Nonlinear Dynamics and Systems Theory, **15** (1) (2015) 43–49

# Researches Defining the Characteristics of Hyperelastic and Composite Materials with Gas Phase in the Vehicle–Pedestrian System

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Received: March 31, 2014; Revised: December 22, 2014

**Abstract:** The aim of this work is to develop methods of describing the properties of materials based on knowledge of: basic materials, technologies (gas pressure formed during foaming) using the theory of hyperplastic materials, in particular using Ogden's model and its modifications. The aim also goes on to analyze the possibility of energy dissipation between a pedestrian and a vehicle on impact. The energy created during the impact will be dissipated by the element of protection made of a hyperdeformable material. The resulting description can be used for the applicability of hyperelstic models, and therefore in the whole range of deformation of the polymer-based composites and elastic composites of metals (excluding plasticity). This thesis further presents analytical methods of hyperelastic materials using Finite Elements Method. Using FEM it is possible to verify used materials, define the materials models and show the effectiveness of the designed component without performing any expensive impact tests. The presented methods and applications of the characteristics of hyper elastic 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.

**Keywords:** *energy dissipation; intensive construction; hyperelstic materials; gas phase; gasar; crushable foam.*

**Mathematics Subject Classification (2010):** 93A30.

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## 1 Introduction

Hyperelastic materials and composites with the gas phase have wide applications due to their thermal properties and ability to absorb energy tremendously. The structure of these materials resembles closed cells, in which we find two phases: the solid phase, from which the material is formed and the gas phase, which is formed as a result of ongoing physical or chemical phenomena during the stages of production. The relevant properties of the structure are obtained not only by the choice of the way of producing, but also through appropriate selection of materials and proper design of the structure geometry.

The study's aim is to develop a methodology and an overall assessment of the analysis of elements made of hyperelastic foams and composites with gas phase. The main aspect that has been considered is to determine the properties of the materials, as well as to assess the potential energy dissipation by elements made of the above-mentioned materials. The methods of modeling hyper elastic materials and composites with the gas phase are applicable to the structure to increase the safety of the passengers in the vehicle and outside the vehicle as well as of the materials used in motorcycle and bicycle helmets. The used materials have a high capacity to transfer the kinetic energy during impact, which is compensated by the destruction process (crushing, breaking). The developed methodology of analysis using the Finite Element Method allows to not only determine the properties of the tested materials, evaluate the ability to dissipate energy, but above all, without the need for costly impact tests, to show the effectiveness of the protective elements.

To determine the properties of any selected materials two experimental stages are involved, which take into account the intended use [5]. The first step is to conduct experimental research carried out in accordance with standard specifications: PN-EN ISO 604:2004, PN-EN ISO 604:2006, PN-H-04320:1957 [2].

In the second stage, using the theory of hyperelastic materials and MES - Abaqus, simulating the specified data set experimentally during the first stage, we select the appropriate model, the description of which is the most consistent. Owing to the simulation we can properly determine the coefficients of the model. For the analysis it is necessary to use polynomial models, such as Ogdens model or hyperfoam model. Conducted experimental studies were performed using strength machines located at the Faculty of Automotive and Construction Machinery Engineering and Department of Materials Science and Engineering of the Warsaw University of Technology.

## 2 The Material

Tests of samples, made of foamed polypropylene used for the implementation of the protective elements, which is a plastic material having the form of interconnected gas filled granules, were carried out. After several studies it can be noticed that there are bubbles in the interior of the granules called the cell structure. Due to the type used for research of the testing machine, the samples were made in two sizes: 80mm x 80mm and height of 40mm, and 20mm x 20mm and 30mm height. The variety of foams having a density from 25 to 220 g/dm$^3$. Tests were also carried out for samples of different shape, which made it possible to assess the impact on the mechanical ability of the shape of the material [6, 7].

Also, the tests were carried out of pedestrian protection element used in the VW car Skoda Fabia II (Figure 1). For energy absorber (pedestrian protection element) a fastening element was made, which makes it possible to mount the machine for strength

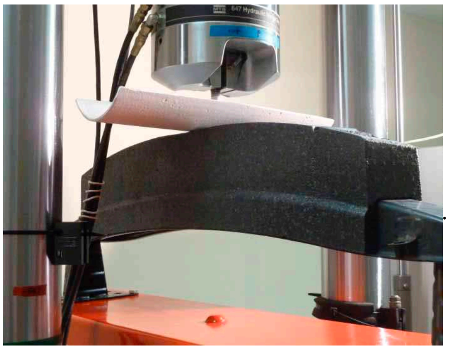

**Figure 1**: Energy absorber used in the VW car Skoda Fabia II.

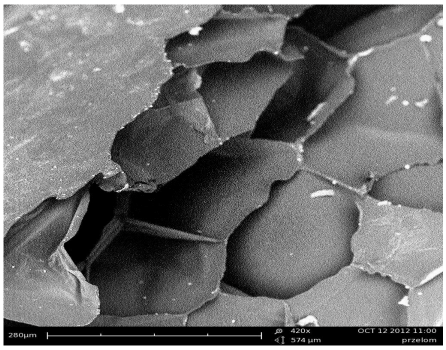


**Figure 2**: SEM image of pedestrian safety element fracture made of polypropylene foam.

research.

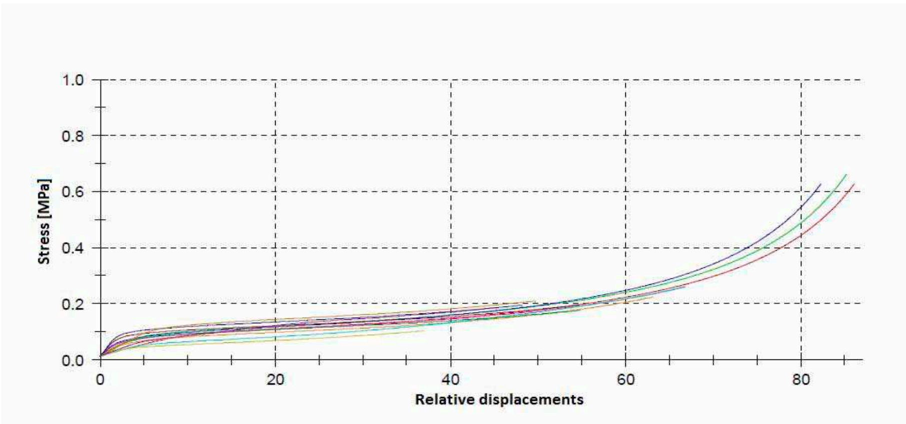


**Figure 3**: Series of compression curves set experimentally.

## 3 Methodology of Research

### 3.1 Determination of structure of the material

The material from which the sample was made, was not linked to the other form of gas-filled granules. Material with such structure is suitably formed in forming machines, during the formation of the granules taking the form of closed-cell structures creating a material having a relatively high rigidity (Figure 2). The use of granules of different sizes effects on the alteration properties of the foam. To determine the 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 of Warsaw University of Technology.

During the study, there were no adhesive substances between the granules. The material has a high temperature resistance, up to about 150$^o$C, excellent thermoformability and shape memory (large capacity to return to its original shape after static and dynamic loads). Due to the fact that the process of formation of the foam is expanding - foaming granules of material such as polypropylene with water vapor and using pressure, the granules are combined with each other while increasing the volume. More than 90% of the volume of foam produced in the process is air.

### 3.2 Experimental studies

Static test for plastic compression is different, due to the nature of the deformation. Stress-strain characteristics obtained in the compression test for the tested materials are shown in the drawing (Figure 3).

In all tests the temperature changes have been recorded by the pyrometer. The compressive strength was determined using a sample testing machine Q-test 10 of MTS and Zwick / Roell Z005. The samples were prepared in the form of cuboids. The research component of pedestrian protection, 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, the second machine – 1 mm/s. Tests were also made for the cold samples, which were cooled with dry ice. During the course of the test, recordings were made according to the compression force between the piston and the piston displacement, which constituted the first part of the experimental testing. On this basis, the following samples were made for graphs showing the dependence of the deformation stress. Taking into account the effect of the initial temperature, the samples were studied with the initial temperature 23$^o$C and -15$^o$C. On this basis, the hysteresis loop was determined as in the case of quasi-static compression.

### 3.3 The simulation studies

Analysis of simulation models was made using a system Abaqus FEA (Finite Element Method), which allows us to fit models that exist in the database, according to the theory of hyperelastic materials. Simulations were made by using the EXPLICIT module. Numerical analyses were performed for the samples appropriately modeled and for the security of the element. The models were constructed using the Catia V5R19. During the simulation, the effect of friction during deformation of the foam structure led to the crimping of a gas-filled cell. For safety element model, the structure model takes into account the issue of the structure of the material contact problem. The evaluation of dynamic loads: stresses, accelerations and deformations occurring during the impact against a pedestrian, allows for the ability of a material to absorb the energy. Except for the actual values of the coefficients, $\alpha_i$ leads to a nonlinear model, which allows for the description of materials and compressibility [4].

Ogden's model can include different cases (Figure 4). If we accept the description of the coefficients $\alpha_i = 2, 4, 6, ...$, then we have a polynomial model, including various special cases: models of Mooney-Rivlin (Figure 5), Yeoch and Neo-Hookean (Figure 6). By introducing the equation of $\alpha_i$ coefficients with fractional values, we obtained nonlinear model already in the first approximation [4]. The values of the coefficients are determined based on experimentally defined approximations of the stress - strain. The data of Ogden's material model were determined on the basis of research conducted at the Institute of Mechanical Engineering at the Faculty of Automotive and Construction Machinery Engineering and Department of Materials Science and Engineering, Warsaw University of Technology. The material has been described by the third row of the

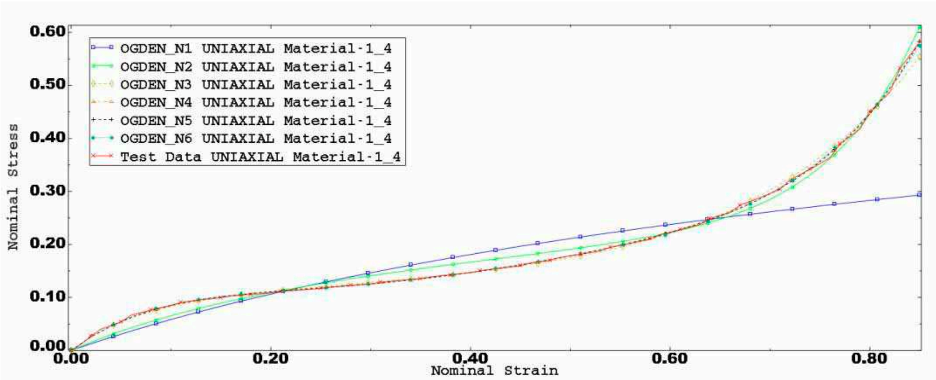


**Figure 4**: Series of compression curves set experimentally. Ogden's models.

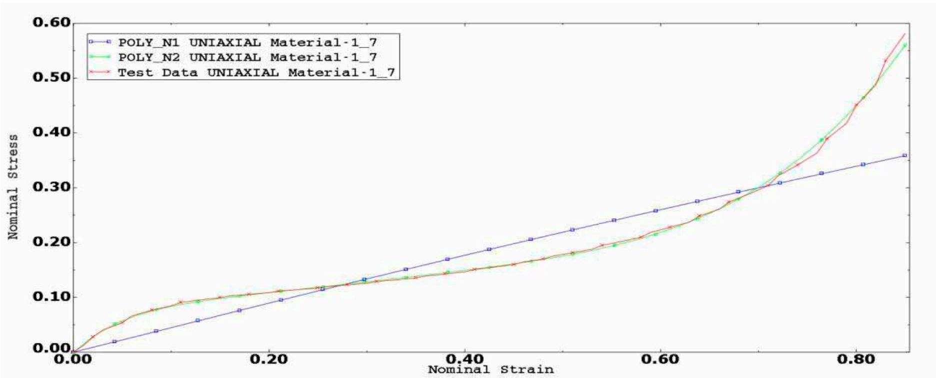


**Figure 5**: Series of compression curves set experimentally. Polynomial- Mooney-Rivlin model.

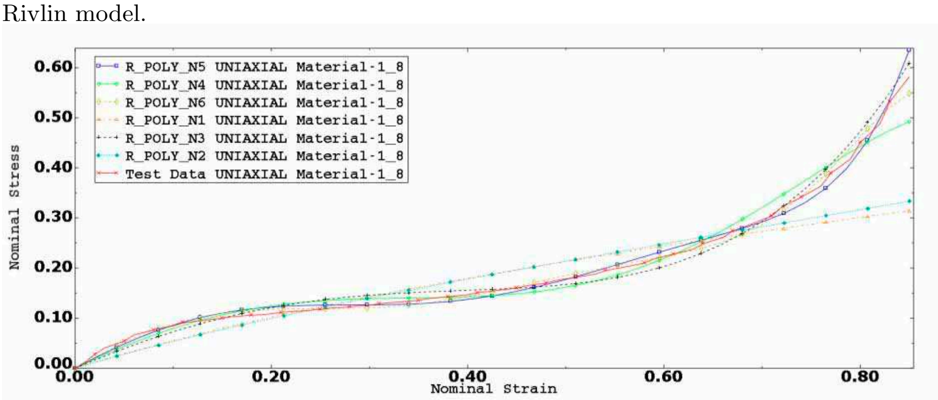


**Figure 6**: Series of compression curves set experimentally. Reduced Polynomial-Neo-Hookean model.

Ogden's model [1]. The coefficients of Ogden's material impact attenuator model, used in the simulation, are presented in Table 1.

For modeling foam, we can modify the Ogden's model with the introduction of real

| i | $\mu_i$ | $\alpha_i$ | $D_i$ |
|---|---|---|---|
| 1 | -1062310,50 | 7,701 | 8,6448 |
| 2 | 781324,564 | 8,0848 | 0 |
| 3 | 776736,53 | -11,4395 | 0 |

**Table 1**: Description of the foam properties of the third row Ogden's model – coefficients.

exponent in the second part of the equation which describes the volume deformations (in this case, they are also non-linear dependances) (Table 2). In the calculations using the FEM application we can choose the hyperelastic model, for which the set of properties have been described.

| i | $\mu_i$ | $\alpha_i$ | $D_i$ |
|---|---|---|---|
| 1 | -832131,49 | 16,20948 | 8,935334 |
| 2 | 831230,727 | 16,21166 | 0 |
| 3 | -2528968,43 | -1,172925 | 0 |

**Table 2**: Description of the foam properties of the hyperfoam model – coefficients.

To select the model which reflects the actual behavior of the material for which we carry out experimental studies, the results from both studies should be compared (compare the results with the results of experimental tests of the numerical model). For the materials considered, series of comparisons have been made for different types of models. The final results of the process revealed that the most consistent stresses waveforms in the real and numerical studies have occurred for the Ogden's model.

## 4 Conclusions

The results of the analyses allow us to conclude that the testing methodology and impact simulation of element (pedestrian protection element) and test samples can assess the effectiveness of the protection of pedestrians and assessment of hyperelastic materials and composites with the gas phase. Research has shown that during the tests the energy dissipation is followed by the foam elements. The study of these documents and the existing elements of pedestrian protection is very important because it not only makes it possible to determine the extent to which we can protect the victims of accidents, but also reduce the consequences of such accidents. Detailed research and analysis allow us to see what events occur during a crash in the applied material. Model foam structures take into account the phenomenon of energy dissipation. The nature of the energy dissipation phenomena varies with the speed of deformation. Such dependencies are determined by numerical simulation of deformation. To build the model, the information on the manner of their production emanate from the achievements of material engineering.

It is important to analyze the problems occurring at the interface between the contact surface and within the material at the contact surfaces of the hyperdeformable element (foamed structure) with other structural elements made of steel or other materials. This thesis affords us the ability to integrate aspects of material engineering in the making of foam structures to the mechanics of materials and structural strength (evaluation of elastic and plastic properties in terms of high-speed deformation) and the operation of vehicles in the range of passive safety. Compression tests of executed samples of the material were carried out to develop models that correspond to the material used. This thesis further contributes to the development of the use of Finite Element Method to simulate rapidly-variable loads - possible methods are not yet fully exploited. The tests are considered to expand the applicability of modern construction materials, plastic and composites. Completed studies are not possible without the correct description of the properties of this type of materials. The use of well-known models for hyperelastic materials: reduced polynomial, Ogden's and non-linear models, allows us to have the correct description of the properties of the tested materials. Isotropic materials are analyzed in the theory of hyperelasticity, which presupposes the existence of the positive features of elasticity and specific energy of the natural state of the body. It will consider any form of deformation of the body for large deformations and processes that take into account the thermal effects during manufacturing. Models materials together with modifications may be used to evaluate the energy absorption, proposed to be used in the description of the simulation performed using the program Abaqus. For the materials considered the relationship between stresses and strains, which are dependent on the material properties can be determined. The use of the modified Ogden's model makes it possible to accurately determine the description of the material, which makes it possible to increase the accuracy and effectiveness of the simulation. The carried out research allow for an even better way to make a selection of the material and its properties.

## Acknowledgment

I would like to thank the Organising Committee of the 12th Conference on Dynamical Systems – Theory and Applications for the possibility of presenting, and publishing of our article in the conference proceedings in *Dynamical Systems Theory* – summary of 34 best papers of university teachers and students, researchers and engineers.

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