

## ELASTIC BEHAVIOUR OF CELLULAR POLYURETHANE MATERIALS AS CORE MATERIAL IN SANDWICH PANELS

B. Buffel<sup>1\*</sup>, F. Desplentere<sup>1</sup>, B. Dekeyser<sup>2</sup>, M. Moesen<sup>3</sup>, I. Verpoest<sup>3</sup>

<sup>1</sup>*KHBO Expertise Centrum Kunststoffen, Department IW&T, KHBO, Zeedijk 101 B-8400 Oostende*

<sup>2</sup>*Recticel International Development Centre, Recticel, Damstraat 2 B-9230 Wetteren*

<sup>3</sup>*Department of Metallurgy and Materials Engineering, Catholic University Leuven, Kasteelpark Arenberg 44 - bus 2450 B-3001 Heverlee*

\**bart.buffel@khbo.be*

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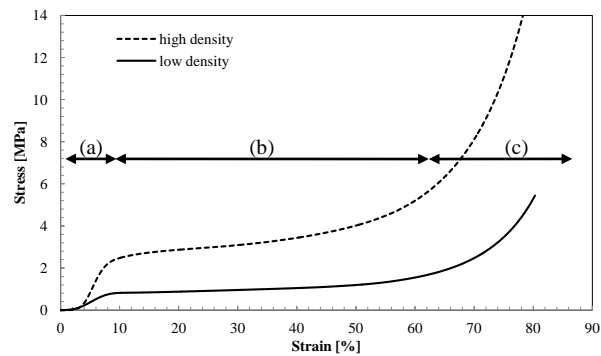
### Abstract

*Within this work the linear elastic properties of a cellular sandwich core material are investigated. This core material is a complex of two different types of polyurethane foams. Compression tests were performed on the complex material and on both constituents separately. After accounting for a significant sample size effect, in the case of the open cell foam constituent, all materials revealed a primary bending deformation mechanism and a high dependency on foam density. Finite Element modelling was used to evaluate the elastic response of the open cell foam. The surface energy of the Kelvin cell geometry was minimised using surface evolver software [7]. The influence of foam density and shape anisotropy are analysed in a parametric study.*

### 1 Introduction

Because of their efficient use of structure and material, sandwich panels are often used in applications where weight-saving is critical: aerospace, automotive, sport equipment, etc. [1,2]. Cellular materials are one of the possibilities when selecting an appropriate core material. Next to the compression and shear properties, polymer foams exhibit excellent thermal insulation properties. Due to the direct link between foam density and all other relevant core properties, (stiffness, strength, thermal insulation) an optimization of the sandwich panel design is possible. Therefore the focus of this research is to understand and characterise the elastic behaviour of these cellular materials.

The complete characteristic compressive response of cellular materials is defined by a linear elastic zone followed by a collapse plateau and finally densification of the material (Fig. 1). Modelling the initial elastic zone has been subject of many different researches. The power law model developed by Gibson & Ashby [1,3] is based on a cubic structure which deforms primarily by in plane deformation of the cell wall of a closed cell structure or by bending of the cell edges in the case of an open cell structure. These two deformation mechanisms can be identified by the value of the power law exponent which is respectively 1 or 2. Warren and Kraynik [4] confirmed this simplified model by applying its principles on the Kelvin Cell geometry.



**Figure 1.** Characteristic compressive stress-strain response for cellular materials. The linear elastic zone (a), collapse plateau (b) and densification zone (c) are indicated.

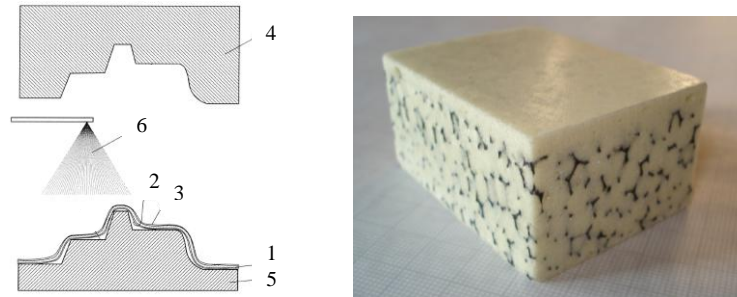
More detailed models include cell shape anisotropy, plateau border shaped cell edges and a non uniform cross section of the cell edge along its length. This problem was solved both analytically and by means of FE-modelling using the Kelvin cell geometry as representative volume element [4-6]. Models with the highest level of detail were constructed via Surface evolver software [4,7] and more recently using computed tomography scanning procedures [8]. Related studies identified the most important factors influencing the elastic behaviour of cellular materials: distribution of solid material in the cell edges and cell walls, curvature or waviness of the cell walls, thickness of the cell walls and variation in cell geometry [9-12].

The first part of this study briefly presents a recently developed production process in which two different types of polyurethane foams are involved. Secondly, the results of the compressive tests performed on these cellular materials, are discussed. Special attention was given to a pronounced sample size effect which occurred when testing flexible open cell foams. In the last part, two FE-models of the open cell foam were build with different cross sectional shapes of the cell edges. Previous studies [5] have indicated that it is crucial to represent the true microstructure of a foam as good as possible in order to obtain an accurate prediction of the variables which describe the mechanical behaviour of the structure. Therefore the surface energy of the Representative Volume Element (RVE) in the second FE-model was minimised to achieve the typical plateau border shaped cell edges. The influence of foam density and geometrical anisotropy was investigated.

## 2 Materials and testing methods

### 2.1 Material processing

The three different materials analysed in this study are polyurethane foams manufactured by Recticel. The closed cell rigid foam is produced via the chemical reaction between isocyanate and the hydroxyl groups of the polyol component. CO<sub>2</sub> is released from the reaction between water and isocyanate to form the cellular structure. During this process, it is crucial to balance the concurring foaming and curing reactions. To achieve this balance, additives like surfactants and catalysts are added to the formulation. The flexible open cell foam is produced in two steps: after producing a closed cell foam in the first step, this intermediate is reticulated to create an open cell foam. During the reticulation process the foam is placed inside a closed vessel and a hydrogen / oxygen gas mixture is added. A spark ignites the gasses and the following explosion melts the cell walls to obtain an open celled microstructure.



**Figure 2.** (left) Production process sandwich panel with complex foam core. Open cell foam spacer (1), skin reinforcement material (2) & (3), upper and lower mould (4) & (5), spray application of the rigid foam reaction mixture (6). (right) Sandwich panel with glass mat skins and foam complex as core material.

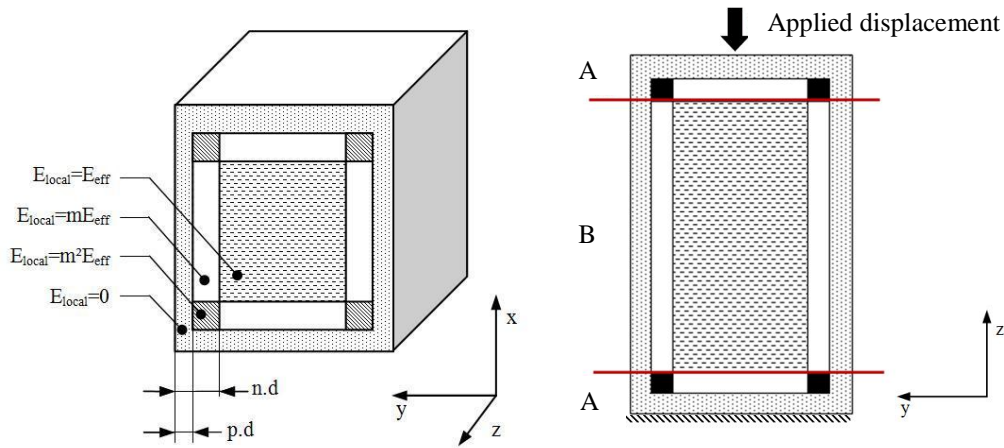
The production process of the sandwich panel with complex foam core (Fig. 2) starts by placing the stack on the lower mould half. This stack consists of the open cell foam with the appropriate reinforcement on top and bottom of it. Next, the rigid foam reaction mixture is sprayed on top of it and the mould is closed. Initially the liquid reaction mixture slowly flows through the thickness of the stack. During the foaming reaction the rigid foam is formed and joins all different components to form a lightweight sandwich panel. During the course of this study, the reinforcement skins were not applied in order to solely produce the complex foam.

## 2.2 Experimental

Compressive experiments were performed on the flexible open cell foam and the rigid closed cell foam separately as well as on the complex foam made up of these components. All compression samples had a square base and a height to width ratio of 2/3. The dimensions of the samples were measured with a pneumatically controlled measuring device with a contact surface of 4cm<sup>2</sup>. Especially in the case of the flexible open cell foams this procedure with constant contact pressure proved to be very useful to reduce standard deviation on the sample volumes. In combination with the sample weight, the determination of the sample density is straightforward.

The compression tests were performed in the rise direction of the foam at a constant strain rate of  $1,6 \cdot 10^{-3} \text{ s}^{-1}$  [13]. In addition to the ASTM standard, the stiffness of the foams was defined as the slope of the tangent in the bending point in the linear elastic zone of the stress-strain curve. All compression tests were repeated 30 times and statistically analysed with a p-value for significant difference equal to 0,05. The solid material density of the open cell foam was found to be 1160 kg/m<sup>3</sup> after performing a submerging test. The relative density  $\varphi$ , can thus be calculated by dividing the foam density by the solid material density.

The size effects model developed by Onck et. al [14,15] was used to account for the sample size effects which occurs when testing flexible cellular materials due to less constrained boundary conditions on the outer edges of the samples. This model divides a sample in different zones with a local stiffness. This local stiffness can be expressed as a function of the stiffness of the bulk material  $E_{\text{bulk}}$ , the cell size  $d$  and factor  $m$  ( $0 < m < 1$ ) which indicates the percentage of residual stiffness with respect to  $E_{\text{bulk}}$ . The exponent of  $m$  is a function of the number of sides with less constrained boundary conditions of each zone. The values of  $n$  and  $p$  indicate the width of these zones with lower stiffness (Fig. 3).

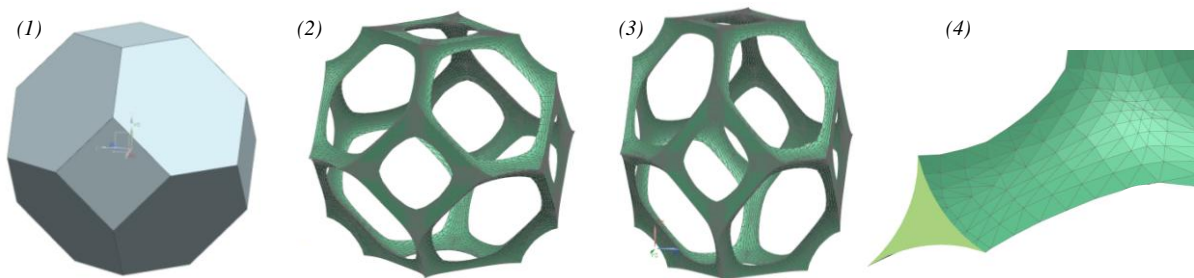


**Figure 3.** (left) Schematic representation of the size effects model used in compression,  $d$  = cell size,  $m$  = ratio between local stiffness and stiffness of the bulk material  $[0,1]$ ,  $p$  and  $n$  are the width of the zones with lower stiffness. (right) Application of the model of Onck along the height of the samples to account for damage effects.

The model of Onck et.al. was used to account for damage effects in the top and bottom zones of the sample induced during the cutting or sawing preparation step. In the right image in Fig. 3 these additional zones are indicated and possess similar zones with lower stiffness discussed earlier. The local stiffness of the zones in the corners of the sample are however a function of  $m$  to the power of 3 since the cell edges are less constrained by 3 sides.

### 2.3 FE modelling of the open cell foam

The Kelvin cell geometry (Fig. 4) was selected as RVE for the FE-modelling because of its relative simple topology compared to other unit cells proposed in literature [16]. Moreover an ordered structure based on the Kelvin cell geometry satisfies plateau's laws which describe the fundamental principles for the surface tension driven formation of cellular materials.



**Figure 4.** (1) Closed cell Kelvin cell geometry with 6 quadrilateral and 8 hexagonal faces. (2) FE-model of open cell foam after minimizing the surface energy. (3) FE-model with geometrical anisotropy equal to 1,2 with increased alignment of the cell edges. (4) Cell edge with plateau border cross sectional shape which varies along its length

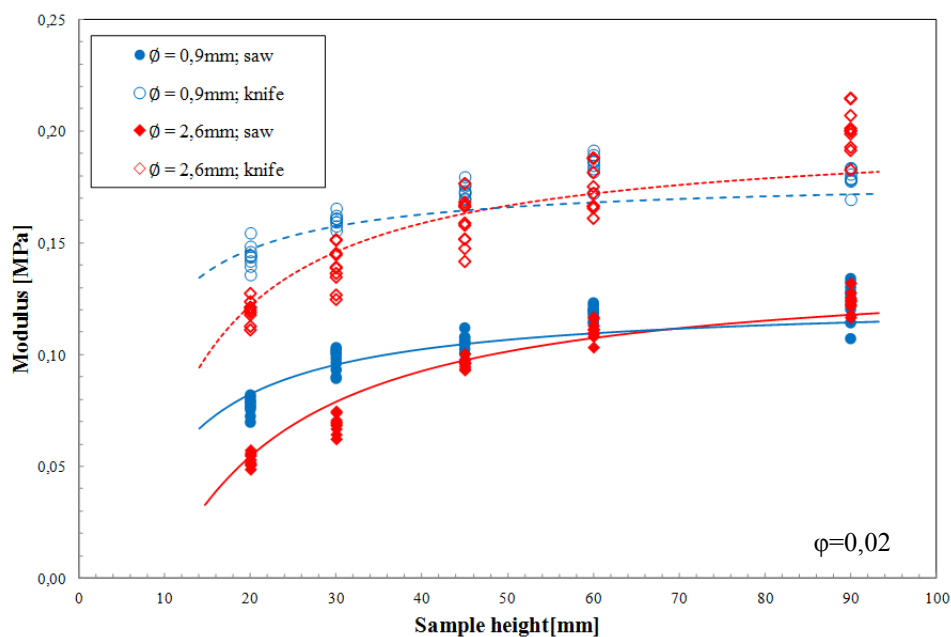
Surface evolver software was used to create a wet foam in which the cross sectional shape of the cell edges is governed by minimal surface energy. This step introduces the typical plateau border shape to the cell edges (see Fig. 4). This geometry was imported in the commercially available FE-software NX 8.0 with Nastran solver and periodic boundary conditions were applied. After performing the appropriate compression and shear loading simulations, a homogenisation procedure revealed the engineering constants of the cellular structure. To account for the elongation of the cells in the rise direction of the foam, geometrical anisotropy (see Fig. 4) could be applied during an intermediate step. This anisotropy was defined as the

ratio between the height and the width of the cell. The solid material properties of the polyurethane material were taken from Gong et al. [5] ( $E = 69\text{MPa}$ ,  $\nu = 0,49$ ).

### 3 Results & Discussion

#### 3.1 Experimental compression tests

Two flexible foams with different cell sizes (0,9 and 2,6mm) but identical density ( $24\text{kg/m}^3$  or a relative density  $\varphi$  of 0,02) were selected to perform compression tests. During sample preparation, a difference was made between samples cut with a knife or with a saw. The resulting stiffness of the foam samples as a function of sample size and sample preparation is given in Fig. 5.

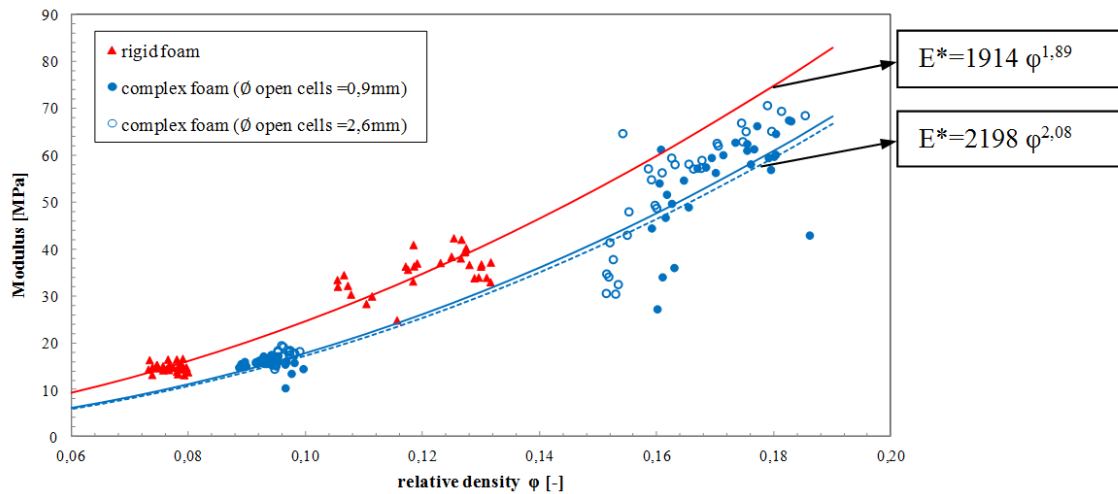


**Figure 5.** Flexible foam stiffness as a function of sample size and sample preparation for two different cell diameters (0,9 and 2,9 mm) of an open cell foam with a density of  $24\text{kg/m}^3$ . The sample size and damage effect is well fitted by the model described in §2.2 and Fig. 3. The resulting stiffness of the bulk material of the open cell foam is  $0,18\text{MPa}$  for both foam types.

The data in Fig. 5 indicate that the measured stiffness increases with increasing sample size. All data are fitted well with the proposed model in §2.2 which points out that an asymptotic value is reached at a sample height of 50mm in the case of the foam with the smallest cell size. Within the selected samples sizes the asymptotic value is not completely reached by the model for the foam with the largest cell size. However no significant difference between the two largest sample sizes could be detected. When the sample size is expressed as a function of the cell diameter, the data indicate a minimum sample size of 50 times the cell diameter. This value is larger than other sample sizes indicated in literature [1,17]. The samples prepared with a knife possess a much stiffer response to the compressive load. This difference is 35% for the largest samples. Based on this data it is concluded that the stiffness of the open cell foam is  $0,18\text{MPa}$ .

Since the cell sizes of the rigid foam are on the order of 0,15mm and the samples have a width of 30mm no size effect was encountered during the compression tests on these materials.

Samples were made out of solely closed cell rigid foam and out of the complex foam described in §2.1. Two flexible open cell foams with different cell diameter were used to produce two types of complex foam. The stiffness of these materials as a function of density, is given in Figure 6.



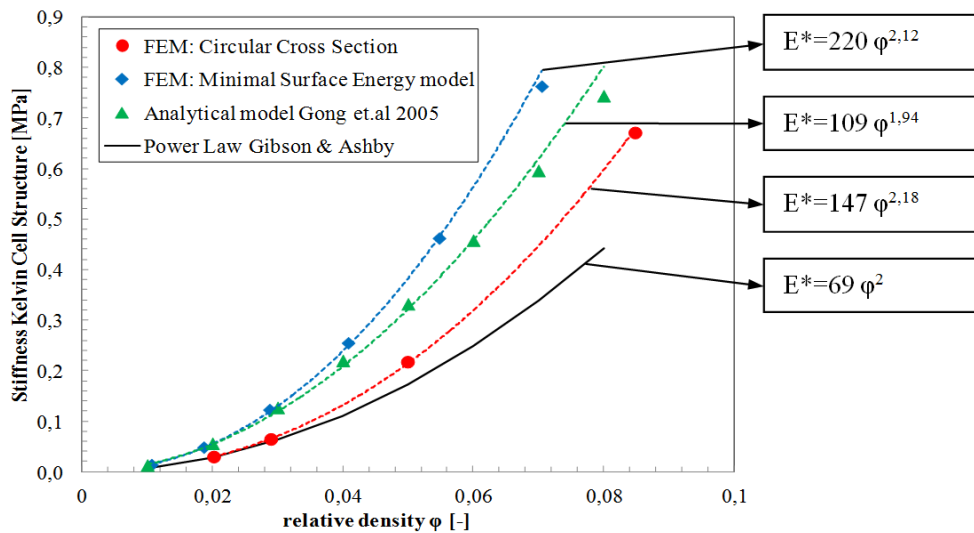
**Figure 6.** Stiffness of the closed cell rigid foam and complex foam (rigid + open cell flexible foam) as a function of density. Experimental data are fitted with the power law model by Gibson and reveal a bending dominated deformation mechanism. The diameter of the open cell foam cells has no significant influence on the stiffness of the complex foam.

After fitting the power law model through the experimental data, the value of the exponent suggests a bending dominated deformation mechanism for both the rigid foam and the foam complex. Despite the fact that these foams possess closed cells, the cell faces buckle or rupture at stresses so low that their contribution to the stiffness is negligible [18] making the bending of the cell edges the primary deformation mechanism.

The stiffness of the complex foam can be fitted using the same power-law model and behaves similarly as a function of density with the bending of the cell edges again as primary deformation mechanism. The cell size of the open cell foam used inside the complex foam has no significant influence on the stiffness. As a result, the average of both fittings is reported in Figure 6. When comparing the complex foam to the rigid foam, the latter possesses a higher stiffness with respect to an identical total foam density. This is due to the flexible open cell foam which consumes a part of the total weight of the foam and thus lowering the density of the remaining rigid foam when keeping the total density constant.

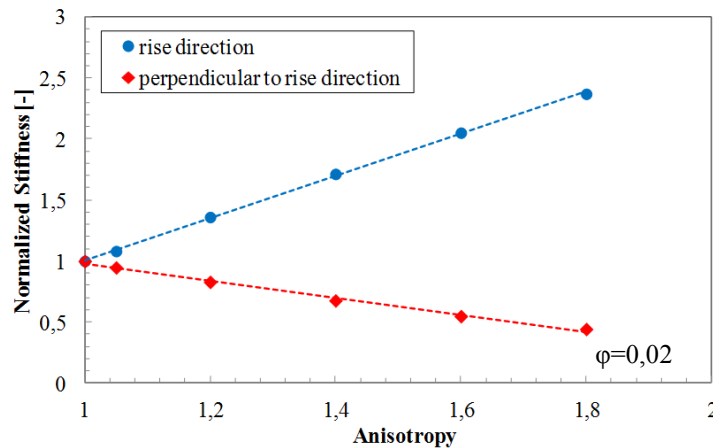
### 3.2 FE modelling of the open cell foam

Preceding the FE-model with minimized surface energy, a model was built in which the cell edges have a circular cross section. A radius of curvature equal to the strut diameter was applied in the nodes where the cell edges meet. The stiffness of both models is compared to the power law model and the more advanced analytical model of Gong et.al. [5] in Figure 7. The results of the FE-modelling indicate that the plateau border shaped cell edges in the model with minimized surface energy have a pronounced effect on the stiffness. The curves in Figure 7 also shows that the stiffness of the models increases with increasing detail of the real foam topology. Since the exponent of the power-law fittings on the FE-models is close to two, both models deform primarily by bending of the cell edges.



**Figure 7.** Stiffness of the flexible open cell foam as a function of density. The FE-models developed during this study envelop the analytical model of Gong et. Al. [5]. The power law model by Gibson and Ashby serves as a lower boundary for the more complex models.

The influence of the elongated shape of the cells due to anisotropy, is presented in Figure 8. The stiffness of the Kelvin structure increases and decreases in the elongated rise direction and the direction perpendicular to it. This is mainly caused by the alignment of the edges in the rise direction (Fig. 4).



**Figure 8.** Influence of the geometrical anisotropy on the stiffness of the cellular structure. Results are based on the FE-model with minimized surface energy. The stiffness in rise direction increases with increasing anisotropy, whereas the stiffness in the direction perpendicular to the rise direction decreases. All data are normalised on the stiffness of the Kelvin structure with no anisotropy applied to it.

Compared to the FE-models discussed in literature [5,6], the FE-model with minimized surface energy presented in this study yields very similar stiffness values and trends. The difference with the experimentally determined stiffness of the open cell foam is larger due to the higher stiffness values derived from the sample size effects model. Despite the fact that the materials tested in both studies are made out of polyurethane, a different solid material stiffness could produce this difference.

## 4 Conclusion

Within this study the determination of the stiffness of various cellular materials was discussed. In the case of the flexible open cell material a sample size and preparation damage effect was revealed and dealt with through a theoretical model. This model fits the data well and allows the evaluation of different parameters such as the size of the damaged layer and the stiffness of the bulk material. This leads to the conclusion that sample preparation of cellular materials is crucial to obtain reliable results. No sample size effect was encountered when testing the rigid and closed cell foam due to the significantly smaller cell sizes. The power law model proved to be useful in fitting the stiffness as a function of density.

A FE-model based on the Kelvin geometry cell with minimized surface energy was developed to evaluate the elastic behaviour of an open cell polyurethane foam. Results from this new model are in agreement with the values and trends reported in literature.

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