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DETERMINATION OF MIXED MODE FRACTURE TOUGHNESS OF PUR FOAMS

ODREĐIVANJE ŽILAVOSTI LOMA MEŠOVITOG TIPA KOD PU PENA

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- mixed mode fracture
- polyurethane foams
- fracture toughness
- asymmetric semi-circular bend specimen

Abstract

Polyurethane foams crush in compression and have a brittle fracture in tension, so their failure could be evaluated based on Linear Elastic Fracture Mechanics. Fracture toughness in mixed mode loading is of particular interest because foam cracking weakens the structure's capacity for carrying loads. The mixed mode fracture of three closed cell rigid polyurethane foams with densities: 100, 145 and 300 kg/m^3 are experimentally investigated. Mixed mode fracture tests are performed using a single edge cracked specimen and a mixed mode loading device. The advantages of this specimen are the simple geometry and the ability to produce full range of mixed modes, from pure mode I to pure mode II, only by changing the loading direction. Fracture criteria based on the cellular topology and tensile strength of the solid material is assessed. It is found that the density of foams is the most important parameter influencing the fracture toughness. The crack propagation angles are also determined on the fractured specimens.

Ključne reči
- lom mešovitog tipa
- poliuretanska pena
- žilavost loma
- asimetrična polukružna epruveta za savijanje

Izvod

Poliuretanske pene se drobe pritiskom i krto lome pri zatezanju, tako da se njihovo razaranje može proceniti na osnovu linearno elastične mehanike loma. Žilavost loma pri mešovitom tipu loma je od posebnog interesa jer prsline u peni slabe kapacitet nosivosti konstrukcije. Eksperimentalno je ispitan lom mešovitog tipa kod tri krute poliuretanske pene sa zatvorenim ćelijama, gustina: 100, 145 i 300 kg/m^3. Ispitivanja loma mešovitog tipa su izvedena primenom epruvete sa ivičnom prslinom i uređaja za zadavanje mešovitog opterećenja. Prednosti ove epruvete su jednostavna geometrija i mogućnost primene punog spektra mešovitog opterećenja, od čistog opterećenja tipa I do čistog opterećenja tipa II, i to samo promenom pravca opterećenja. Procenjeni su kriterijumi loma na bazi ćelijske topologije i zatezne čvrstoće materijala u čvrstom stanju. Pokazalo se da je gustina pene najvažniji parametar koji utiče na žilavost loma. Uglovi prostiranja prsline su takođe određeni na ispitivanim uzorcima.

INTRODUCTION

The main mechanical properties of rigid PUR foams are influenced: by the properties of solid material of which the foam is made (polymers, metals, ceramics); by the typical topology (connectivity) and shape of the cell edges and faces (open cells, closed cells, open and closed cells). The most important feature is the relative density ρ^*/ρ_s, with ρ^* being the density of cellular material and ρ_s the density of the solid material of which it is made, /1/. The mechanical strength of PUR foams is remarkable because high compressive and shear strengths allow low-density insulating cores to be faced with relatively thin steel or aluminium, providing relative good overall stiffness and strength. This unique combination of properties (lightweight, high porosity, high insulation and good energy absorption capacity) allows rigid polyurethane foams to be used in many applications, /2, 3/. With its excellent strength-to-weight ratio, insulation properties, durability and versatility, polyurethane are frequently used in building and construction applications (walls and roofs, entry doors and garage doors, floors) and appliances (refrigerator and freezer thermal insulation systems). In addition, rigid polyurethane foam insulates boats from noise and temperature extremes, provides abrasion and tear resistance, and increases load-bearing capacity, adding minimal weight at the same time. Polyurethane foams also enables manufacturers to provide drivers and passengers significantly more automobile "mileage" by reducing weight and increasing fuel economy, comfort, corrosion resistance, insulation and sound absorption (car seats, bumpers, interior "headline" ceiling sections, the car body, spoilers, doors and windows). Foam materials crush in compression, but show a brittle fracture in tension, /4/. Sandwich structures with foam cores are usually loaded in bending, and crack in the foam core can initiate in mode I, mode II or mixed mode.

The knowledge of the fracture properties of foam core becomes an important requirement for the design of such structures. Up to now most results are related to fracture toughness in mode I /5-12/ and only few studies present the mixed mode fracture of polymeric foams, and only for PVC foams. Hallsttröm and Grenestedt, /13/, investigated mixed mode fracture of cracks and wedge shaped notches in expanded PVC foams. Different types of specimens made of Divinycell H100 were investigated and the non singular T-stress is considered in formulation of fracture criteria. It is concluded that for predominantly mode II the use of T-stress improved the facture predictions. Three different densities of PVC foams were investigated by Noury et al. /14/ using a CT specimen with Arcan fixtures to produce mixed mode conditions. The ratio between K_{IIc}/K_{Ic} was found to be between 0.4 and 0.65 depending on foam density. Recently, the asymmetric semi-circular bend (ASCB) specimens are adopted by Marsavina et al. /15/ to determine the fracture toughness for three different densities of polyurethane foams under mixed mode loading. Their experimental results are proof that the equivalent stress intensity factor (ESIF) criterion of Richard is most suitable for this type of foams. They found that the K_{Ic}/K_{IIc} parameter decreases with increasing the relative density of the foam and the crack paths obtained experimentally show curvilinear trajectories, apart of the pure mode I loading when the crack path is a straight line.

Present study assessed the fracture of PUR foam materials under mixed mode loading, using Single Edge Crack (SEC) under mixed mode loading, and relates the results to the tensile strength of the solid material and cellular dimensions.

MATERIALS AND METHOD

Closed-cell rigid PUR foams of three different densities (100, 145 and 300 kg/m^3) are used in the experimental programme. The main mechanical properties of the investigated foams are presented in Table 1, /11, 16, 17/.

Table 1. Main properties of the investigated PUR foams
Tabela 1. Osnovne karakteristike ispitivanih PU pena

Mechanical property (MPa)	Density, (kg/m^3)		
	100	145	300
Young's modulus	30.18	66.89	281.39
Compressive modulus	10.38	62.95	208.22
Flexural modulus	25.73	36.83	164.17
Tensile strength	1.16	1.87	3.86
Compressive yield strength	0.75	2.09	4.95
Flexural strength	1.81	2.54	7.49

The microstructures of the investigated PUR foams are obtained using QUANTATM FEG 250 SEM and are presented at 500× magnification in Fig. 1.

Statistical analysis of the microstructure provides the mean and standard deviation of cell size on the rise direction (named "in plane") and flow direction (named "out of plane") of foams and the cell thickness, Table 2, /15/.

The density of the foams is determined according with ASTM D 1622 /18/, using cubic specimens of 15×15×15 mm, an electronic balance Sartorius LA230S for weighting and a digital calliper Mytotoyo for dimension measurement. The determined mean values of density are also presented in Table 2, and are in agreement with manufacturer data. The mixed mode loading device is shown in Fig. 2.

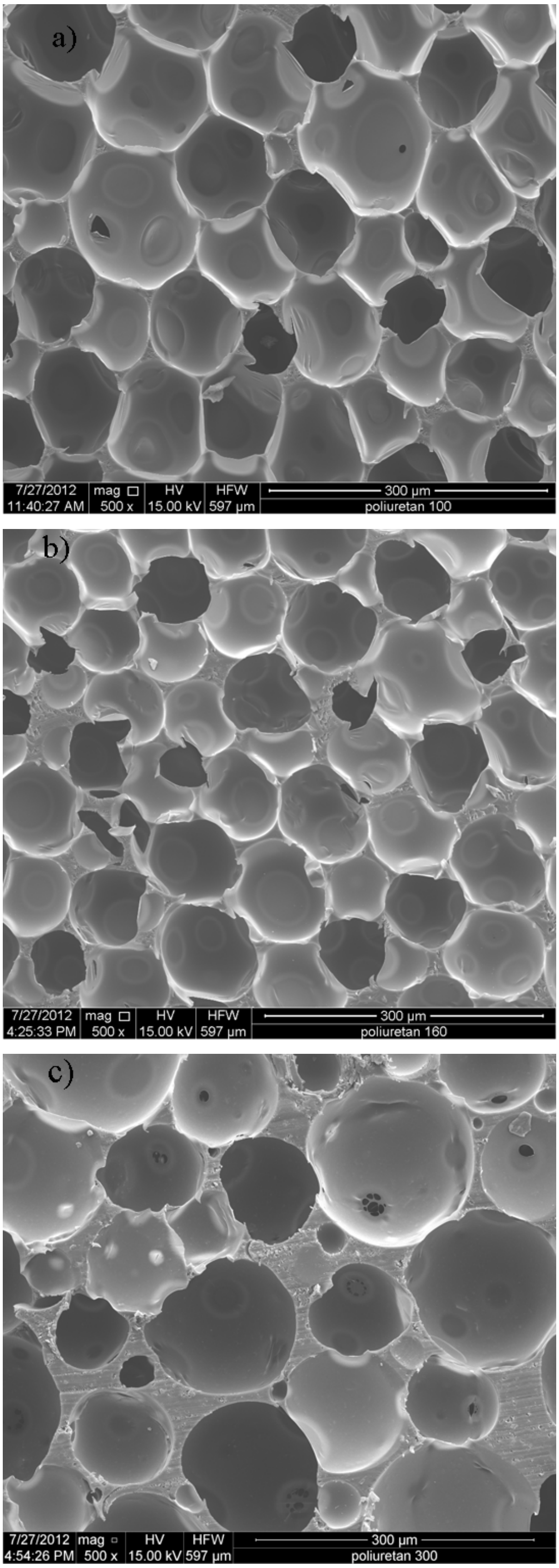

Figure 1. SEM microstructures for investigated PUR foams (500×): (a) 100 kg/m^3, (b) 145 kg/m^3, (c) 300 kg/m^3.
Slika 1. SEM mikrostrukture ispitivanih PU pena (500×): (a) 100 kg/m^3, (b) 145 kg/m^3, (c) 300 kg/m^3

The mixed mode conditions are produced by changing the loading angle, $\beta = 0°$ corresponds to pure mode I, while 90° produces a pure mode II, between them mixed mode is produced. The test specimen is shown in Fig. 3.

Table 2. Statistical analysis of the microstructure.
Tabela 2. Statistička analiza mikrostrukture

Cellular structure property	Density, (kg/m^3)		
	100	145	300
Cell length in plane, (μm)	104.5 ± 9.4	83.8 ± 9.6	68.5 ± 33.9
Cell length out of plane, (μm)	120.2 ± 14.5	88.1 ± 11.2	67.8 ± 32.1
Cell wall thickness, (μm)	2.9-5.8	5.1-13.1	3.8-21.8
Density, (kg/m^3)	100.35 ± 0.25	145.53 ± 0.22	300.28 ± 1.38

Figure 2. Cracked foam specimen in loading grips.
Slika 2. Epruveta sa prslinom u alatu za pritezanje

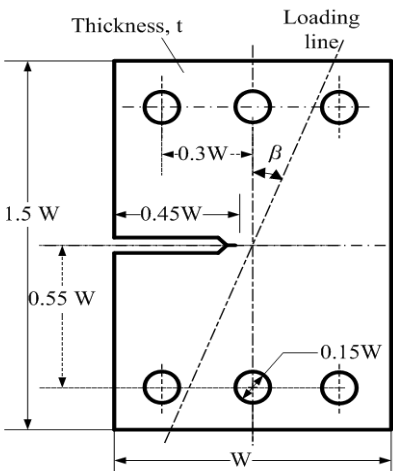

Figure 3. SEC specimen.
Slika 3. Epruveta tipa SEC

The SIF are obtained according with Richard, /19/:

$$K_i = \frac{F_{max}}{Wt}\sqrt{\pi a}\, f_i(\beta,\, a/W), \quad i = \text{I, II} \tag{1}$$

where F_{max} represents the maximum load from the load–displacement recordings, W is the specimen width, t is the specimen thickness and a the crack length, and

$$\begin{cases} f_I = \dfrac{\cos\beta}{1-\dfrac{a}{W}}\sqrt{\dfrac{0.26+2.65\dfrac{a}{W-a}}{1+0.55\dfrac{a}{W-a}-0.88\left(\dfrac{a}{W-a}\right)^2}} \\ f_{II} = \dfrac{\sin\beta}{1-\dfrac{a}{W}}\sqrt{\dfrac{-0.23+1.40\dfrac{a}{W-a}}{1-0.67\dfrac{a}{W-a}+2.08\left(\dfrac{a}{W-a}\right)^2}} \end{cases} \tag{2}$$

The tests were performed on a Zwick/Roell testing machine with 5 kN maximum load, at room temperature with a loading rate of 2 mm/min. Brittle fracture is observed for all tested specimens with an abrupt drop of load to zero after reaching the maximum load (see Fig. 4).

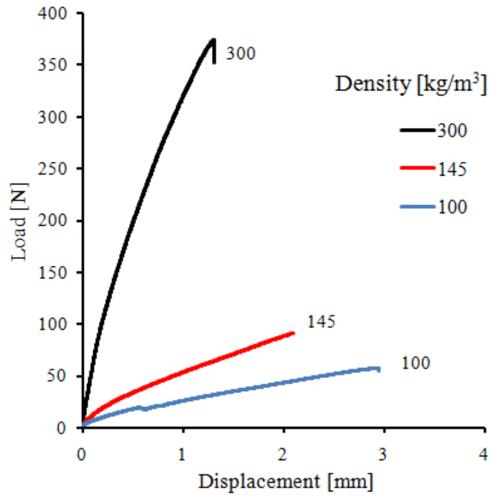

Figure 4. Typical load–displacement curves for mixed mode loading ($\beta = 60°$).
Slika 4. Tipične krive opterećenje–pomeranje za opterećenje mešovitog tipa ($\beta = 60°$)

The linear elastic behaviour is confirmed during the tests when no cushioning and plastic deformations remain after finishing the test.

RESULTS AND DISCUSSIONS

The obtained values of mode I and mode II fracture toughness are presented in Table 3 together with the results reported for Single Edge Notched Bend (SENB) specimen by Marsavina and Linul, /20/, and asymmetric semi-circular bend (ASCB) specimen by Marsavina et al., /10/. It could be observed that higher values of fracture toughness K_{Ic} and K_{IIc} are obtained in the present study than those presented on the other types of specimens. Mode I fracture toughness is higher than the mode II fracture toughness.

Table 3. Fracture toughness results for investigated PUR foams.
Tabela 3. Rezultati žilavosti loma za ispitane PU pene

Spec.	Fracture toughness ($MPa \cdot m^{0.5}$)	Necuron 100	Necuron 160	Necuron 301
SENB	K_{Ic}	0.089±0.003*	0.121±0.003	0.369±0.030
ASCB	K_{Ic}	0.087±0.003	0.131±0.003	0.372±0.014
	K_{IIc}	0.050±0.002	0.079±0.004	0.374±0.013
SEC	K_{Ic}	0.132±0.003	0.140±0.003	0.421±0.014
	K_{IIc}	0.069±0.002	0.095±0.004	0.319±0.013

*Standard deviation

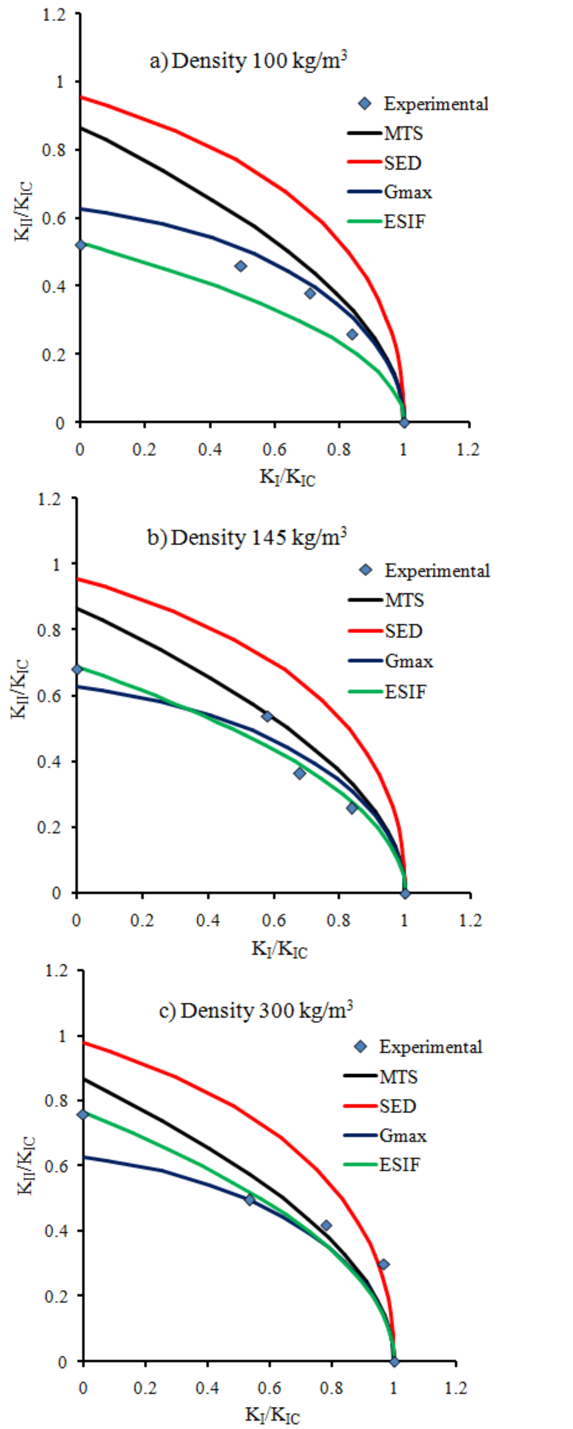

Figure 5. Results of mixed mode fracture of PUR foams and theoretical fracture curves.
Slika 5. Rezultati loma mešovitog tipa kod PU pena i teorijske krive loma

Figure 5 presents the values of the ratio between K_{II}/K_{Ic} versus K_I/K_{Ic}, together with fracture curves predicted by four considered fracture criteria (Maximum Circumferential Tensile Stress (MTS), Minimum Strain Energy Density (SED), Maximum Energy Release Rate Criterion (G_{max}) and Equivalent Stress Intensity Factor (ESIF)).

As it can be observed in Fig. 5 that both Equivalent Stress Intensity Factor and Maximum Energy Release Rate Criterion criteria appear to predict better the mixed mode fracture of rigid PUR foams.

The predictions based on classical fracture criteria (Maximum Tensile Stress and Strain Energy Density) for mixed mode are moderate for this class of cellular materials /11/. Chen et al. /21/ proposed to relate the mixed mode fracture to the tensile strength of the solid material σ_{fs} and the dimensions of the cellular structure (cell length l and the thickness of the cells h, by proposing a relationship:

$$K_{ic} = C_i \frac{\sigma_{fs} h}{\sqrt{l}}, \quad i = \text{I, II} \tag{3}$$

where C_i are coefficients depending on the topology of the cellular structure.

Figure 6 presents the fracture toughness locus for the investigated PUR foams having three different densities. Straight lines are considered to predict the fracture envelope, which means that mixed mode fracture toughness can be easily determined from mode I and mode II fracture toughness and the mode mixing of the applied load. The fracture envelope is plotted taking into account the tensile strength of the PUR material (σ_{fs} = 130 MPa) and the cellular topology (l and h).

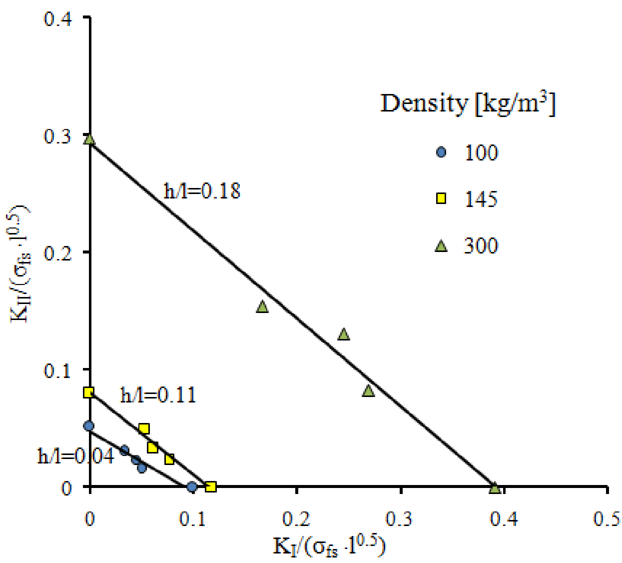

Figure 6. Mixed mode fracture toughness results of PUR foams taking into account the cellular topology (l and h).
Slika 6. Rezultati žilavosti loma mešovitog tipa kod PU pene, uzimajući u obzir ćelijsku topologiju (l i h)

The obtained crack paths for five different loading angles (from pure mode I to pure mode II) are shown in Fig. 7.

Figure 8 presents the mean values and standard deviation of the crack propagation angle θ_c measured on the specimens versus the loading angle together with the theoretical criteria for three different densities. The crack propagation angle is measured on each fractured specimen.

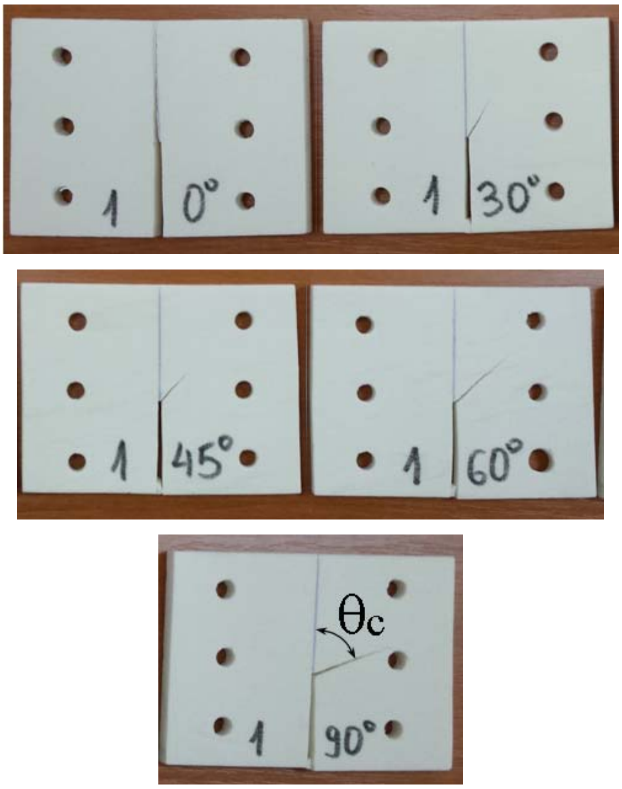

Figure 7. Crack propagation angle measured on the specimens.
Slika 7. Ugao prostiranja prsline izmeren na uzorcima

As was expected, the crack path increases with increasing of the loading angle. The maximum values of crack propagation angle are obtained for pure mode II having values from 66º to 69º.

CONCLUSIONS

The main conclusions of this study are:

- The SEC specimen with a mixed mode loading device is adopted to determine the fracture toughness of rigid polyurethane foams under mixed mode loading. The advantages of this specimen are the simple geometry and the ability to produce full range of mixed modes, from pure mode I to pure mode II, only by changing the loading direction.
- The density of foams is the most important parameter influencing the fracture toughness. The order of magnitude for mode I fracture toughness of PUR foams is between 0.132 MPa·m$^{0.5}$ for density of 100 kg/m^3 to 0.421 MPa·m$^{0.5}$ for density of 300 kg/m^3. These results are higher than those obtained on SENB and ASCB specimens (Table 2). The mode II fracture toughness ranges between 0.069 MPa·m$^{0.5}$ for density of 100 kg/m^3 to 0.319 MPa·m$^{0.5}$ for density of 300 kg/m^3.
- The fracture locus is plotted by dividing the stress intensity factors to the product of tensile strength of the solid material and square root of cell length.
- The crack propagation angles are determined on the fractured specimens.

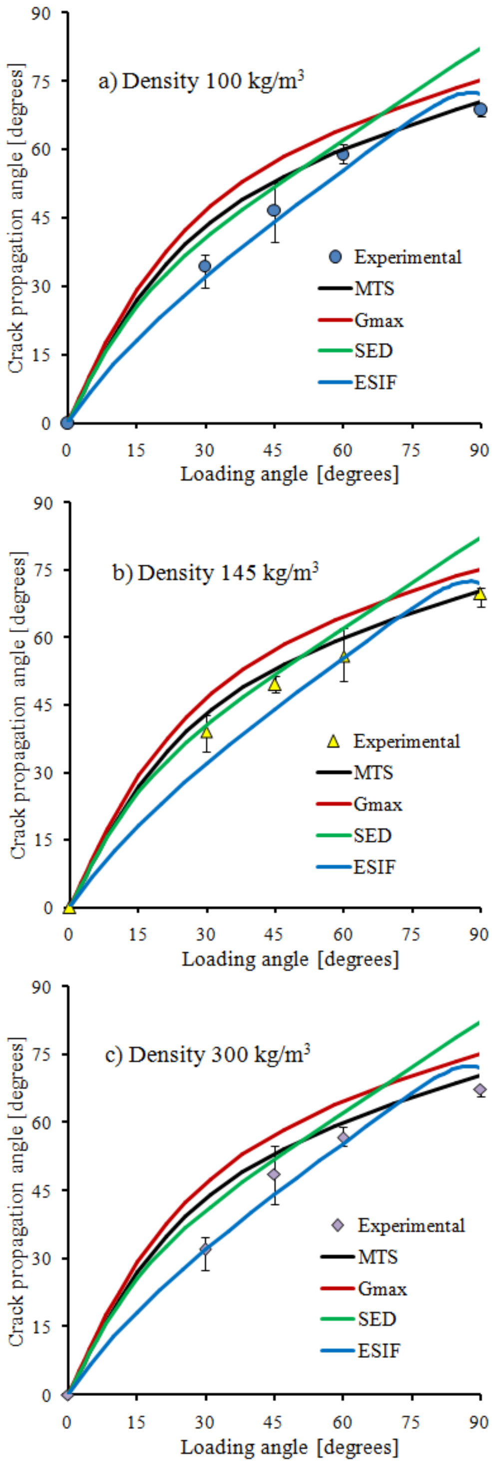

Figure 8. Crack propagation angle versus loading angle and theoretical criteria.
Slika 8. Ugao prostiranja prsline prema uglu opterećenja i teorijski kriterijumi

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