The Fracture of Polyurethane Materials in the Presence of Stress Concentrators

CRISTIANA CAPLESCU, LIVIU MARSAVINA, ILARE BORDEASU*, RAMONA MARIA SECHEI
[1]Politehnica University of Timisoara, 1 Mihai Viteazu Blv., 300222, Timisoara, România

The paper presents the experimental results obtained for the Necuron 1020 rigid polyurethane specimens with stress concentrators, at traction test. The resistances of these specimens are evaluated based on the critical distances theory, obtaining a good agreement with the experimental results.

Keywords: rigid polyurethane, the critical distances theory

The presence of stress concentrators, regardless of their type, generates difficulties in evaluation of the strength of components or structures, the value of strength being different from the one determinated on traction. If, through an adequate design, the introduction of singular stress concentrators (crack or V notch with zero radius at the tip) to a component can be avoided, the presence of the non-singular stress concentrators (circular holes, U and V rounded notches) appears frequently in engineering.

Various studies are dedicated to brittle fracture of components with singular stress concentrators, as sharp V notch, [1, 2]. For experimental verification materials with a brittle behaviour, like polymethyl-methacrylate (PMMA), but also other polymers (PVC, acrylate), duralumin (tested at low temperatures) were used frequently. In exchange, even a non-singular stress concentrator can change in one singular through the initiation of a crack at his tip, the studies dedicated to fracture of components with non-singular stress concentrators are less. So, in [3] are investigated the U shape stress concentrators, in [4] the rounded-tip V shape notches and the central circular hole type in [5]. Experimental verifications are realized for brittle fractures, using ceramic or polymeric materials (most frequently PMMA).

In general, the plastic materials manufacturers are providing limited information regarding the mechanical characteristics in the product data sheet. The paper presents experimental results obtained at traction for *Necuron 1020*, rigid polyurethane used in industrial applications for the realization of master models, aerodynamic and hydrodynamic testing models, fixtures and tooling jigs for automotive industry [6, 7]. The strength of the components with stress concentrators is evaluated on the bases of the critical distances theory, the obtained results being compared with the experimental results.

Experimental part

The traction tests were performed in the Strength of Materials Laboratory from Politehnica University of Timisoara, following the prescriptions of EN ISO 527-1/1993 and EN ISO 527-2/1994 standards, on a Walter+bai machine for static and dynamic tests of 10 [*kN*]. The tests were made at environment temperature, with a load speed of 5 mm/min. There were tested smooth specimens (type A) and specimens with stress concentrators, of different dimensions and geometrical shapes (fig. 1): type B - central circular holes, type C – semicircular notch, type D – U notch, type E - V rounded notch, type F – high radius fillet. Fracture mechanics tests carried out on three points bend notched specimens, provide an average value for the critical stress intensity factor $K_{Ic} = 2{,}72\ MPa\sqrt{m}$, which respects the plain strain condition for a specimen thickness t = 10 mm, [8].

In figure 2 are presented the stress-strain σ - ε experimental curves for some of the tested specimens (strain-gauge measurement base l_o = 2 mm). It is observed a slight non-linearity of σ - ε curves for *Necuron 1020* rigid polyurethane; thereby the accepting of a linear elastic behaviour is justified, without the introduction of some significant errors. Besides that, by reaching a critical

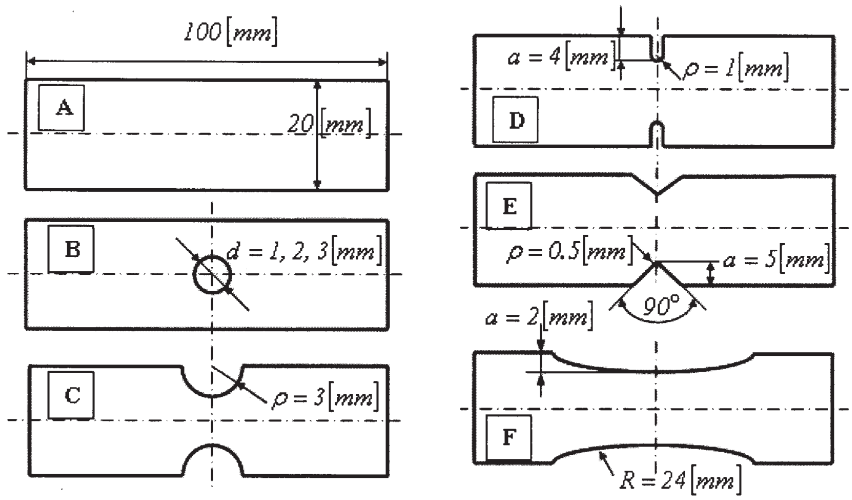

Fig.1. Type of specimens with stress concentrators

* *Tel.: 0747033883*

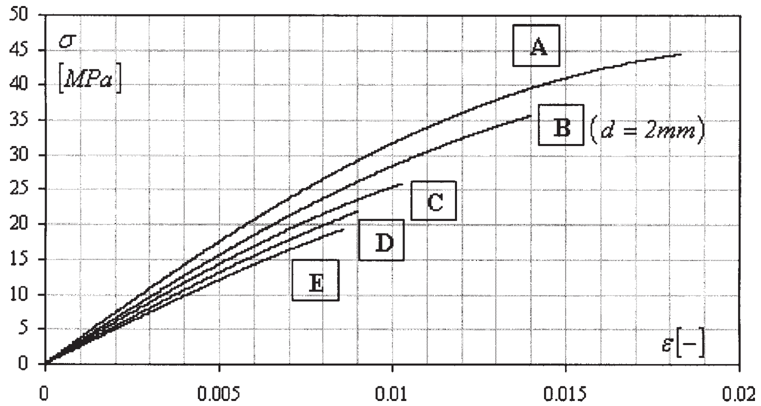

Fig.2. σ–ε curves from some of the tested specimen

level of load, the fracture is instantaneous and indicates that the fracture of *Necuron 1020* rigid polyurethane is brittle.

For each type of specimen were carried out 5 tests, and the ultimate tensile stress σ_u was determined as the ratio between the maximum recorded load F_{max} and the gross area section. With other words the σ_u stress represents the nominal stress applied in the gross section of the specimen, which produces the fracture (table 1). Investigations of fracture surface (fig.3) indicate the decreasing of the roughness with the level of stress concentration, explained by the narrowing of the micro-crack forming zone [9]. In this situation, the coalescence in a principal crack will form a slightly roughness fracture surface. For D specimen, with a higher level of stresses concentration, the existence of a numerous fracture initiation points at the tip of stress concentrator are evident.

Critical distances theory

According to [10], the critical distances theory represents a set of methods (the point method, the line method, the area method, the volume method), which have a common approach – they use a critical length L and a critical stress σ_o as material parameters. The method of critical distances was successfully applied to polymeric materials for the estimation of brittle fracture and experimentally validated for other applications: brittle fracture of the metals at low temperatures, ceramic materials and fatigue of polymeric materials [10].

The use of critical distances method for the prediction of brittle fracture, requires the knowledge of elastic stress field around stress concentrators, obtained through finite elements analyses (or an analytical solution, if it is available) and using two material parameters, critical distance L and critical stress σ_0. The point method is using a fracture criterion which can be states so: the failure will be produced when the stress at an $L/2$ distance measured from the concentrator tip (starting from the maximum stress point) is equal with the critical stress σ_0 (fig.4). So, if we note with r the distance from the concentrator tip, the point method (PM) can be expressed through the relation:

$$\sigma(r = L/2) = \sigma_0 \tag{1}$$

The others three methods, used an average stress value calculated for a specific zone (line, area, volume) of the stress field from the concentrator tip (fig.4).

Correlating the critical distance method and linear elastic fracture mechanics, it can be obtained the expression for critical distance L:

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

where:

K_{Ic} represents the critical stress intensity factor (fracture toughness);

Table 1
EXPERIMENTAL RESULTS

Specimen type	Ultimate tensile stress σ_u [MPa]					Average value
A	42.32	45.14	44.23	44.05	43.04	**43.75**
B (d = 1mm)	40.07	39.10	39.45	40.15	39.24	**39.60**
B (d = 2mm)	35.73	35.80	35.23	36.14	35.91	**35.76**
B (d = 3mm)	31.37	31.54	31.95	31.30	31.09	**31.45**
C	25.93	25.68	25.98	26.08	26.03	**25.94**
D	21.97	21.95	21.80	21.70	21.68	**21.82**
E	19.41	18.98	19.16	19.08	19..37	**19.20**
F	42.26	42.73	41.98	42.15	42.38	**42.30**

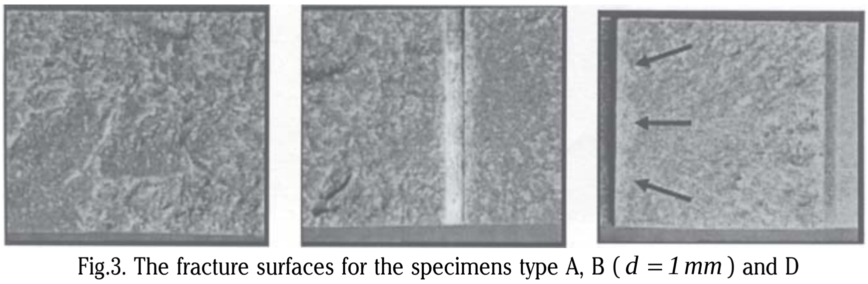

Fig.3. The fracture surfaces for the specimens type A, B ($d = 1\,mm$) and D

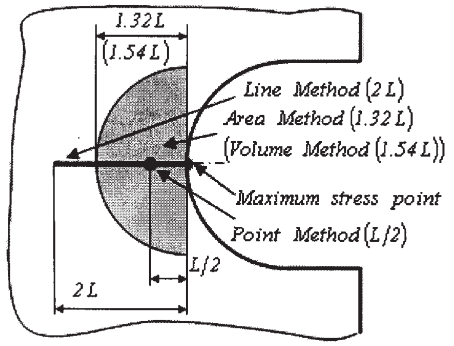

Fig.4. Critical distances theory, [7]

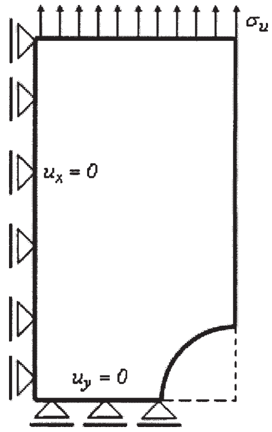

Fig. 5. The boundary conditions for the finite elements analysis

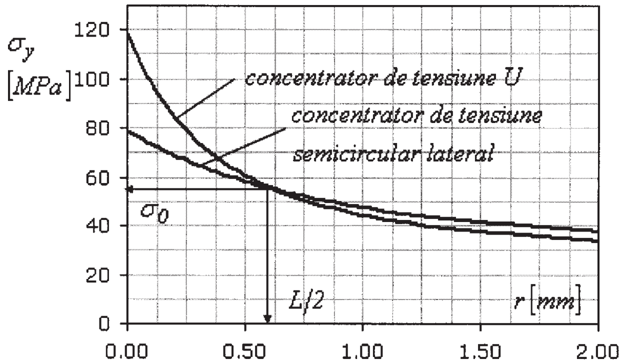

Fig.6. The determination from finite element analysis of the critical values *L* and σ_0

Table 2

THE COMPARISON BETWEEN THE EXPERIMENTAL RESULTS AND THE ESTIMATION BY PM

Specimen	K_t	*Point method*	*Experimental results*	***Relative error [%]***
$B\ (d = 1mm)$	3.00	46.69	39.60	**+ 17.90**
$B\ (d = 2mm)$	3.04	38.00	35.76	**+ 6.26**
$B\ (d = 3mm)$	3.08	32.41	31.45	**+ 3.05**
E	6.06	19.00	19.20	**- 1.04**
F	1.54	36.98	42.30	**- 12.57**

σ_0 - the tensile strength for brittle materials (ceramic materials) and some quasi-brittle materials (fiber reinforced composite, concrete).

Starting from the hypothesis that the theory of critical distances is useful for the prediction of fracture for the problems where the nominal stress field is linear-elastic (ceramic materials fracture, high cycle fatigue), respectively the strains are elastic, excepting of a small area at the concentrator tip (process area), in [11] it was studied the possibility to apply these theories for fracture of polymeric materials.

If the final fracture is preceded by a limited plastic deformation (polymers, materials test at low temperatures), the critical stress σ_0 gets a value which is, in general, higher than the tensile strength determined on smooth specimens (without concentrators). In this modified approach of the critical distances theory, the critical stress σ_0 is determined on the basis of recorded experimental results for specimens with two different stress concentrators, by plotting the distributions of stress versus the distance from the tip concentrators, for maximum load corresponding to fracture. This modification of the critical distances method is explained by the fact that the fracture mechanism is different for a smooth specimen, comparing with the fracture mechanism in the presence of a stress concentrator [9].

Results and discussions

Following this approach for specimens type *D* and *C* the maximum forces recorded at fracture in uniaxial tension were F_{max} = 4364 N and respectively F_{max} = 3187 N, which correspond the ultimate tensile stresses σ_u=21.28 MPa and σ_u=25.94 MPa, calculated for the gross area section. In order to determine the characteristic parameters *L* and σ_o a plane strain finite element analysis was performed, using *PLANE2D* elements with 8 nodes, available in the *CosmosM 2.9* software library. The analysis was performed only for a quarter of specimen, using the symmetric boundary conditions (fig.5). The material properties used in the linear elastic analysis with finite elements are: the Young modulus E = 3300 MPa and the Poisson coefficient v = 0.38.

In the figure 6 are plotted the stress distributions versus the distance *r* from the concentrator tip, resulting the critical distance L=1.180 mm and the critical stress σ_o=55.10 MPa.

With these determined values for *L* and σ_o, the application of point method PM is using only a linear elastic analysis of the components with stress concentrators and requires the plotting of the stress-distance curves.

The estimation of the ultimate tensile stress σ_u, according with relation (1), was based on the proportionality between stresses and applied load in linear elastic regime. The application of point method provides the results of the σ_u presented in table 2, together with the experimentally obtained values and the relative error. From the finite elements analysis it was also determined the theoretical stress concentration factor K_t for every specimen type.

The applicability of method is limited by the absolute dimension of the notch and by the value of K_t. For the B type specimen with diameter 1 mm the error between numerical and experimental value of σ_u is 17.9%, which indicated that this method could not be applied for notches with the absolute dimension comparable with critical distance *L*. Higher errors were also obtained for F type specimens where the stress concentration factor $K_t<2$. Similar observations were pointed out for other polymers [11].

Conclusions

The critical distances theory was applied to estimate the ultimate tensile stress of notched specimens made by rigid polyurethane material *Necuron 1020*. The numerical results are in good agreement with the experimental ones. The limitations of the method were also discussed.

The critical distances theory represent an appropriate tool to evaluate the fracture of the components with stress concentrators and was successfully applied for rigid polyurethane *Necuron 1020*. In the same time is easy to apply and recommended for engineering applications.

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