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Technical Report

Design of small auxetic springs for furniture

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ABSTRACT

Auxetic structures, due to their negative Poisson's ratios, should have a positive effect on the comfort of using seating furniture. The aim of this study was to develop numerical models of auxetic compression springs suitable for seat structures of office and home furniture. Analyses were conducted on real and numerical models of different spring structures having concave cell walls, subjected to uniaxial compression. By changing the modulus of elasticity for the material of the frame and geometry of the internal structure non-linear characteristics of rigidity and negative Poisson's ratios were established for designed springs. Based on numerical calculations structures best adapted to provide functionality for to the seats of resting and work furniture were identified.

1. Introduction

Cellular solids and cellular structures comprise a group of modern materials with elastic properties differing from those of the material forming their skeleton. Properties of these materials may be modelled by selecting appropriate geometric parameters of their structure, including the size and shape of their cells and the thickness of cell walls, as well as by changing the modulus of elasticity of the skeleton material. Cellular solids and structures with a negative Poisson's ratio (auxetic materials) are of particular importance in this aspect. They are characterized by concave cell walls and much lesser rigidity that cellular solids with an identical relative density, but frame topology forming convex polygons. A component with an optimised combination of different materials (including homogeneous and heterogeneous materials) in its different regions for a specific application is termed as a component made of a multiphase perfect material [1]. Cellular structures having negative Poisson's ratios can be designed to have high shear flexure properties. In the paper [2] the elastic limits of hexagonal honeycombs including the ones having negative Poisson's ratios are explored with various cell geometries under simple shear loading. The re-entrant geometry makes honeycombs flexible associated with a high effective bending length.

Materials that become thicker when stretched and thinner when compressed can be used in medicine [3]. For example, blood vessels made from an auxetic material will tend to increase in wall thickness (rather than decrease) in response to a pulse of blood, thus preventing rupture of the vessel.

Modelling and testing of cellular solids, including auxetics, have been performed by many authors. In the paper [4] materials have been constructed whose microstructure is represented exactly by the auxetic models. These materials are subjected to an axial strain and the measured Poisson's ratio is compared to the predictions by the models. The models are found to predict some behavior reasonably well but only when model parameters are measured from the experimental data.

Alderson and Alderson [5] reviewed status of research into auxetic materials, with particular focus on those aspects of relevance to aerospace engineering. Developments in the modelling, design, manufacturing, testing, and potential applications of auxetic cellular solids, polymers, composites, and sensor/actuator devices are presented.

Bezazi and Scarpa [6,7] investigated mechanical behavior of conventional and negative Poisson's ratio thermoplastic polyurethane foams under tensile and compressive cyclic loading. Various polyethylene foams were subjected to thermo-mechanical processing with the aim of transforming them into re-entrant materials exhibiting negative Poisson's ratio [8]. Some authors [9] have studied negative Poisson's ratio polymeric cellular solids (re-entrant foams) to ascertain the optimal processing procedures which give rise to the smallest value of Poisson's ratio. The non-linear stress–strain relationship was determined for both conventional and re-entrant foams; it depended upon the permanent volumetric compression achieved during the processing procedure.

Auxetic ultra high molecular weight polyethylene has been fabricated by omitting the extrusion stage usually required to form the characteristic nodule-fibril microstructure of this material [10]. This article examines the mechanical properties of cylindrical compacts subjected to between one and four successive sintering treatments.

In recent years several auxetics have been fabricated by modifying the microstructure of existing materials, including foams and microporous polymers [11–13]. Some researchers [14–17] presented a new mechanism to achieve a negative Poisson's ratio.

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This is based on an arrangement involving rigid squares, triangles, rhombs and parallelograms connected together at their vertices by hinges. Wojciechowski [18] showed that the cyclic trimers form a mechanically stable and elastically isotropic non-chiral phase of negative Poisson ratio. Spadoni et al. [19] investigated the flat-wise compression behavior of an innovative cellular structure configuration. The considered layout has a hexagonal chiral geometry featuring cylinders, or nodes, joined by ligaments, or ribs. The resulting assembly is characterized by a number of interesting properties that can be exploited for the design of alternative honeycombs or cellular topologies to be used in sandwich construction.

The earliest studies by Gibson and Ashby [20] presented a relatively simplified model of an auxetic, which mechanical properties differed from experimental results [21]. Newer models [5,16,17] are more consistent with experimental data, but they concerned solely polyurethane foams. Those studies, although they supplied a sufficient theoretical and computational background, frequently failed in terms of a direct indication of geometrical parameters of cells and their walls as well as elastic properties of the skeleton, so that a structure with expected properties might be obtained. We particularly lack solutions concerning modelling of single auxetic springs under pressure.

Support for the user's body on a conventional seat made with the use of typical springs and/or polyurethane foams is connected with a situation when vectors of internal forces P_i in the seat are directed outwards (Fig. 1a). As a consequence, friction forces T are generated between the user's body and the seat, causing tensioning of the cover fabric, clothing and the skin on the user's body. According to Liu [22] support for the body on a seat made from auxetics results in vectors of internal forces P_i being directed inwards (Fig. 1b). In this way undesirable friction forces T are eliminated and comfort of furniture use is improved. Such properties of auxetics should meet the requirements imposed on materials used in the construction of seats of office or lounge furniture [23].

Auxetic seats of office and home furniture can be composed of springs with a negative Poisson's ratio, arranged parallel. In order to design a comfortable seat it was decided first to design new single auxetic springs. Thus the aim of this study was to develop numerical models of small springs, characterized by negative Poisson's ratios.

2. Materials and methods

Seating furniture is used in different places: office, schools, hospitals, waiting rooms, flats, etc. Depending on the location and individual requirements of the user, seat rigidity should be markedly varied to provide a minimal, uniformly distributed pressure. Examples of simple auxetic springs were presented in literature [23,24]. In view of this variation and the significantly different usage time of seating furniture four types of springs exhibiting auxetic properties were designed (Fig. 2). Designed models were printed at a 1:1 scale applying the 3D Selective Laser Sintering (SLS) technology. Each spring was printed in two copies. The first batch of springs was printed on polyamide with modulus of elasticity $E = 630$ MPa and Poisson's ratio $\nu = 0.3$. The second batch of springs was printed from a plastic with modulus of elasticity $E = 133$ MPa and Poisson's ratio $\nu = 0.3$. This value was selected heuristically on the basis of a series of multiple numerical calculations. Then models were subjected to uniaxial compression on a Zwick 1445 testing machine. In tests the applied rate of travel for the pressure bar was 10 mm/min, recording the load value accurate to 0.01 N, while the value of displacement was recorded accurate to 0.01 mm. Load was imposed until structure failure or loss of stability and/or an increase in rigidity caused by spring cell collapse.

The numerical calculations for the designed springs were performed using an Autodesk® Algor® Professional 2011 computer program, computing by the finite elements method (FEM). All solid models of the structure as in Fig. 2 were recorded in the STP format and imported from Autodesk® Inventor® Professional 2011 system to the Algor® system. Then meshes of 20-node solid elements with elastic properties of the applied plastic were plotted onto the models. For each of the models the diagram of uniaxial compression was used, applying loads with the direction, sense and maximum force value recorded on the testing machine (Fig. 3). It was also assumed that each of the applied loads reached within 1 s after 100 identical steps had been performed. When creating the numerical model it was assumed that the structure may lose stability and cell walls may press on one another. Thus for all the pairs of spring surfaces, frictionless contact was defined, indicating respective master and slave surfaces.

Results of calculations comprised vertical displacements of point A lying on the symmetry axis of the model and moving along the direction of load action, and horizontal displacements of points C and D lying on the horizontal symmetry axis of the model. Poisson's characteristics for individual models were determined on the

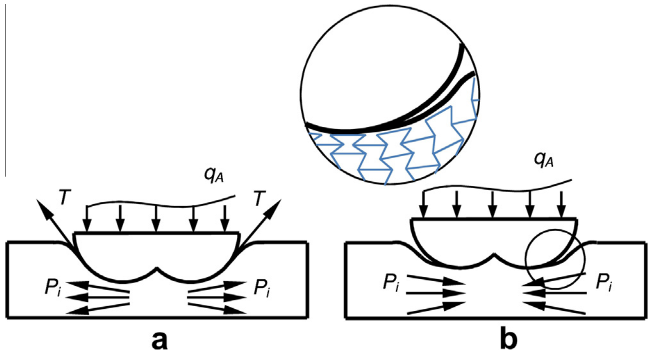

Fig. 1. Support for the body on: (a) conventional, and (b) auxetic seats.

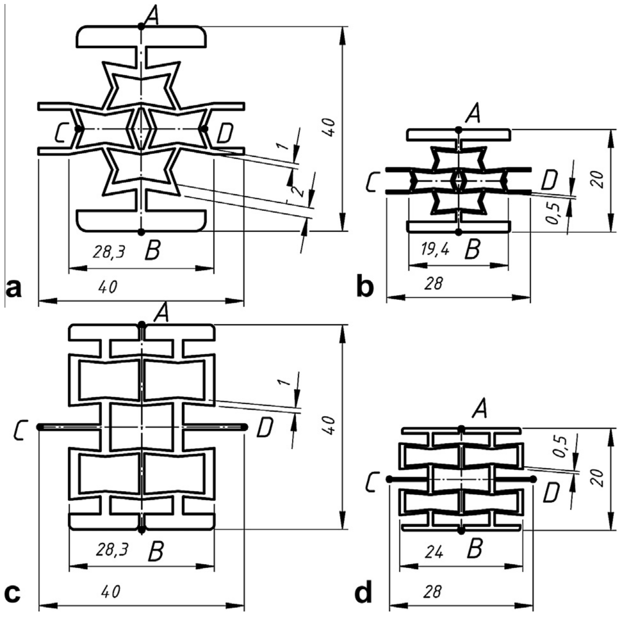

Fig. 2. Designs of springs with auxetic structure: (a) model A, 25 mm in thickness, (b) model B 20 mm in thickness, (c) model C 28 mm in thickness, and (d) model D 23 mm in thickness.