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Dorota JASIŃSKA*, Małgorzata JANUS-MICHALSKA*, Jerzy SMARDZEWSKI**

A STUDY ON THE DESIGN OF AUXETIC STRUCTURE OF SEAT SKELETON

SUMMARY

This paper presents numerical study of deformation and stresses in seat skeleton elements subject to static and dynamic pressure loads. Elastic skeleton made of polyamide or elastomer is taken as an example of a seat material. Auxetic type of seat structure ensures the reduction of real contact stresses between human body and seat, making it more comfortable than typical. FEM analysis is performed using ABAQUS system. Numerical calculations are carried out to determine the nonlinear stiffness characteristics of seat springs. The study makes possible the selection of material and structural topology fulfilling design constraints and additional recommendations concerning structural flexibility, stability and optimal reduction of contact stresses. This paper presents an application of the theoretical prediction to solve the practical problem.

***Keywords**: auxetic structures, seat, utility load, contact problem*

STUDIUM PROJEKTOWE NAD AUKSETYCZNĄ STRUKTURĄ SZKIELETU SIEDZISKA

Artykuł przedstawia studium obliczeniowe elementów szkieletu siedziska wykonanych z elastomeru lub poliamidu poddanych typowym obciążeniom statycznym i dynamicznym od siedzenia. Auksetyczne własności struktury szkieletu siedziska powodują redukcję naprężeń kontaktowych między ciałem człowieka i siedziskiem, czyniąc je bardziej komfortowym w użytkowaniu. Obliczenia przeprowadzono programem ABAQUS metodą elementów skończonych. W wyniku otrzymano nieliniowe charakterystyki sprężyn siedziska. Studium obliczeniowe pozwala na wybór materiału i kształtu sprężyn spełniających warunki projektowe dotyczące wytrzymałości, podatności stabilności oraz optymalnej redukcji naprężeń kontaktowych. Praca prezentuje zastosowanie teoretycznych rezultatów do rozwiązań stosowanych w praktyce.

***Słowa kluczowe**: struktury auksetyczne, siedzisko, obciążenie użytkowe, zagadnienie kontaktu*

1. INTRODUCTION

Furniture design for comfort becomes very important in new product development. The subjective feeling of sitting comfort can be described by objective mechanical parameters. Contact stress distribution is taken as a measure of comfort. Two kinds of stresses represent contact interaction between human body and seat: normal, which reflects the load pattern, and tangent, which affects contact area. Subjective personal sensation of comfort depends on average pressure, maximum pressure, the size and symmetry of the contact area as reported by Ebe and Griffin (2001), Zhao, Xia and Wu (1994), Park and Kim (1997).

It is known from mechanical considerations that in contact with medium exhibiting negative Poisson's ratio the type of contact, and stress distributions are significantly affected, while the chances for reducing stress concentrations are generally increased (Scalia 2000). This is illustrated on examples given by Szefer and Kędzior (2002). Negative Poisson's ratio materials are called auxetics, due to the fact that they expand in perpendicular direction, when subject to tensile load. The structure of auxetics and the reason of such behaviour were investigated and described by Lakes (1993), Stavroulakis (2005). Auxetics also reveal untypical mechanical properties, such as high deformability in elastic range and unusual ratios of elastic constants (Janus-Michalska 2009; Lakes 1993; Stavroulakis 2005).

Negative Poisson's ratio materials, particularly foams have found use as antibedsore mattress covers Wang Y., Lakes (2002), due to the reduction of contact stresses.

Cellular materials with various microstructures constitute a special kind of elastic media. Examples of auxetic cellulars and application of their properties are widely given in literature (Lakes 1993; Stavroulakis 2005). The type of microstructure defines kind of symmetry and elastic constants. Thus, the auxecity in selected directions and required magnitude of Poisson's ratio may be tailored according to designer demands. Elastic behaviour and elastic constants obtained for various combinations of internal structure geometric parameters are described in paper by Janus-Michalska (2009). The analysis is based on material properties of the solid phase and topological arrangement of cellular structure.

The theoretical problem of material design for anisotropic elastic cellular bodies with respect to contact problem is presented by Jasińska and Janus-Michalska (2008 and developed in 2010). Special attention is paid to materials exhibiting anisotropic properties, especially to materials having re-entrant structure, which yield negative Poisson's ratio in a certain range of directions. Proper choice of microstructural geometrical parameters can determine expected elastic properties. These properties and orientation of material symmetry axis with respect to load direction significantly influence contact stress distribution and may play an important role in reducing peak contact pressure.

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Seat design is an example of application of the features mentioned above. The development of a new, more comfortable seat is the goal of structural modeling. A new design can be tested against offered degree of comfort by computer simulations using models of the human and the seat (Smardzewski *et al.* 2000).

In this work, the idea of auxecity is adopted from cellular materials to cellular macrostructures, which exhibit global auxetic effect. It is expected that auxetic seat structures should offer improved sitting comfort .

Three-dimensional real contact and stiffness problems of small size auxetic springs constituting a part of elastic seat cushion are considered. The analysis is performed using FEM. Calculations are performed to simulate the contact between seat structure and utility load represented by indenter. The model provides insight into deformation modes and changes in stress field due to variations of geometric and material parameters of seat structure.

The study of various structures allows for a selection of such one that also fulfills design constraints concerning stresses in structural members and global deformation. It optimises the seat skeleton shape to improve ergonomic quality.

2. STRUCTURAL MODELLING OF AUXETIC STRUCTURES

The examples of auxetic structures are based on skeleton topology, forming concave polygons called 'reentrant' structures, which are responsible for negative Poisson's ratio effect. This behaviour originates from particular structural characteristics on the cellular level that give rise to the unfolding of basic structural elements upon stretching and folding back in upon compression.

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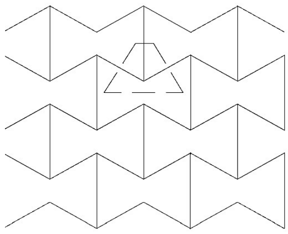

Fig. 1. Segment of infinite auxetic structure

However, while ordered structures are convenient to analyse macroscopic deformations in response to external forces, there is currently very little understanding on the modelling of deformations in non repetitive structures.

Auxetics have been identified among smart materials having significant technological potential.

3. SEAT DESIGN REQUIREMENTS

The seat must resist static and dynamic loads acting upon it and conditions of use. It is assumed here that the seat structure ceases to be able to carry out functions, for which it is designed when a limit state occurs. The following two states are considered: ultimate limit stress state and serviceability limit state.

The first one is that reduced von Mises stress at each point of the structure fulfills the condition (1) for each static and dynamic load:

$$\sigma^M \leq f_d \tag{1}$$

where:

f_d – limit stress value,
$f_d = k \cdot R_m$, R_m – rupture modulus for elastic brittle material model,
$k = 0.5$ – safety factor.

Additionally this limit state encompasses stability requirements for compressed members. For structures considered in this work this means that for symmetric structure loaded by uniform pressure the deformation mode should also be symmetric.

The serviceability limit state concerns deformation. For seat the vertical deflection should not exceed 40% of its height and horizontal displacements – 4% of its width and depth.

The ratio of displacements results in approximate value of Poisson's ratio between $-0.1 \leq \nu_{XY} \leq 0$.

Additionally comfort condition is reccomended. It means that contact stresses are limited by the value of 4,265 kPa given by Smardzewski *et al.* (2000) and Park *et al.* (1998). This is limit value of pressure closing lights vascular.

4. MATERIALS

Two kinds of materials are considered: PA6 polyamide and elastomer. Two types of polyamide and three types of elastomer are used to give a variety of elastic moduli and limit stresses. Material properties for the elastic brittle material have been set as given in Table 1.

Table 1

Material	Young's modulus	Rupture modulus R_m	ρ
Polyamide a PA6	1800 MPa	45 MPa	1.13 g/cm^3
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Elastomer c (FIBRO)	133 MPa	59 MPa	1.11 g/cm^3

5. STUDY OBJECTIVES

The primary objective of this study is to propose the optimum geometry and material for seat skeleton. It's elastic elements can be treated as auxetic springs in the direction perpendicular to loading. The examples of spring geometry are given in Figure 2.

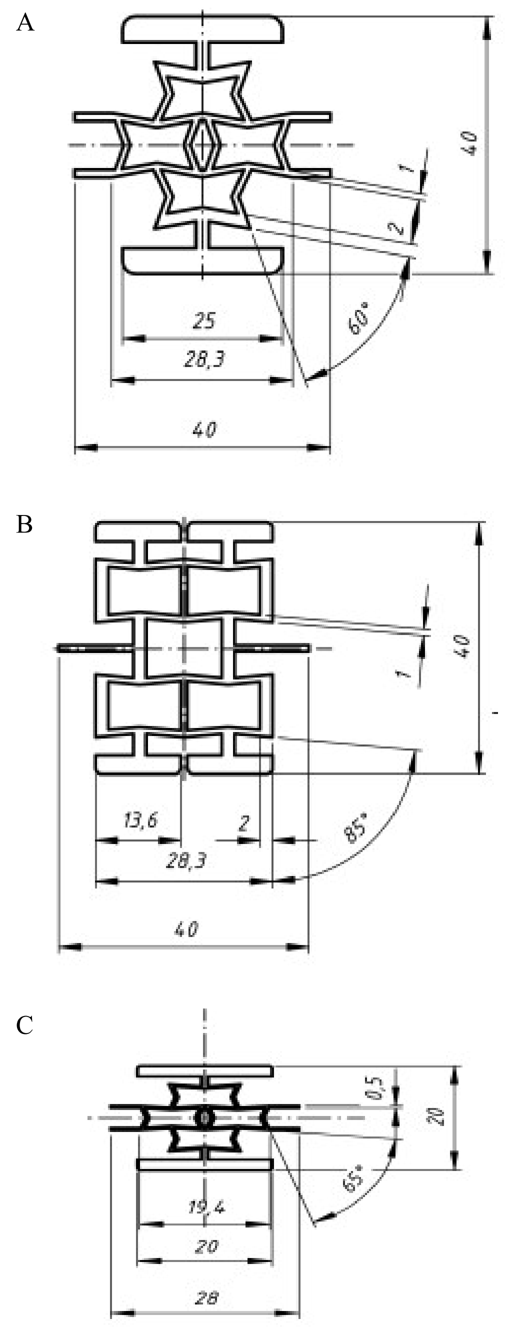
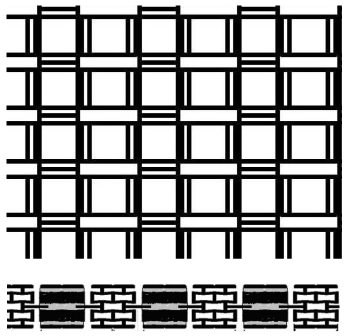


Fig. 2. The structures of seat skeleton springs analyzed in this study A, B, C

Arrangement of seat structure is to be auxetic in two perpendicular directions. This is because the skeleton itself constitutes a complex three-dimensional structure. In this study, the following three-dimensional structural representation of seat was proposed, consisting of auxetic members as shown in Figure 3.



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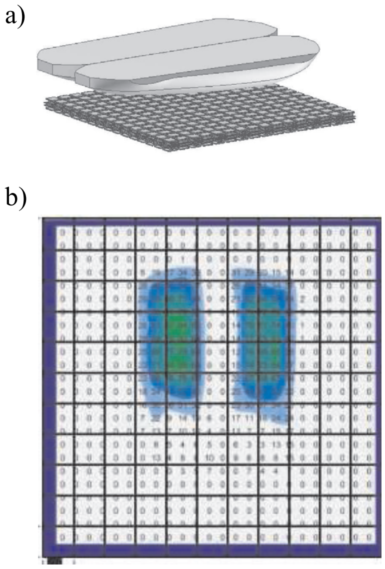


Fig. 4. Intender simulating human buttocks (a), pressure load distribution (b)

The average pressure simulated by stiff intender (Fig. 4b.) loaded by typical weight of human body is 0.02 106 N/m^2 and maximum pressure is 0.072 106 N/m^2 (Verver *et al.* 2004)).

It is recommended for the average pressure to deliver a vertical displacement of 20%–30% of spring height, for maximum pressure vertical displacement should not exceed 40% of spring height.

Dynamic load corresponds to the fall of 76 kg body from the height of 600 mm.

6. SCOPE OF THE STUDY

Numerical analysis to determine the nonlinear load displacement path for static loading and stiffness characteristics for dynamic loading are reported in this paper. There are two factors that contribute to the nonlinearity of this system:

- large displacements typical for geometric nonline-arity.
- contact of spring elements.

Stress maps are reported as well. Strength of given structures for static and dynamic loads is verified by reduced Mises stress maps.

7. NUMERICAL ANALYSIS

Two sample structures are selected to illustrate numerical predictions. Springs A, B, C are tested for all given types of materials. Calculations are performed using ABAQUS system.

Discretization: The model comprises of 2 layers of 8-node hexahedron (brick) elements.

A linear isotropic material model has been used to describe the skeleton material properties.

At first each spring subject to static load is analyzed to choose the best material.

Load -deflection paths for spring A are illustrated in Figure 5a. Four materials do not fulfill design recommendations concerning deflection and the spring is to stiff as result. For elastomer a. the path is typical for loss of stability, and the deflection mode is illustrated in Figure 5b. This leads to the conclusion that the spring geometry (sensitive to instability) is unacceptable for proposed materials.

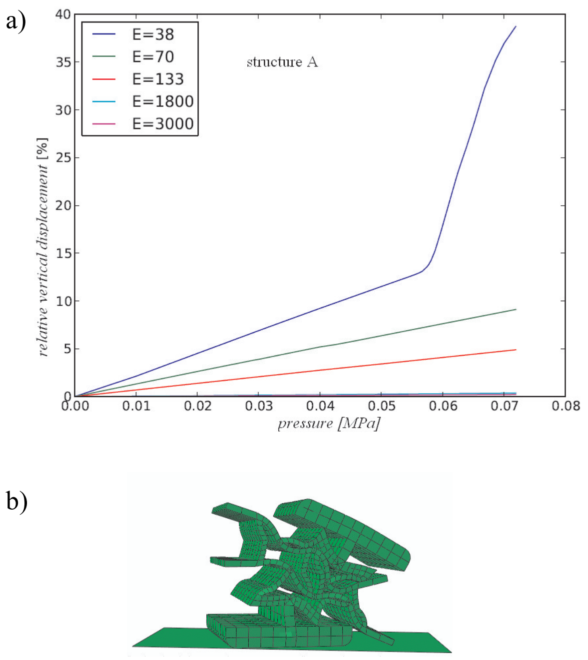


Fig. 5. Load – deflection paths for spring A made of proposed five materials (a), deformation mode for loss of spring stability (b)

The analysis of spring B yields reasonable paths for elastomers, (for polyamide the springs are to stiff). For elastomer c the spring fulfills design reccomendations and load deflection paths show that for loads ranging in between average and maximum the spring structure becomes stiffer (due to contact between spring elements), this is an advantage for such a structure.

For this selected material the reduced von Mises stress map is given in Figure 6b. Poisson's ratio for this structure is about –0.1. 3D arrangement satisfies the required condition $-0.1 \le \nu_{XY} \le 0$. The exact value depends on the type of arrangement and is good for designing comfort condition.

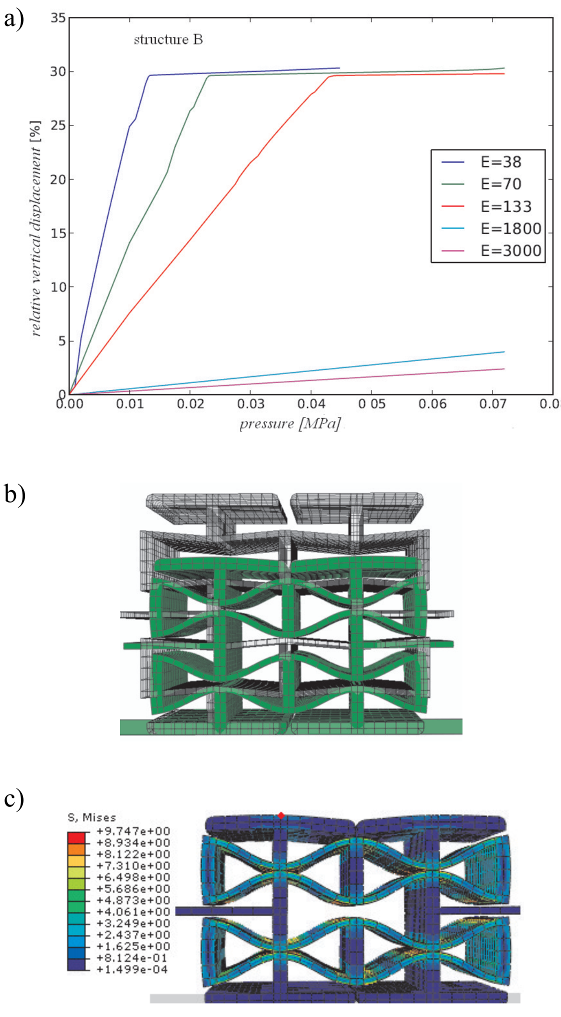
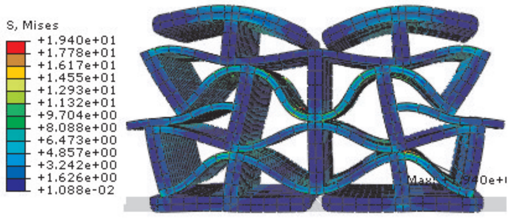


Fig. 6. Load – deflection paths for spring B made of proposed five materials (a), deformation mode (b), Mises stress distribution (c) for spring B, material: elastomer c

Dynamic analysis is carried out based on the assumption that the load is applied instantaneously and is equivalent to 76 kg mass falling off the height of 600 mm. Such assumption is on the safe side as the estimated stresses are higher than the stresses determined for the real loading speed. Dynamic simulation is carried out using the ABAQUS implicit software. For dynamic analysis stress condition is essential.

The results of calculations are illustrated on the example of B structure made of polymer material exhibiting $E = 133$ MPa (Fig. 7).



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Structure C is analysed for three materials. The results are presented in Figure 8.

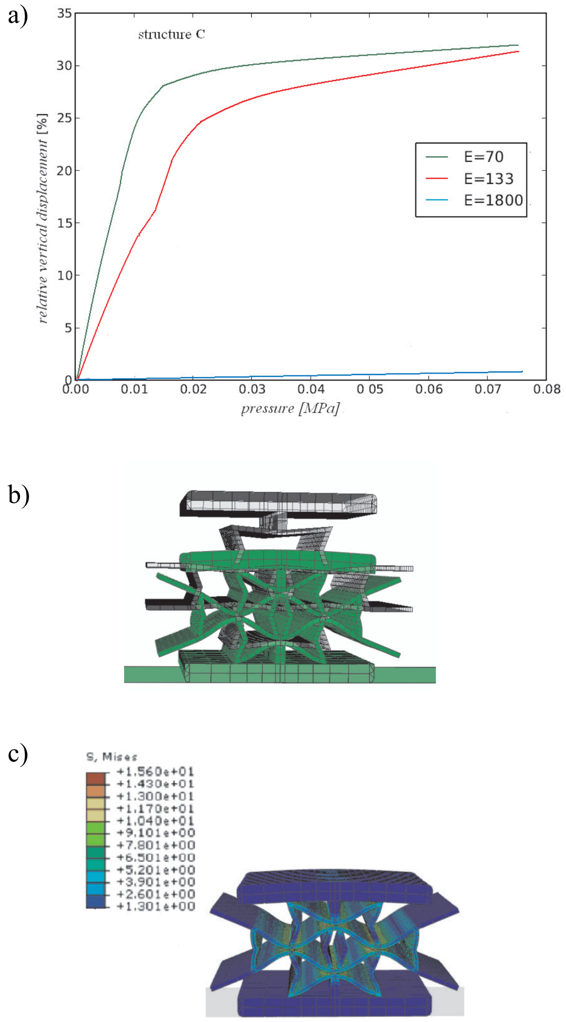

Fig. 8. Load – deflection paths for spring C made of proposed materials (a), deformation mode (b), von Mises stress distribution (c) for spring C, material: elastomer c

The analysis of spring C yields reasonable paths for elastomers, (for polyamide the springs are to stiff). For elastomers b and c the spring satisfies design reccomendations.

8. CONCLUSIONS

Parametric study shows that selection of structural geometry is crucial for stable seat work.

Properly selected stiffness of elastic material, characterized by Young modulus, may support satisfaction of load-deflection reccommendations. Auxetic type of structure gives Poisson's ratio required for predictions of contact stress peak reduction. Numerical predictions follow the anthropotechnical design trend of furniture for seating. New seat structure type development may be supported by computer simulation and optimisation.

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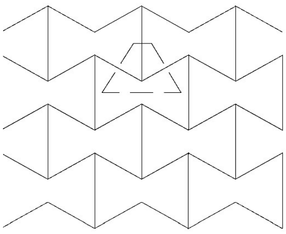

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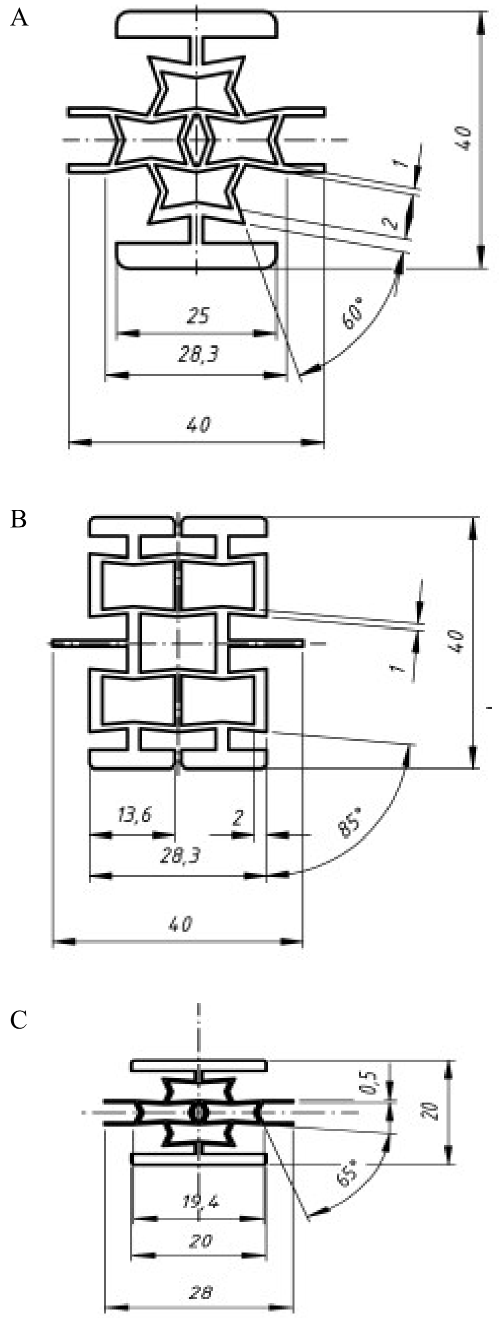

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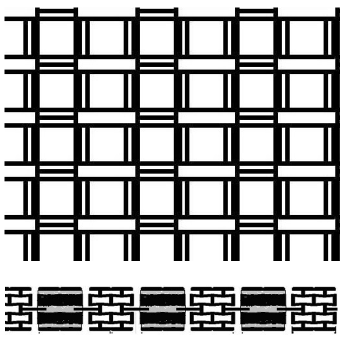

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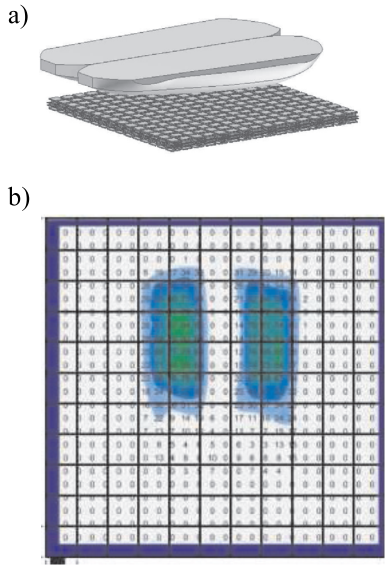

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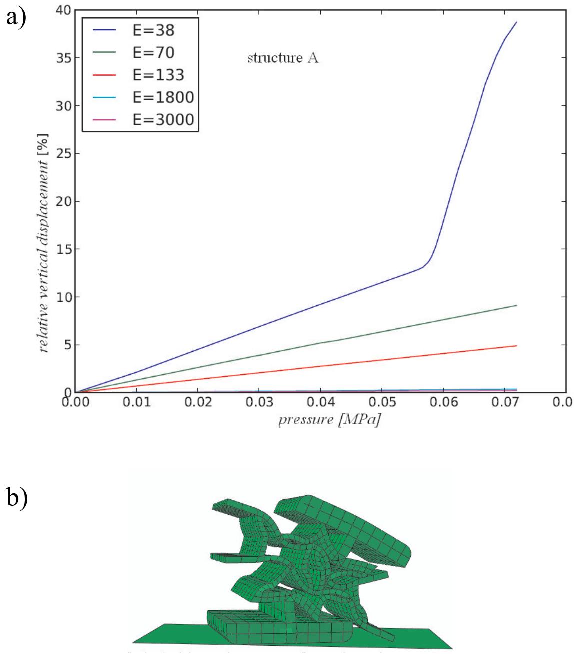

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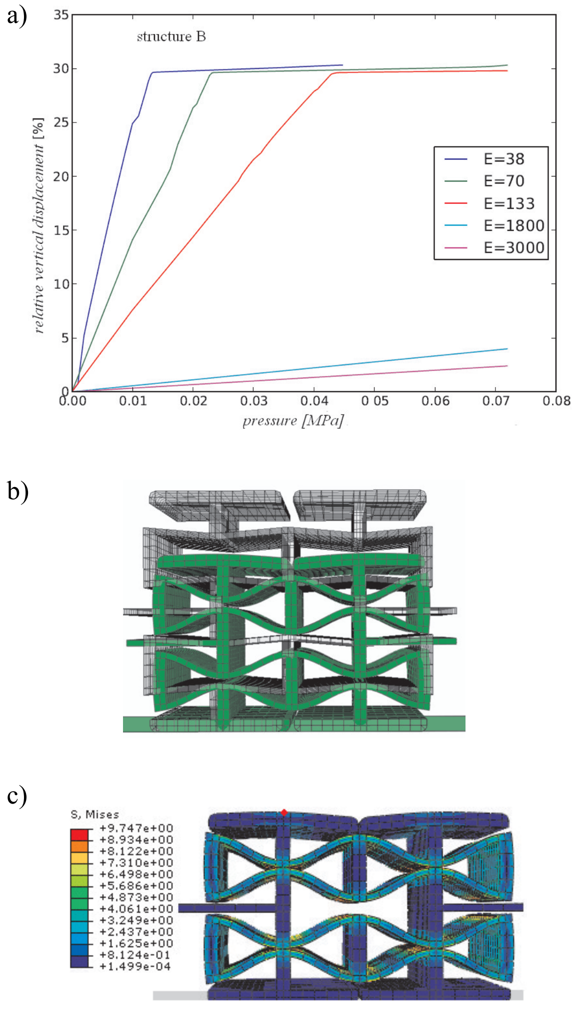

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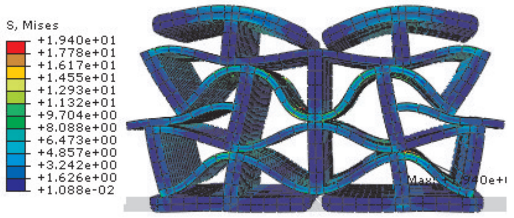
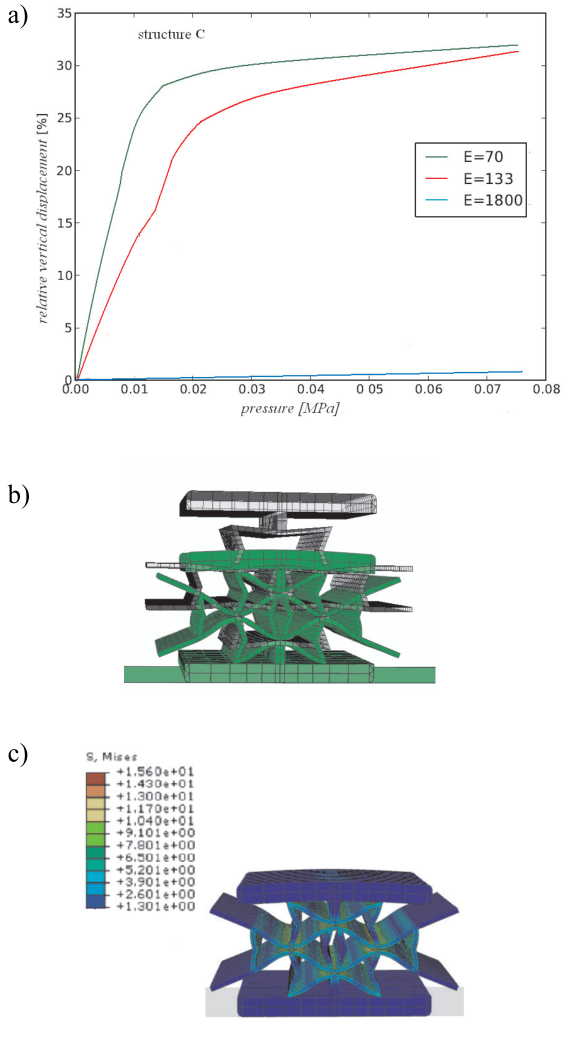


Fig. 7. Maximum stress distribution in deformed structure

Structure C is analysed for three materials. The results are presented in Figure 8.



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Parametric study shows that selection of structural geometry is crucial for stable seat work.

Properly selected stiffness of elastic material, characterized by Young modulus, may support satisfaction of load-deflection reccommendations. Auxetic type of structure gives Poisson's ratio required for predictions of contact stress peak reduction. Numerical predictions follow the anthropotechnical design trend of furniture for seating. New seat structure type development may be supported by computer simulation and optimisation.

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