Damage Identification and Influence on Mechanical Properties of Closed Cell Rigid Foams

Liviu Marsavina[1,*], **Dan M. Constantinescu**[2], **Emanoil Linul**[1], **Tudor Voiconi**[1], **Dragos A. Apostol**[2], **Tomasz Sadowski**[3]

[1] Department Mechanics and Strength of Materials, Politehnica University of Timisoara, Timisoara 300222, Romania
[2] Department of Strength of Materials, University POLITEHNICA of Bucharest, Bucharest 060042, Romania
[3] Solid Mechanics Department, Lublin University of Technology, Lublin 20-618, Poland
* Corresponding author: msvina@mec.upt.ro

Abstract The effect of damage on mechanical properties of closed-cell foams is numerically investigated. Representative 3D cell structures are considered for the finite element analysis. In the first instance the mechanical properties were obtained on un-damaged structures. The obtained numerical values for Young's modulus and Poisson's are compared with experimental results. Two types of experimental methods were used to determine the mechanical properties of rigid polyurethane foams: Static compression tests providing stress – strain curves and mechanical properties as Young's modulus, yield stress, plateau stress, densification and Digital Image Correlation used for identification of the damage mechanism, observation of bands of deformation, Young's modulus and Poisson's ratio. The influence of density on mechanical properties is also investigated. Two types of damages/defects were defined randomly in finite element analyses by considering missing cell walls and filled cells. The results show that the missing cell walls create a decrease of Young's modulus, while the filled cells produce the increase of Young's modulus.

Keywords Rigid foams, Damage, Mechanical properties, Numerical analysis, Micromechanical models

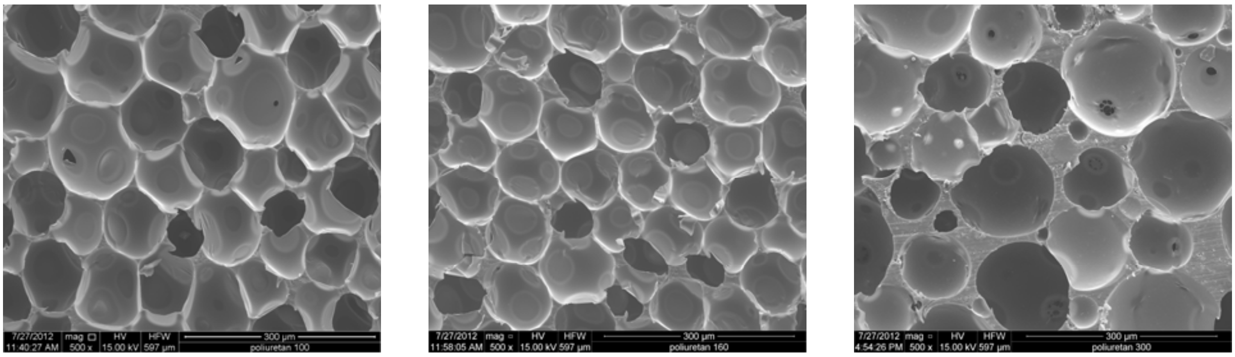
1. Introduction

Polyurethane foam materials are widely used as cores in sandwich structures. The main characteristics of PUR foams are lightweight, high porosity and good energy absorption capacity, [1,2]. Foam materials crush in compression, while in tension they fail by propagation of a single crack, [3]. Many attempts were performed in order to determine experimentally the compression properties of plastic foams [4-13]. On the other hand, analytical micro-mechanical models based on deformation and fracture of single cell were developed to predict the mechanical properties of foams in compression [14,15]. In recent years the finite element analysis (FEA) micro-mechanical models were used in order to study the effect of damage of cellular structure on the compression properties [16,17]. Usually these models were constructed using 2D beams.

This paper presents the results of mechanical properties for three polyurethane foams under compression loading investigating the effect of density, loading direction and loading rate. The Digital Image Correlation (DIC) technique is employed during compression tests in order to identify the damage mechanisms of foams. Afterwards, using a 3D representative volume of the foam, the effect of damage (missing cells and filled cells) was studied.

2. Experimental program

In order to identify the mechanical properties of the rigid polyurethane (PUR) foams an extensive experimental program was performed. Closed cell rigid PUR foams with three different densities (100, 160 and 301 kg/m^3) were considered for the experimental program, Fig. 1.



a. density 100 kg/m^3 b. density 160 kg/m^3 c. density 301 kg/m^3

Figure 1. SEM microstructures of closed cell rigid PUR foams (500x).

2.1. Static compression tests

Static compression testes were carried out using a LBG 100kN universal testing machine in the Strength of Materials from POLITEHNICA University of Timişoara, respectively on a Walter+bai 50 kN static and fatigue testing machine from Laboratory of Strength of Materials from University POLITEHNICA of Bucharest. Tests were performed according to ASTM D 1621 at room temperature. Cubic specimens with 50 mm length were used for foam densities 100 and 160 kg/m^3 and with 25 mm length for the 301 kg/m^3 density. The engineering stress-strain diagram shows the non-linear behavior of polyurethane foams in compression, Fig. 2. The following regions could be identified: an initial linear elastic response leading to yield, a small softening in stress after yield, a post-yield plateau and a final sharp rise in compressive stress, corresponding to foam densification. It can be observed that density has a major influence on the behavior of PUR foams.

The influence of the loading direction: in plane (rise direction) and out of plane (transverse direction) is shown in Fig.3. Foam behaviour in transverse direction shows a small hardening after the yield point and no softening.

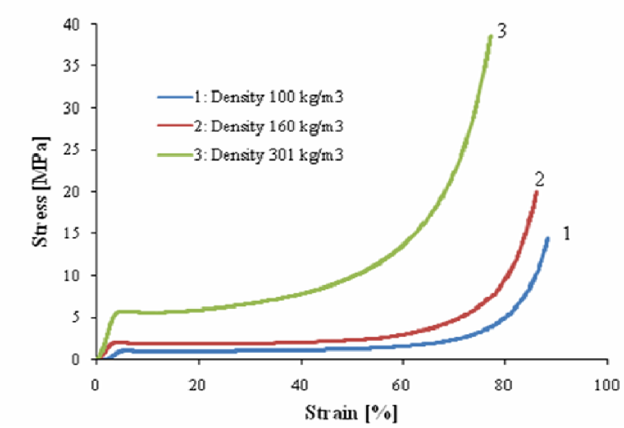


Figure 2. Effect of density.

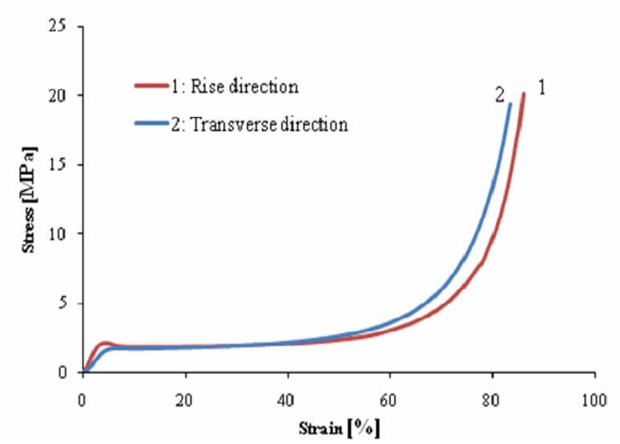


Figure 3. Effect of loading direction.

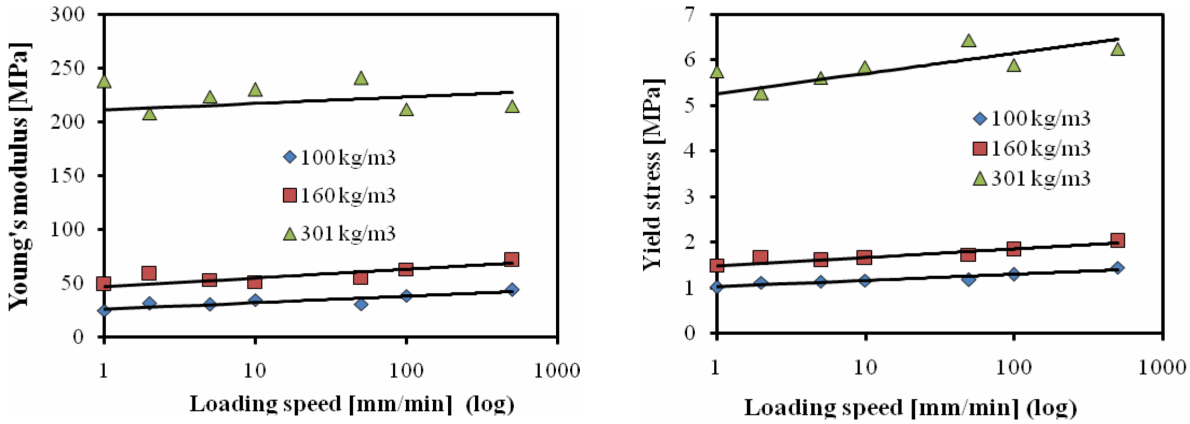
The compression properties (Young's modulus, yielding stress, plateau stress and densification strain) obtained for the three investigated rigid PUR foams are summarized in Table 1 for a 5 mm/min loading rate.

Table 1. Compression properties of rigid PUR foams

Foam density [kg/m^3]	100		160		301	
Loading direction	rise	transverse	rise	transverse	rise	transverse
E [MPa]	40.38	31.92	81.76	50.83	202.25	201.83
σ_y [MPa]	1.15	1.17	2.09	1.77	5.74	6.69
σ_p [MPa]	1.06	1.14	1.88	1.83	5.98	6.65
ε_d [%]	56.2	55.4	54.4	52.4	54.8	52.5

Young's modulus, yield stress and plateau stress increases with density. For low density foams Young's modulus values are higher in the rise direction, while for the foam with 301 kg/m^3 density Young's modulus are equal in both direction. Also the densification strain is slightly higher in rise direction for all investigated foams. The yield stress and plateau stresses are quite similar in both directions for low density foams, but are higher in transverse direction for foam with 301 kg/m^3 density.

Loading rates between 0.6 and 500 mm/min were used to investigate the influence of loading rate. It could be observed in Fig. 4 that increases in loading rate produces an increase of Young modulus (with approximately 50 % for foam densities 100 and 160 kg/m^3, respectively with 80 % for 301 kg/m^3 foam density) and yield stress (with approximately 67 % for foam densities 100 and 160 kg/m^3, respectively with 73 % for 301 kg/m^3 foam density).



a. Young's modulus b. Yield stress

Figure 4. Effect of loading rate on mechanical properties of PUR foams.

2.2. Digital image correlation investigations

The damage mechanisms of the foams were investigated by the 2D (DIC) technique, using a 5 MPixels camera and by applying a random speckle of paint on the specimen surface. Some analyses were done by using the 3D approach and 2 MPixels cameras. In this case the ARAMIS system was calibrated using a 35 x 28 mm caliber and a facet of 27 x 15 pixels; thus a 44 % facet overlap has been obtained.

Images were recorded at different loads and then processed with the ARAMIS system. A typical engineering stress-strain curve for the foam with 160 kg/m^3 density and major strain plots taken in the relevant parts of the curve is shown in Fig. 5. It can be observed that on the yield point crush bands inclined approximately 45^0 occur, tendency which extends on the plateau and densification regions.

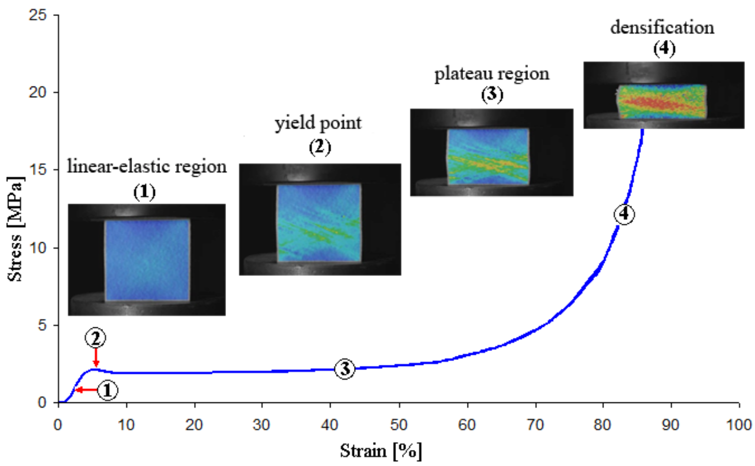


Figure 5. Engineering stress–strain curve with major strain images from ARAMIS system

The DIC measurements in the linear-elastic region allow the determination of Young's modulus E, and Poisson's ratio ν.

For the foam with a density of 301 kg/m^3 (closer to a porous solid) the deformation bands tend to be less inclined. For a loading speed of 1 mm/min in Fig. 6 are shown the following: the current stage in the engineering stress-strain curve (here one in the plateau region is chosen), the vertical displacements and Mises strains in that moment, and the variation of the Mises strains along a vertical line taken in the middle of the specimen (figure upper-left) at different stages of loading – the one represented hereby being depicted by a red curve. In the last registered stage (the last curve) the foam deteriorates significantly – close to 100% – and the curve becomes discontinuous.

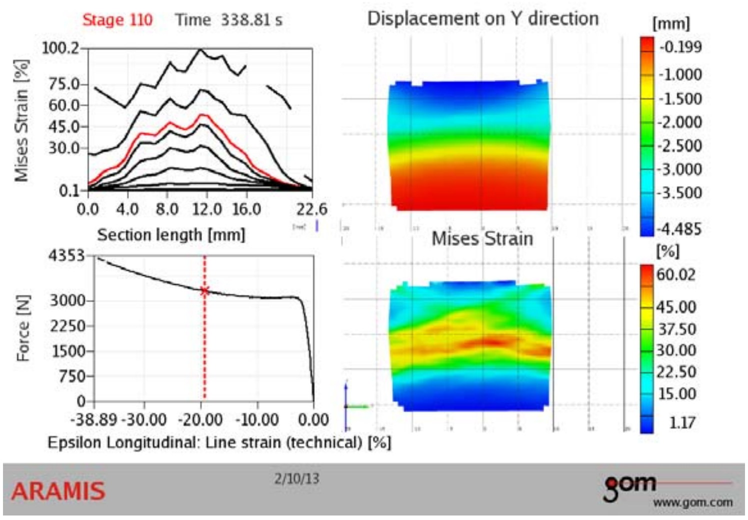
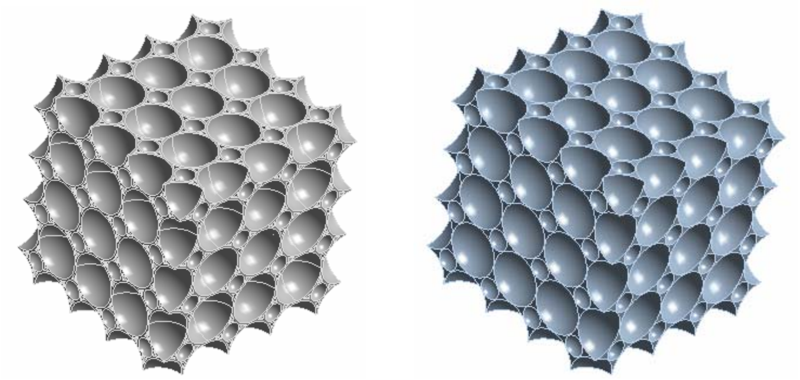


Figure 6. Mises strains and vertical displacements in the plateau region

3. Numerical simulation

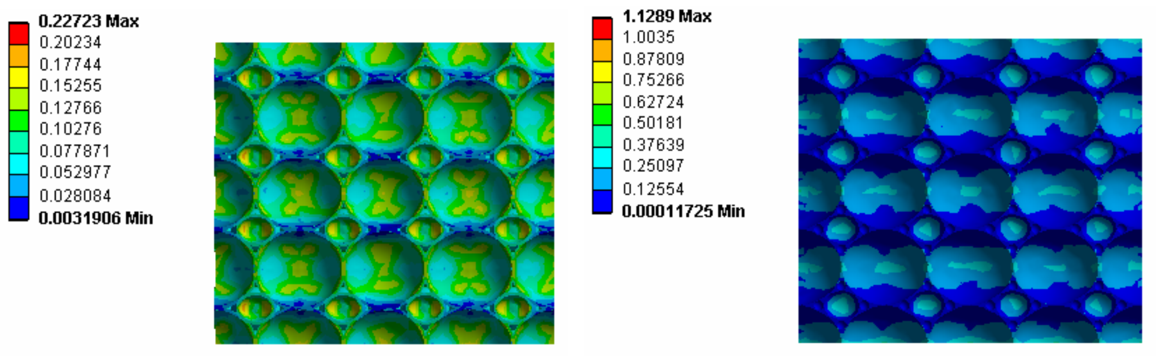
Based on the statistical analysis of the closed cells microstructures the geometric parameters were determined and the 3D representative volume (RVE) of the foams was built. Two strategies were considered: a model based on tangent hollow spheres for low density foams (Fig. 7a), respectively a solid cube from which were extracted spheres for higher density foams (Fig. 7b). Polyurethane was considered the material for the cell walls with Young's modulus E_s=1600 MPa and Poisson's ratio ν= 0.4.



a. Hollow spheres b. Solid with spherical cells

Figure 7. 3D models of the foam RVE

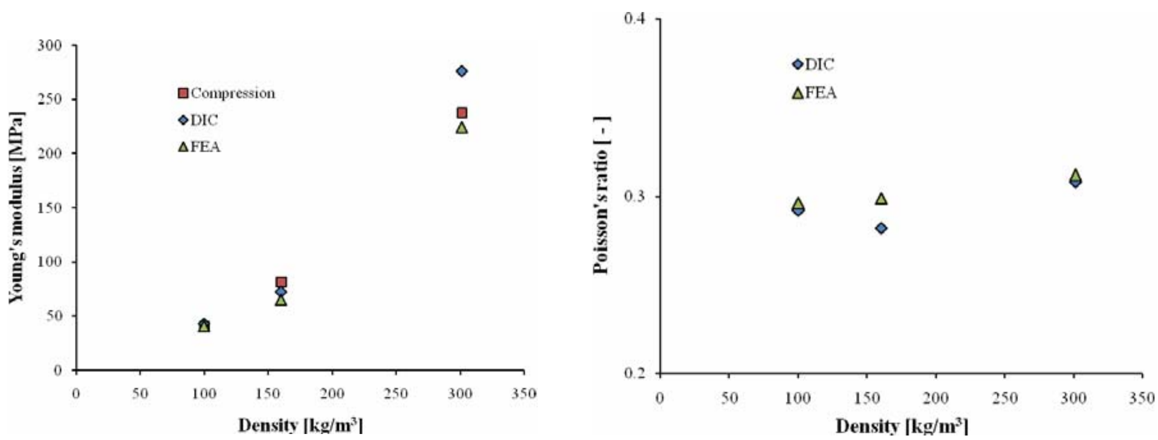
Imposing the periodic boundary conditions and a displacement on the top of the RVE the elastic properties (Young's modulus and Poisson ratio) were determined. Figure 8 presents the results of the equivalent Mises strain.



a. Hollow spheres b. Solid with spherical cells

Figure 8. Equivalent Mises strains

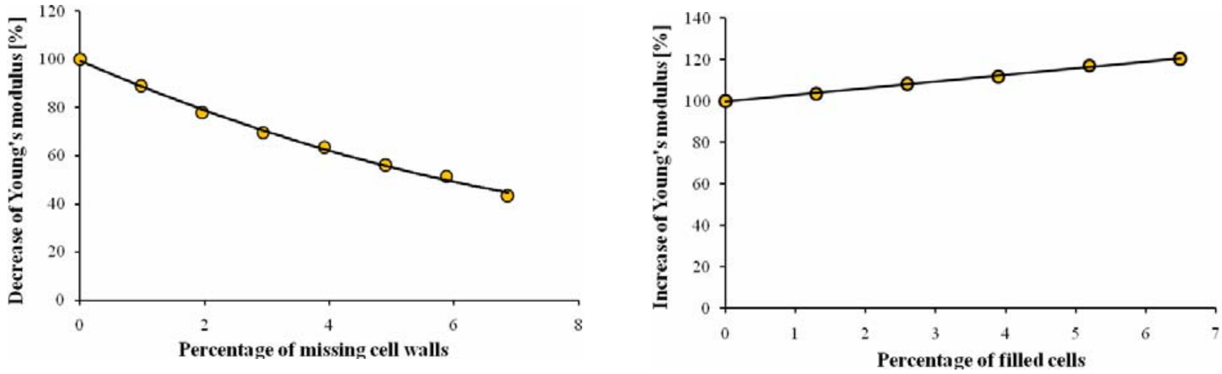
Figure 9 presents a comparison between experimental (compression and DIC) and numerical results of Young's modulus (Fig. 9a) and Poisson's ratio (Fig. 9b). A good agreement was obtained between experimental and numerical values for Poisson's ratio and Young's modulus for low density foams. For the higher density foam (301 kg/m^3) a difference of 16% was obtained between compression and DIC values of Young's modulus which could be explained on different methodologies used to record the specimen deformations.



a. Young's modulus b. Poisson's ratio

Figure 9. Comparison between experimental and numerical values of elastic properties of PUR foams

Missing cell walls (for each cell only a single wall was eliminated) and filled cells were considered in the FE analyses in order to investigate the effect of the damage of cellular structures on mechanical properties. Figure 10 presents the influence of damage expressed in terms of normalized Young's modulus (ratio between Young's modulus for damaged structure and for undamaged structure). It can be observed that 7% of missing cell walls decrease the Young modulus with 57%, while 7% of filled cells produce an increase of Young's modulus with 20.5%.



a. Missing cell walls b. Filled cells

Figure 10. Comparison between experimental and numerical values of elastic properties of PUR foams

4. Conclusions

Two experimental methods (compression tests and Digital Image Correlation) were used to determine the mechanical properties of rigid polyurethane foams. The effect of density, loading rate and loading direction were investigated. Ranking the investigated parameters it could be observed that the density has the major influence on mechanical properties, followed by strain rate, and the minor influence is the loading direction.

DIC measurements prove to be a powerful tool in establishing the local damage characteristics and the bands of deformation for the PUR foams. The density of the foam appears to influence the inclination of the deformation bands.

Finite Element Analysis was performed on 3D representative models to predict the elastic constant of polyurethane foams. The predicted values are in good agreement with the experimental ones which validates the numerical methodology. Then the effect of damage, represented by missing cell walls and filled cells, on Young modulus was systematically investigated.

Acknowledgements

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