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Experimental investigations and numerical simulations of notch effect in cellular plastic materials

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Abstract. Cellular plastics are light weight structures with many applications in civil, aeronautical, automotive and mechanical engineering. Properties of cellular materials depend on the properties of the solid material, on the shape and dimensions of the cellular structure and on the relative density of the cellular material. Most of cellular plastic materials are crushing in compression and have a brittle behavior in tension. The effect of notches represents an important issue in such materials, taking into account that for packing applications for example, notches/holes should be introduced in the cellular material. This paper investigates the effect of notches in compression for three different densities 100, 145 and 300 kg/m^3 polyurethane (PUR) foams. Experimental investigations were performed on rectangular blocks of 100x100x25 mm with 16, 28 and 40 mm central holes. The mechanism of damage was monitored with an IR camera FLIR A40M. Purpose of the numerical simulations was to calibrate a material model, based on compression test for un-notched specimens using the CRUSHABLE FOAM models implemented in ABAQUS SIMULIA. Then the material models were used to simulate the experimental tests on notched blocks. Good agreement was obtained for the load - displacement curves obtained experimentally and from simulation. Also the plastic deformation patterns observed experimentally by IR thermograpghy were obtained numerically using the CRUSHABLE FOAM material model.

1. Introduction

Cellular plastics are light weight structures with many applications in civil, aeronautical, automotive and mechanical engineering. Properties of cellular materials depend on the properties of the solid material, on the shape and dimensions of the cellular structure and on the relative density of the cellular material, [1, 2]. Most of cellular plastic materials are crushing in compression and have a brittle behavior in tension, [3]. Components made of cellular or porous materials may have micro-structural defects like cracks, filled cells or missing walls holes induced by manufacturing process, [4]. On the other hand macro-structural notches or holes may be introduced in design of components. The influence of notches on the strength of the structures is an important issue, which should be considered on the design stage. Up to now there are only few studies investigating notch effect on foam and porous materials mainly regarding metallic foams [5-7] and polymeric foams [5, 8, 9]. The notch effect was experimentally investigated [5, 8, 9], but also computational studies [6, 7, 10] were performed.

Two approaches were considered for the characterization of notch effect in compression of PUR foams experimental investigations and finite element analysis. The experimental investigations in compression were performed on a three different densities (100, 145 and 300 kg/m3), closed cell rigid

PUR foam. IR thermography was used to identify the plastic deformations. A numerical assessment of CRUSHBLE FOAM model was carried out in order to represent the behavior of notched specimens.

2. Experimental investigations

Polyurethane (PUR) materials of three different densities (100, 145 and 300 kg/m^3) manufactured by Necumer GmbH, Germany under commercial designation Necuron (100, 160 and 301) were investigated. Microscopic investigations of these materials show a closed cell structure [11].

Square specimens (W = 80 mm) having a thickness *b* of 25 mm with central hole of different diameters (D = 16, 28 and 40 mm), were used, figure 1. One face of the specimens was sprayed with matt black paint in order to have a constant emissivity for thermographic measurements. The experimental tests were performed using a universal testing machine LBG 100 kN on displacement control (v=2 mm/min) and at room temperature, figure 1.

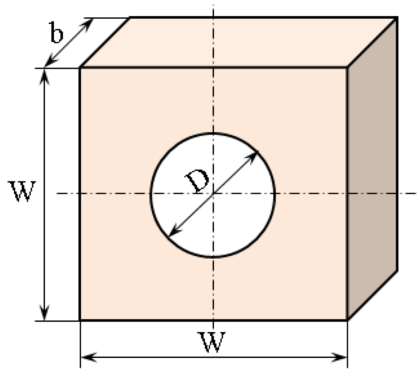


Figure 1. Specimen with holes

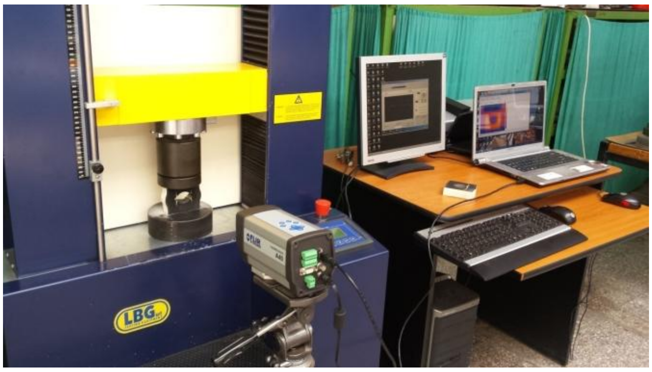
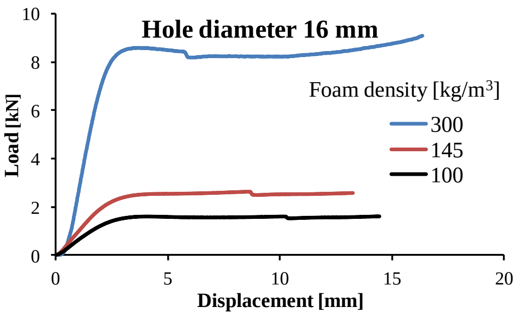
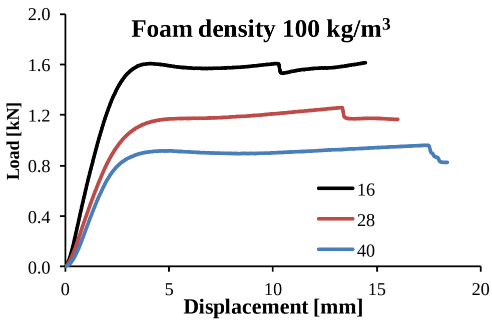


Figure 2. Experimental set-up

Typical load - displacement curves for the three foam densities are shown in figure 3.a for 16 mm hole diameter. An increase of supported load with increase of density was observed. A drop of load occurs after the plateau stress is reached, at this point the ultimate tensile stress is reached on the hole upper and bottom edges, where tensile occurs and a crack initiates. The load carrying capacity of holed foams decreases with increasing the hole diameter, figure 3.b plotting results for foam of 100 kg/m^3 density.



a) influence of density



b) influence of hole diameter

Figure 3. Load-displacement curves

Figure 4 presents the ratio between the maximum net stress of notched specimen σ_{max} and the ultimate tensile strength of the foam σ_{UTS} versus ratio between hole diameter D and specimen width W. For all three investigated foams a notch insensitive response in compression was observed, which could be explained by the ability of foams to crush at a constant plateau stress σ_{pl}.

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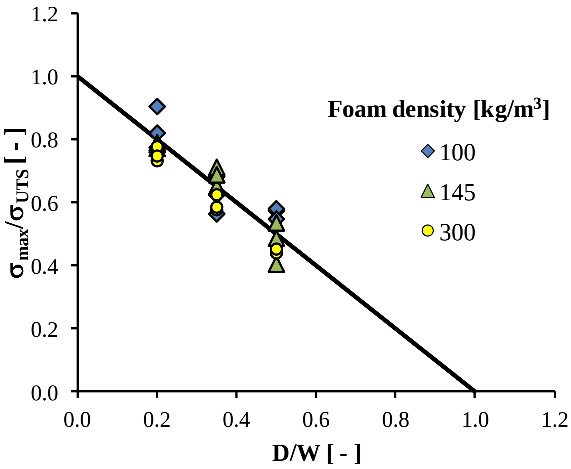
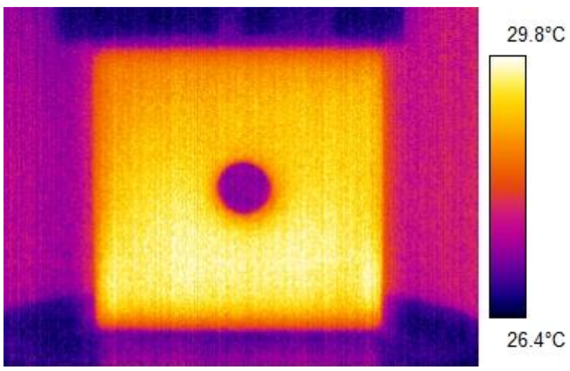
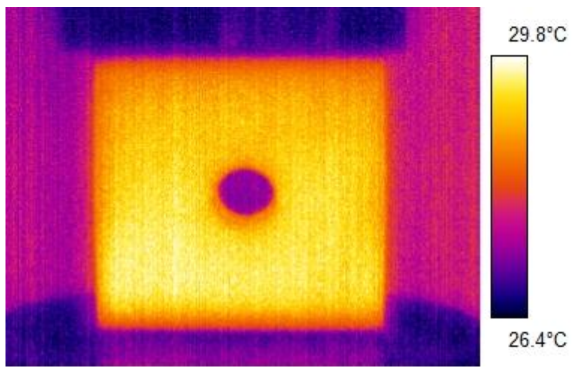


Figure 4. The effect of hole diameter on the compressive strength of PUR foams blocks with central holes

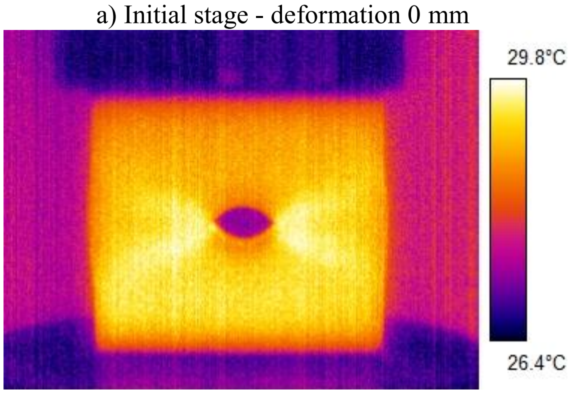
Thermography was used in order to identify the damage mechanism. A FLIR A40M infrared camera was used to measure emitted infrared radiation from the specimen which increases with plastic deformations occurred in the foam specimens due to loading. For example in figure 6 are presented different stages of temperature distribution, corresponding to different load stages (displacements 0, 4.2, 8.5, 10.5 and 11.7 mm), from the compression test of foam density of 145 kg/m^3, with a central hole of 16 mm. After a short linear elastic part, the temperature starts to increase in the vicinity of the hole due to plastic deformations (figure 5. b, c), than a crack initiates and propagates from the top and bottom surfaces of the hole (figure 5. d, e). The increase of temperature could be also seen plotting the temperature variations together with load-displacement curve, figure 6.



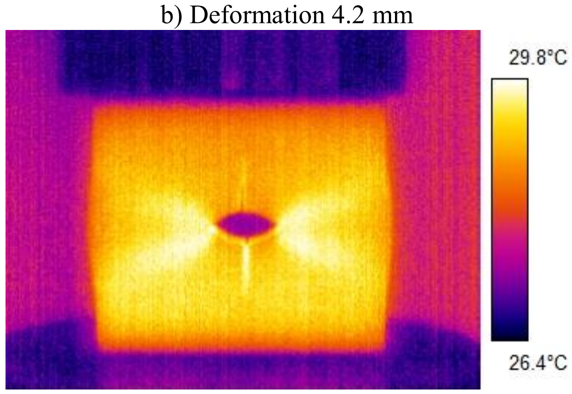
a) Initial stage - deformation 0 mm



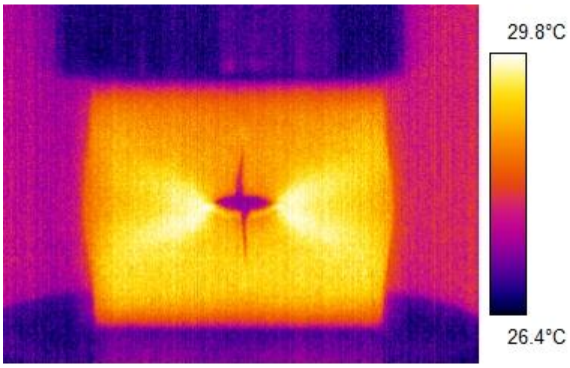
b) Deformation 4.2 mm



c) Deformation 8.5 mm



d) Deformation 10.5 mm



e) Deformation 11.7 mm

Figure 5. Temperature distributions at different load stages from compression testing of 145 kg/m^3 foam with a hole of 16 mm.

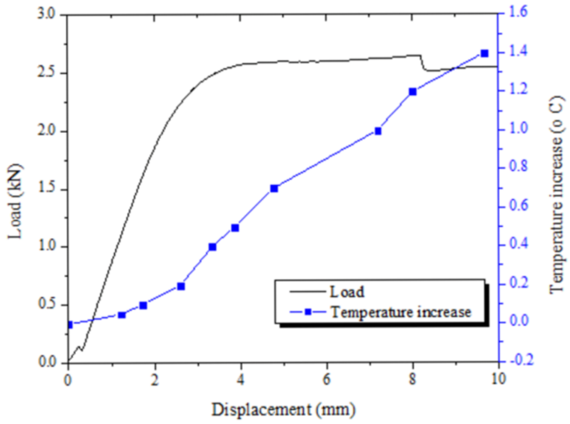


Figure 6. Load - displacement curve for foam density block of 145 kg/m^3 with hole with 16 mm diameter and the temperature increase.

From the thermographic measurements the angle of maximum temperature (figure 7), which corresponds to bands of deformation of cellular structure of the foams and the maximum temperature increase on these directions (figure 9) were determined. It could be observed that angle of the bands of deformation increases with increasing hole diameter, but is not influenced by the foam density. In contrary the maximum temperature increases with increasing density from 0.8ºC for 100 kg/m^3 density to 1.6ºC for 300 kg/m^3 density.

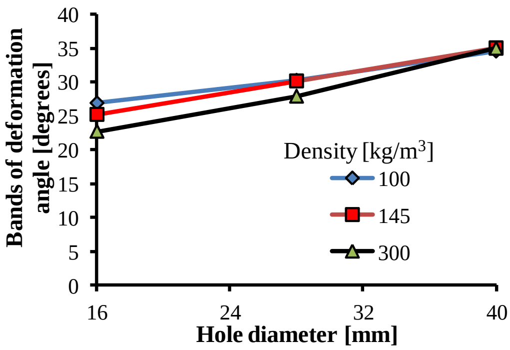


Figure 7. Bands of deformation angles

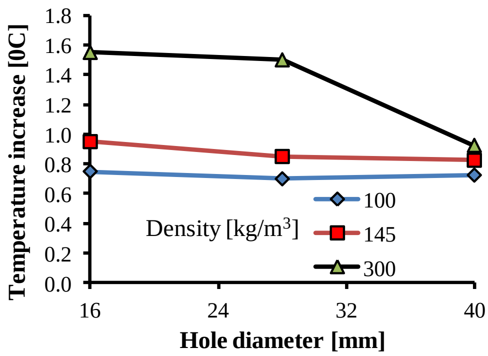


Figure 8. Maximum temperature increase on the band of deformation direction

3. Numerical simulation

The CRUSHABLE FOAM plasticity models were proposed [12] and implemented [13] in order to analysis the behavior in compression of crushable materials (like foams, balsa wood). These models are able to describe the damage in compression characterized by cell wall buckling processes. Two types of crushable foams models are implemented in ABAQUS: volumetric hardening and isotropic hardening. The isotropic hardening model uses for the yield surface an ellipse centered at the origin in the $\sigma_e - \sigma_m$ stress plane. The yield surface evolves in a self-similar manner, and the evolution is governed by the equivalent plastic stress [13]:

$$\sigma_e^2 + \alpha^2 \sigma_m^2 = B^2 \tag{1}$$

where σ_e represents is the von Mises stress and σ_m is the mean stress, α defines the shape of the yield surface in relation with the relative magnitude of the axes. This parameter is computed based on the ratio between the initial yield stress in uniaxial compression σ_C^0 and initial yield stress in hydrostatic compression p_C^0: $k = \sigma_C^0 / p_C^0$:

$$\alpha = \frac{3k}{\sqrt{9-k^2}} \tag{2}$$

The size of the of the yield ellipse on σ_e - axis is:

$$B = \sigma_C \sqrt{1+\left(\frac{\alpha}{3}\right)^2} \tag{3}$$

with σ_C the absolute value of the yield stress in uniaxial compression.

The specimens (80x80x25 mm) with holes (diameter 16, 28, 40 mm) used in the experiments were modeled in ABAQUS software. 3D 20 node quadratic solid (C3D20) elements were used, with a refined mesh near the hole, resulting 11850 elements connected in 53483 elements. A convergence study was carried out resulting the present mesh topology. The boundary conditions represent the experimental setup: 0 displacements of vertical direction were imposed at the bottom side of the specimen, while 15 mm displacements were applied on the top side.

The uniaxial compression experimental stress - strain data (20 points for each foam density) were used to define the CRUSHBLE FOAM material model. The isotropic hardening feature was implemented by k=1 and the plastic Poisson ratio ν_p=0. Self contact on hole edges was defined.

A typical result from simulation, vertical reaction force from bottom edge versus applied displacement is shown in figure 9, together with experimental load - displacement curve for foam density of 100 kg/m^3 and a 28 mm hole diameter. It could be observed that the numerical result fall between the experimental curves indicating a good agreement. The CRUSHBLE FOAM model allows to indentify the plastic equivalent strain, figure 10. The shape and path of plastic equivalent strain is similar with the termographic distribution of temperature increase due to plastic deformation.

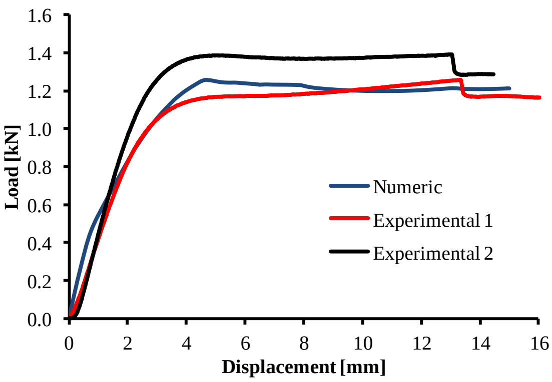


Figure 9. Comparison between experimental and numerical simulation results for 100 kg/m3 foam density and a hole of 28 mm0 diameter

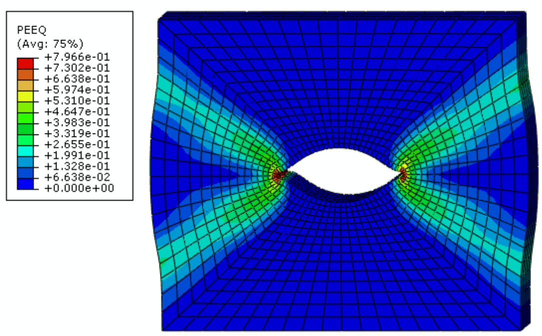


Figure 10. The effective plastic strain for modeling of 145 kg/m3 foam density with a 16 mm hole diameter

4. Conclusions

The paper presents two methods for investigation of notch effect in PUR foams under compression loading. The experimental procedure consists in compression tests performed on PUR foam (densities 100, 145 and 300 kg/m^3) blocks (80x80x25 mm) with central holes of different diameters (16, 28 and 40 mm).

From the practical point of view thermography, as a full filed temperature measurement, could be employed to investigate the damage of components or structures made of PUR foams.

On the other hand CRUSHABLE FOAM model is able to reproduce the behaviour of PUR foams in compression and could be used for designing of PUR foam components and structures above to the yielding point.

Acknowledgement

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