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STRUCTURAL INTEGRITY ASSESSMENT FROM THE ASPECT OF FRACTURE MECHANICS

PROCENA VEKA KONSTRUKCIJE SA ASPEKTA MEHANIKE LOMA

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Keywords
- polypropylene (PP)
- J integral
- critical crack tip opening (CTOD)

Abstract

An increasing diversity of operations and different materials, as well as different working conditions lead to various construction solutions. Structural design is the preparation of structures that shall be efficient in fulfilling anticipated exploitation conditions, both economically and safely, i.e. there will be no damage resulting in the loss of structural functionality in service. In practice, however, there are fractures that can occur during construction, assembly, and exploitation. Fracture may be caused by overloads, by static fracture, or by dynamic loads, and by fatigue. Upon calculation of static structural durability, normal and tangential stresses are taken into account, while the dynamic durability calculation defines structural resistance to crack formation and its propagation under dynamic loading. The aim of this paper is to demonstrate the possibility of applying fracture mechanics to structural integrity assessment. To this end, the basic concepts of linear elastic fracture mechanics will be explained.

Ključne reči
- polipropilen (PP)
- J integral
- kritično otvaranje vrha prsline (CTOD)

Izvod

Sve veća raznolikost delovanja i sve više različitih materijala kao i različiti uslovi rada dovode do različitih konstruktivnih rešenja. Projektovanje konstrukcije je priprema konstrukcije koja će predviđene eksploatacione uslove ispuniti efikasno, ekonomično i sigurno, odnosno, da u toku eksploatacije ne dođe do oštećenja, usled čega bi konstrukcija izgubila funkcionalnost. Međutim u praksi se javljaju lomovi koji mogu nastati u toku izrade, montaže, eksploatacije. Pojava loma može biti uzrokovana preopterećenjem, kao statički lom, ili nastanak prsline uzrokovan dinamičkim opterećenjem, usled zamora. Pri proračunu statičke izdržljivosti konstrukcije u obzir se uzimaju normalni i tangencijalni naponi, dok se pri proračunu dinamičke izdržljivosti definiše otpornost konstrukcije na stvaranje prsline i njeno širenje pod dejstvom dinamičkog opterećenja. Cilj rada je da se prikažu mogućnosti primene mehanike loma na procenu integriteta konstrukcije. U tom cilju su objašnjeni osnovni koncepti linearno elastične mehanike loma.

INTRODUCTION

Mechanical parts made of plastic materials are loaded during operation. Because of the desire for quality performance, increased reliability and prolonged service life, it is necessary to know fracture mechanics properties.

During the process of manufacture and due to the geometrical shapes of parts, regimes that include deformation by press may create faults in the material where cracks develop. It is precisely with the knowledge of fracture mechanics properties that it is possible to determine the crack sensitivity of machine parts made of plastic materials.

EXPERIMENT

Polypropylenes (PP) have good electrical and thermal insulation properties and are resistant to corrosion. They are numerous and diverse and used for making parts in the automotive industry, ski equipment, transport equipment, etc.

Specimens from this material are tested for determining tensile strength, according to the EN 1002-1 standard, 1990. Tests are carried out at ambient temperature (+22 °C) by AMSLER testing machine. The force-displacement dependence is measured. Based on the measured values (Table 1), stress-strain diagrams are constructed, as shown in Fig. 1.

Table 1. Mechanical properties of PP material.

Specimen label	Size	R_{eH}	R_{eL}	R_{p1}	R_m	A_s	Z	Fracture	Remarks
	(D, $t_s \times b$) (mm)	(N/mm^2)	(N/mm^2)	(N/mm^2)	(N/mm^2)	(%)	(%)		
PP	3.72 × 6.06			25.3	31.00	11.82			9.36

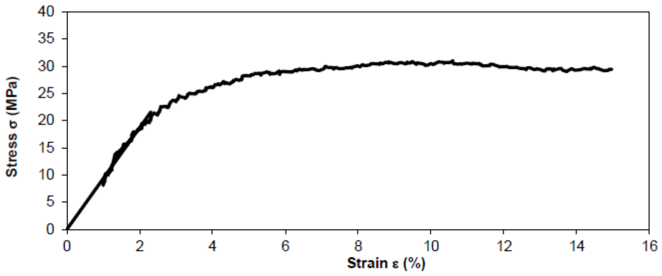

Figure 1. Stress-strain diagram for PP material.

In order to determine the critical value of J-integral and the critical crack tip opening (CTOD), i.e. the material resistance curve, it is necessary to perform experimental tests in accordance with ASTM E 1820 and ASTM D 5045.

The SEM specimens, Fig. 2, are cut from the material. The mechanical notch is rectangular, and the crack is initiated as prescribed by the ASTM D 5045 standard (standard for plastic materials).

Table 2 depicts the characteristic sizes of the tested specimens. As verified are identical measured sizes of all 5 tested specimens. Material mechanical characteristics are probed for 2 samples and given in Table 3. The produced notch- and pre-crack sizes are shown in Table 4,

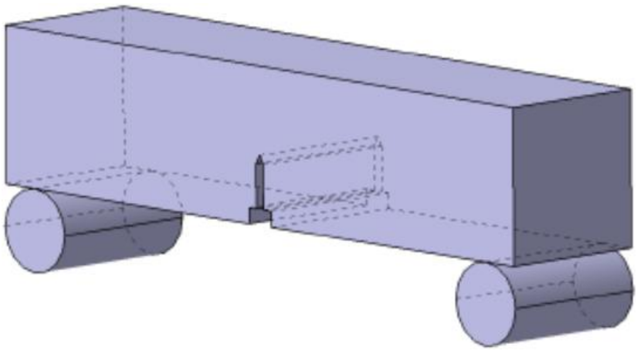
Figure 2. Shape of bending specimen.

Table 2. Dimensions of the specimen.

Specimen type:	Compact Tension C(T) specimen ASTM E1820-15						
Identification:	PP						
Orientation:	L-T						
SE(B) specimen basic dimensions							
Measurements		1	2	3	4	5	Average
width	W (mm)	10.12	10.12	10.12	10.12	10.12	10.120
thickness	B (mm)	3.69	3.69	3.69	3.69	3.69	3.690
length	L (mm)	70.00	70.00	70.00	70.00	70.00	70.000
notch thickness	B_N (mm)	3.69	3.69	3.69	3.69	3.69	3.690
equivalent thickness	B_E (mm)	3.69	3.69	3.69	3.69	3.69	3.690
notch length	a_N (mm)	2.00	2.00	2.00	2.00	2.00	2.000
notch width	N (mm)	0.05	0.05	0.05	0.05	0.05	0.050
knife thickness	z (mm)	0.00	0.00	0.00	0.00	0.00	0.000
support span	S (mm)	40.000	40.000	40.000	40.000	40.000	40.00

Table 3. Material characteristics.

Material mechanical properties					
Values		Probe 1	Probe 2	Probe 3	Mean
elastic modulus	E (N/mm^2)	4100	4100		4100
Poisson's ratio	ν (–)	0.42	0.42		0.42
yield strength (YS)	σ_{YS}, $R_{p0.2}$ (N/mm^2)	25.3	25.3		25.3
ultimate tensile strength (UTS)	σ_{TS}, R_m (N/mm^2)	31	31		31.0
effective yield strength	σ_Y (N/mm^2)	28.15	28.15		28.15
ratio YS/UTS	σ_{YS}/σ_{TS}	0.8161	0.8161		0.8161

Table 4. Dimensions of the notch.

Fatigue crack (FC)			Physical fracture crack (PFC)		
FC area	A_0 (mm^2)		PFC area	A_p (mm^2)	
average FC length	a_0 (mm)	4.889	Average PFC length	a_p (mm)	6.759
remaining ligament	b_0 (mm)	5.231	Remaining ligament	b_p (mm)	3.361
ratio	a_0/W (–)	0.4831089	Ratio	a_p/W (–)	0.6678452
shape function	$f(a_0/W)$ (–)	2.5253626	Shape function	$f(a_p/W)$ (–)	5.012048

In accordance with ASTM E 1820, a normalization method for crack growth monitoring is used (Fig. 7). A sample test configuration is shown in Fig. 4, and a specimen with crack in Fig. 5. Values of force, displacement and crack opening for each specimen are measured separately (Fig. 6). All specimens were fractured in order to determine crack extension. The fracture surface is inspected and crack ligament measurements are carried out. Tests are performed at room temperature on the Smitweld 1405 testing machine using an extensometer of 0.005 mm accuracy.

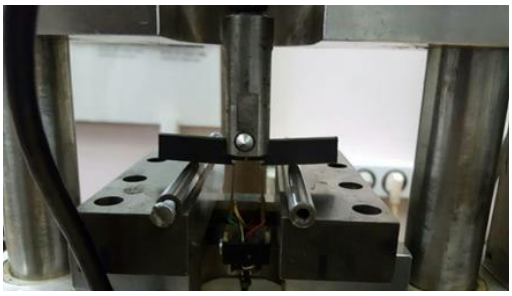
Figure 4. Sample testing.

Figure 5. Specimen with crack.

Results are determined and the J-R material resistance curve is plotted, as shown in Fig. 8.

As the engineering critical value, the value of the parallel cross-section is taken at a 0.2 mm crack propagation (Fig. 8). The maximum value to be considered is limited to J_{max}, since with values $J > J_{max}$, plastic deformation becomes significant that fracture behaviour ceases to depend only on the material, but also on the remaining ligament.

Test results are given in Table 5.

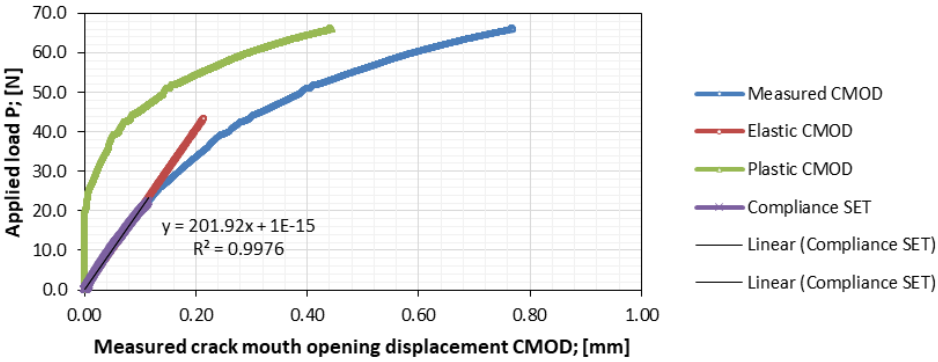

Figure 6. Force load–CMOD diagram.

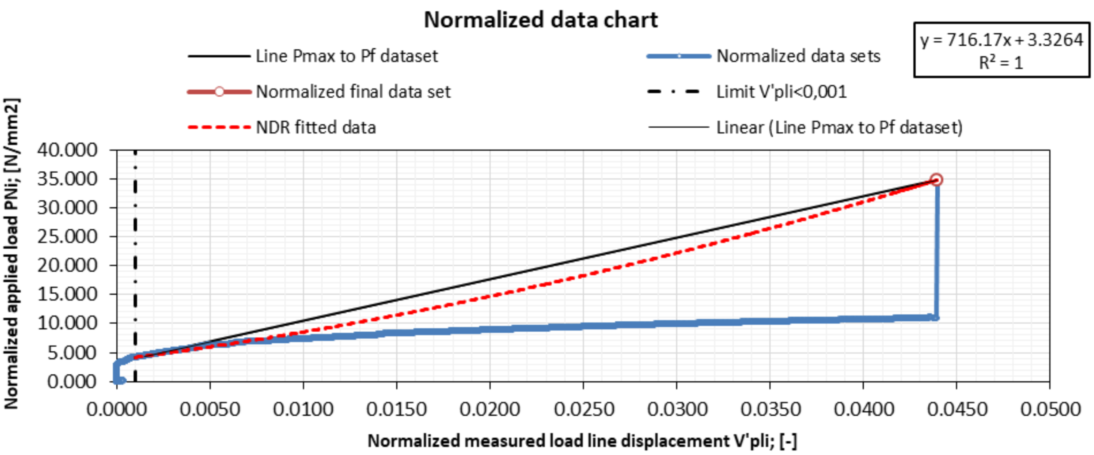

Figure 7. Normalization method.

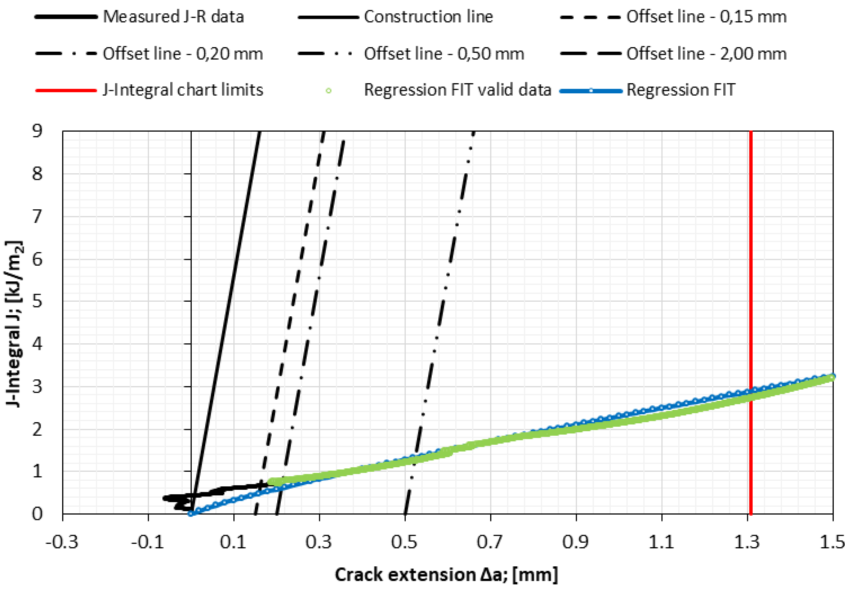

Figure 8. J integral resistance curve.

Table 5. Test results.

J-integral calculation procedure				
Estimated value	$J_{Q(1)}$ (kJ/m^2)	0.61338		
Evaluated crack extension	$\Delta a_{Q(1)}$ (mm)	0.2108948		
Evaluated value	$J_{Q(1)}$ (kJ/m^2)	0.6135305		
Coefficient k	k (–)	1.00	See data sheet p.6	
$J_{Q(1)}$ convergence criteria (%)		0.0245311	CRIT. STATUS=	Passed
Evaluated SIF from $J_{Q(1)}$	K_{JIc} (MPa·m$^{1/2}$)	1.7474251		
Qualification of J_Q as J_{Ic}				
Qualification criteria 1	$B > 10 \cdot J_Q/\sigma_Y$	Passed		
Qualification criteria 2	$b_0 > 10 \cdot J_Q/\sigma_Y$	Passed		
Qualification of J_Q as J_{Ic}	STATUS=	YES		

CONCLUSIONS

On the basis of the input data, which are a combination of geometry and the weight of individual parts, the demand of forces and moments that stress the construction are calculated. By using them, the occurrence of stresses in certain parts of structural components are observed, and these values are checked. If they do not meet the required (allowed) stresses, i.e. if calculated values are larger than maximal allowed, a new selection of the material, or a remodelling of the structure is required.

However, if the component has a crack, the problem is further complicated, i.e. it is necessary to apply fracture mechanics.

The K_{Ic} is determined according to ASTM E 399 with quite strict criteria. If these criteria are slightly or loosely implemented, the valid value of K_{Ic} parameter is not obtained, and in this case the ASTM E 1820 standard is used.

Values of fracture toughness for plane strain conditions K_{Ic} for a notch specimen are relatively small, and the obtained data are in accordance with the literature data, that is, the mechanical properties of the material have a significant impact on its resistance to crack development, both in the elastic and in the plastic area.

Using the basic formula of fracture mechanics and introducing the value of conventional yield strength, $R_{p0.2} = \sigma$, assuming that the shape factor is equal to one, the approximate values for critical crack length a_c are calculated, that is, the element in exploitation can have a crack to the specified length without danger of fracture.

On the basis of the obtained results it is possible to optimize the shape and size of the net critical cross section.

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