

PARTICULARITIES OF THE ASYMMETRIC FOUR-POINT BENDING TESTING OF POLYURETHANE FOAMS

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Mixed mode four-point testing is performed on polyurethane foams. Taking into account that there is no standard method for the experimental determination of the fracture toughness, different geometrical configurations were used. This paper presents the results on the fracture toughness obtained experimentally for three different densities of polyurethane foams. Asymmetric four-point bending specimens were used for determining the fracture toughness in mode I and in a mixed mode, and discussions on the influence of the geometrical configuration of the experimental setup are done.

Keywords: mixed-mode, polyurethane foams, asymmetric four-point bending, digital image correlation.

1. Introduction

Foam materials have a cellular structure and hence behave in a complex manner, especially under conditions of progressive crush. This crush behaviour is dependent on the geometry of the microstructure and on the characteristics of the parent material. Foam materials are often used as cores in sandwich construction, and in this application the material can be subjected to multi-axial stresses prior to and during crush. Well-known advantages of cellular metals are their excellent ability for energy absorption, good damping behaviour, sound absorption, excellent heat insulation and a high specific stiffness combined with a low weight. The combination of these properties opens a wide field of potential applications, i.e. as core materials in sandwich panels. A good knowledge of the behaviour of different grades of foams is important for being able to design high performance sandwich composites adapted to the special needs of a particular application.

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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. It is to be mentioned that foams have an anisotropic morphology. The direction in which the foam expands the most during reaction and expansion is called the foam rise direction. The other two principal directions are called flow directions (usually on these directions the foam mechanical properties are about the same). 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 behaviour. So, they can be treated using fracture criteria of Linear Elastic Fracture Mechanics (LEFM).

Consequently, the mode I fracture toughness K_{Ic} 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/m^3 . At higher densities the correlation became non-linear. The same behaviour 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. It is to be noted that a correlation between the static fracture toughness and relative density ρ/ρ_s (ρ being the foam density and ρ_s density of the solid material from which foam is made) was proposed in [1]. 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. Burman [6] presented fracture toughness results for two commercial foams, Rohacell WF51 (density 52 kg/m^3) and Divinycell H100 (density 100 kg/m^3). The mode I fracture toughness K_{Ic} was obtained on Single Edge Notch Beam (SENB) specimens and has values of $0.08 \text{ MPa}\cdot\text{m}^{0.5}$ for WF51, respectively $0.21 \text{ MPa}\cdot\text{m}^{0.5}$ for H100. He also determined the Mode II fracture toughness using End-Notch Flexure (ENF)

specimens, with values of $0.13 \text{ MPa}\cdot\text{m}^{0.5}$ for WF51, respectively $0.21 \text{ MPa}\cdot\text{m}^{0.5}$ for H100.

The geometry and loading conditions for an improved test configuration called the asymmetric semi-circular bend (ASCB) specimen is presented in [15, 16]. In this case a semi-circular specimen that contains an edge crack emanating normal to the flat edge of the specimen is loaded asymmetrically by a three-point bend fixture. In order to use accurately the analytical solutions for these two testing configurations the loading points have to be sufficiently far from the crack as not to influence the crack tip stress and strain fields. Various tests under mixed-mode bending for ASCB specimens were presented before in [17, 18].

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, [19], 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.

2. Testing configuration

An asymmetric four-point bend specimen (A4PB) is used in these tests having the geometry presented in Fig. 1. All tested specimens had $B = 12.5 \text{ mm}$, $W = 25 \text{ mm}$, and $b_1 + b_2 = 100 \text{ mm}$. An initial geometrical configuration considered $b_1 = 40 \text{ mm}$, $b_2 = 60 \text{ mm}$, and $a/W = 0.5$. For $c = 0$, Mode I should vanish according to the relations written below, from which one can calculate the stress intensity factors for a reference problem with an infinite specimen, [14], subjected to a force Q and a varying bending moment M

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

$$K_{II}^R = \frac{Q}{W^{1/2}} \frac{(a/W)^{3/2}}{(1-a/W)^{1/2}} F_{II}(a/W). \quad (2)$$

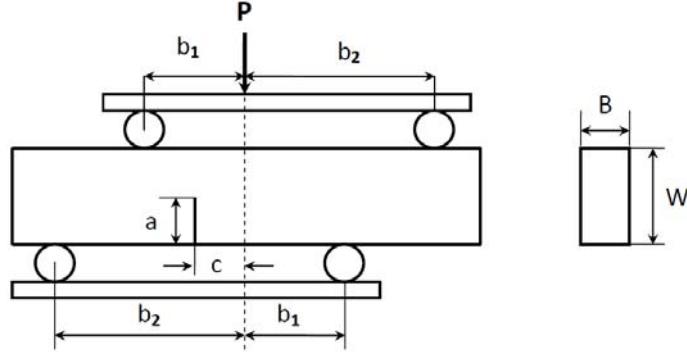


Fig. 1. Geometry of the specimen and loading configuration

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 $M = cQ$. The expressions to calculate $F_I(a/W)$ and $F_{II}(a/W)$ can be found in [14].

The reference solution of Eqs. 1 and 2 is accurate (finite element results show this in [20]) as long as the distance of the nearest loading point to the crack tip 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. Such calculations were done for some geometries and further discussions were presented in [20], as these authors introduced two more correction factors (one for each mode), besides the ones established in [14].

3. Results obtained in mode I loading

Tests were performed on closed-cell Necuron polyurethane foams of densities 100, 145 and 300 kg/m³. Tests were carried out on a Zwick Z010 (10 kN) machine. Speeds of testing were considered as 1, 10, and 100 mm/min.

In Mode I, three-point bending (3PB) tests considered hereby are only for $b_1 + b_2 = 100$ mm and the force P applied in the middle. The obtained Mode I average critical toughness is given in Table 1. Average values are obtained for each speed from 4 to 7 tests.

Table 1

Mode I fracture toughness for three densities of polyurethane foam

Foam density [kg/m ³]	Speed of testing [mm/min]	K_{Ic} [MPa \sqrt{m}]
100	1	0.0722
	10	0.0741
	100	0.0735

145	1	0.0797
	10	0.0881
	100	0.0861
300	1	0.341
	10	0.343
	100	not tested

Results indicate that, for these speeds of testing, mode I fracture toughness slightly increases and then decreases for each of the densities under discussion. For all following tests we kept only the loading speed of 1 mm/min as to better observe local phenomena with the digital image correlation method. The mode I fracture toughness K_{Ic} will be later used for the evaluation of mixed mode results by normalizing K_I and K_{II} to K_{Ic} .

4. Remarks on the mixed mode testing

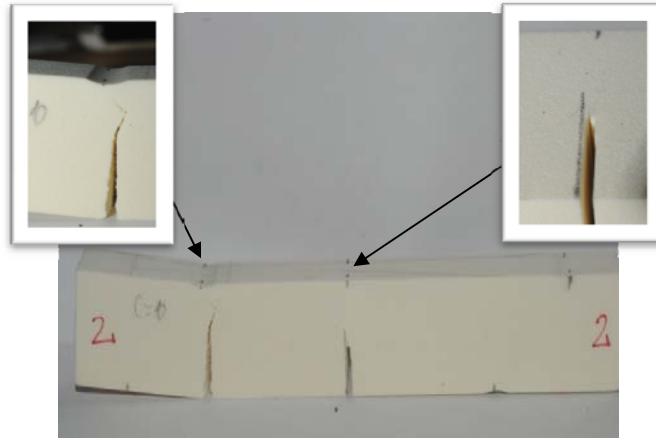
Initially the span (distance between loading or supporting cylinders, Fig. 1) was considered as being $b_1 + b_2 = 100$ mm. Three sets of geometrical arrangements, named configurations, were adopted for the beginning, as presented in Table 2. In all tests the ratio $a/W = 0.5$ was adopted, with the initial crack (cut with a razor blade) positioned in the middle of the specimen. Although formally the condition $c < 5$ mm discussed previously was preserved at the limit, the local crushing of the polyurethane foam gave sometimes the undesired failure of the specimens. The values of c result as imposing the previously mentioned condition which should not affect the crack tip due to the close boundaries. As shown in Fig. 1, loading was applied top-down in a four-point bending (4PB) arrangement, through loading cylinders having a diameter of 10 mm.

Table 2

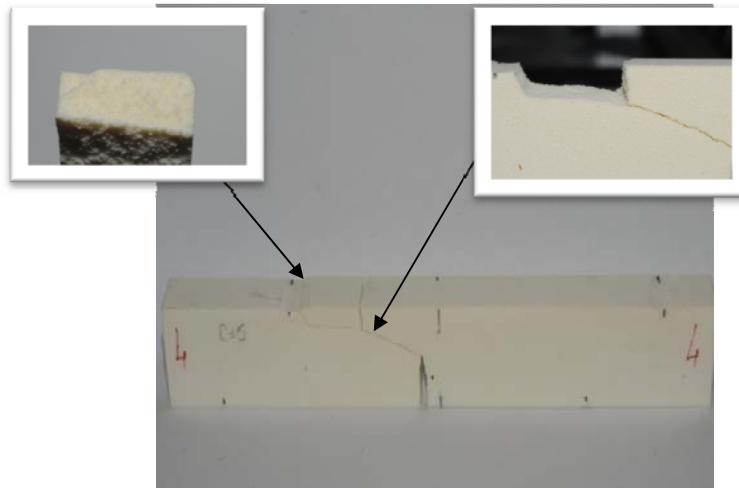
Geometry of the specimens and resulting c values

Dimensions	Configuration 1	Configuration 2	Configuration 3
b_1	40 mm	42.5 mm	45 mm
b_2	60 mm	57.5 mm	55 mm
a	12.5 mm	12.5 mm	12.5 mm
W	25 mm	25 mm	25 mm
B	12.5 mm	12.5 mm	12.5 mm
It results	$c < 5$ mm	$c < 7.5$ mm	$c < 10$ mm

In Fig. 2 is presented the failed specimen for $c = 0$ (Configuration 1) - according to Eqs. 1 and 2 only Mode II should be obtained. The foam had for these tests a density of 100 kg/m^3 . Due to the loading conditions the foam was crushed severely closer to the crack location and a secondary propagating crack developed. This crack was the one which finally led to the undesired failure of the specimen.

Fig. 2. Failure of an 4PB specimen with $c = 0$

A similar behaviour of the tested specimen resulted when $c = 5$ mm, as presented in Fig. 3. This time the main crack propagated as being oriented towards the nearest loading point, and bifurcated close to the outer surface. One branch turned suddenly to the surface, while the other continued its path to the loading cylinder.

Fig. 3. Failure of a 4PB specimen with $c = 5$ mm

Indeed, many tests came to be unsuccessful due to undesired crack propagation or local crushing and couldn't be considered for further evaluation of the results. As a proof of the previous phenomenological observations, a digital image correlation analysis done with the Aramis system gave a clear evidence of the severe local crushing of the foam around the loading cylinders as seen in Fig.

4. Minor strains, as compression is produced around the cylinders, are greater in absolute value in the area of loading than at the crack tip.

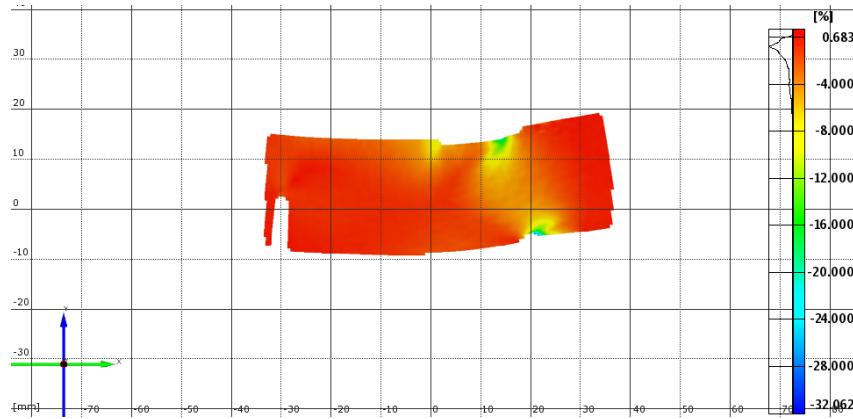


Fig. 4. Minor strain map for a tested specimen of density 100 kg/m^3

It was noticed that if the difference $b_2 - b_1$ is greater (for relatively small distances the shearing of the foam between the loading points and the local crushing of the foam produce extensive local damage) the crack propagates in a stable manner from the tip of the initial artificial crack of ratio $\frac{b_2}{b_1}$. Unfortunately, depending on the configuration of testing (see Table 2) and the distance c the crack doesn't propagate or propagates somewhere else and, as before, undesired failure invalidates the test.

5. Results for mixed mode testing

For each of the three b_1 values, the c value is increased up to the established limits for the three configurations, modifying therefore the mode mixity. In fact for $c = 0$ (pure mode II) it is almost impossible to propagate the crack.

The tests were done considering the following geometrical parameters: Configuration 1 ($b_1 = 40 \text{ mm}$), $c = 1, 2.5, 4.5 \text{ mm}$; Configuration 2 ($b_1 = 42.5 \text{ mm}$), $c = 1, 2.5, 4.5, 7 \text{ mm}$; Configuration 3 ($b_1 = 45 \text{ mm}$), $c = 1, 2.5, 4.5, 7, 9.5 \text{ mm}$. It is to be underlined that it is difficult to perform a valid test for small c values, especially if $b_2 - b_1$ is small, as for Configuration 3.

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). An overview of these criteria and the used formulae are presented elsewhere [17, 18].

The results obtained for experimental data of valid tests are represented in a plot (Fig. 5) for K_{II}/K_{Ic} as a function of K_I/K_{Ic} , compared to the theoretical ones for a foam with the density of 300 kg/m^3 .

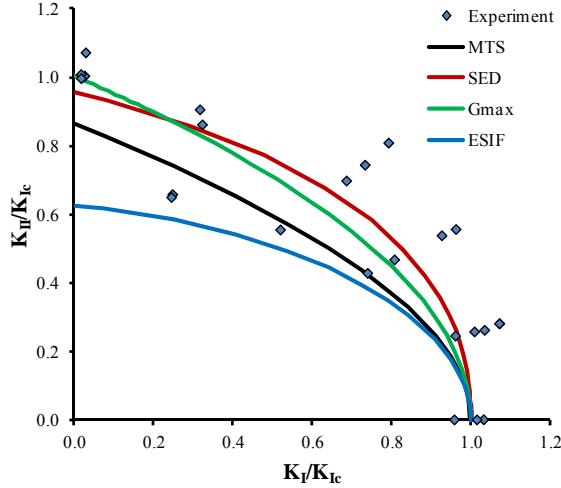


Fig. 5. Normalized experimental results compared to consecrated criteria

The theoretical loci represent failure envelopes which consider a certain global parameter as becoming critical. It is difficult to make an interpretation of these results as the spread of experimental data is significant. Some of them match the MTS criterion, others the G_{\max} criterion. For experimental results obtained close to pure mode II, the G_{\max} criterion is attained. If mode I is dominant, for $K_I/K_{Ic} > 0.6$ some of the experimental data are much outside the envelopes, that is failure is produced later than theoretically predicted. Let's remember that all criteria are established under LEFM assumptions for homogeneous and isotropic materials. For the polyurethane foams neither of these assumptions is in fact valid. Foams are anisotropic materials and the behaviour of the material is different if the crack is along the rise or the flow direction. They are not homogeneous as at the microstructure level micro cracks and various damages of the cells are to be seen. However, their failure is essentially brittle at macroscopic level, especially if the density is greater (for Fig. 4 is 300 kg/m^3), and the only available failure envelopes in the literature are based on LEFM.

6. Conclusions

The experimental setup configuration has a significant influence on the success of the test in providing a valid result. The up to now obtained results led us to the necessity to increase the span length which is going to be further

considered as being 110 mm and 120 mm in order to increase the distance $b_2 - b_1$ and to avoid the local shearing and crushing of the foam in the area of loading points. On the other hand, in trying to propagate easier the crack, the a/W ratio will be increased to 0.7.

The normalized values of the mode I and mode II SIFs are the ones which can be plotted as to represent the locus of a failure envelope established experimentally (for a detailed discussion see [18]) which can be compared to well-established mixed-mode criteria known in the literature. However, the anisotropy of the tested materials is leading to a significant scatter of the obtained experimental results. An endeavor is to be able to select the correct and proper ones.

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