The notch effect on fracture of polyurethane materials

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ABSTRACT. This paper investigates the fracture properties and notch effect of PUR materials with four different densities. The asymmetric semi-circular bend specimen was adapted to perform mixed mode fracture toughness tests. This semi-circular specimen with radius R, which contains an edge crack of length a oriented normal to the specimen edge, loaded with a three point bending fixture, was proved to give wide range of mixed modes from pure mode I to pure mode II, only by changing the position of one support. Different types of notched specimens were considered for notch effect investigations and the Theory of Critical Distances was applied. It could be seen that the critical distances are influenced by the cellular structure of investigated materials.

KEYWORDS. Polyurethane materials; Notch effect; Fracture toughness; Theory of critical distances.

INTRODUCTION

Polyurethane (PUR) materials are polymers composed of a chain of organic units joined by urethane links. Low density polyurethanes (30 - 200 kg/m^3), having closed cell foam structure, are used to manufacture flexible, high-resilience seating; rigid foam insulation panels; microcellular foam seals and gaskets, high durable elastomeric wheels and tires, automotive suspension bushings, [1]. While for higher density polyurethanes (> 200 kg/m^3), with a porous solid structure, the main applications are fixtures and gauges, master and copy models, draw die moulds, hard parts for electronic instruments. The properties of these materials are influenced by the properties of solid material, by the cellular structure topology and the relative density, [2, 3].

Cellular and porous materials crush in compression, while in tension fail by propagating of single crack. Most of the rigid polymeric foams have a linear – elastic behavior in tension up to fracture, and a brittle failure, [4].

Components made of cellular or porous materials may have micro-structural defects like cracks, filled cells or missing walls holes induced by manufacturing process, [5]. On the other hand macro-structural notches or holes may be introduced in design of components. The influence of notches on the strength of the structures is an important issue, which should be considered on the design stage. Up to now there are only few studies investigating notch effect on foam and porous materials mainly regarding metallic foams [6 - 8] and polymeric foams [6, 9]. The notch effect was experimentally investigated [6, 9], but also computational studies [7, 8] were performed.

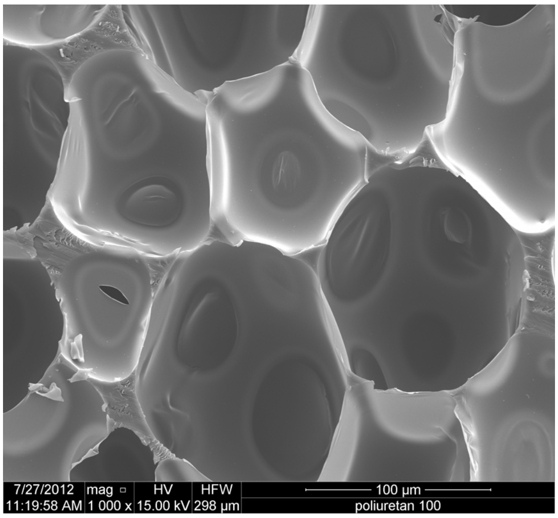
The Theory of Critical Distances (TCD) was proved to be an useful engineering tool to predict the failure of notched components for different types of materials [10 - 12]. This paper proposes the use of TCD approach to quantify the notch effect in cellular and porous materials. A correlation of characteristic length and inherent stress to microstructure dimensions and ultimate tensile stress of the material is proposed, which could be used in design to quantify the notch effect of cellular and porous materials.

MATERIALS

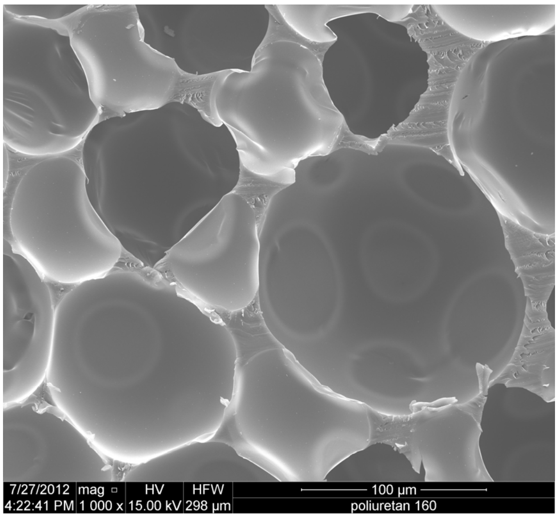
Polyurethane (PUR) materials of four different densities (100, 145, 300 and 708 kg/m^3) manufactured by Necumer GmbH, Germany under commercial designation Necuron (100, 160, 301 and 651) were investigated. At low densities 100 and 145 kg/m^3 the materials have a closed cellular structure, while the PUR materials of higher densities show a porous solid structure. The microstructures of the investigated materials (at 1000x magnification) were obtained using QUANTA™ FEG 250 SEM and are presented in Fig. 1. The results of statistic analysis of microstructures are shown in Table 1 together with the experimentally determined values of the densities according with ASTM D 1622-08 [13].

Necuron	100	160	301	651
Cell diameter, [µm]	104.5±9.4*	83.8±9.6*	68.5±33.9*	49.1±30.2*
Cell wall thickness, [µm]	2.9-5.8	5.1-13.1	3.8-21.8	4.7-37.6
Density (determined), [kg/m^3]	100.35±0.25*	145.53±0.22*	300.28±1.38*	708.8±3.45

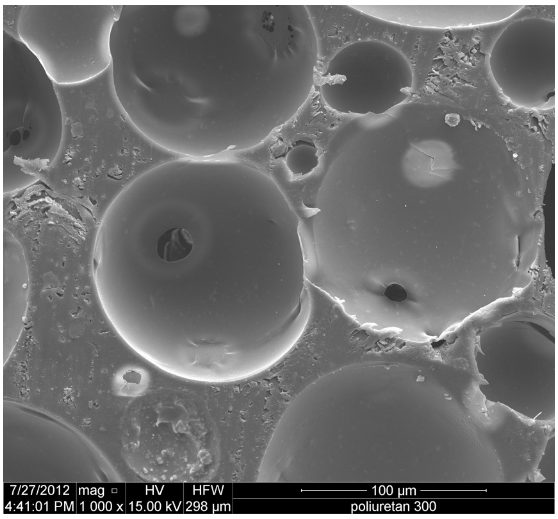
Table 1: Characteristics of the microstructure and determined densities. (* standard deviation values)



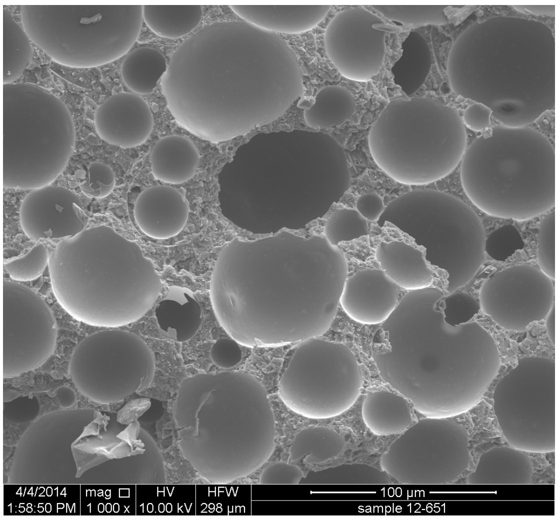
a) Necuron 100



b) Necuron 160



c) Necuron 301



d) Necuron 651

Figure 1: Microstructures of the investigated materials.

The microstructures of all low density PUR materials show a closed cell structure, while the high density materials highlighted a porous solid structure. For all PUR materials a circular shape of cells or pores could be considered with cell diameter and thickness of cell walls as microstructure parameters. The statistical analysis of the microstructure shows a decrease of cell diameter and an increase of cell wall thickness with increasing density.
Tensile tests were performed using dog bone specimens with a gage length of 50 mm and a cross section in the calibrated zone with 10 mm width and 4 thickness, according to EN ISO 527 [14]. The test specimens were cut from PUR panels in flow direction. Four specimens were tested for each material at room temperature and with a loading rate of 2 mm/min using a Zwick/Roell Z005 testing machine with a 5 kN loading cell.
Mode I and mode II fracture toughness were determined using Asymmetric Semi-Circular Bend (ASCB) specimens [15]. This semi-circular specimen with radius R=40 mm and thickness t=10 mm, which contains an edge crack of length a=20 mm oriented normal to the specimen edge, loaded with a three point bend fixture, was proved to give a wide range of mixed modes from pure mode I (S_1=S_2=30 mm) to pure mode II (S_2=2.6 mm), only by changing the position of one support, Ayatollahi et al. [16], Marsavina et al. [17], Negru [18]. Table 2 summarizes the mechanical and fracture properties of the investigated materials.

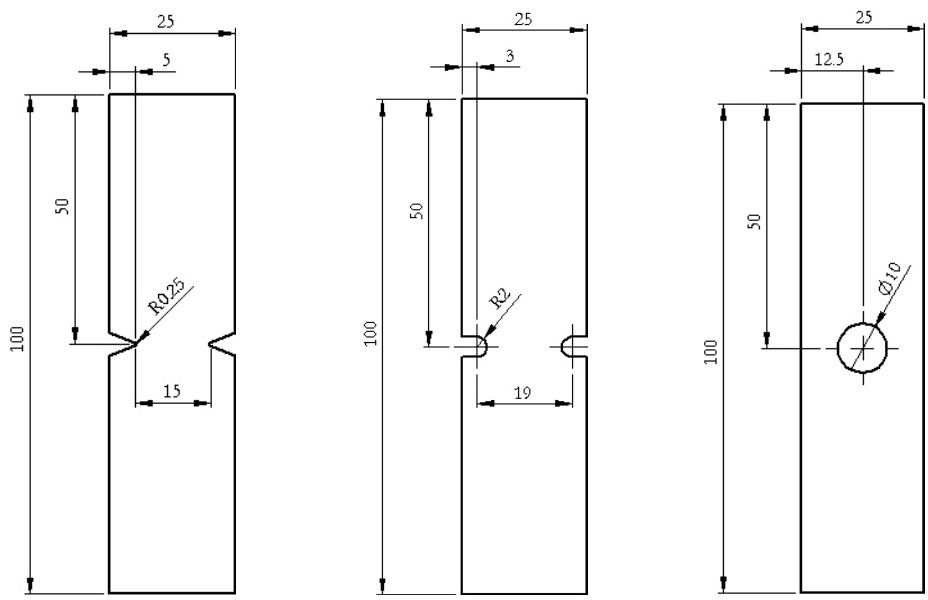
Necuron	100	160	301	651
Ultimate tensile stress, σ_u [MPa]	1.16±0.024*	1.87±0.036*	3.86±0.092*	17.40±0.32*
Young's Modulus, E [MPa]	30.18±1.75*	66.89±1.07*	281.39±2.92*	1250±15.00*
Mode I fracture toughness, K_{Ic} [MPa m$^{0.5}$]	0.087±0.003*	0.131±0.003*	0.372±0.014*	1.253±0.027*
Mode II fracture toughness, K_{IIc} [MPa m$^{0.5}$]	0.050±0.002*	0.079±0.004*	0.374±0.013*	1.376±0.047*

Table 2: Mechanical and fracture properties of PUR materials. (* standard deviation values)

From Table 2 it could be observe that at low densities K_{Ic} is higher than K_{IIc} while at higher densities $K_{IIc} > K_{Ic}$.

NOTCHED SPECIMEN TESTS

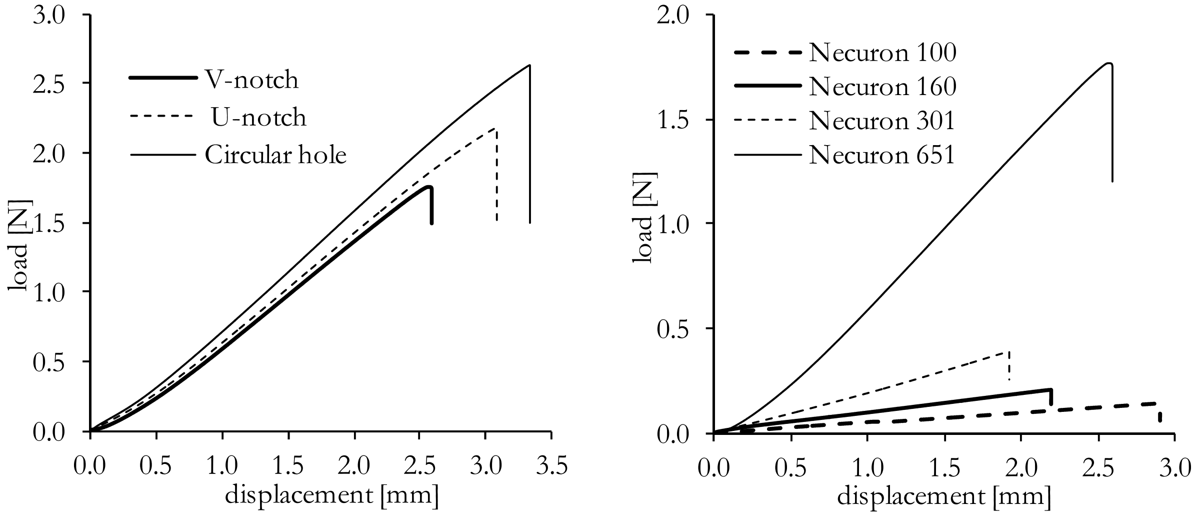
The experimental tests were performed on 5 kN Zwick/Roell Z005 testing machine at room temperature in displacement control at a crosshead speed of 2 mm/min. Fig. 2 presents the notch shapes and the geometrical parameters of specimen used for tensile tests. For each type of notch three specimens were tested.



a) Lateral V-notches b) Lateral U-notches c) Circular hole

Figure 2: Notch shapes and geometrical parameters of used specimens.

Typical load - displacement curves for the Necuron 651 material and different notch shapes are shown in Fig. 3.a, while Fig 3.b presents the influence of density on mechanical properties for lateral rounded V-notches. It could be observed from Fig. 3.a that the maximum load was obtained for circular hole specimen, while the V-notch specimen give the lower value of maximum load. Also, the maximum load increase with increasing PUR material density, Fig. 3.b.



a) Influence of notch shapes b) Influence of density

Figure 3: Load-displacement curves.

For all tested specimens a linear load-displacement behavior was obtained with an abrupt drop of load to zero after reaching the maximum load and brittle fracture was observed. The linear elastic behavior was confirmed during the tests when no plastic deformations remain after finishing the test. The maximum load values resulted from experimental tests are listed in Table 3.

Necuron / F_{max},[N]	100			160			301			651		
V-notch	166.7	143.1	149.1	194.0	186.8	209.1	392.7	376.94	398.5	1827.0	1786.9	1869.1
U-notch	216.1	181.3	190.6	260.9	256.8	270.3	432.88	484.0	452.5	2137.3	2104.7	2177.6
Circular hole	190.5	178.6	159.0	239.0	252.9	295.3	487.38	472.5	471.5	2144.1	2631.8	2047.1

Table 3: The maximum load values.

EVALUATION OF NOTCH EFFECT USING TCD

According to [10] the Theory of Critical Distances (TCD) represents a group of four methods (Point Method, Line Method, Area Method and Volume Method) which have a common approach, i.e. they use the characteristic length L and the inherent stress σ_0 as material parameters. The TCD postulates that brittle fracture in notched components can be predicted by using the linear-elastic stress field acting in the area of the notch tip.

Concerning the mode I loading, the Point Method assumes that brittle fracture occurs when the maximum principal stress σ_1 at the critical distance L/2 from the notch tip, along the bisector, reaches the inherent stress σ_0:

$$\sigma_1\left(r=\frac{L}{2},\theta=0\right)=\sigma_0 \tag{1}$$

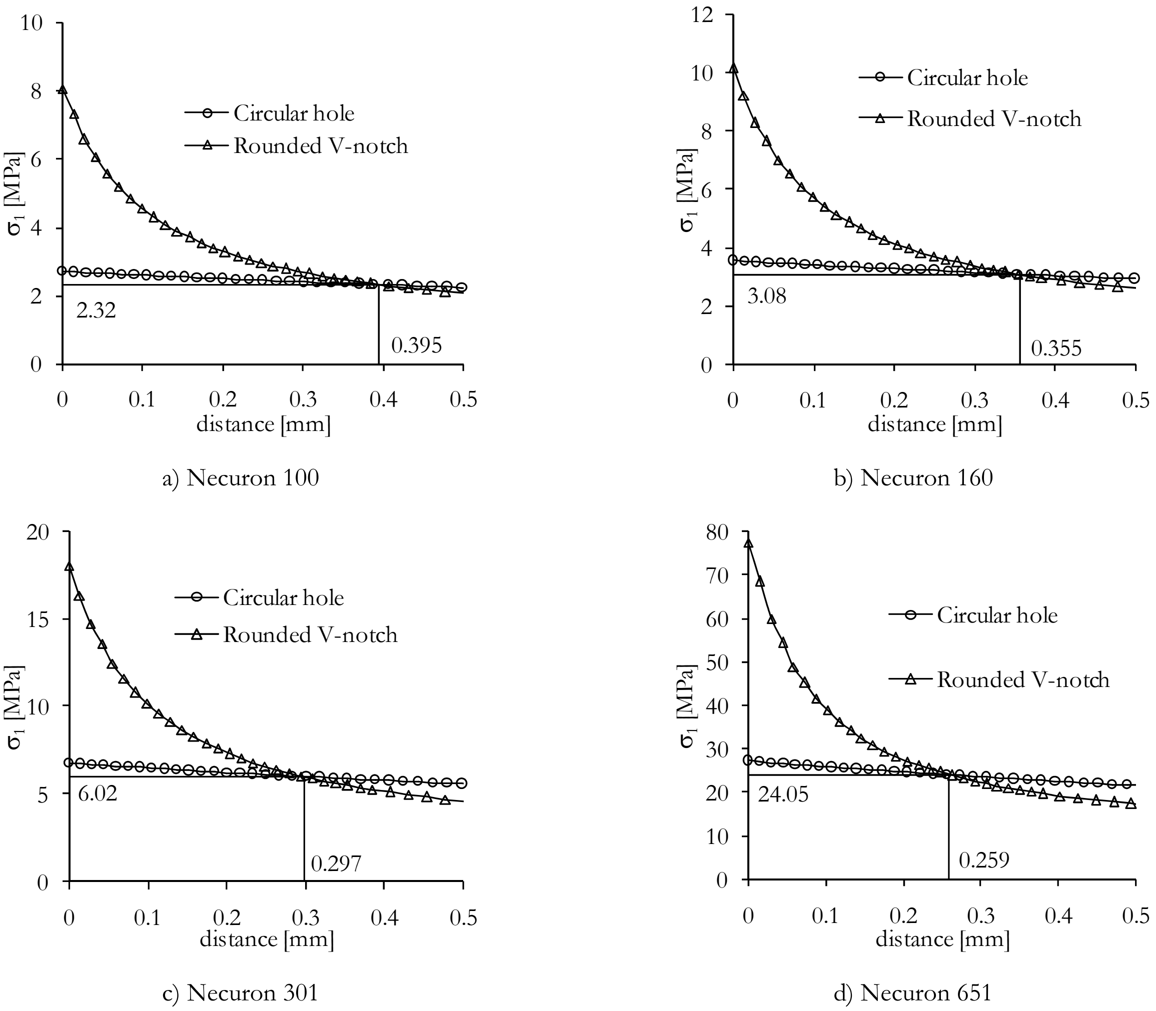
where r and θ are the polar coordinates.

Unfortunately, the inherent stress σ_0 is a material property whose definition varies as the type of material to be assessed changes, [11]. For the situations where the material presents a linear-elastic behavior up to fracture (e.g. ceramics, composites and other brittle or quasi-brittle materials), inherent stress σ_0 is equal to ultimate tensile strength σ_u and the characteristic length L can be determined as follows:

$$L = \frac{1}{\pi}\left(\frac{K_{Ic}}{\sigma_0}\right)^2 \qquad (2)$$

K_{Ic} representing the plane strain fracture toughness. In those situations in which the final fracture is preceded by a limited amount of plastic deformation (metals tested at low temperature) or the fracture of the plain specimens occurs by different mechanisms to those governing fracture of notched components (polymers), the inherent stress σ_0 is larger than σ_u. In these cases the L and σ_0 material constants can be determined by using two experimental results obtained under mode I loading for specimens having different geometrical features, [12]. Thus, plotting at fracture condition the linear-elastic stress-distances curves for a relatively blunt notch and a sharp notch, the intersection point allows the determination of the material constants L and σ_0.

Following this strategy, the linear-elastic stress-distances curves were plotted for all four polyurethane materials, using the experimental results presented in Table 3. As is recommended in [12], the circular hole and the rounded V-notch were used as different stress concentrators in order to obtain accurate estimations for material constants L and σ_0. The stress-distance curves along the notch bisector for maximum principal stress σ_1 were obtained through a linear-elastic finite element analysis. The Abaqus 6.13 software was used to generate the quarter finite element models, using the symmetric boundary conditions. The models were meshed using CPS8R plane 8-node bi-quadratic elements with a suitably high mesh density in the area of the notch tip. The mean values of critical fracture forces were applied as a tensile stress at the ends of the specimens. The results are presented in Fig. 4, and are summarized in Table 4.



a) Necuron 100 b) Necuron 160

c) Necuron 301 d) Necuron 651

Figure 4: Determination of L and σ_0 material constants.

Necuron	100	145	300	651
Length, L [mm]	0.790	0.710	0.594	0.518
Inherent stress, σ_0 [MPa]	2.32	3.08	6.02	24.05

Table 4: Summarized data for material constants L and σ_0.

An attempt to relate the material constants to the cell diameter and ultimate tensile stress of the cellular and porous materials was carried out. Fig. 5.a presents the variation of characteristic length L versus the cell diameter, and Fig. 6.b shows the plot of inherent stress with ultimate tensile stress. Both representations show a linear variation, and indicate an easy way to estimate the material constants (L and σ_0) based on material microstructure (cell diameter) and mechanical properties (ultimate tensile stress).

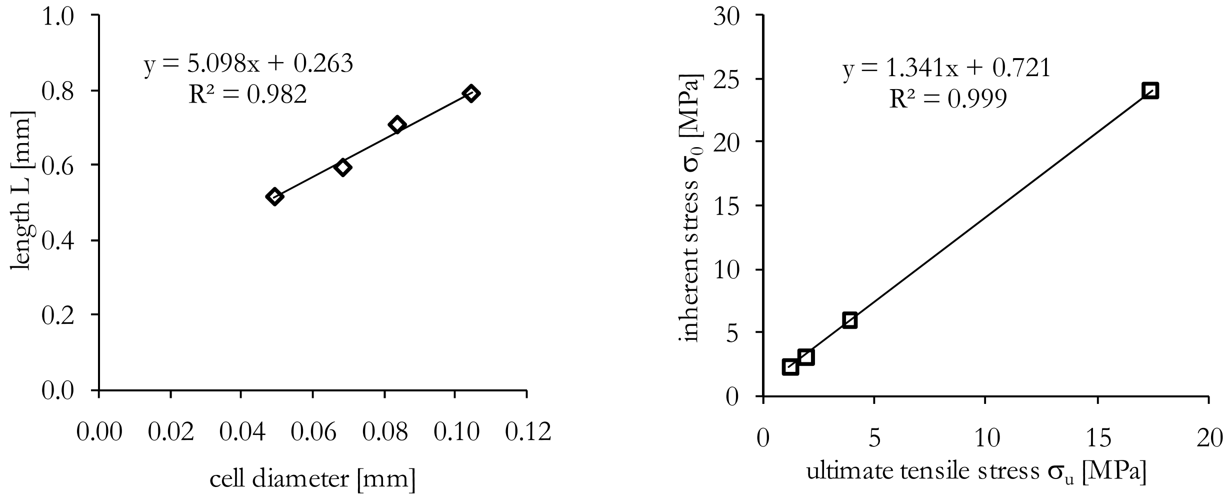


Figure 5. Influence of the relative density on material constants L and σ_0.

Validation of these material constants was performed on other notched geometry, respectively lateral U notches. Starting from the stress-distance curves obtained for an applied tensile stress equal cu 1 [MPa], the failure forces were predicted by simply rescaling these curves until the maximum principal stress σ_1 reaches the inherent stress σ_0 value at the critical distance L/2. The predictions, as can be seen in Fig. 6, are in agreement with the experimental results, the relative errors falling between ±15 [%], which represents a reasonable engineering approximation.

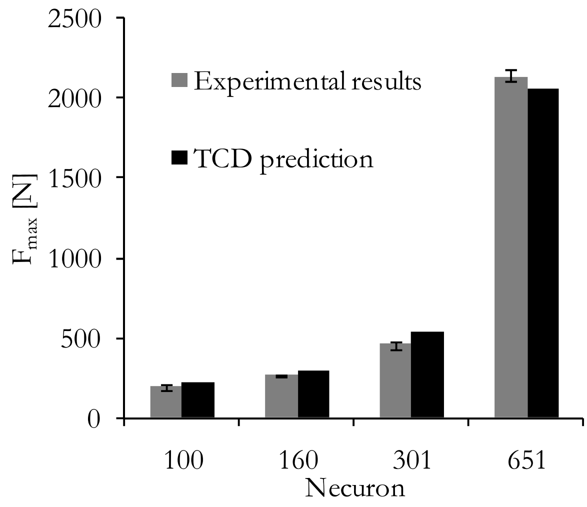


Figure 6. Failure force predictions for U-notched specimens.

CONCLUSIONS

Four PUR materials having a cellular and porous microstructure were considered for the study of the notch effect. Three different types of notches were used: circular hole, symmetric lateral U-notch and V-notch. The theory of critical distance was employed and the characteristic length and inherent stress were determined from the circular hole and V-notch geometry. To validate the results these material characteristics were used to predict maximum load for the U-notch geometry. The estimated values are in good agreement with the experimental ones. Also were proposed linear correlations between characteristic length and cell structure diameter, respectively inherent stress and ultimate tensile stress.

ACKNOWLEDGMENTS

Mr. T. Voiconi was supported by the strategic grant POSDRU/159/1.5/S/137070 (2014) of the Ministry of National Education, Romania, co-financed by the European Social Fund – Investing in People, within the Sectoral Operational Programme Human Resources Development 2007-2013. The experimental work was carried out in the framework of the grant from the Romanian National Authority for Scientific Research, CNCS – UEFISCDI, project PN-II-ID-PCE-2011-3-0456, contract number 172/2011, which also supported the authors E. Linul and L. Marsavina.

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