

Experimental and XFEM Analysis of Mode II Propagating Crack in a Polyurethane Foam

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Mode II testing is performed on a polyurethane foam as a particular case of mixed-mode four-point testing. Crack initiation and propagation in Mode II depends on the geometrical parameters of the testing configuration. Numerical XFEM simulations are done in order to clarify the situations in which the crack doesn't propagate and failure is produced in the region of supports. A combined experimental-XFEM analysis is recommended to fully understand the particularities of the behaviour of cellular materials.

Keywords: polyurethane foam, asymmetric four-point bending, Mode II, XFEM, crack propagation

Aeronautical, automotive or naval structural integrity is of great importance and any presence of imperfections can reduce significantly the load bearing capacity. 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, high crushability, and good energy absorption capacity.

Without a better understanding of progressive failure, the fracture criteria and predictive capabilities will be limited. Interface cracking is generally a mixed mode cracking, as both normal and shear stresses develop just ahead of the crack tip, [1, 2]. Experiments have shown that fracture energy can depend on mode mixity, [3-5]. Foam materials, used extensively in such applications, 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).

Powerful numerical methods are needed for being capable to model correctly crack initiation and propagation. The introduction of the eXtended Finite Element Method (XFEM) represents undoubtedly, the major breakthrough in the computational fracture mechanics field, made in the last years. XFEM are numerically implemented mostly by means of standalone codes. However, during the last years an increasing number of commercial FEA software are adopting the XFEM technique; among these, the most famous and widely employed is AbaqusTM.

Fracture toughness in mixed mode loading is of particular interest because foam cracking weakens the structure's capacity for carrying loads. Present paper assesses the Mode II toughness of polyurethane foams and analyzes the crack initiation and propagation for such a loading by combining experimental and numerical analyses.

Comments on XFEM formulation

The eXtended Finite Element Method (XFEM) is an extension of the FEM, and its fundamental features were

described by Belytschko and Black [6], based on the idea of partition of unity presented in [7], which consists on local enrichment functions for the nodal displacements to model crack growth and separation between crack faces. With this technique, discontinuities such as cracks are simulated as enriched features, by allowing discontinuities to grow through the enrichment of the degrees of freedom of the nearby nodes with special displacement functions. As the crack tip changes its position and path due to loading conditions, the XFEM algorithm creates the necessary enrichment functions for the nodal points of the finite elements around the crack path/tip. Compared to CZMs, XFEM excels in simulating crack onset and growth along an arbitrary path without the requirement of the mesh to match the geometry of the discontinuities neither remeshing near the crack [8]. In [9] Moës, et. al., used XFEM to create a technique for simulating crack propagation in two dimensions without remeshing the domain. Later Moës and Belytschko [10] integrated cohesive zone modelling (CZM) into the XFEM framework to overcome the CZM shortcoming because the XFEM is particularly effective in dealing with moving arbitrary discontinuities. The extension to three dimensions was begun by Sukumar et al. [11], where they used the two dimensional enrichment functions for planar cracks, and then extended in [12].

The implementation of the eXtended Finite Element Method in commercial FEA softwares is still limited, and the most famous one including such capabilities is AbaqusTM. However, due to its relatively recent introduction, XFEM technique in AbaqusTM has been proved to provide trustable results only in few simple benchmark problems involving linear elastic material models.

Experimental part

Determining a Mode II stress intensity factor (SIF) can represent a difficult task when an anisotropic material is used, especially when a polyurethane foam is considered. Due to the cellular structure an ideal crack it is impossible to create and in most cases a razor blade is used to create it. This is usually the problem when creating a XFEM model due to the fact that by using a finite element model the crack is considered as ideal, having a clear length, disregarding any possible bluntness that can be found in reality at the crack tip.

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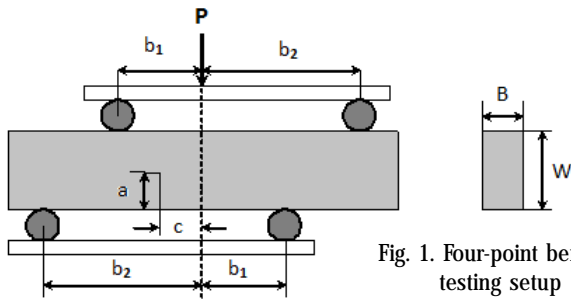


Fig. 1. Four-point bending testing setup

By considering a four-point bending fixture positioned in an asymmetric manner (fig. 1), one can perform a test by having the crack positioned in the same plane as the one of symmetry of the specimen ($c = 0$), and a Mode II crack will be obtained.

The height of the sample is in these tests $W = 25$ mm and $W = 30$ mm. The distance between the supports and the loading points will be considered as equal to four times the height of the sample, that is 100 mm and, respectively 120 mm. The specimens have been cut out of a sheet of polyurethane foam Necuron 301 of 325 kg/m^3 density, produced by Necumer. Tests were performed on a Zwick-Roell Z010 testing machine, using 1 mm/min as testing speed.

Results and discussions

Mode I SIF is increasing with parameter c , while Mode II SIF decreases when parameter c increases. That is, by increasing the value of parameter c the distance of the crack to the nearest loading point becomes smaller, resulting in a decrease in the shear stress at the crack tip, Mode I becoming dominant with the increase of c .

Two different heights were used in performing the experimental tests, the results obtained for $W=25$ mm being presented in figure 2. SIF values in Mode I and Mode II are calculated by using established relations.

By increasing W to a value of 30 mm, we studied again the phenomena observed for $W=25$ mm, trying to understand what happens for extreme values of parameter c . In Table 1 the experimental setups used for $W=30$ mm are presented.

The reference solution established by He and Hutchinson [13] is accurate as long as the distance of the nearest loading point is greater than $1.4W$. That is $(b_1 - c) > 1.4W$.

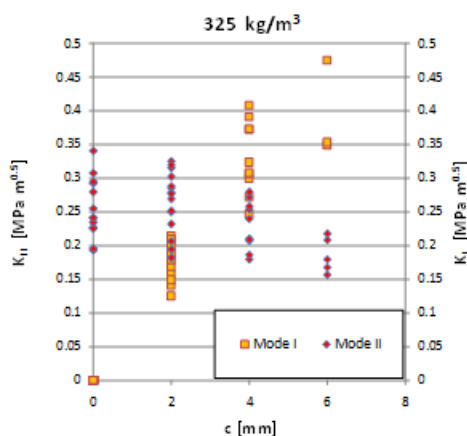


Fig. 2. Mode I and Mode II SIF variation with respect to parameter c

For the b_1 values (table 1), considered in experimental testing, limitations for c values do result, as to fulfill this condition.

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. By using the configurations described in table 1 the obtained results were plotted in figure 3.

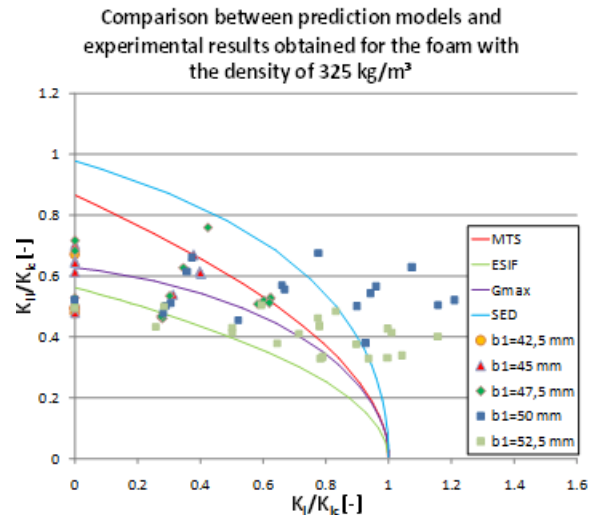


Fig. 3. Test results plotted against prediction models for $W = 30$ mm

The obtained results revealed that there is a dependency between the crack propagation and the b_1 distance. This means that by increasing the distance b_1 the results are starting to become more scattered and for c close to the maximum limits the obtained results are not following any criteria. Starting from this conclusion we describe a critical distance as being $\delta = b_2 - b_1$ for which the crack will not propagate or it will propagate under certain special conditions.

For tests performed using $\delta = 20$ mm and $c=0$ we observed that the crack did propagate for one test, but the values were not predictable by any criteria, while for $\delta = 15$ mm we were unable to propagate correctly the crack for three values, as $c = 0.2$ and 4 mm.

Even if these results can be explained for extreme values of the parameter c , where mode mixity is fully dependable on the fact that parameter c multiplies Mode I SIF value, they don't explain why the crack doesn't propagate for certain conditions.

In order to investigate and clarify this issues we had to perform XFEM simulations for the tested setups.

XFEM analysis of crack propagation

Constructing a good 2D XFEM model requires knowing how the analyzed material performs under different loading conditions. Compression, tensile and fracture toughness

Table 1
SETUPS FOR $W=30$ mm

Dimensions	Setup 1	Setup2	Setup3	Setup 4	Setup 5
b_1 [mm]	42.5	45	47.5	50	52.5
b_2 [mm]	77.5	75	72.5	70	67.5
a [mm]	20.4	20.4	20.4	20.4	20.4
W [mm]	30	30	30	30	30
B [mm]	12.5	12.5	12.5	12.5	12.5
c [mm]	< 0.5	< 3	< 5.5	< 8	< 10.5

data obtained from experiments are used in order to construct the model that will help investigate the behaviour of the studied foam under mixed-mode testing.

The model functions upon a simple requirement, that is initiating a crack when a certain maximum principal strain value is achieved. By calculating all the time this value the crack is initiated and then propagated on a direction. The maximum principal strain is found to be usually equal to the strain at which the foam breaks in tension.

The cellular material has been analyzed using the hyperfoam model from Abaqus™ by inserting tabular compression testing data, that will be used to describe the crushing behaviour of the material in the supports and loading areas.

The damage evolution is defined by the released energy G (crack driving force), and represents the area enclosed by the stress and strain curve for the element.

Because we are dealing with a mixed mode test the G energy represents the equivalent energy which is consumed in order completely propagate the crack. The formula for this energy is written as

$$\left(\frac{G_I}{G_{Ic}}\right)^n + \left(\frac{G_{II}}{G_{IIc}}\right)^n = 1 \quad (1)$$

In this power law relation we considered that n is equal to 1 for this application, while G_{Ic} and G_{IIc} are the critical values for the released energy determined in Mode I and Mode II.

Tensile and fracture toughness tests results have been used in order to calculate the values needed for relation (1) and presented in table 2.

Table 2
INPUT DATA FOR THE MODEL

E [MPa]	ν [-]	K_{Ic} [MPa \sqrt{m}]	K_{IIc} [MPa \sqrt{m}]	Maximum principal strain [-]
282	0.31	0.34	0.31	0.073

Using the input data presented in table 2 we were able to fully understand the behavior of the material when performing tests for $W=30$ mm in the case of Setups 4 and 5. The load is applied by considering a displacement load and measuring the reaction forces that appear in the support region. In order to propagate the crack it is

compulsory to determine the stress values that appear near the loading and support areas. This is done by creating a tie node that sums all the forces that are measured in this region.

In figure 4 one can observe that the equivalent stress values are well above the crushing and shear values of the material, reaching approximately 18 MPa.

The model is able to analyze the crack propagation during mixed mode testing, being able to describe the crack path for any c value. The model revealed that in order to propagate a crack in the sample is needed a very high force value when testing in Setups 4 and 5 configurations, as it is to be seen in figure 5.

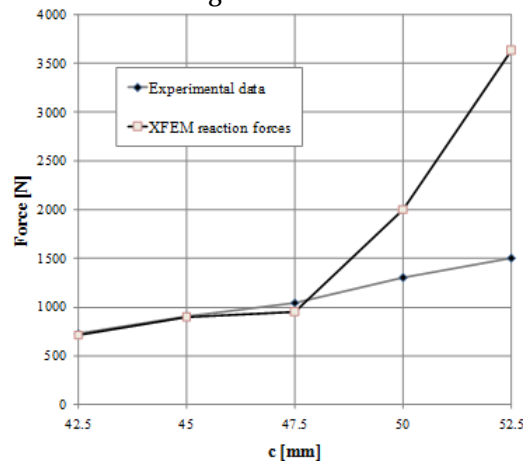


Fig. 5. Comparison between experimental and XFEM data

In figure 5 the experimental data has been obtained by calculating and plotting the mean values of the forces obtained in the experiments. This is typically a usual practice, but the standard deviation values should be considered specially when testing an anisotropic material because for a particular setup one can obtain a broad range of force values which can be justified by the anisotropy or by the fact that the crack was blunt or different defects were present inside the material.

One of the most important characteristic of the model is being able to describe what happens in some cases when crack propagates in the support or loading region. The model approximated correctly the values for $b_1 = 42.5$, 45 and 47.5 mm, and with the decrease of δ the model requires a larger value of the force in order to propagate the crack. In reality we observed that this value is not obtained due to the fact that at the same time the crack propagates in the loading area and becomes dominant.

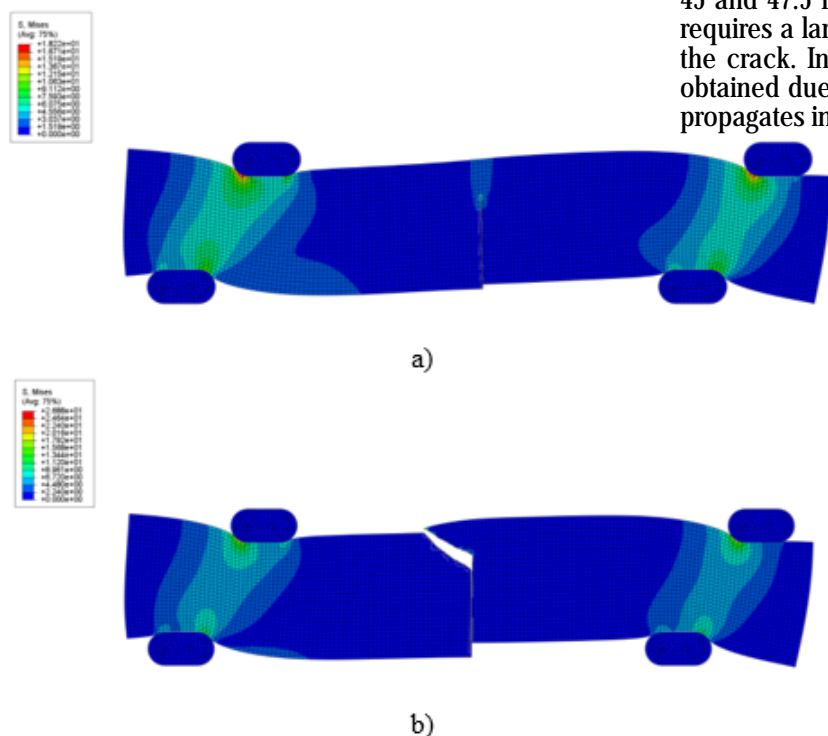


Fig. 4. Von Mises stress values at:
a) initiation; b) full propagation
of the crack

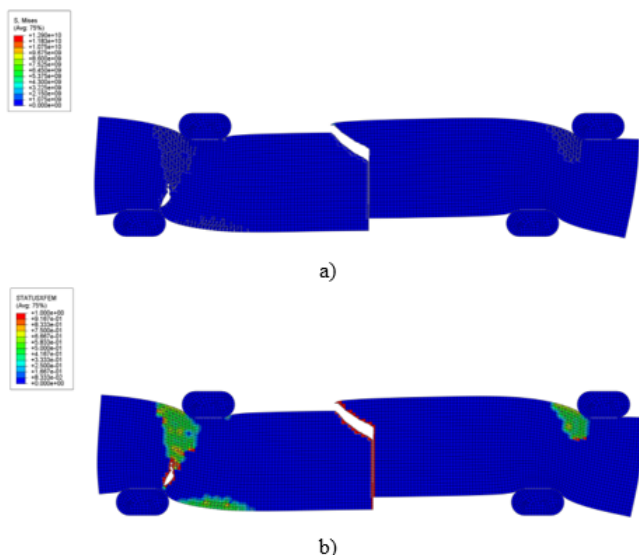


Fig. 6. Crack propagated in the support and loading region: a) von Mises stress values; b) XFEM element status

In order to perform all of these analyzes one must understand how XFEM propagates a crack based on the critical G energy. The parameter called StatusXFEM can take values from 0 to 1 and represents the amount of G energy that has been used to propagate the crack through an element. This parameter is used to understand what happens in the loading region and can be seen in figure 6.

As shown figure 6a the von Mises stress values are quite high in the support region, leading to the development of new cracks. This is supported by the fact that in figure 6b one can observe that almost the entire region is subjected to a high stress, the StatusXFEM variable is almost 0.5 (green color elements), crack being initiated, but as soon as value 1 (red color elements) is reached the crack is propagated. This means that the energy has been consumed to propagate a crack in the loading and support region and this is found to happen also in the experimental setups for $\delta = 15$ and 20 mm.

Conclusions

Mixed-mode testing of polyurethane foams is in some situations followed by undesired failure in the region of supports without any propagation of the main crack. In

Mode II testing it is sometimes difficult to propagate the crack due to the geometrical constraints of the testing configuration. Some of the experimental results obtained for SIFs are not to be comparable with the theoretical predictions.

XFEM simulations are done to study the crack initiation and propagation and explain the failure produced elsewhere. It proves to be a powerful method of analysis if the model is correctly calibrated. Therefore, a combined experimental-XFEM analysis can lead to proper results for assessing the failure of polyurethane foams in various loading conditions.

Acknowledgements: The work done by Dr. Drago Alexandru Apostol has been supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and the Romanian Government under the contract number POSDRU/159/1.5/S/137390/. The work done by PhD student Florin Stuparu has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/107/1.5/S/76909. The work of the other co-authors has been supported by a grant of the Romanian National Authority for Scientific Research, CNCS - UEFISCDI, project PN-II-ID-PCE-2011-3-0456, contract number 172/2011.

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Manuscript received: 18.01.2016