Habib Khellafi
Mostefa Bendouba ✉
Hadj Miloud Meddah

https://doi.org/10.21278/TOF.484062523
ISSN 1333-1124
eISSN 1849-1391

EXPERIMENTAL AND NUMERICAL ANALYSES OF DUCTILE FRACTURE OF POLYMERIC MATERIALS

Summary

Most failures of structural components in service are related to the presence of geometric micro-defects in the material that occurred during its processing. In other words, real materials often contain internal defects such as micro-cracks or cavities. During the deformation process, under sufficient load, these internal defects can propagate and, at the same time, new micro-defects occur in the area of stress concentration (inclusions, voids, etc.). This phenomenon influences the macroscopic properties of the material, gradually decreasing its mechanical strength. The process of structural deterioration of the material, resulting from the nucleation and growth of micro-defects, is called damage. This paper focuses on the application of a three-dimensional finite element method based on a local approach in order to study the effect of nucleation and growth of micro-voids on the failure of polymer materials. A parametric analysis was carried out to study the sensitivity of the fracture parameters of the Gurson-Tvergaard-Needleman (GTN) model in terms of the stress-strain behaviour and ductility of the material in service. The numerical results obtained from those parametric studies were validated by comparing them with the experimental results in terms of stress-strain behaviour.

Key words: *Ductile fracture; the Gurson-Tvergaard-Needleman (GTN) model; Finite element analysis; Stress field; Growth and coalescence*

1. Introduction

The current technology requires materials with a combination of properties superior to those provided by conventional materials, as has often been demonstrated in the aeronautical and aerospace, automobile, and sports industries. This need has been satisfied to a large extent by the development of composite and polymeric materials that are designed to have a set of specific properties to meet technical requirements. Among the existing materials, polymers are the most outstanding materials. The behaviour of polymers is not linear and requires calculating the behaviour of the stress-strain function to obtain the functional parameters that make up a large deformation model.

The term "ductile fracture" is used ambiguously in the literature, mainly with two meanings. In micromechanical investigations, the term refers to the type of fracture resulting from nucleation, growth, and coalescence of voids in the material. On the other hand, in macroscopic applications, it is related to the large deformation of the material before failure occurs. At the microscopic level, ductile fracture has for a long time been attributed to a process that involves concurrent and mutually interactive mechanisms, which include: (i) the nucleation of voids or inclusion cohesion; (ii) the growth of void induced by plastic deformation and void bonding (coalescence); (iii) plastic flow located between two voids; and (iv) the final opening of a crack in the material. Studies of the growth of micro-voids in metals were carried out by Mc-Clintock [1] and Rice and Tracey [2].

Rice and Tracey described the void deformation as a function of the ratio between the hydrostatic stress and the equivalent stress, called the triaxiality parameter. Their models exhibited failure when the accumulated damage variable reached a critical value. Recently, the triaxiality parameter has been studied by Topilla and Toros [3].

Gurson [4] considers the plasticity function of a porous material and adds a new parameter whose goal is to take into account the nucleation, coalescence, and growth of voids during the damage. Later, Tvergaard [5] and Tvergaard and Needleman [6] improve the model developed by Gurson [4] by considering the volume fraction of voids as a function of the nucleation of new voids and the growth of existing voids during the damage. It is known that the polymer material, when used for polymer pipes, offers several advantages: good resistance to wear and corrosion, low density, low cost, ease of installation, durability and reasonable mechanical resistance, and the ability to be produced in complex shapes [7, 8]. Tvergaard and Needleman showed that the fracture behaviour of a high-density polyethylene (HDPE) pipe is related to the loading condition, the shape, and the position of the crack in the wall of the pipe.

Through the determination of the damage parameters inherent in the Gurson-Tvergaard-Needleman (GTN) damage model and a subsequent comparison of the predicted outcomes with experimental results, a satisfactory level of agreement was attained by Topilla and Toros [3]. This agreement, in turn, enabled the identification of the complete set of parameters required for the GTN damage model.

In other words, it is known that during the process of forming solid materials, the plastic instability phenomena often control the appearance and performance of the finished product, according to Moulai et al. [9], Khellafi et al. [10], and Zaim et al. [11,12]. These authors examined the effect of stress triaxiality on the mechanical behaviour response of polyvinylchloride (PVC), polybutylene terephthalate (PBT) and thermoplastic copolyetherester (TPC) under large plastic strain. They have concluded that the damage evolution of PVC and PBT in service has been influenced by the level of stress triaxiality. On the other hand, it is known that the voids have different expansion rates in different directions under service loading and that changing this parameter changes the critical strain of unstable (coalescing) voids, according to Kim et al. [13].

In general, the ductile fracture process is influenced by several microstructural and mechanical factors. Among the microstructural factors, the size and geometry of the particle (inclusion or second-phase particle) and volume fraction corresponding to the particle can be mentioned. Among the mechanical factors, we should mention the resistance of the particle matrix interface, the matrix resistance, and the present stress level at the interface. Zhang et al. [14] presented phenomenon-based hybrid experimental testing and finite element simulations to describe the fracture behaviour of pipe-grade polyethylene. Their results show that with the consideration of damage evolution, the constitutive equations enable the finite element simulation to determine the whole stress–strain relationship during both the necking and fracture processes.

Samal et al. [15] used an extended classical Gurson-Tvergaard-Needleman (GTN) model as a non-local damage parameter in the finite element formulation. They indicated that the evolution of the non-local damage is related to the actual void volume fraction and conclude that the different GTN parameters have a great effect on the fracture behaviour of the materials. A further examination of this subject can be found in Refs. [16–21]. In other words, for the case of polymeric materials, the fracture has been carried out both in dynamic [22, 23] and quasistatic [24] regimes and examined from experimental, numerical, and analytical points of view.

Based on the above, it can be noted that the nucleation of voids is caused by second-phase particles (phases are the different micro-structures of the material) that break or cohesion from the matrix material during plastic deformation. The size and shape of the second-phase particles or inclusions play a very important role in the nucleation mechanism. In addition, the ductile fractures, especially the failure of polymer materials, are not fully understood and represent a very active research field. In this study, we focus on the determination and optimization of the GTN parameters in order to predict the mechanical behaviour and ductile failure of polyvinylchloride (PVC). Full details and information about this polymer can be found in [10].

2. Gurson–Tvergaard–Needleman (GTN) Model

In ductile fracture, the only adjustable microstructural parameter in the Gurson model [4] is the volume fraction of the cavity f; the matrix is supposed to be rigid and isotropic, and it meets the Von Mises plasticity criterion. Tvergaard and Needleman [6] developed the Gurson model by adding the description of the coalescence of cavities by internal striction (the GTN model). The constitutive equation of the GTN model is expressed as:

$$\Phi\left(\sum ,\bar{\sigma}, f\right) = \frac{\sum_{eq}^{2}}{\bar{\sigma}^{2}} + 2 q_1 f^{*} \cosh\left(\frac{3}{2} q_2 \frac{\sum_m}{\bar{\sigma}}\right) - 1 - \left(q_1 f^{*}\right)^{2} = 0 , \tag{1}$$

where q_1 and q_2 are the damage coefficients involved in the load function, which mainly depend on the plasticity of the matrix [6]; σ_y corresponds to the flow stress with strain hardening of the material without cavities.

From the nucleation of cavities or pre-existing cavities, the volume fraction of cavities f begins to increase under the effect of plastic deformation cumulated with the growth rate [6]:

$$\dot{f}croissance = \left(1 - f\right) \dot{\varepsilon}_{kk}^{p} , \tag{2}$$

with $\dot{\varepsilon}_{kk}^{p}$ representing the hydrostatic plastic deformation.

The evolution of porosity is the result of the germination of new cavities and the growth (coalescence) of already existing cavities. This evolution is described in the following form:

$$\dot{f} = \dot{f}nucluation + \dot{f}croissance \tag{3}$$

The coalescence is described by the acceleration of the growth rate of cavities in the GTN model. The function f^* represents the effective porosity, and it is necessary to describe the appearance of coalescence beyond a critical porosity f_c; the effective porosity is expressed as follows:

$$f^{*}\left(f\right) = \begin{cases} f & \text{if } f \le f_c \\ f_c + \delta\left(f - f_c\right) & \text{if } f > f_c \end{cases} , \tag{4}$$

with $\delta = \dfrac{f_u^{*} - f_c}{f_F - f_c}$,

where $f_u = 1/q_1$ is the effective porosity at break and f_f is the porosity at break.

3. Experimental procedure

The tensile tests were carried out on a conventional INSTRON 1341 hydraulic machine (Figure 1a). Tensile specimens were machined with the dimensions and geometry according to the ASTM D 638 standard [25] shown in Figure 1b with dimensions expressed in millimetres. The quasi-static tension test was carried out under a crosshead speed of 0.04 mm s^{-1}. The tensile test bench is connected to a video-metric system (video-traction), which is based on the precise measurement of the local geometry of a specimen during deformation. This is made possible due to a video camera connected to a micro-computer equipped with an image analysis system. The elastic properties obtained for this polymer material (PVC) at room temperature were: Young's modulus, $E = 650$ MPa; Poisson's ratio, $\upsilon = 0.4$; and the yield strength, $\sigma_e = 40$ MPa. The uniaxial stress–strain curve of this material at room temperature for a level of strain rate equal to 0.001 s^{-1} ($d\varepsilon/dt = 0.001$) is given in Figure 1c.

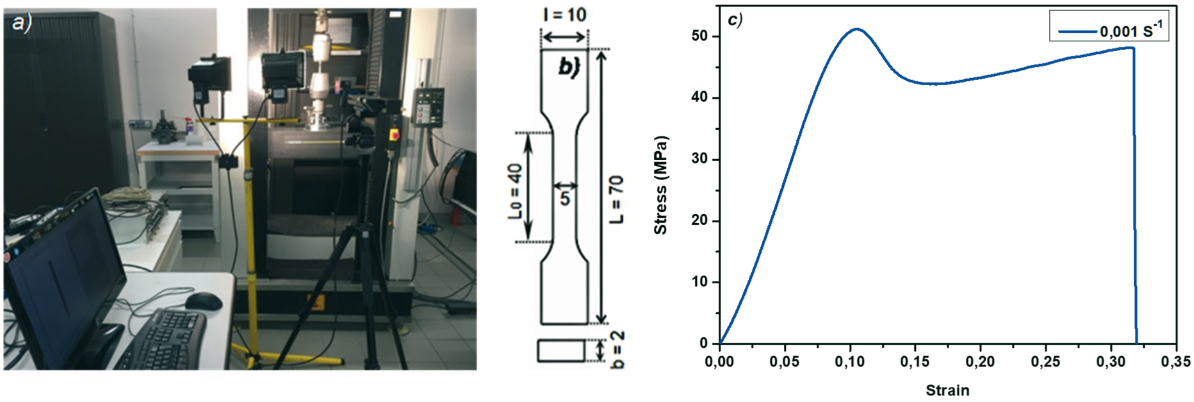

Fig. 1 a) The traction machine with the measuring system; b) Specimen geometry (all dimensions in mm); c) Uniaxial stress–strain curve of the PVC at room temperature and $d\varepsilon/dt = 0.001$.

Thirteen specimens were tested at various speeds (the speed ranged from 0.05 to 0.2 ms^{-1}). The breaking of major specimens occurred at the end of the useful area near the transition radius of the specimens, while in other specimens, the rupture occurred in a more central area, as can be seen in Figure 2. The usable area is calculated from the width and thickness of the specimen, and their breaking usually occurs where the area is smaller. This phenomenon can be explained by the existence of porosities in the specimens during the processing of polymer materials, which has led to a change in the site of the crack initiation and growth in the weakest area of the specimen. The same conclusion has been reached by other authors [9, 26].

Fig. 2 Typical failure mode of PVC specimens

4. Finite element analysis

Ductile fracture develops relatively slowly and is accompanied by a large plastic deformation. The growth of a crack in a ductile material is said to be stable because the crack stops propagating unless there is an increase in the stress level. In this type of fracture, the occurrence of three main stages is observed: (a) formation of a free surface or void over the inclusion or secondary phase particles dispersed in the material; (b) growth of the void (or voids) around the particle; and, finally, (c) coalescence of adjacent voids [6]. The damage to polymeric materials is not fully understood and represents a very active research field.

The focus of this study is numerical simulation using the finite element method to predict the overall behaviour of a PVC material based on the damage GTN model. In this context, computational modelling, particularly the finite element analysis (FEA), is a good choice. An innovative and useful approach to the problem of damage to polymeric materials is to use FEA in conjunction with the data obtained from experiments. When a detailed evaluation of the damages that occurred or a description of the stress and strain fields in the structure are of interest, the finite element method [27] becomes the most used method due to the possibility of determining all the variables (mechanical quantity) with great precision.

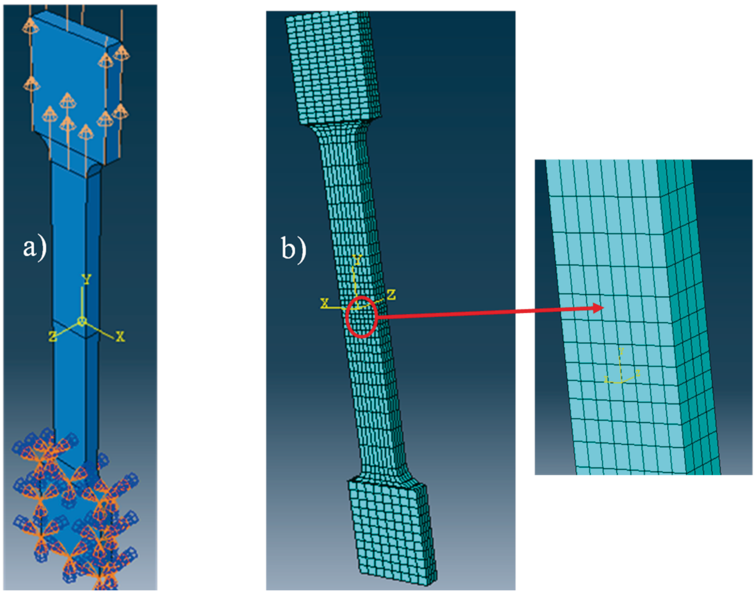

Fig. 3 a) Illustration of the specimen geometry with the boundary and loading conditions, b) Meshing of the specimen.

This study is a contribution to a parametric analysis in order to optimize the fracture parameters of the GTN model for a polymeric material; it is necessary to understand the effects of fracture parameters on the mechanical behaviour of a PVC material. Figure 3 shows a PVC plate according to ASTM D638 M1A [25] and the boundary conditions employed in the finite element models. A three-dimensional solid element (hexahedral elements: C3D8R) is used for the modelling; this element is defined by eight nodes, each having three degrees of freedom. A mesh sensitivity study was carried out. The typical model for this study contains 3240 nodes and 2272 elements for the specimen under tension loading. The properties of the material used in the modelling are the same as those listed in Section 3, Experimental procedure.

The theory of incremental plasticity is introduced to the modelling of the material nonlinearity. The Newton–Raphson iterative method is used as an approach to solving nonlinear equations by finite elements.

5. Results and discussion

The objective of this numerical study is the analysis of the fracture behaviour of the PVC materials using the three-dimensional finite element method. Figure 4 shows the distribution of the Von Mises stresses within the flat test specimen for a strain rate equal to 0.001 ms^{-1} and for the calculation times. The figure shows the evolution of the Von Mises stress at different increments during the tensile test simulation.

The results show that the maximal stress is concentrated in the weakest area of the specimen. Consequently, the presence of the very high stress gradient at this location can favour the crack growth, which leads to a sudden failure by the presence of the service loading. Also, we note that the results of the numerical simulation have the same crack initiation and rupture mechanisms as the experimental results. These comparisons demonstrate the ability of finite element modelling, taking into account the ductile failure of material, to predict faithfully the global mechanical behaviour of a PVC material.

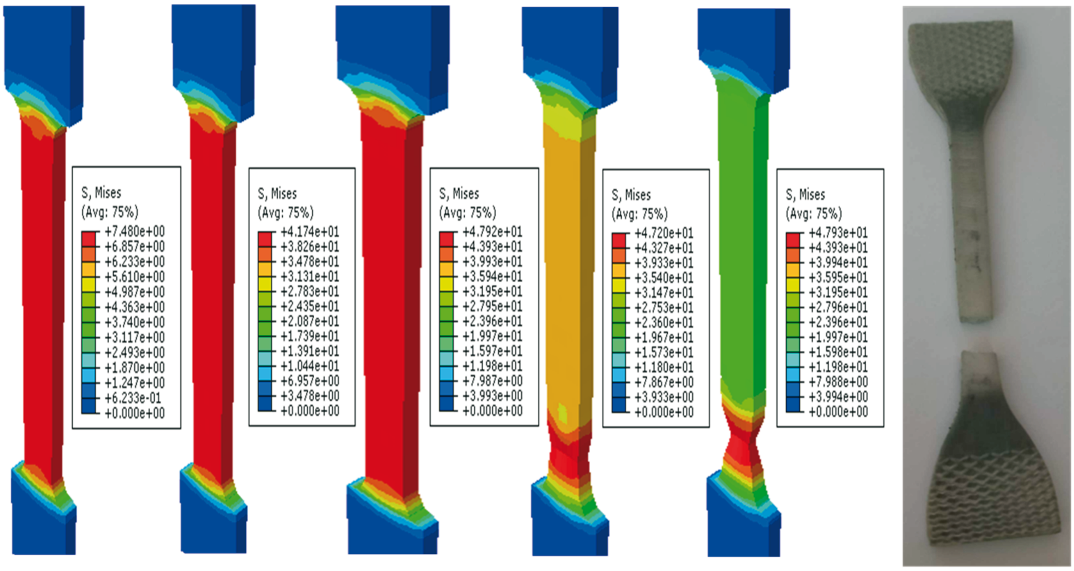

Fig. 4 Stress distribution in a flat specimen for various level loadings (numerical and experimental)

5.1 Parametric study

Micromechanical models describe the nucleation-growth-coalescence damage mechanism of cavities as a function of the stress and strain states. These models take into account the stress state and the microstructural factors that are required in the finite element simulation. In this study, the GTN model is used in order to analyse the damage to the PVC material tested. In this form, this model requires eight parameters: q_1, q_2, f_n, f_f, f_c, where q_1 and q_2 are the coefficients introduced by Tvergaard, and f_n is the parameter that can be determined from the volume fraction of inclusions. The parameters related to the nucleation stage, nevertheless, remain difficult to identify experimentally. The volume fractions of critical cavities f_c and f_f ruptures are adjusted by the fitting of the numerical and experimental results from tensile tests. In this section, we focus on a parametric study in order to determine the effect of these parameters on the mechanical response of the PVC material in service.

5.1.1 Effect of the q_1 parameter

The effect of q_1 on the mechanical response of the PVC material in terms of stress versus strain is shown in Figure 5. These results show that the shape of any stress-strain curve is similar with respect to the value of the q_2 parameter. An increase in the value of the q_1 parameter reduces the plastic deformation, which accelerates the crack growth. We conclude that the sensitivity of the behaviour of the PVC material to the $q_1$parameteris very strong. For the value of q_1 = 0.5, it is noted that there is no significant change in the stress-strain curve (see Fig. 5.a).

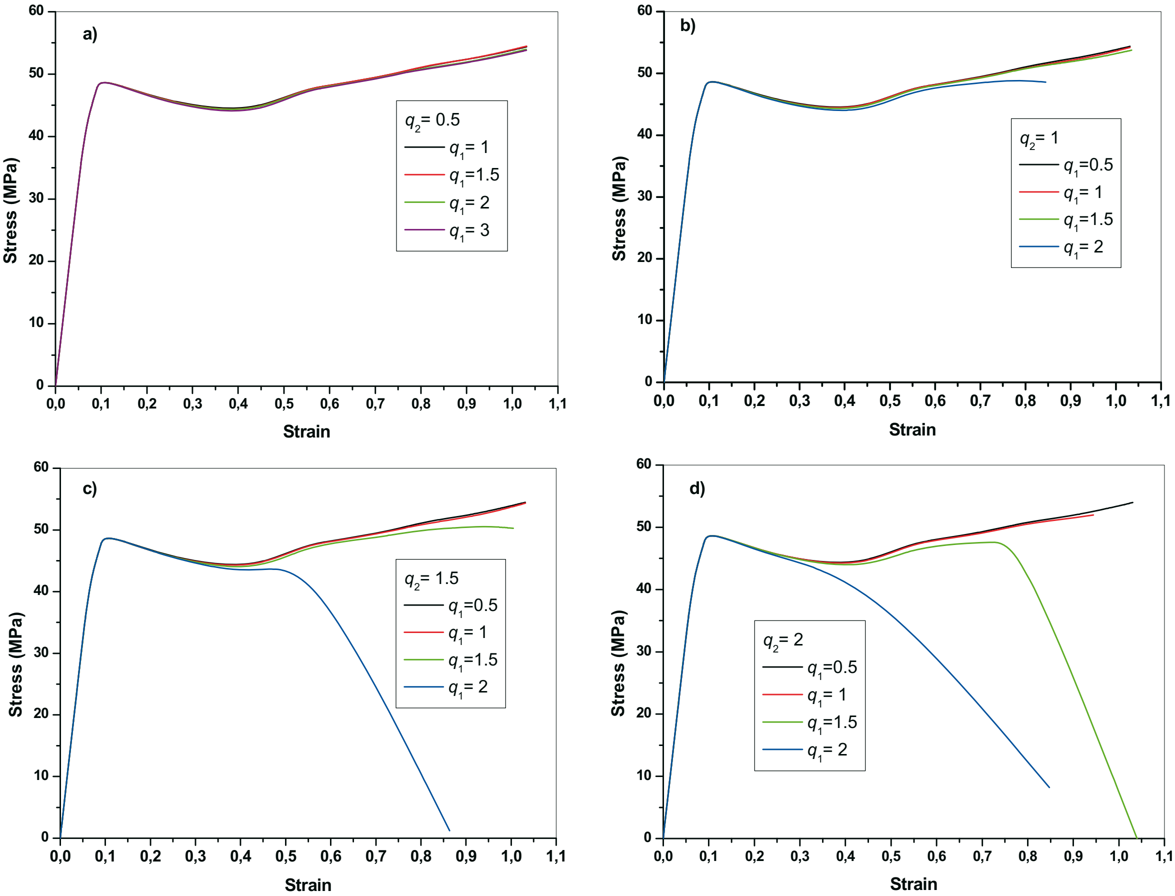

Fig. 5 Effect of the q_1 parameter with a) q_2= 0.5, b) q_2= 1, c) q_2= 1.5, and d) q_2= 2

Bi-linear behaviour, that is, pre-cracking (elastic behaviour) and post-cracking to the total failure (appearance and development of the damage within the volume of the material), is also noted.

5.1.2 Effect of the q_2 parameter

The effect of q_2 on the mechanical response of the PVC material in terms of stress with respect to strain is shown in Figure 6. We observe that the effect of the $q_2$parameter is similar to that of q_1; this means that increasing values of q_2 significantly reduce the plastic deformation of the material. In other words, the reduction in the value of q_2 leads to fewer defects in the PVC material and makes it possible to retard the crack initiation and growth. We recall also that the combination of the q_1 and q_2 parameters for given loading conditions and the environmental effect (temperature, time) tends to reduce significantly the lifetime of any material in service.

In addition, the GTN parameters are not easy to determine, especially for polymer materials. This behaviour has been confirmed by other authors [28] in terms of loading-displacement response of materials.

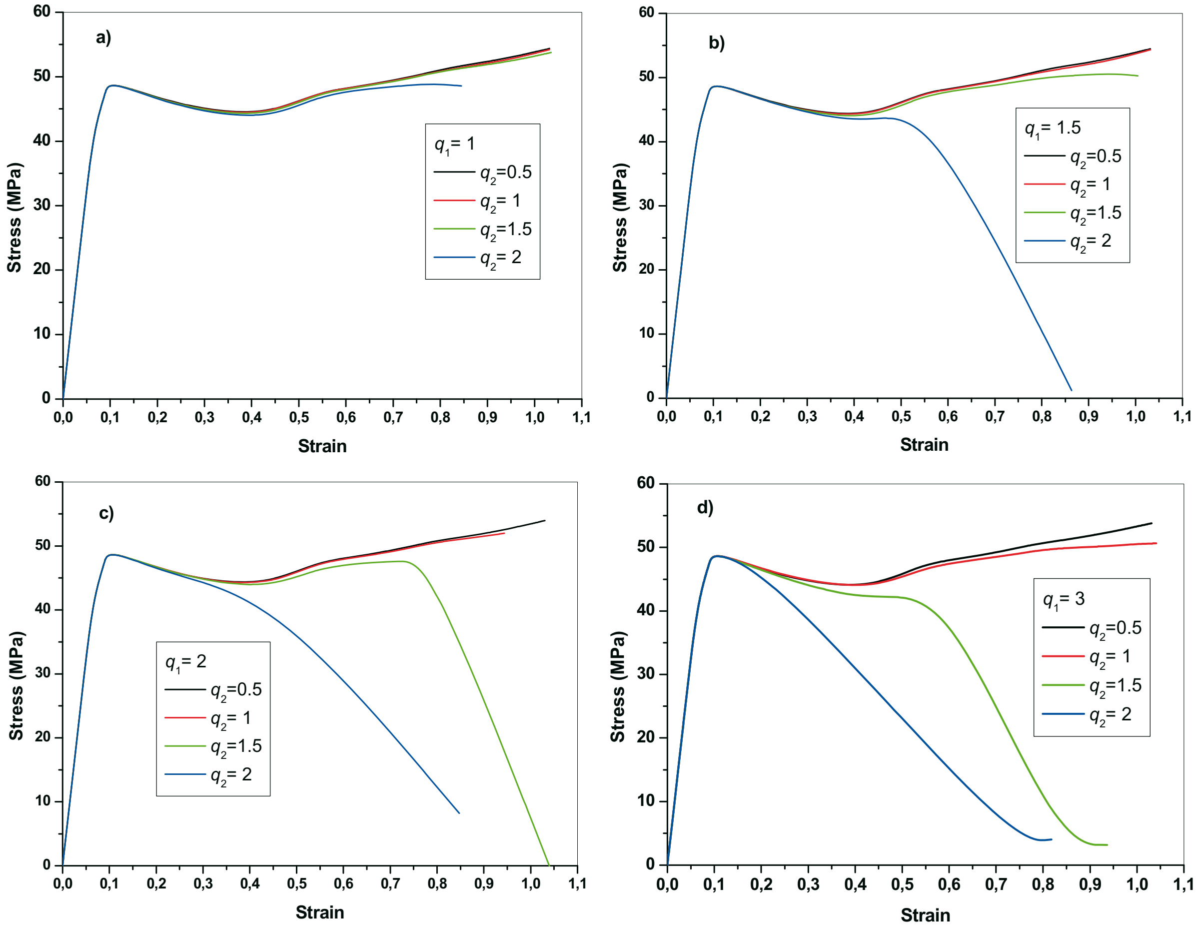

Fig. 6 Effect of the q_2 parameter with: a) q_1= 1, b) q_1= 1.5, c) q_1= 2, and d) q_1= 3

5.1.3 Optimization of the f_c, f_f, and f_n parameters

Several studies, e.g., [26-28], have shown that the micromechanical parameters of the GTN model are very important factors that affect the ductile failure behaviour of materials. In this section, the effects of these parameters (f_c, f_f, and f_n) on the fracture behaviour of the PVC material are analysed (Figure 7). From this figure, one can see that the f_n parameter has a great effect on the mechanical response of the material; a decrease in the f_n value leads to the improvement of the PVC material behaviour in service. The effect of the parameters f_f and f_c is the inverse of that of the f_n parameter (see Figures 7a and 7b). We also recall that, in order to predict the ductile failure of any mechanical component based on the micromechanical approach, we need a local approach such as the damage GTN model. The latter requires several parameters, which are not easy to determine for polymer materials. Zhang et al. [29] acquired f_c from tensile tests and found an infinite number of pairs of (f_0, f_c) that gave identical predictions. One attractive feature of this model is that ductile failure of the material is exclusively linked to the micro-void nucleation parameter, and the nucleation parameter, in many cases, can be determined without metallurgical examinations. In the same context, experimental and numerical investigations have been carried out by Kiran and Khandelwal [30] to determine the complete set of the GTN model parameters. They found a unique combination of f_c and f_f values that best match the experimental load-displacement history, while Benseddiq and Imad [31] suggested that the f_n parameter can be evaluated by microscopic examination of the undamaged material.

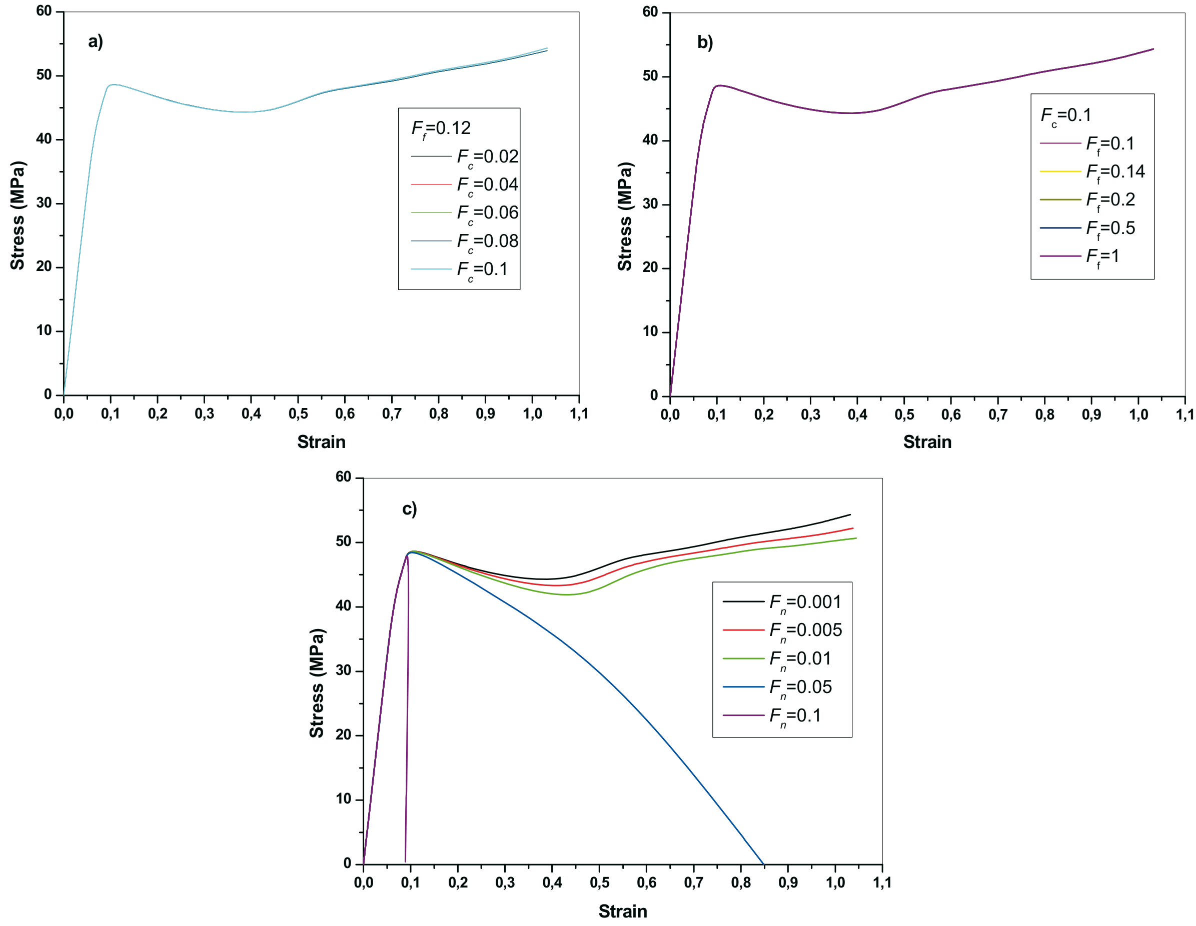

Fig. 7 Effects of f parameters: a) f_f , b) f_c , and c) f_n

5.1.4 Validation of FEM

Accurate identification of remaining GTN model parameters (q_1, q_2, q_3, f_f, f_c, and f_n) is crucial for a successful ductile fracture analysis. Figure 8 shows the comparison of finite element results predicted by the GTN model and experimental stress-strain curves for the same PVC material. We notice that a good correlation was found between experimental stress-strain records and the finite element simulation results, thus confirming the validity of the present numerical analyses of the polymeric material damage.

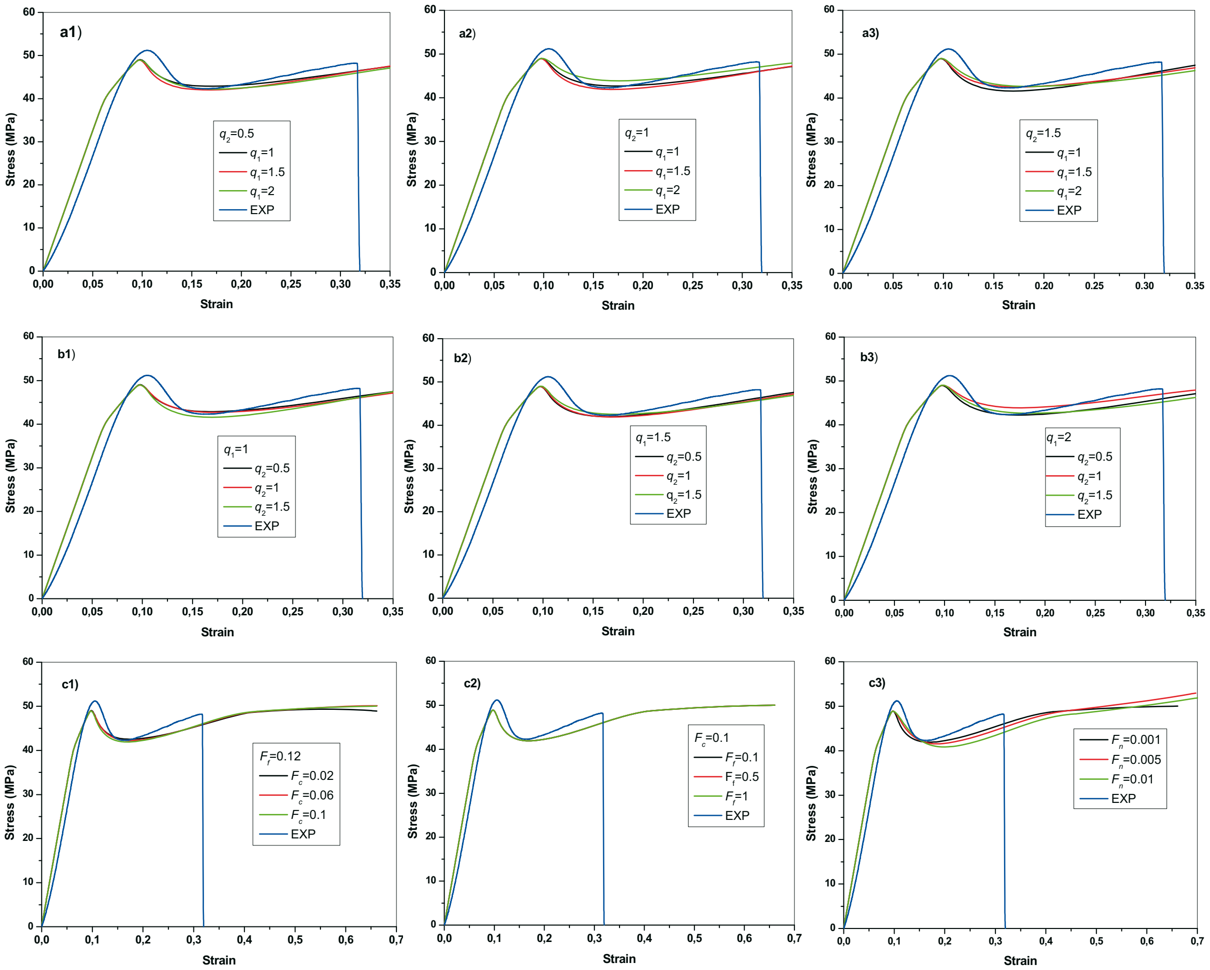

Fig. 8 Ductile fracture prediction of the GTN material model compared with the experimental results

The identified optimum calibratedvalues of the GTN model for the PVC material tested in this research are:

$$q_1 = 2,\ q_2 = 1,\ q_3 = q_1^2 = 4,\ f_f = 0.12,\ f_c = 0.02 \text{ and } f_n = 0.001.$$

6. Conclusion

It is known that the macroscopic behaviour of a material is determined by phenomena that occur at microstructural scales, in which it is extremely difficult to carry out an adequate experimental evaluation. This study was carried out in order to analyse the effect of some parameters of the GTN damage model on the mechanical response of a polymeric material under tensile loading. This model does not explicitly account for strain rate. However, it can indirectly capture this effect by calculating the strain rate based on the loading rate and predefined solution time. This calculated strain rate then influences the void growth within the model.

The GTN damage model relies on ten constants obtained through expensive and lengthy experiments. This study proposes a more efficient method for determining six of these constants for the PVC polymer material tested, requiring only quasi-static tensile tests combined with numerical techniques.

The obtained results allow us to draw the following conclusions:

- The fracture prediction was assessed using the GTN model using the finite element method.
- The GTN model faithfully reproduces the macroscopic mechanical behaviour of the PVC material in terms of stress versus strain.

- A good correlation was found between the experimental stress-strain records and the finite element simulation results; these results validate the present numerical analyses of the polymeric material damage.
- The validity of the finite element damage analyses is checked by comparing their results with the experimental test.
- The efficiency of the model is extended to predicting the deformed geometry, including necking patterns, crack initiation sites, and propagation paths. This was confirmed by comparing the simulated sections with those obtained from fractured samples in experiments.

REFERENCES

[1] McClintock, F. A. A. Criterion for Ductile Fracture by the Growth of Holes. Journal of Applied Mechanics. Jun 1968, 35(2): 363-371. https://doi.org/10.1115/1.3601204

[2] Rice J.R; Tracey D.M. On the ductile enlargement of voids in triaxial stress fields. Journal of the Mechanics and Physics of Solids, 1969, (17): 201. https://doi.org/10.1016/0022-5096(69)90033-7

[3] L. Topilla, S. Toros. Analysis of the fracture behaviour of dual-phase steels using the Gissmo and Johnson cook models. Transactions of Famena. 2023, 47(3): 79-95. https://doi.org/10.21278/TOF.473040522

[4] Gurson, A. Continuum theory of ductile rupture nucleation by void and growth: part 1. Yield criteria for porous flow rules ductile media. Journal of Engineering Materials and Technology 1977, (99): 2–15, https://doi.org/10.1115/1.3443401

[5] Tvergaard, V. Influence of voids on shear band instabilities under plane strain condition. International Journal of Fracture. 1981, (17): 389–407. https://doi.org/10.1007/BF00036191

[6] Tvergaard, V.; Needleman, A. Analysis of the cup-cone fracture in a round tensile bar, Acta Metallurgica. 1984, 32(1): 157–169. https://doi.org/10.1016/0001-6160(84)90213-X.

[7] Benhamena, A.; Bachir Bouiadjra, B.; Amrouche, A.; Mesmacque, G.; Benseddiq, N.; Benguediab, M. Three finite element analysis of semi-elliptical crack in high density poly-ethylene pipe subjected to internal pressure. Materials and Design. 2010, 31 (6): 3038–3043. https://doi.org/10.1016/j.matdes.2010.01.029

[8] Benhamena, A., Aminallah, L., Bachir Bouiadjra, B., Benguediab, M., Amrouche, A., Benseddiq, N. J integral solution for semi-elliptical surface crack in high density poly-ethylene pipe under bending. Materials and Design. 2011, 32 (5):2561–2569. https://doi.org/10.1016/j.matdes.2011.01.045

[9] Moulai A.; B., Ould Chikh, B.; Meddah, H.M.; Bachir Bouiadjra, B. Plasticity Effect on the Mechanical Behaviour of an Amorphous Polymer, International Journal of Engineering Research in Africa. 2019, (43):1-19. https://doi.org/10.4028/www.scientific.net/JERA.43.1

[10] Khellafi, H.; Meddah, H.M.; Ould Chikh, B.; Bouchouicha, B.; Benguediab, M.; Bendouba, M. Experimental and Numerical Analysis of the Polyvinyl Chloride (PVC) Mechanical Behaviour Response, CMC, 2015, 49-50(1): 31-45. https://doi.org/10.3970/cmc.2015.049.031

[11] Zaim. A.; Benattou B.;Meddah H. M, Ould Chikh. E. The Stress Triaxiality Effect under Large Plastic Deformation of a Polybutylene Terephthalate (PBT), International Journal of Engineering Research in Africa. 2018, 34: 13-28. https://doi.org/10.4028/www.scientific.net/JERA.34.13

[12] Zaim. A.; Chikh El Bahri, O.; Benattou, B. Thermo-Mechanical Characterization of a Thermoplastic Copolyetherester (TPC): Experimental Investigation. Fibers and Polymers, 2018, 19(4): 734-741. https://doi.org/10.1007/s12221-018-7455-1

[13] Kim, J., Gao, X., Srivatsan, T.S., 2003. Modeling of crack growth in ductile solids: a three-dimensional analysis. Int. J. Solids Struct. 2003, 40: 7357–7374. https://doi.org/10.1016/j.ijsolstr.2003.08.022

[14] Zhang, Y.; Jar, PYB.; Xue, S.;Li, L. Numerical simulation of ductile fracture in polyethylene pipe with continuum damage mechanics and Gurson-Tvergaard-Needleman damage models. July 2019Proceedings of the Institution of Mechanical Engineers Part L Journal of Materials Design and Applications 233(12), 2455-2468.https://doi.org/10.1177/1464420719863458

[15] Samal, M.K.; Seidenfuss, M.; Roos, E.; Dutta, BK, & Kushwaha, HS. A Mesh Independent GTN Damage Model and Its Application in Simulation of Ductile Fracture Behaviour. Proceedings of the ASME 2008 Pressure Vessels and Piping Conference. Volume 3: Design and Analysis. Chicago, Illinois, USA. July 27–31, 2008. pp. 187-193. ASME, https://doi.org/10.1115/PVP2008-61026

[16] Gholipour, H.;Biglari, F.R.; Nikbin, K., Experimental and numerical investigation of ductile fracture using GTN damage model on in-situ tensile tests, International Journal of Mechanical Sciences (2019), 164(1):105170 https://doi.org/10.1016/j.ijmecsci.2019.105170

[17] Rahimidehgolan, F.; Majzoobi, G.; Alinejad, F.; Fathi Sola, J. Determination of the Constants of GTN Damage Model Using Experiment, Polynomial Regression and Kriging Methods. www.mdpi.com/journal/applsci. Applied Sciences, 2017, 7(11): 1-20. https://doi.org/10.3390/app7111179

[18] West, O.; Lian, J, Münstermann; S.;Bleck. Numerical Determination of the Damage Parameters of a Dual-phase Sheet Steel. ISIJ International, 2012, 4(52): 743–752. https://doi.org/10.2355/isijinternational.52.743

[19] Farahani, B. V.; Amaral, R, Paulo.;Tavares,P.J.; Santos A.D. Material characterization and damage assessment of an AA5352 aluminium alloy using digital image correlation. Journal of Strain Analysis 2019. 1-17. https://doi.org/10.1177/0309324719892727

[20] Benzerga, A.A. Micromechanics of coalescence in ductile fracture. Journal of the Mechanics and Physics of Solids. 2002, (50): 1331–1362. . https://doi.org/10.1016/S0022-5096(01)00125-9

[21] Liu. P. F.;Zheng , J. Y. Finite element analysis of tensile behaviour of ductile steel with defects. Journal of Failure Analysis and Prevention. 2010, (10): 212–217. https://doi.org/10.1007/s11668-010-9337-8

[22] Kopp, J.B.; Fond. C.; Schmittbuhl, J, Noel. Dynamic fracture in rubber toughened polymers: the influence of the fracture surface roughness. Procedia Structural Integrity 2016, (2): 468–476. https://doi.org/10.1016/j.prostr.2016.06.061

[23] Nezbedová, E.; Hodan, J.; Kotek, J.; Krulis, Z.; Hutař, P.; Lach, R.lifetime of polyethylene (pe) pipe material prediction using strain hardening test. Deformation and Fracture Behaviour of Polymer Materials,2017, (247): 203-210. https://doi.org/10.1007/978-3-319-41879-7_14

[24] Lach, R.; Grellmann, W. Time-dependent fracture behaviour of polymers at impact and quasi-static loading conditions. Deformation and Fracture Behaviour of Polymer Materials, 2017, (247): 3-21. https://doi.org/10.1007/978-3-319-41879-7_1

[25] ASTM D 638, American Society for Testing and Material Standard. Test Method for Tensile Properties of Plastics; 2002

[26] Manaia, J P., Francisco A. P, Abílio M. P. de Jesus. Elastoplastic and fracture behaviour of semi-crystalline polymers under multiaxial stress states. Frattura ed Integrità Strutturale, 2018, 13(47): 82-103. https://doi.org/10.3221/IGF-ESIS.47.08

[27] Abaqus, 2014. Version 6.14 User's Manual, Dassault Systèmes Simulia Corp.; Providence, RI, USA

[28] Farbaniec, L.;Couque. H.; Dirras. G. Influence of Triaxial Stress State on Ductile Fracture Strength of Polycrystalline Nickel. International Journal of Fracture. 2013, (182): 267–274. https://doi.org/10.1007/s10704-013-9854-z

[29] Zhiliang, Z.; C Thaulow.; J. Ødegård. Complete Gurson model approach for ductile fracture. Engineering Fracture Mechanics, 2000, 67(2): 155-168. https://doi.org/10.1016/S0013-7944(00)00055-2

[30] Kiran, R.;Khandelwal, K.., 2014b. Gurson model parameters for ductile fracture simulation in ASTM A992 steels. Fatigue & Fracture of Engineering Materials & Structures (2016), 37: 171-183. https://doi.org/10.1111/ffe.12097

[31] Bensеddiq, N.;Imad, A. A ductile fracture analysis using a local damage model. International Journal of Pressure Vessels and Piping. 2008, (85): 219–227. https://doi.org/10.1016/j.ijpvp.2007.09.003

Submitted: 25.12.2023

Accepted: 13.5.2024

Khellafi Habib
Bendouba Mostefa*
Meddah Hadj Miloud
University Mustapha Stambouli of
Mascara, Mascara, Algeria
*Corresponding author:
m.bendouba@univ-mascara.dz