energy dissipation, intensive construction, hyperelastic, foam

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THE IDENTIFICATION PROPERTIES OF POROUS FOAM

Abstract

The aim of this work is to develop methods of describing the properties of such materials based on knowledge of: basic materials, technologies (gas pressure formed during foaming) using the theory of hyperplastic materials. The resulting description can be used for the applicability of hyperelastic models, and therefore in the whole range of deformation of the polymer-based composites and elastic composites of metals (not included plasticity). Thesis presents analysis methods of hyperelastic materials using Finite Elements Method. Using FEM it is possible to verify used material, define materials models and show effectiveness of designed component without performing expensive impact tests. Presented methods and applications of the characteristics of hyperelastic materials and composites with the gas phase are used to determine the proper selection of parameters (material properties), increasing the opportunities for a proper assessment of the effectiveness of safety devices.

1. INTRODUCTION

Porous polyurethane foams are widely used in the construction of motor vehicles in particular in the protective structures – systems and energy-dissipating units [5]. Used materials are foamed polypropylene, in the form of pressure, not interconnected granules. Process of static compression for the analyzed polymer foams was determined [11] with the energy absorption and energy dissipation efficiency. By using different sizes of granules elements we obtain different densities in the range of 25 g/dm³ to 220 g/dm³. The surface porosity and surface properties are dependent on the release of active ingredients and the process of formation. The analyzed foams have a high pore volume, mainly inside the macropores. Energy consuming structure is formed in the

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molding process by the blowing. The loose granules are delivered under pressure into the mold where the steam are subject the influence of the formation to yield any shapes and dimensions. Opportunities of foams are very large, in particular, is a high energy absorption and a memory shape – which occur even after multiple loadings. Absorption capacity of the analyzed structure, methods of influencing the properties depending on the external conditions are presented in the literature [6-10]. These properties are of crucial importance in the production of automotive components, which are responsible for ensuring maximum passive safety in automobiles. The products such as energy absorbers to car bumpers is one example of the wide range of applications in order to improve vehicle safety. Components for safety absorb the impact energy that is dissipated by the work done on the deformation of the structure. One factor in this regard is that the impact energy which occurs in the case of a vehicle, wherein the absorbing element is mounted element made of a foam material during the collision should be discharged or directed in such a way that the vehicle does not permanently damage. Furthermore, the vehicle can protect the bumper a pedestrian, in other words in the event of a collision with a pedestrian, the bumper should provide a high level of energy absorption with a large stroke in order to minimize deformation, thereby reducing injury to pedestrians.

The present work is devoted to the presentation of the methods of analysis and description of the properties of the foam materials used, among others, the "security elements". Verification of the properties was carried out on the basis of experimental studies and simulations performed using the Finite Element Method. The proposed method of describing the properties of foam materials are widely used primarily for the analysis of protective devices used in vehicles. At analyses included the process of foamed materials producing, wherein we define: a base material, technology (gas pressure generated during the foaming), using the theory of the material growth and temperature. Simulation analyzes were made using Abaqus system. Description of the material properties was performed using the Ogden's model and its modify-cations. The presented method of analysis of materials enables appropriate deployment model, hyperflexible and its modifications resulting in even better determination of the materials characteristics.

2. STRUCTURE AND CHARACTERISTICS OF THE MATERIAL

Foam materials are widely used, due to its thermal properties, the ability to high energy absorption [13]. The structure of materials like closed cells that can be found in two phases: a solid phase material which is formed and the gas phase, which is formed by taking a physical or chemical phenomena during the preparation steps. The relevant properties of the structure we obtain not only by the choice of how to produce, but also through appropriate selection of the materials used and the appropriate design of the structure geometry. Determination of properties of selected materials was carried out in two stages and takes into account the intended use. The first step is to conduct experimental research carried out in accordance with PN-EN ISO 604:2004, BS EN ISO 604:2006, PN-H-04320: 1957. The second step is to research the actual protection element pedestrian protection element used in VW cars. The material from which samples were made was in the form of granules unconnected filled with a gas which occupies about 97% of the volume. In the description of the material properties must therefore take into account the base material and gas [4]. The use of pellets of different sizes contributes to changes properties of the foam. For the determination of properties of the structure it was necessary to conduct a study which was carried out in the Department of Integrated Process Engineering at the Faculty of Chemical and Process Engineering, Warsaw University of Technology. The research was conducted using a scanning electron microscope Phenom G2 Pro – picture of section structure is shown in figure 1.

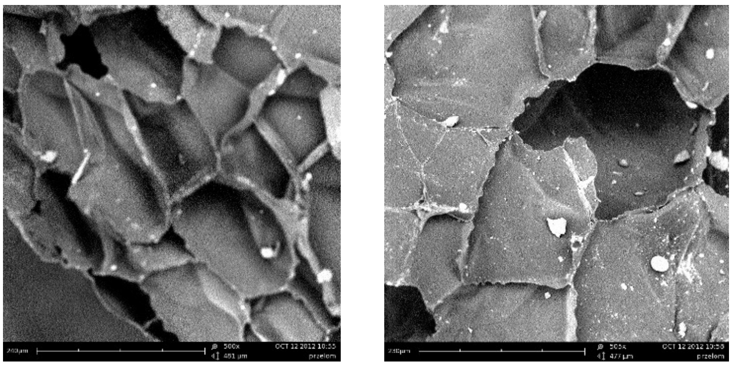

Fig. 1. SEM image of section structure – polypropylene foam [source: own study]

During the studies, there was no adhesive substances between the granules. The material has a high resistance to temperature around. 150 °C, excellent thermoformability and shape memory (large ability to return to its original shape after static and dynamic loads). Given that the process of creating foam is expanding - foaming material granules such as polypropylene with water vapor and using a pressure, the granules connect to each other while increasing the volume. More than 90% of the volume of the foam produced in the process is air.

Was determined roughness of the test material:

- Average surface roughness 80-130 μm. Grains protruding above the surface to a height of 200-400 μm.
- The inhomogeneous surface of samples. The current fine grains with a diameter of 10-30 μm and a few larger – diameter of ~100 μm. Density decomposition grains ~40/ μm.

3. RESEARCH METHODOLOGY

3.1. Research methodology – experimental studies

Static test for plastic compression is different due to the nature of the deformation [12]. Stress-strain characteristics of the sample obtained for the test compressive materials. The compressive strength of samples was determined using testing machines: Q-test 10 from MTS and Zwick/Roell Z005. The samples was made in the the form of cuboids. The studies of pedestrian protection element, due to the large size, compression test took place only on the first machine. The compression rate at 23^{o}C for the first machine was 5 mm/min, for the second machine 1 mm/s. During the course of the trial were recorded according to the compression force between the piston and the piston displacement, which constituted the first part of the experimental studies. On this basis, the following of samples were made for the charts showing the dependence of the stress deformation as well as the hysteresis loops in the case of quasistatic compression tests. Example experimentally determined hysteresis loop is shown at figure 2.

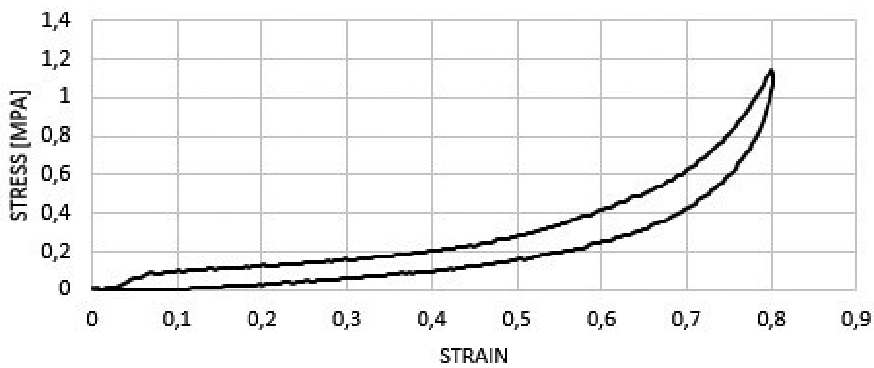

Fig. 2. Example experimentally determined hysteresis loop [source: own study]

3.2. Research methodology – simulation studies

Analysis of simulation models were made using MES (Finite Element Method) ABAQUS, which allows you to fit existing models in the database according to the theory of hyperelastic materials. Simulations were made by using the EXPLICIT module, the calculation takes into account all the necessary in this case non-linear phenomena: the theory of finite deformation by Almancy's in Euler's coordinates (referenced to the actual configuration of the body during deformation). Numerical analyzes were performed for the adequate modeled samples and security element [14]. During the simulation, the effect of friction during deformation of the foam structure – clamping a gas-filled cell. For safety component model and the model of the structure of the material was included contact issue. The evaluation of dynamic loads: stresses, accelerations and deformations occurring during the impact a pedestrian allows to determine the ability of the material to absorb energy. The adoption of the actual values of coefficients αi leads to a nonlinear model, which allows for a description of materials with much compressibility. For modeling of foams, we can modify the Ogden's model with the introduction of the actual exponent in the second part describing dependences of the volume deformations (in this case they are also dependence non-linear). The calculations using the FEM, we can choose the hyperelastic model. To select the most reflects the actual behavior of the material model, for which we perform experimental studies, should the results of both analyzes to compare (compare the results of experimental tests with the results of the numerical model). For the materials considered, a number of comparisons for different types of models. Completed studies have shown that foam materials exhibit a range exceeding 50% strain rapid increase in stresses. Description of the models of the theory of hyperelastic materials: polynomial or Ogden's is insufficient due to the adoption of linear dependencies in the component describing the volumetric strain. As a solution proposed to use a modified Ogden's model called HYPERFOAM, in which the elasticity functional is described of dependence:

$$W = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2} \left[\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3 + \frac{1}{\beta_i} \left(\left(J^{el} \right)^{-\alpha_i \beta_i} - 1 \right) \right] \tag{1}$$

in which are accepted indications**:**

volume deformations ratio $\beta_i = \dfrac{\nu_i}{1 - 2\nu_i}$; ν_i – Poisson's ratio, $J^{el} = \bar{\lambda}_1 \bar{\lambda}_2 \bar{\lambda}_3$ – volume , $\bar{\lambda}_i$ – extend relevant of the deviatoric parts, α_i – real exponents.

Notations in formula (1) has been adopted by monograph [1], used also the articles [2], [3]. Another alternative is to utilize material description LOW DENSITY FOAM, wherein the curve is given a description of the stress – strain separately for the compression and stretching. The studies also showed that the porous foam materials have a significant damping level. The calculation is made as a Rayleigh's model with the component of the damping matrix proportional to the inertia matrix. Impact simulation was performed with a body weight of 1000 kg (representing vehicle) moving at a speed of 11.1 m / s (40 km/h – maximum speed by the findings of the European Directive) to the impactor – the body of weight m=70kg (corresponding to the mass of human body). Model of the vehicle is equipped with a bumper made of hyperdeformable material elastic characteristics described by (1) and the attenuation by the Rayleigh's model. It was assumed that the bonds are one-sided - only compressive forces. The course forces during the impact until the rebound. In the case of a system without damping the maximum force is: 6130N. According to the findings of security organizations vehicles (e.g. EuroNCAP), the maximum force (leg) is about 8000N. The value obtained is therefore less than the limit. Is also specified allowable bending moment - 225N, the value is dependent on the value of the point of impact – bending moment is greater than the allowable. The material used in the pedestrian protection element has a high level of damping – confirmed this the hysteresis loop which was experimentally made. With regard to the level of damping of 0.25 dimensionless of impact simulation gave the force of 5694N. Damping affects a significant reduction in the speed with which the impactor is ejected after impact – it is approximately 18m/s. Example of force during the impact is shown at figure 3, speed at figure 4.

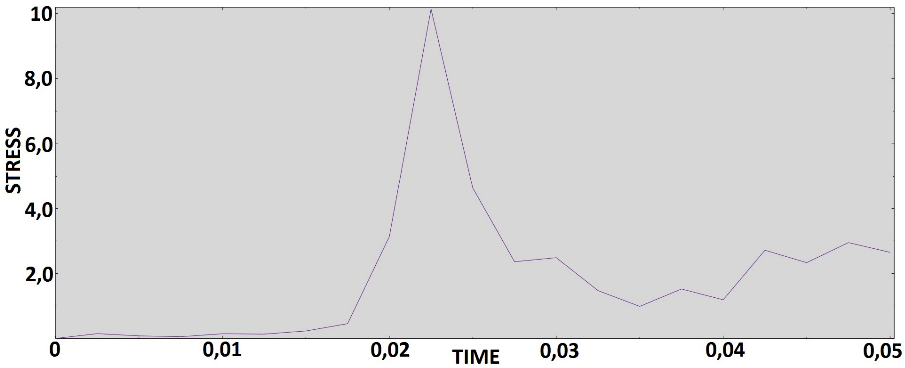

Fig. 3. Example of force during the impact [source: own study]

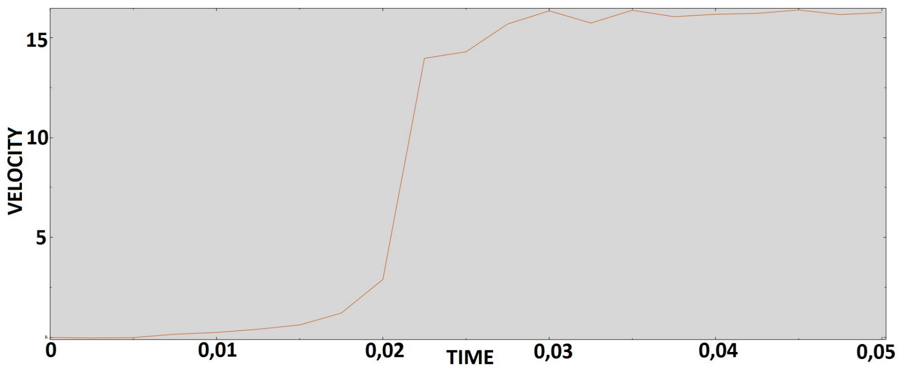

Fig. 4. Example of speed during the impact [source: own study]

4. CONCLUSIONS

The results of analyzes support the conclusion that testing methodology and simulation of reconstruction of the hysteresis loop allow to describe the properties of foam materials. Research has shown that during the trial the energy dissipation occurs through the foam material. Detailed research and analysis allow you to see what phenomena occur during compression tests. It is important to the analysis of contact problems occur at the interface between inside the surface of the material, including the gas occurring inside the structure (porous structure). Our research suggests the ability to integrate issues of engineering materials in the production of foam structures to the mechanics of materials and structural strength (evaluation of elastic and plastic properties in terms of high-speed deformation). Research and analysis allow you to see what phenomena occur during a collision in the applied material. Models foam structures take into account the phenomenon of energy dissipation. The nature of the phenomenon of energy dissipation varies with the speed of deformation. Models of materials, including modifications, can be used to assess the ability of absorbing energy and are proposed for use in describing a simulation performed using the program Abaqus. The work contributes to the development of the use of Finite Element Method to simulate the fast-changing loads - possibilities methods are not yet fully utilized. For the materials considered can determine the relationship between stress or deformations, which are dependent on properties of the material. Use of modified Ogden's model enables a description of the material and also increases the accuracy and effectiveness of the simulation conducted. For isotropic materials analyzed are considered arbitrary deformations of the body for large deformations and processes that take into account the thermal effects during manufacturing.

REFERENCES

[1] WARD M., *Mechanical properties of polymers as structural plastics*, PWN Warsav, 1975.

[2] OSIŃSKI J., RUMIANEK P.: *Application of modified Ogden's model for describing features of composites with gas phase*. Machine Dynamics Problems, 2/2012, pp. 64-75.

[3] OSIŃSKI J., RUMIANEK P.: *Simulation of energy dissipation during impacts with hyperelastic elements*. Machine Dynamics Problems, 2/2012, pp. 77-83.

[4] DUDZIAK M., MIELNICZUK J.: *Non-classical models of the materials in machine design*. Publisher Institute for Sustainable Technologies, Radom 2001.

[5] GIBSON L. J. AND ASHBY M. F.: *Cellular Solids: Structure and Properties*, (1997) Cambridge: Cambridge University Press.

[6] LIANG CUI, KIERNAN S., GILCHRIST D. M.: *Designing the energy absorption capacity of functionally graded foam materials.* Materials Science and Engineering, Volume 507, Issues 1-2, 15 May 2009, pp. 215-225.

[7] COURTNEY W. A., OYADIJI S. O.: *Preliminary investigations into the mechanical properties of a novel shock absorbing elastomeric composite,* (2001) J. Mater. Proc. Technol. 119, pp. 379-386.

[8] HOLNICKI-SZULC J., PAWLOWSKI P. AND WIKLO M.: *High-performance impact absorbing materials – the concept, design tools and applications*. Smart Material Structure, 12, 2003, pp. 461-467.
[9] ULLRICH M.: *Caught between the constraints of interior design and safety.* (2003) IVehE 26–7.
[10] Hayes W. C., Robinovitch S. N. and McMahon T. A., *Bone fracture prevention method.* (1996) US Patent Specification 5545128 A.
[11] AVALLE M., BELINGARDI G., MONTANINI R.: *Characterization of polymeric structural foams under compressive impact by means of energy absorption diagram*, (2001) International Journal of Impact Engineering 25, pp. 455-472.
[12] SURAJ S. D., MCKINLEY G. H.: *Adaptive energy-absorbing materials using field-responsive fluid-impregnated cellular solids.* Institute of physics publishing, Smart materials and structures, Volume 16 (2007), pp. 106-113.
[13] DI LANDRO L., SALA G., OLIVIERI D.: *Deformation mechanisms and energy absorption of polystyrene foams for protective helmets*. Polymer Testing (2002) 21, pp. 217-228.
[14] OSIŃSKI J., RUMIANEK P.: *Research determining the properties of composites with gas phase in the car – pedestrian system: methods and application*. Dynamical Systems – Theory, Lodz University of Technology (2013).