

Crack Length Influence on Stress Intensity Factors for the Asymmetric Four-point Bending Testing of a Polyurethane Foam

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Mixed mode four-point testing is performed on polyurethane foams. This paper presents only the results on the stress intensity factors (SIFs) obtained experimentally for a density of 325 kg/m³, although tests were done for three foam densities. An asymmetric four-point bending setup was used for determining the critical SIFs in Mode I and Mode II, and discussions on the influence of the initial crack length on the SIF values are done. As initial crack length is increased the theoretical predictions give a better comparison to experimentally obtained results.

Keywords: mixed-mode, polyurethane foams, asymmetric four-point bending, crack length

Polyurethane (PUR) foam materials are widely used as cores in sandwich composites, for packing and cushioning. They are made of interconnected networks of solid struts and cell walls incorporating voids with entrapped gas. The main characteristics of foams are lightweight, high porosity and good energy absorption capacity, [1, 2]. Foam materials crush in compression, while in tension fail by propagating of single crack, [3]. Most of the rigid polymeric foams have a linear - elastic behaviour in tension up to fracture, and a brittle failure behavior. So, they can be treated using fracture criteria of Linear Elastic Fracture Mechanics (LEFM).

Consequently, the fracture toughness of such foams became an important characteristic, because cracks weakened the foam structures capacity of carrying load. Many experimental efforts have been made in recent years to determine the fracture toughness of different types of foams: plastic [4-7], carbon [8] and metallic [9, 10]. McIntyre and Anderson [11], using single edge notch bend specimens made of rigid closed-cell polyurethane foams, measured the K_{Ic} for different densities. They found that the fracture toughness is independent of crack length and proposed a linear correlation between fracture toughness and density, for foam densities smaller than 200 kg/m³. At higher densities the correlation became non-linear. The same behavior was observed by Danielsson [12] on PVC Divinycell foams and Viana and Carlsson on Diab H foams [5]. Brittle fracture without yielding produced in Mode I was observed in these experiments. Kabir et al. [7] used the procedure described by ASTM D5045 [13] for determining the fracture toughness of polyvinyl chloride (PVC) and polyurethane (PUR) foams. They investigated the effects of density, specimen size, loading rate and of cell orientation. Density has a significant effect on fracture toughness, which increases more than 7 times when the foam density increases 3.5 times. They also presented the results of the established fracture toughness for H130 foams measured with crack orientation in two directions: rise and flow. The fracture toughness is higher with 27% when the crack is orientated parallel to the rise direction.

Present paper deals with the influence of the initial crack length on the values of the stress intensity factors (SIFs) in mixed-mode by using a four-point bending configuration. Obtained values are compared with those given by using

well-established criteria and comments on particularities of the obtained results are done.

Theoretical basis

The experiments in mixed-mode are done on established setups, one of the most common being the four-point bend specimen. This can create the pure mode I or II and the mixed modes I and II. The four-point bend specimen is loaded in two forms: symmetric and asymmetric. The symmetric bend specimen creates the pure mode I and the mixed mode, but the asymmetric specimen creates mode II in addition to the mixed modes I and II. In [14] a fundamental reference solution is given for an infinitely long cracked specimen loaded by a constant shear force and the corresponding bending moment. Small corrections need to be applied for a finite four-point loading geometry. Initial tests were already reported, [15], showing the difficulties to perform such tests. In the present paper results on the mode I and mode II stress intensity factors are presented for different geometry configurations of the experimental setup.

Asymmetric four point bending represents a good method to determine de Mode II stress intensity factor for an isotropic material. The method itself has been investigated by many researchers, but He and Hutchinson [14] have thoroughly studied it and even proposed corrections that take into account the ratio between the length of the initial crack and the height of the sample. These correction are suitable for ratios less than 0.5, but by increasing it the values of the corrections no longer influence the main results.

The experimental setup is presented in figure 1 and consists of two four point bending fixtures positioned in an asymmetric configuration.

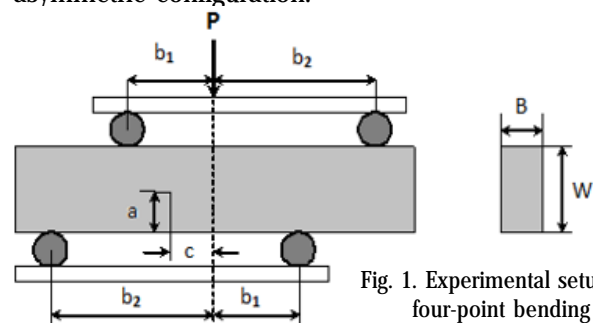


Fig. 1. Experimental setup for four-point bending

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The formulas that are used to determine the values of the stress intensity factors, [14], for each mode are to be calculated as:

$$K_I^R = \frac{6cQ}{W^2} \sqrt{\pi a} F_I \left(\frac{a}{W} \right) \quad (1)$$

$$K_{II}^R = \frac{Q}{W^{\frac{3}{2}}} \left(\frac{a}{W} \right)^{\frac{3}{2}} F_{II} \left(\frac{a}{W} \right) \quad (2)$$

In relations (1) and (2) the shear force Q which acts between the inner loading points is given by $Q = P(b_2 - b_1) / (b_2 + b_1)$ and $M = cQ$ are force and moment defined per unit thickness. All tested specimens had $B = 12.5$ mm, $W = 25$ mm, and $b_1 + b_2 = 100$ mm. In this paper crack length a to height W ratios are 0.5 and 0.68.

The reference solution of Eqs. 1 and 2 is accurate (finite element results show this in [15]) as long as the distance of the nearest loading point is greater than $1.4W$. That is $(b_1 - c) > 1.4W$. For our b_1 value (initially considered as 40 mm) it results $c < 5$ mm, as to fulfill this condition. For loading points nearer to the crack, He and Hutchinson [14] established that a correction of the above relations is needed, as these are valid only for a reference specimen.

It is relatively clear that if parameter c is chosen to be zero, mode I will no longer influence the test, thus the setup will lead to a shear load, resulting a mode II crack propagation. The ratio between crack length and the height of the samples is taken into account when each stress intensity factor is being calculated upon using the following relations:

$$F_I \left(\frac{a}{W} \right) = 1.122 - 1.121 \left(\frac{a}{W} \right) + 3.740 \left(\frac{a}{W} \right)^2 + 3.873 \left(\frac{a}{W} \right)^3 - 19.05 \left(\frac{a}{W} \right)^4 + 22.55 \left(\frac{a}{W} \right)^5 \quad (3)$$

$$F_{II} \left(\frac{a}{W} \right) = 7.264 - 9.37 \left(\frac{a}{W} \right) + 2.74 \left(\frac{a}{W} \right)^2 + 1.87 \left(\frac{a}{W} \right)^3 - 1.04 \left(\frac{a}{W} \right)^4 \quad (4)$$

Experimental part

All specimens were produced by cutting them from a panel of polyurethane foam with density 325 kg/m^3 . The polyurethane foam is named Necuron 301 and produced by Necumer. The crack has been produced artificially by using a razor blade and cutting the foam to the desired initial crack length a .

The tests have been performed on a Zwick-Roell Z010 testing machine, capable of measuring a force up to 10 kN. The distance between the supports has been considered to be four times the height of the sample, that is 100 mm. The purpose of these tests was to determine the variation of the stress intensity factors with respect to parameter c . Speed of testing was always considered as being 1 mm/min, [16].

The specimens were tested using different values for the parameter c , by considering its values in the range specified for each tested setup. As an example, for Setup 2 we tested for values of c equal to 1, 2.5, 4.5 and 7. For each selected value of parameter c we considered a minimum of five tests in order to validate the results. The setups used are presented in table 1.

By using these setups we were able to determine the stress intensity factors presented in figure 2. It is to be mentioned that now a/W is 0.5.

The results show that there is a little difference between the values obtained for c as 1 and 2.5, and we can even say

Dimension	Setup 1	Setup 2	Setup 3
b_1 [mm]	40	42.5	45
b_2 [mm]	60	57.5	55
a [mm]	12.5	12.5	12.5
W [mm]	25	25	25
B [mm]	12.5	12.5	12.5
c [mm]	< 5	< 7.5	< 10

Table 1
SETUPS USED
FOR RATIO
OF 0.5

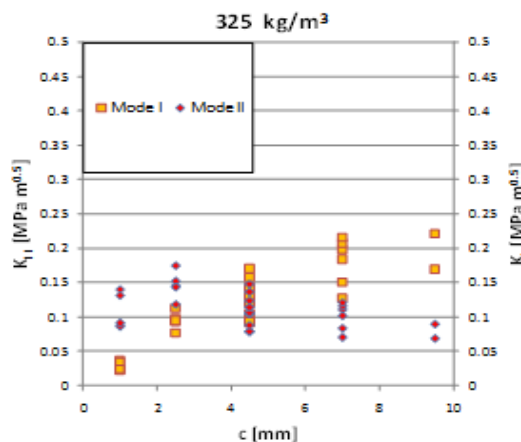


Fig. 2. Stress intensity factors for Mode I and Mode II function of c , for $a/W = 0.5$

that for $c = 2.5$ the Mode II values increase a little bit suggesting that it could be a problem in propagating the crack correctly.

Another important drawback represented the fact that the cracks don't propagate at all in some cases, specially for Setup 3, where the difference between b_2 and b_1 is approaching the value of 10. For this case the samples started to break in the supports region due to the crushing of the foam in that area.

The stress intensity factors obtained experimentally are normalized to the mode I fracture toughness and compared to the theoretical predictions obtained with consecrated criteria: maximum circumferential tensile stress (MTS), minimum strain energy density (SED), maximum energy release rate (G_{max}), equivalent stress intensity factor (ESIF). Thus, for each criterion, results a curve which represents the failure for Mode I and Mode II cohabitation.

The results obtained from experimental data of valid tests (for some tests the crack didn't propagate) are represented in figure 3; the experimentally obtained ratios K_{II}/K_{Ic} are to be represented as a function of K_I/K_{Ic} , and then are compared to the theoretical ones.

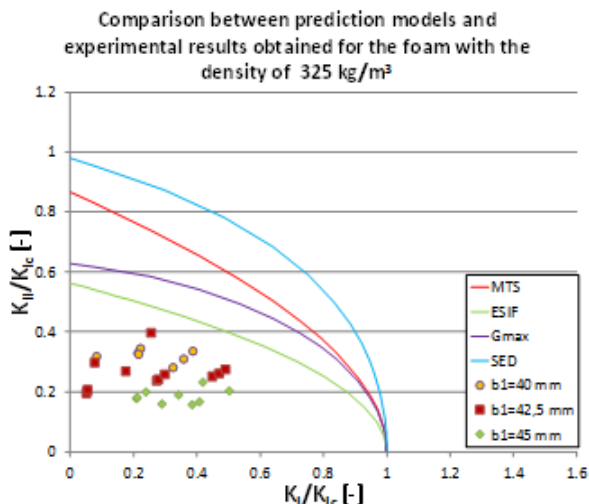


Fig.3. Variation of normalized SIFs compared to the theoretical predictions for $a/W = 0.5$

Table 2
SETUPS USED FOR RATIO OF 0.68

Dimension	Setup 1	Setup 2	Setup 3
b_1 [mm]	37.5	40	42.5
b_2 [mm]	62.5	60	57.5
a [mm]	17	17	17
W [mm]	25	25	25
B [mm]	12.5	12.5	12.5
c [mm]	<2.5	<5	<7.5

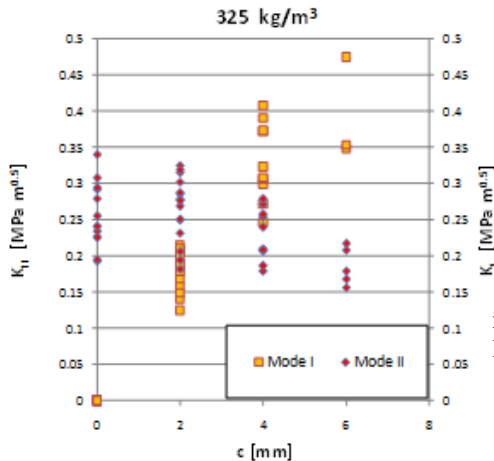


Fig. 4. Stress intensity factors for Mode I and Mode II function of c , for $a/W = 0.68$

As one can notice the values are well below the proposed criteria for establishing the critical locus of failure, and this comparison suggests that the crack didn't propagate correctly. Therefore, we decided to increase the ratio a/W to 0.68.

Another issue is related to the fact that some specimens broke near the supports, which cannot lead to a valid test. We decided to increase the difference between b_2 and b_1 and started to perform tests for $b_1 = 37.5$ mm instead of $b_1 = 45$ mm, as an example. The setup configurations are presented in table 2.

Using these configurations we were able to perform valid tests by determining the critical stress intensity factor (toughness) in Mode II for $c = 0$, and afterwards by increasing each time with 2 mm the value of the parameter c . The variation of the SIFs was obtained for all the testing setups. By taking this decision the results improved significantly, as to be seen in figure 4.

Even if the results are quite scattered, a pattern of variation is to be noticed clearly, mainly the fact that Mode I SIFs increase with parameter c while Mode II SIFs decrease with this parameter. This is a normal behaviour as Mode I values are proportional to the parameter c .

To validate these tests, by plotting the experimentally obtained values together with those given by the theoretical criteria, one can observe in figure 5 that the results improved considerably and can be predicted using some of the already mentioned criteria.

The results obtained for using the highest values of c for $b_1 = 40$ mm and $b_1 = 42.5$ mm fall outside the prediction criteria which suggest the fact that the crack propagated in an unstable manner.

Conclusions

Mixed-mode testing of a polyurethane foam is done by using a four-point bending configuration. The crack propagation is monitored and corresponding SIF values in Mode I and Mode II are calculated. The experimental results of normalized SIFs are compared to the those obtained by theoretical predictions, using well-established criteria. It was found that the geometrical configuration of the specimen and of the testing device makes difficult the crack propagation for $a/W = 0.5$, damage and failure in

Comparison between prediction models and experimental results obtained for the foam with the density of 325 kg/m^3

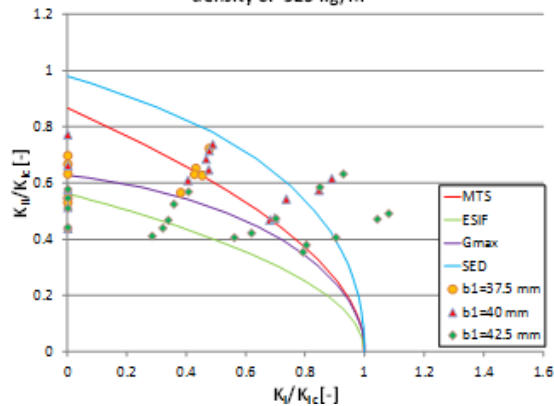


Fig.5. Variation of normalized SIFs compared to the theoretical predictions for $a/W = 0.68$

the loading area becoming dominant. By increasing the crack length ($a/W = 0.68$) it is to be underlined that, although a scatter of data exists, the experimental critical SIFs can be established.

Some theoretical criteria are able to predict quite correctly the normalized values of SIFs, but usually Richard's criterion (ESIF) is the one that predicts better the behaviour of cellular materials, as a polyurethane foam.

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