Influence of geometrical parameters on fracture toughness for open cell foams

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Abstract

The paper presents the influence of geometrical parameters on fracture toughness for open cell foams. This study was carried out for Mode I fracture using a finite element micromechanical analysis. Two cell shapes were considered: rectangular and honeycomb. For determination of Mode I fracture toughness a simple 2D solid model was used in FRANC2D/L code. Simulation was performed for open cell polyurethane foams (PUR) of 5 different densities. For estimation of fracture toughness the applied loads were progressively increased up to reach the fracture strength for each solid material in the first un-cracked strut in front of crack.

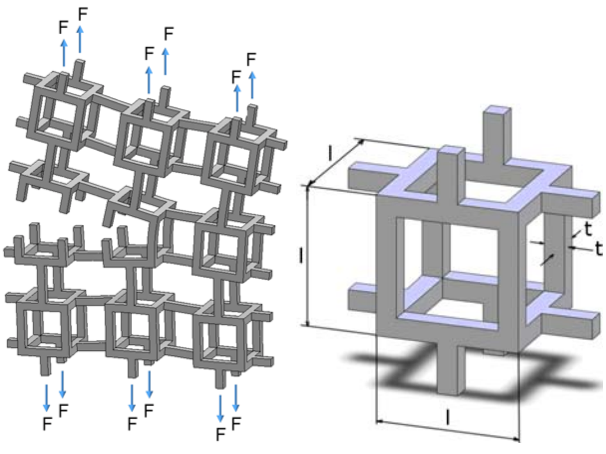
Keywords: finite elements, fracture toughness, micromechanical model, polyurethane foam, open cell.

1. Introduction

A cellular solid is made up of an interconnected network of solid struts or plates which form the edges and faces of cells, [1, 2]. Network-type models are often used as micromechanical tools. The cellular material shows anisotropic structure and micromechanical models may take into account for properties and response, [3-6]. Finite element modelling methods are used to describe the behaviour and mechanical properties of structures, [6].

Different models have been developed to predict the mechanical behaviour of cellular materials in order to find and analyze the failure mechanism by which cell walls deform under load. Gibson and Ashby considered that at cell size scale, a crack can be extended in a discrete mode, [1]. Every time the row of cells along of the crack front breaks the crack extends with the length of the cell, (figure 1a).

Micromechanical models relate the fracture toughness of the foam K_{Ic} to the fracture strength of the cell walls σ_{fs}, and the relative density ρ^*/ρ_s. The geometric characteristics of an open cell are the cell length l, and the thickness of strut t, (figure 1b).



a) b)

Figure 1: a) Cracked cellular structure; b) cell geometry

The analytical micromechanical models must be validated with experimental results, [7-9]. If the foam is loaded, the walls of the cell deform elastic. The load is transmitted through foam as a discrete set of forces and moments through cells edges. These forces and moments can be calculated based on linear elastic continuously stress field in the vicinity of the crack. Comparing with experimental data for cellular materials with open-cell the relationship between fracture toughness K_{IC} normalised to fracture strength of solid material σ_{fs} and cell size l function of relative density is, [1]:

$$\frac{K_{IC}}{\sigma_{fs}\sqrt{\pi l}} = 0.65\left(\frac{\rho^*}{\rho_s}\right)^{3/2} \tag{1}$$

In recent years Finite Element Analysis (FEA) was used extensively in order to solve the micromechanical models for fracture toughness estimation of cellular materials, [2, 10, 11].

2. Finite element micromechanical analysis

The paper presents a micromechanical model for determination of the fracture toughness for open cell materials using Finite Element Analysis implemented in FRANC2D/L code. Two cases were considered:

-cell length quasi-constant l=0.52-0.60 mm, and variable cell wall thickness, t=0.02; 0.05 and 0.1 mm;

-cell wall thickness, t=0.05 mm constant and variable cell length, l=0.55; 0.75 and 0.95.

The mechanical characteristics of solid material (density ρ, fracture strength σ_{fs}, Young modulus E, and Poisson's ratio ν) considered for fracture toughness determination are listed in Table 1. Both the fracture toughness and the tensile strength of brittle foams depend on the fracture strength of solid material.

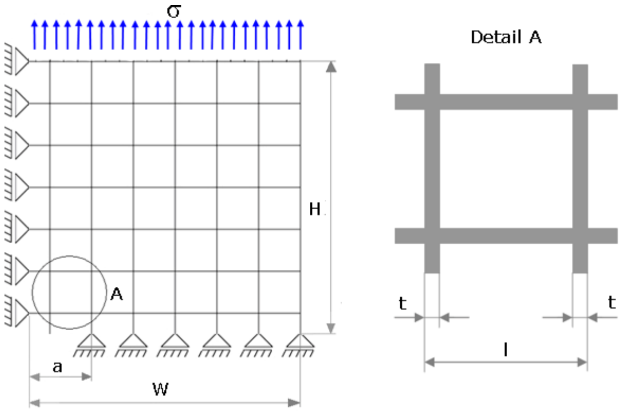
Table 1: Mechanical characteristics

Material properties of solid PUR	ρ_s [kg/m^3]	σ_{fs} [MPa]	E [MPa]	ν [-]
	1170	130	1600	0.40

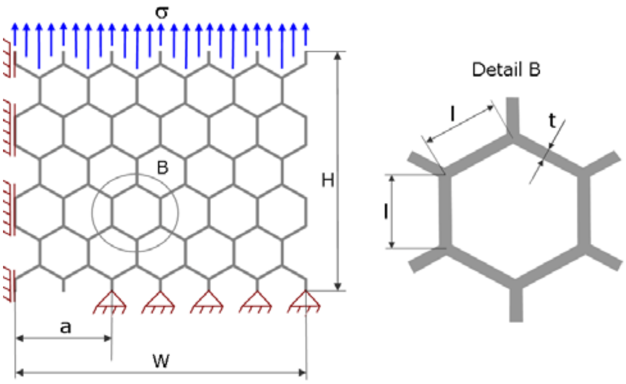
Cellular materials such as polyurethane (PUR) foams are orthotropic homogeneous materials, but at a micro structural level the layer of cells is considered isotropic, linear elastic and brittle, [1].

These details about the microstructure are particularly important to understand and describe the deterioration and fracture of the material, [12-14].

In figure 1 are presented the plane strain micromechanical models used in this analysis. Figure 1a presents the model with rectangular cells and figure 1b shows the model with honeycomb cells. Also, in same figure are presented imposed boundary conditions



a)



b)

Figure 1: Micromechanical model dimensions and boundary conditions: a) rectangular cells, b) honeycomb cells

A quarter of a central cracked plate was modelled using plain strain conditions. The 2D solid models used 100 cells for the rectangular structure with 19400 - 8 nodes isoparametric elements connected in 77200 nodes for the smallest analysed density, while for the honeycomb structure a number of 30 cells were considered with 4320 elements and 15235 nodes. The symmetric boundary conditions were imposed, and the applied load σ was imposed perpendicular to the crack, in order to produce a Mode I loading. The crack is created by breaking the ligaments of the cells, [2, 15].

Mode I fracture toughness was obtained by progressive loading of the model with increasing the applied load σ until the maximum stress $\sigma_{y,max}$ in the first unbroken strut reaches the fracture strength of the solid σ_{fs}.

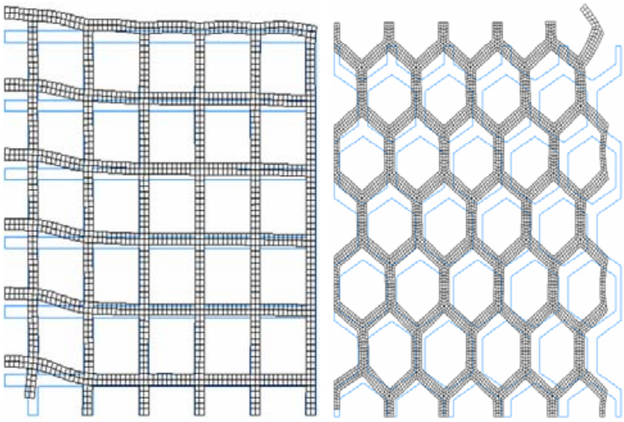
The fracture toughness of cellular material was determined by:

$$K_{IC} = K_I = \sigma \sqrt{\pi a}\, F_I\left(\frac{a}{W}\right) \tag{2}$$

where *a*, [mm], represents the crack length, *W*, [mm] width of the model and $F_I(a/W)$ a non-dimensional function from stress intensity factors handbooks.

$$F_I\left(\frac{a}{W}\right) = \frac{1-0.5\left(\frac{a}{W}\right)+0.37\left(\frac{a}{W}\right)^2-0.044\left(\frac{a}{W}\right)^3}{\sqrt{1-\left(\frac{a}{W}\right)}} \tag{3}$$

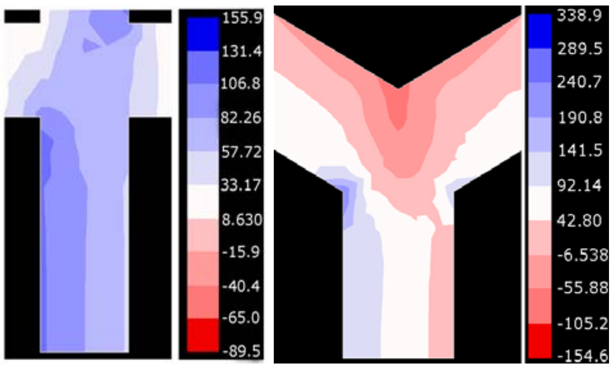
Figure 2 shown the deformed meshes for crack length a = 0.85 mm (fig.1.a rectangular model) and a=0.55 mm (fig.1.b honeycomb model) loaded in Mode I fracture.



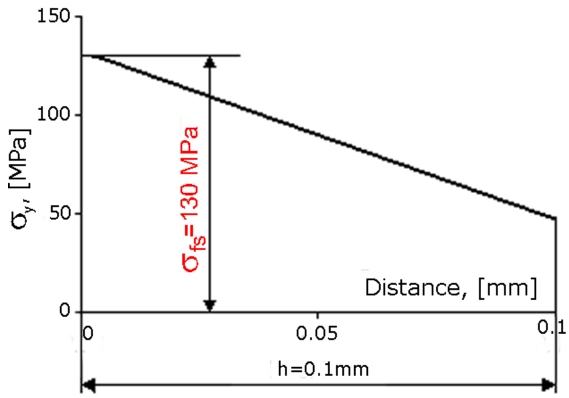
a) Rectangular b) Honeycomb

Figure 2: Deformed meshes loaded in Mode I

Figure 3 present stress distribution σ_y in first unbroken strut for Mode I loading. A combined stress tensile with bending occurs in the first strut which confirm the hypothesis from micromechanical model of Choi and Sankar, [10].



a) Contur plot (rectangular and honeycomb cells)



b) Line plot

Figure 3: Stress distribution σ_y in first unbroken strut for mode I loading

In figure 4 is presented the variation of fracture toughness with number of cells for foam with 0.105 relative density.

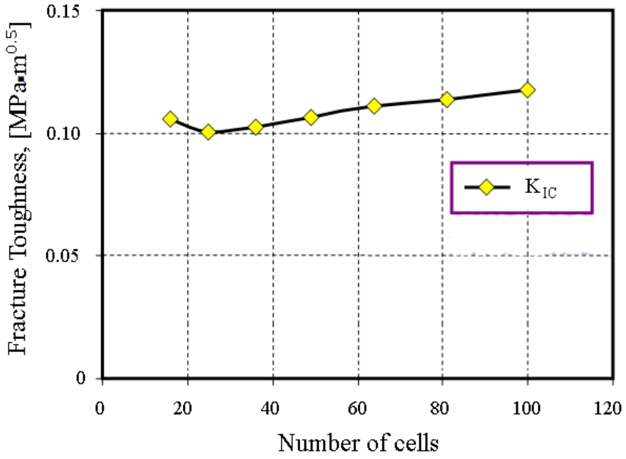


Figure 4: Variation of fracture toughness with number of cells

As the model size increases, fracture toughness converges to a value approximately equal to 0.119 MPa $m^{0.5}$ as shown in figure 4, [10].

The relative difference in fracture toughness between minimum value and the maximum one is 14,3%. This difference decreases between models with 64 cells and 100 cells to 5.4%. The influence in computational time between models with 64 and 100 cells is insignificant and 100 cells model was used for fracture toughness evaluation.

Figure 5 presents the influence of the crack length on fracture toughness for PUR foam with relative density of 0.077, 0.105, 0.133, 0.182 and 0.333.

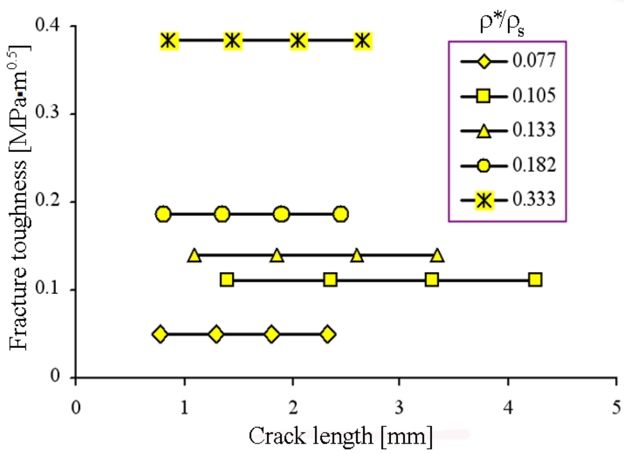


Figure 5: Variation of fracture toughness with crack length

Four different crack lengths were considered for each density (between 0.77 and 4.25 mm), keeping the size of the foam constant. The relative differences in fracture toughness were 1.3% indicating that the predicted fracture toughness could be considered independent on crack length.

Variation of fracture toughness versus relative density by Mode I for polyurethane foam is shown in figure 6. The representation is made for both cases (with l quasi-constant-t variable and t constant-l variable). Fracture toughness values are between 0.051 MPa $m^{0.5}$ (for relative density 0.077) and 0.384 MPa $m^{0.5}$ (for relative density 0.333), were obtained for PUR foam.

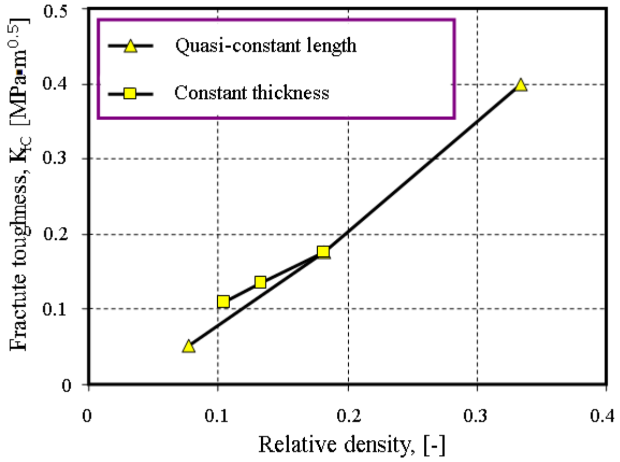


Figure 6: Mode I fracture toughness as a function of relative density for two cases

3. Results and discussion

In Table 2 are presented the Mode I fracture toughness values, obtained from finite element simulations for the two cell geometries: rectangular and honeycomb.

Table 2: Mode I fracture toughness results

L [mm]	t [mm]	ρ/ρ_s [-]	Cell geometry	$K_{IC,PUR}$ $[MPa\sqrt{m}]$
0.52	0.02	0.077	Rectangular	0.051
0.60	0.10	0.333	Rectangular	0.384
0.35	0.10	0.333	Honeycomb	0.402
0.55	0.05	0.182	Rectangular	0.186
0.75	0.05	0.133	Rectangular	0.141
0.95	0.05	0.105	Rectangular	0.112

In figure 7 are shown data for normalised fracture toughness of PUR foams compared with Gibson-Ashby model.

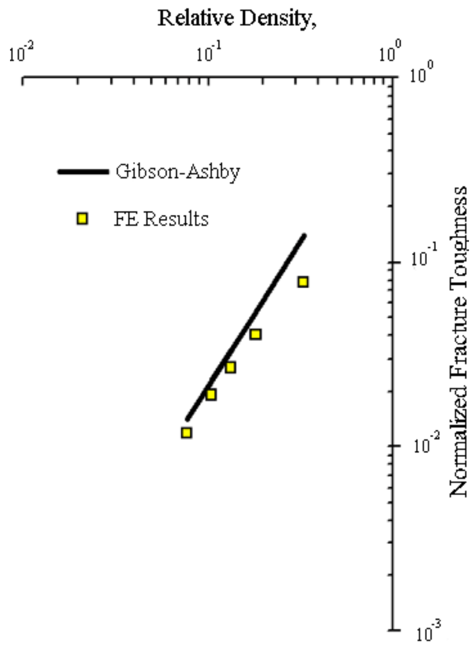


Figure 7: Normalized Fracture Toughness versus Relative Density

The fracture toughness is normalized with respect to the fracture strength of solid material σ_{fs}, and the cell size, l and plotted against relative density ρ^*/ρ_s. The solid line indicates the Gibson-Ashby model for open-cell foams and has a slope of 3/2. A good agreement could be observed between predicted fracture toughness from present study and Gibson – Ashby model, [1].

4. Comparison with experimental data

The results of the experimental fracture toughness [5, 16, 17] versus relative density for the investigated PUR foams are shown in figure 8 together with the estimated FEA values of the fracture toughness.

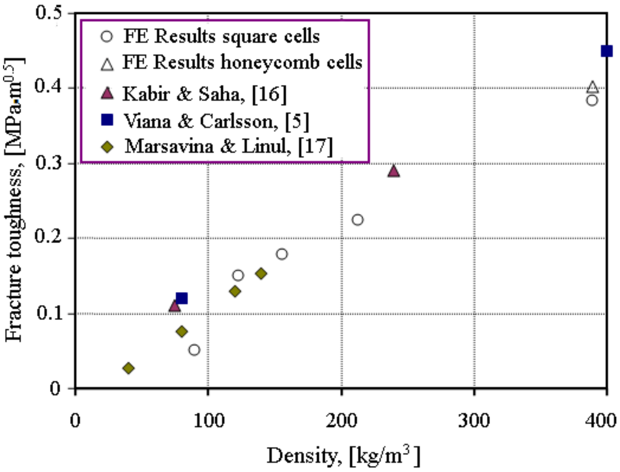


Figure 8: Comparison of estimated Mode I fracture toughness by FE micromechanical model and experimental data

Determining the fracture toughness was according with the procedure described by ASTM D5045, [18]. A good agreement could be seen, which validates the predictions of the fracture toughness based on the micromechanical finite element analysis.

5. Conclusions

Considering the micromechanical models analyzed above, following concluding remarks can be drawn of which the most important are:

- A simple 2D solid micromechanical finite element model was proposed for predicting the fracture toughness of cellular polymers. Fracture toughness was estimated when the maximum stress $\sigma_{y,max}$ in the first unbroken strut equals the fracture strength of solid material;
- The stress distribution in the first un-cracked struts shows a complex stress (bending and tension), (figure 3b);
- The estimated fracture toughness was independent on crack length, (figure 5), indicating that the obtained values could be considered a material property;
- The estimated values for fracture toughness of plastic foams are in the range 10^{-3}- 10^{-1} MPa $m^{0.5}$.
- Experimental data results of fracture toughness validate the micromechanical FEA predictions, (figure 8);
- Both models (rectangular and honeycomb cells) give similar values, but they must be used according with the real cellular structure;
- Fracture toughness is strongly dependent on foam density.

6. Acknowledgment

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