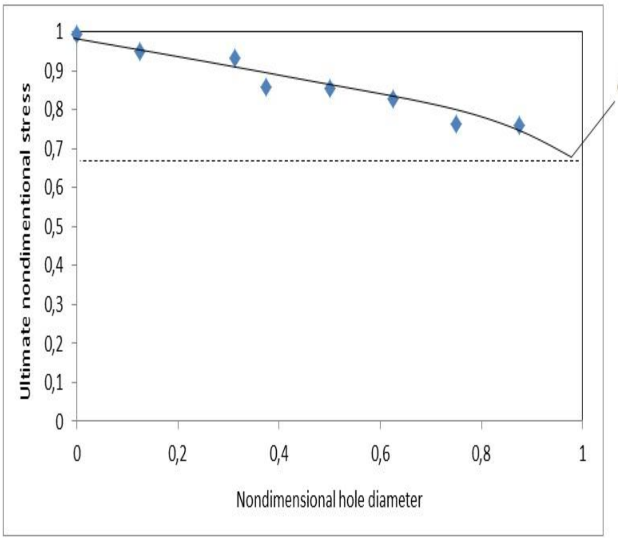

Figure 5. Evolution of the ultimate nondimensional stress versus the nondimensional hole diameter

Figure 5 illustratesthe ultimate nondimensional stress evolution versus thenondimensionalholediameter; the curve shows a decrease of the material ultimate stress while the nondimensional hole increases. The intersection with the interval limit allows us to determine a stress limit below which we estimate that the damage occurred to the material remains acceptable, this stress limit has as value $\sigma_l = 24.82\ MPa$.Figure 6 reports the variation of the resistance loss with the nondimensional diameter of the holes. It shows that the resistance loss is remarkable and it becomesincreasingly important when approaching the critical value of the default already prescribed.The aim of this representation is to show the resistance loss of the material due to the damage accumulation, this damage itself is due to the notch and its evolution in the structure.Fatigue behavior of the material,ascharacterized through its endurance limit,allows us to determine the endurance limit that will be used later for the quantification of the material damage. The endurance limit was determines for the ABS smooth samples, throughfatigue test, and takes as value $\sigma_0 = 18\ MPa$ [16].

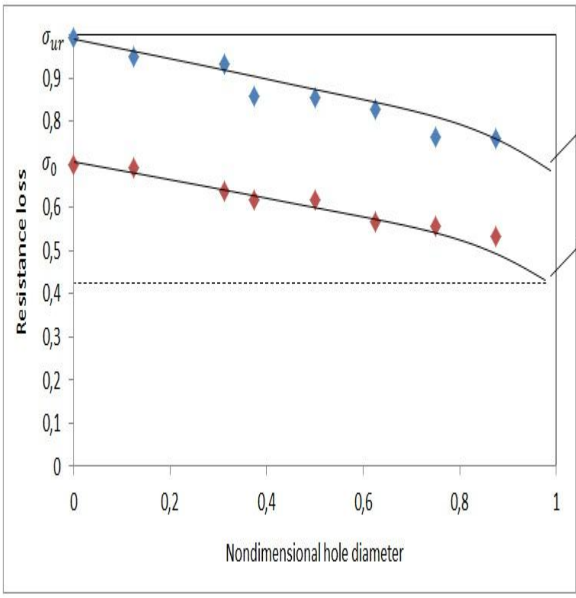

Figure 6. The resistance loss in static tension

Both curves of Figure 6 have the same shapelike the one giving the variation of the ultimate limit. Both show a resistance decrement while the nondimensional hole diameter keep increasing. Theintersection between the later curve andthe boundary of the interval of study gives a value $\sigma_0^* = 7.2\ MPa$which is considered thesafe endurance limitvaluebelow which nofatigue failure will occur.

V. DAMAGE IN THE ABS NOTCHED PLATES

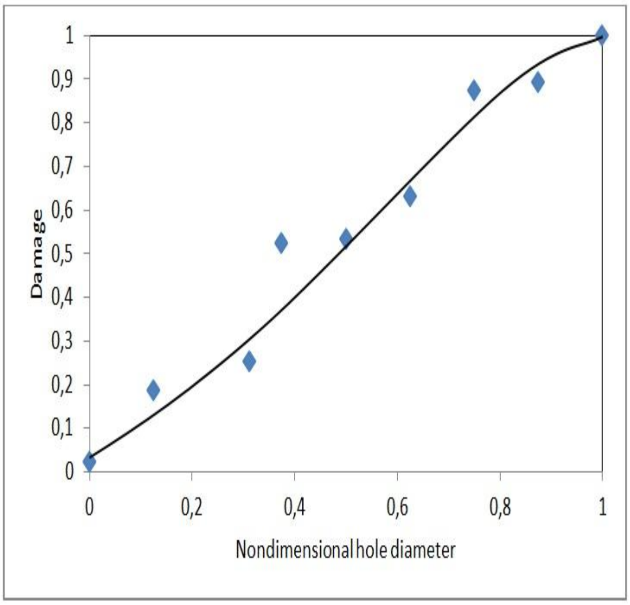

Figure 7. Evolution of the damage versus the fraction of life

For quantifying the damage occurred into the notched structure, we propose a damage variable based on presentation demonstrated above in equation (5). The proposition of this variable was taken by analogy with cumulative damage theory proposed by Gatts [17] and retaked by Bui-Quoc [9]. The proposed approach present the damage evolution into a notched structure, and link the damage state of the material to an intrinsic property which is its residual stress.The damage on the notched samples with the non-dimensional hole diameters is shown in the figure 7. The damagenearlyfollowsa linear variation.At theinitiation, the damage is negligible$(D \approx 0)$for a smooth flat plate. As the hole size increases,the damage acceleratesa maximum value of 0.9is reached where failure occurred.The initiation area is characterized by the highest mechanical characteristics for the materials, while the point of failure is marked by their remarkable degradation.

VI. STRESS CONCENTRATION IN THE NOTCHED ABS PLATES

The concept of a stress concentration factor is often employed by designers to account for the increase of stress at a concentration point, the nominal stress being multiplied by a stress concentration factor to obtain and estimate of the local stress at the point.Generally, Stress concentration is a phenomenon of a local stress increasing in an area which contains geometric modifications [18].It appears in a discontinuity of a part or a structure for examplewith the presence of a notch after machining. The area of stress concentration is most often the site of crack initiation.In many cases, particularly in which the stress is highly localized, a mathematical analysis proves difficult or impracticable. Then, experimental or mechanical methods of stress analysis are used. The vicinity of the incident formis characterized by a heterogeneous stress distribution leading to the stress concentration, thus stress concentration factor is defined as “the quotient of the maximal applied stress to the corresponding nominal stress” [19]:

$$K_t = \frac{\sigma_{max}}{\sigma_{nom}} \quad (6)$$

The severity of the stress concentration depends on both the notchgeometry and the notchconfiguration. Stress concentration is an important factor to be considered during every structural design, as issues such as sudden break can be avoided either by reducing or by avoiding it [20].
The stress concentration factor variation relative to the specimen ratio hole diameter to width is shown in the figure 8.

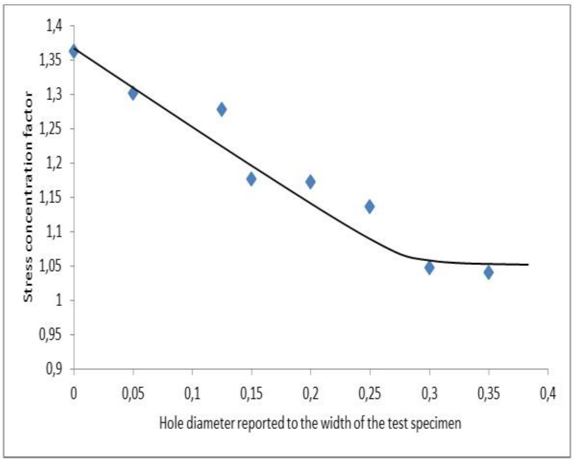

Figure 8.Evolution of the stress concentration factor with the hole diameterbased on the ratio D/W for notched plate

Thestress concentration factor decreases with the ratio D/W.This means that stress concentration increases with a reduction of D/W.Additionally, this concentration tends towards stability when the ratio D/W increases, thus the maximum stress is equal to the nominal stress, and the large size of the defect has no effect on this ratio.

VII. CONCLUSION

The objective of this work was to characterize the damage behavior of a thermoplastic flat plate. It found that the uniaxial tensile test was the most practical approach and the closest representation of the real state of deformation during the real solicitation.Thistechnique was used to describe the damage occurring to the material. The unified damage theory was used in the aim to give a more complete damage model that can more faithfully describe the state of the material. This approach was applied to several materials; however the results reported in this article are only based on ABS.The results obtained have highlighted the applicabilityof the reporteddamage approach. The proposed approach involves the use of theintrinsic parameters ofthematerial, thusa rigorous description of the damage state of the materials. These preliminary studies are essential steps towards the full achievement of our mid-term goals of performing and developing tools for modeling and simulatingof thermoplastic forming processes.

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