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STRESS CONCENTRATION EFFECT ON FRACTURE BEHAVIOUR OF POLYURETHANE MATERIAL

UTICAJ KONCENTRACIJE NAPONA NA PONAŠANJE LOMA POLIURETANSKOG MATERIJALA

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- rigid polyurethane
- critical distances theory

Abstract

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

Ključne reči

- kruti poliuretan
- teorija kritičnih rastojanja

Izvod

U ovom radu su predstavljeni eksperimentalni rezultati dobijeni ispitivanjem trakcije kod epruvete od Necuron 1020 krutog poliuretana sa koncentratorima napona. Svojstva otpornosti kod ovih uzoraka su sračunati na osnovu teorije kritičnih rastojanja, čime je postignuto dobro slaganje sa rezultatima eksperimenta.

INTRODUCTION

The presence of stress concentrators, regardless of their type, generates difficulties in the evaluation of the strength of components or structures, the value of strength being different from the one determined on traction. If, through 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 or V rounded notches) appears frequently in engineering.

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

In general, plastic material manufacturers are providing limited information regarding the mechanical characteristics in the product data sheet. This paper presents experimental results obtained at traction for Necuron 1020, rigid polyurethane used in industrial applications for the realisation of master models, aerodynamic and hydrodynamic testing models, fixtures and tooling jigs for the automotive industry, /5/. The strength of the components with stress concentrators is evaluated on the basis of the critical distances theory, the obtained results being compared with the experimental results.

EXPERIMENTAL TESTS

Traction tests are 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 are made at environmental temperature, with a load speed of 5 mm/min. Smooth specimens (type A) and specimens with stress concentrators are tested, of different dimensions and geometry shape (Fig. 1): type B – central circular hole, type C – semicircular notch, type D – V rounded notch, type E – U notch, type F – high radius fillet (thickness t = 10 mm).

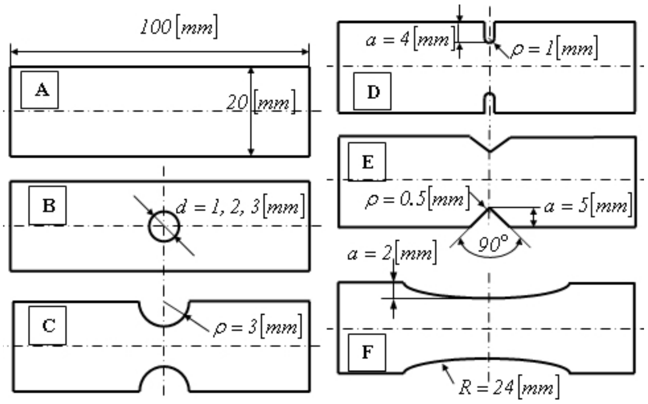

Figure 1. Types of specimens with stress concentrators.
Slika 1. Tipovi epruveta sa koncentratorima napona

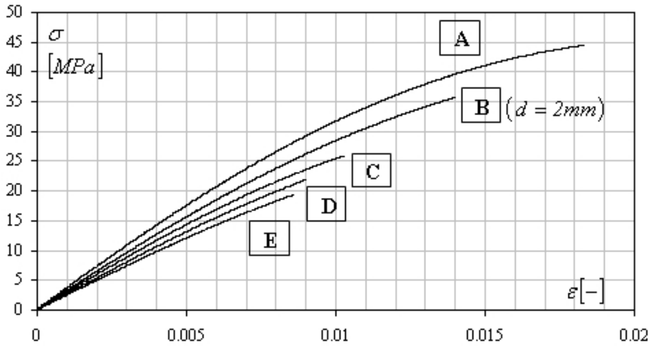

Figure 2. Stress-strain curves of some tested specimens.
Slika 2. Krive napon-deformacija nekih ispitivanih uzoraka

In Fig. 2 presented are the stress-strain σ–ε experimental curves for some of the tested specimens (strain-gauge measurement base l_0 = 25 mm). A slight non-linearity of the curves is observed for the 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 level of load, the fracture is instantaneous and indicates that the fracture of Necuron 1020 rigid polyurethane is brittle.

For each type of specimen 5 tests were carried out, and the ultimate tensile stress σ_u is determined as the ratio between the maximum recorded load $F_{\max}$ and the gross area section (Table 1). In other words, the σ_u stress represents the nominal stress applied in the gross section of the specimen, which produces the fracture.

Investigations of the fractured 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, /6/. In this situation, the coalescence in a principal crack will create a slightly rough fracture surface. For D specimens, with a higher level of stress concentration, the existence of numerous fracture initiation points at the tip of the stress concentrator is evident.

Table 1. Experimental results.
Tabela 1. Eksperimentalni rezultati

	Specimen type							
	A	B (d = 1 mm)	B (d = 2 mm)	B (d = 3 mm)	C	D	E	F
σ_u (MPa) (average)	43.75	39.60	35.76	31.45	25.94	21.82	19.20	42.30

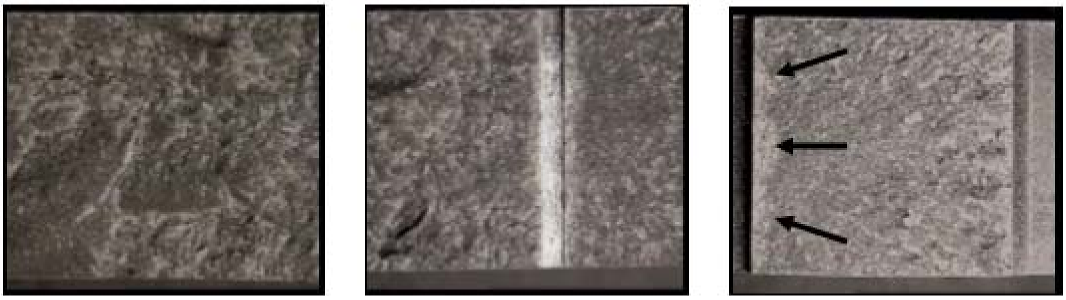

Figure 3. Fracture surfaces for specimens type A, B and D.
Slika 3. Površina preloma za epruvete tipa A, B i D

CRITICAL DISTANCES THEORY

Method presentation

According to /7/, the critical distances theory represents a set of methods (point method, line method, area method, volume method), which have a common approach – they use a critical length L and a critical stress σ_0 as material parameters. The method of critical distances is successfully applied to polymeric materials for estimating brittle fracture /8/ and is experimentally validated for other applications: brittle fracture of metals at low temperature, ceramic materials and fatigue of polymeric materials, /7/.

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 element 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 uses a fracture criterion which can be stated as: the failure is to be produced when the stress at an L/2 distance measured from the concentrator's tip (starting from the maximum stress point) is equal to the critical stress σ_0 (Fig. 4). So, if we note with r the distance from the concentrator tip, the point method can be expressed by the relation:

$$\sigma\big|_{r=L/2} = \sigma_0 \tag{1}$$

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

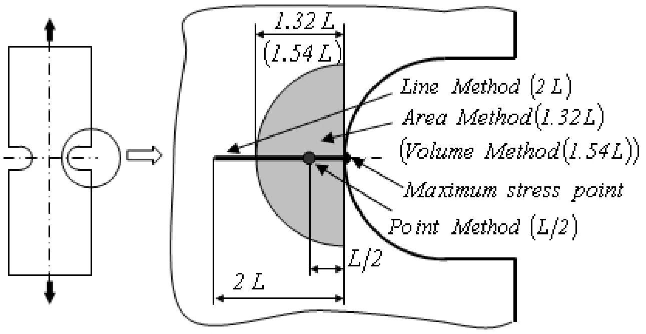

Figure 4. Critical distances theory, /7/.
Slika 4. Teorija kritičnih rastojanja, /7/

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

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

where K_{Ic} represents the critical stress intensity factor (fracture toughness), σ_0 is the tensile strength for brittle materials (ceramic materials) and some quasi-brittle materials (fibre reinforced composite, concrete). Starting from the hypothesis that the theory of critical distances is useful for the prediction of fracture for problems where the nominal stress field is linear elastic (ceramic materials fracture, high cycle fatigue), respectively the specific strains are elastic, except a small area at the concentrator tip (process area), in /9/ the possibility to apply these theories for the fracture of polymeric materials is studied.

If the final fracture is preceded by a limited plastic deformation (polymers, material tests at low temperature), 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, compared to the fracture mechanism in the presence of a stress concentrator, /6/.

RESULTS AND DISCUSSIONS

Following this approach for specimen types D and C the maximum forces recorded at fracture in uniaxial tension are $F_{\max} = 4364$ N and $F_{\max} = 5187$ N respectively, that correspond to ultimate tensile stresses $\sigma_u = 21.82$ MPa and $\sigma_u = 25.94$ MPa, calculated for the gross area section. In order to determine the characteristic parameters L and σ_0 a plane strain finite element analysis is performed, using PLANE 2D elements with 8 nodes, available in the Cosmos M2.9 software library. The analysis is performed only for a quarter of a specimen, using symmetric boundary conditions (Fig. 5). Material properties used in the linear elastic analysis with finite elements are: Young modulus $E = 3300$ MPa and Poisson coefficient $\nu = 0.38$.

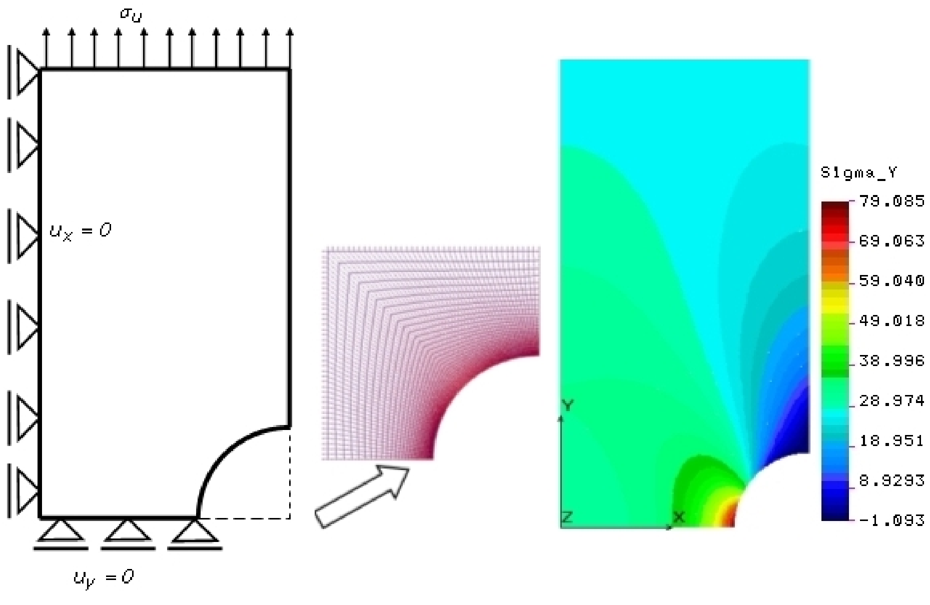

Figure 5. The boundary conditions for FEA, mesh detail and σ_y stress distribution for type C specimen.
Slika 5. Granični uslovi za FEA, detalji mreže i raspodela σ_y napona kod epruvete tipa C

Stress distributions σ_y versus the distance r from the concentrator tip are plotted in Fig. 6, resulting in the critical distance $L = 1.180$ mm and the critical stress $\sigma_0 = 55.10$ MPa.

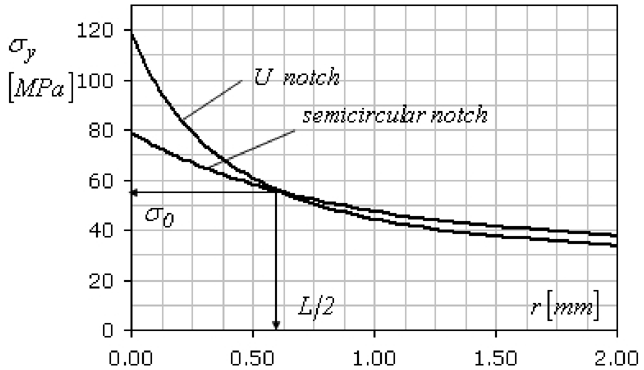

Figure 6. Determination of critical values L and σ_0 from FEA.
Slika 6. Određivanje kritičnih veličina L i σ_0 iz FEA

With these determined values for L and σ_0, the application of the point method uses only the linear elastic analysis of components with stress concentrators and requires the plotting of stress-distance curves. The estimation of the ultimate tensile stress σ_u, according to Eq. (1) is based on the proportionality between stresses and the applied load in the linear elastic region. The application of point method provides the results of the σ_u presented in Table 2, together with experimentally obtained values and relative error. From FEA the theoretical stress concentration factor K_t for every specimen type is also determined.

Table 2. Comparison of experimental results and PM estimation.
Tabela 2. Poređenje eksperimentalnih rezultata i PM procene

Specimen	K_t	σ_u (MPa)		Relative error (%)
		Point method	Experimental results	
B (d = 1 mm)	3.00	46.69	39.60	+17.90
B (d = 2 mm)	3.04	38.00	35.76	+6.26
B (d = 3 mm)	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

The applicability of the method is limited by the absolute dimension of the notch and by the value of K_t. For the B type specimen with diameter l (mm) the error between numerical and experimental value of σ_u is 17.9%, which indicates that this method could not be applied for notches of absolute dimension comparable with critical distance L. Higher errors are also obtained for F type specimens where the stress concentration factor $K_t < 2$. Similar observations are pointed out for other polymers, /9/.

CONCLUSIONS

The critical distances method is applied to estimate the ultimate tensile stress σ_u of notched specimens made of rigid polyurethane material Necuron 1020. Numerical results are in good agreement with the experimental ones. Limitations of the method have also been discussed.

The critical distances method represents an appropriate tool to evaluate the fracture of components with stress concentrators and is successfully applied for rigid polyurethane Necuron 1020. At the same time it is easy to apply and is recommended for engineering applications.

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