TWO-SCALE MODELING OF THE MECHANICAL BEHAVIOR

OF A COMPOSITE FOAM

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The closed-cell foam is a composite with gas and solid phases. At the microlevel, the polystyrene foam was considered as a regular cellular structure whose complex of mechanical properties depends on the properties of polystyrene as an elastic-plastic material. At the macrolevel, the foam was regarded as a solid hyperelastic compressible medium, whose constants were determined in the ANSYS package according to the corresponding calculated deformation diagrams in uniaxial tension/compression, pure shear, and two- and three-axial compression. This technique was tested in the problem on indentation of a rigid sphere into the foam. The calculated indentation curves are in satisfactory agreement with experimental data.

Introduction

Foam materials with closed cells are often regarded as composite structures with two — gas and solid — phases [1-3]. Since these materials possess such advantages as a low density, high damping, and high heat and noise insulation, they are widely employed in aircraft and transport as load-carrying elements of three-layer structures (sandwich panels), as well as in protective structures (armor vests and helmets) [4-6], which absorb energy at local impacts [3, 6, 7-10]. In some studies (see, for example, [6, 7, 11-15]), the process of energy absorption by foams is divided into three stages: elastoplastic deformation of cells, buckling of cell walls, and origination and growth of cracks.

The mechanical properties of foams have been estimated in uniform compression, tension, shear, bending, and indentation [3, 6-8, 10-12, 14-24]. The decrease in the mechanical characteristics of foam materials compared with those of the

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continuous initial one is determined by the foaming ratio (the apparent density) and by microstructural parameters: dimensions and shapes of the cells and the thickness of their walls [5-7].

In [9, 13-14, 20, 25-30], it is suggested to estimate the homogeneous deformation of foams by using analytical or numerical models of the elastic behavior of an elementary open/closed cell under various external loadings.

The inelastic behavior, the change in volume (compressibility), and large deformations make it necessary to examine in more detail particular features of the stress–strain state of walls of foam cells and to analyze the behavior of micromodels by numerical methods. However, the models of microlevel are too "heavy" for use in calculations of real structures, for which the application of continuum models is more preferable [8, 12, 15-17, 19, 31].

We should note that the modern packages of finite-element analysis (ANSYS, ABAQUS, and LS-DYNA) contain a set of nonlinear models of materials, including compressible ones, which take into account their plasticity, destruction, and anisotropy. However, the number of variable parameters in such models amounts to tens, and no approved technique of their determination exists. Therefore, the problem of search for low-parameter models adequately describing the nonlinear effects observed is still topical.

The present study is dedicated to an experimental investigation of the elastoplastic behavior of a PPS-250 closed-cell foam plastic based on polystyrene in tension, compression, and shear; a micromodel of cell of the foam plastic is developed (the SolidWorks package), and its nonlinear mechanical behavior in the ANSYS package of finite-element method (FEM) is analyzed. The deformation curves of the elementary cell in uniaxial tension/compression, shear, biaxial tension/compression, and triaxial compression are derived to estimate the change in volume, which is difficult to realize experimentally. The calculation diagrams of elastoplastic deformation of the elementary polystyrene cell were laid at the basis of determination of the parameters of the hyperelastic Mooney–Rivlin material for predicting the behavior of the foam plastic upon its monotonic indentation (macromodel).

1. Experiment

Tests in quasi-static uniaxial tension, compression, pure shear, and indentation were carried out on an INSTRON 5882 universal testing machine. During manufacture, the microstructural parameters of foams can change within the volume of a part, which can lead to a noticeable variation in density [1, 5, 21, 30] and to the corresponding scatter of mechanical properties, as was observed for the foam material examined here.

1.1. Compression of foam plastic. Polystyrene foam specimens of dimensions $5 \times 5 \times 5$ mm were compressed between plane steel plates at a speed of crosshead motion of 1-20 mm/min. In processing experimental data, it was found that a change in deformation rate did not lead to significant changes in the mechanical characteristics of the material. Therefore, all the tests were carried out at a speed of crosshead motion of 5 mm/min. Figure 1a shows the material deformation diagrams with the elastic modulus $E = 280$ MPa and the yield point in compression $\sigma_c = 5.8$ MPa. The range of deformations examined does not include the section of hardening, therefore, the character of deformation of the material is close to perfectly elastoplastic.

1.2. Tension of foam plastic. The tension tests were performed on prismatic $110 \times 20 \times 5$-mm specimens fixed in flat-jaw clamps of INSTRON 2710-106. The clamps had a thin rubber covering to increase friction. The engineering pressure–strain curves are shown in Fig. 1b, where the yield stress in tension $\sigma_t = 7.50$ MPa. The distinction in the values of yield stress in tension and compression is negligible — it depends on specimen volume and may be neglected in simulation.

1.3. Pure shear of foam plastic. The shear tests were carried out on specimens geometrically similar to those of ASTM D5379-93 standard: 150 mm long and 40 mm wide, with two symmetric V-shape cuts at 90° and depth of 10 mm made in the working part. All standard dimensions were twofold increased because of small breaking loads of the foam plastic. The specimens were fixed along their lateral surfaces in the flat-jaw clamps of INSTRON 2710-106, with the lower (motionless) clamp displaced by 75 mm to ensure that the loading corresponds to the transverse shear with a zero bending moment in the calculated section. Such a testing scheme excludes crumping of the material under supports in the device and is recommended
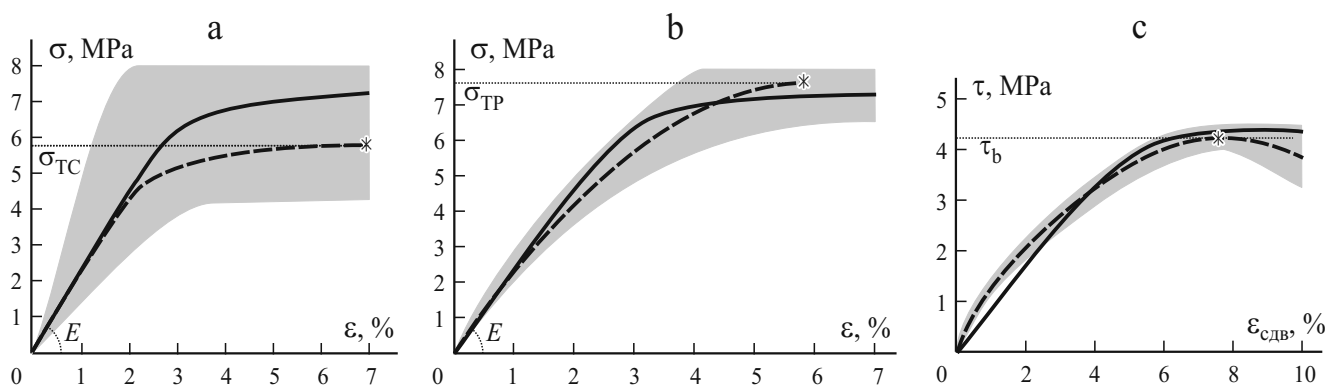
Fig. 1. Engineering stress-strain diagrams of the foam plastic in compression (a), tension (b), and shear (c): (——) — calculation and (– – –) — the average experimental curve; the grey color marks the scatter ranges of experimental data.
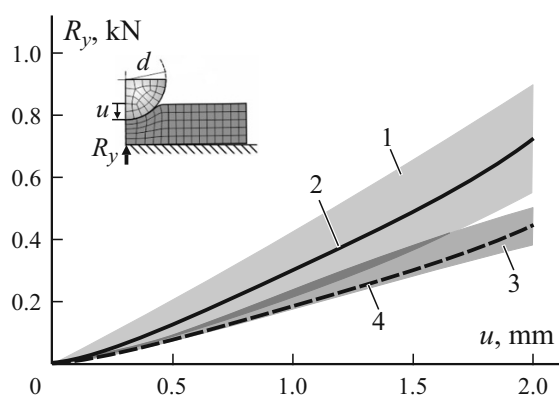

Fig. 2. Experimental (1, 3) and calculated (2, 4) relations between the load R_y and penetration depth u of indenters of diameter d = 10 (1, 2) and 5.54 mm (3, 4). The grey color marks the scatter ranges of experimental data.

by the above-mentioned standard (Iosipescu scheme). As a result, shear stress – strain diagrams were obtained (Fig. 1c). The average value of the shear strength of PPS-250 was τ_{sh} = 4.24 MPa.

 1.4. Indentation of foam plastic. Steel spheres of diameter D = 10 and 5.5 mm were pressed into the surface of the PPS-250 foam plastic at a speed of crosshead motion of 5 mm/min. The indenter was fixed on the upper clamp and did not contact the surface of specimen before the tests. The spheres were introduced into the specimen at a depth of 2 mm. The scatter ranges of load R_y –penetration depth u diagrams for different indenters are presented in Fig. 2.

2. Calculations

 The structure of the foam plastic was investigated by analyzing the microphotos of fracture surface obtained on a Dino-Lite Pro digital microscope with a 200× magnification (Fig. 3). The analysis showed that the diameter of cells changed according to the normal law of distribution, with an average value of 155 µm and a coefficient of variation of 28%. From the images, it was impossible to determine the thickness of cell wall in the real foam plastic; therefore, its thickness was calculated from the condition that the average density of the foam is equal to the density of the cell considered (Fig. 4). It was found that the thickness of the wall of the cell must be 15 µm.
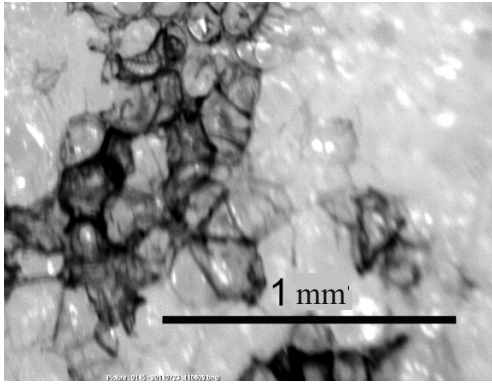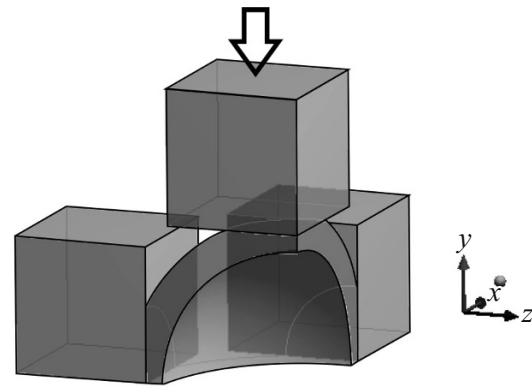
Fig. 3. Surface of polystyrene foam.

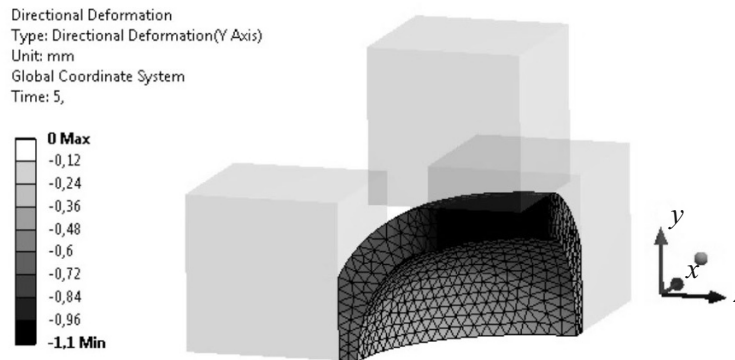Fig. 4. Model of microstructure of the polystyrene foam in the ANSYS Workbench package.

Fig. 5. Deformations of the microstructure model.

The PPS-250 polystyrene foam has a structure consisting of closed cells with rather thick walls, therefore, as a calculation model, we assumed the scheme of repeating element in the form of a 1/8 of a thick-wall spherical shell with plane sections on which the conditions of mirror symmetry, according to the contact of no-separation type with the auxiliary rigid cube elements in the ANSYS Workbench finite-element package (the Static Structural calculation scheme), were assigned (Fig. 5). This type of contact ensures the equality of normal displacements at all points of the contact surface and the absence of restrictions on displacements in the contact plane.

Deformations of the model in the cases of uniaxial tension–compression, pure shear, and biaxial and triaxial tension–compression were calculated to estimate the change in volume. The mechanical properties of the monolithic polystyrene were given by the model of a perfectly elastoplastic material with an elastic modulus $E = 3.5$ GPa, Poisson ratio $\mu = 0.35$, and yield stress $\sigma_t = 60$ MPa. The loading of the model was kinematic, with automatic determination of the responses of supports (cubes) for calculation of average stresses.

The calculated deformation curves lay inside the corresponding scatter bands of experimental data (see Fig. 1).

The deformation curves of the model in bi- and triaxial tension/compression were further used to estimate the compressibility of the foam in determining parameters of the model of hyperelastic continuous material of the Mooney–Rivlin type in the problem of indentation.

Then, the problem of the local contact interaction between the foam plastic and a spherical indenter was solved. The material of the foam plastic was assumed isotropic, hyperelastic, and compressible, but that of the indenter was considered

rigid. Since the problem is axisymmetric, a 2D model in the ANSYS Workbench package (the Static Structural calculation scheme) was used in our calculations. According to the results obtained in a preliminary computation of tension, biaxial tension, shear, and triaxial compression (volume changes) curves of the foam plastic in the ANSYS Workbench package, the parameters of the continuous compressed hyperelastic three-parametric Mooney–Rivlin material were determined automatically: C_{10} = 59.27 MPa, C_{01} = –44.74 MPa, C_{11} = 8.99 MPa, and D_1 = 5.26·10^{-4} MPa^{-1}. The diameter of the sphere was 10 mm, the radius of foam region — 15 mm, and thickness — 5 mm. The contact between the specimen and sphere was regarded as frictional (with a friction coefficient of 0.2) and the contact between the specimen and the base as a compression-only-support (with the possibility of separation). The loading was kinematic: the spherical indenter was moved by 2 mm in 200 steps. Since the microstructure of the foam plastic was nonuniform, the coefficient of variation of cell diameter was high (28%), and the size of the finite element had to include a representative sample of cells whose properties had to differ from those of the parent population by no more than 5% at a confidence probability of 0.95. Following the recommendations given in [32], the size of the finite element was chosen to be 1 mm. The calculated load–penetration depth curve is shown in Fig. 2 (curve 2).

For verification of the model, an additional calculation of indentation by a sphere 5.54 mm in diameter was performed. The resulting curve 4 lay inside the scatter band of experimental data (see Fig. 2).

Conclusions

For calculating the elastic deformation of elements of sandwich structures containing a foam core, a two-scale (micro/macro) approach is suggested, which consists in carrying out a detailed elastoplastic analysis of the stress–strain state of an element of the cellular microstructure in various types of loading. This analysis was used as the basis for constructing the model of a continuous hyperelastic compressible body of the Mooney–Rivlin type for macromodeling (indentation by a rigid sphere). The results of macromodeling (the loading–penetration depth curves) agree rather well with experimental data.

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