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## A COMFORT COMPARISON OF A FOAM SEAT AGAINST A SEAT WITH AN AUXETIC SPRING SKELETON

### PORÓWNANIE KOMFORTU SIEDZISKA FOTEŁA PIANKOWEGO I SIEDZISKA O SZKIELECIE AUKSETYCZNYM

#### Abstract

This paper presents a comfort analysis of two different office chair types. The first is made of foam and the second is comprised of auxetic springs with foam upholstery. Several steps of quasi-static loads are chosen for comfort analysis in order to assess the dependence of measures of comfort on the mechanical properties of the applied structural solutions. Numerical analysis is performed by means of ABAQUS software – this allows the comparison and selection of optimal structures with respect to comfort requirements.

*Keywords: seat structure, FEM modelling, comfort analysis*

#### Streszczenie

W artykule przedstawiono analizę komfortu dwóch siedzisk foteli biurowych o różnych konstrukcjach. Pierwsze siedzisko jest typowym piankowym, drugie jest konstrukcją złożoną ze szkieletu o połączonym układzie sprężyn poliamidowych pokrytych pianką wyścielającą. Analizę komfortu i jego zmienności przeprowadzono dla kilku stadiów obciążenia kwazistatycznego, co pozwoliło na określenie jakościowych zależności między własnościami mechanicznymi zastosowanych strukturalnych rozwiązań a miarami komfortu. Zamodelowano struktury siedziska fotela biurowego za pomocą MES w środowisku ABAQUS. Analiza wyników pozwala oszacować przydatność zastosowanych rozwiązań konstrukcyjnych pod względem spełnienia warunków projektowych komfortu użytkownika.

*Słowa kluczowe: siedzisko fotela, analiza komfortu, modelowanie MES*

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## 1. Introduction

A variety of materials with differing mechanical properties are used nowadays for designing composite structures in order to achieve special requirements. Existing solutions are replaced with new ideas which can be easily verified through numerical prototypes, which can be created whilst avoiding the cost of experiments on real structures. Innovative solutions are based on designers' engineering intuition.

One of the new smart materials which can introduce untypical mechanical properties is negative Poisson's ratio material (NPR material). The term 'auxetics' relates to negative Poisson's ratio materials due to the fact that they expand in a perpendicular direction when subjected to a tensile load. Auxetic materials are of particular interest due to their counterintuitive behaviour and improved properties such as enhanced strength, fracture toughness, energy absorption and indentation resistance [1, 2]. Auxetic materials can be used for a wide range of applications: auxetic fibers, threads, technical textiles, fasteners, shock absorbers, sound absorbers, curved body parts for the aerospace industry, wing panels, protection materials for the construction of crash helmet, protective clothing, car bumpers and also furniture. Different types of auxetic materials include auxetic bio-materials, auxetic foams, auxetic honeycombs, auxetic microporous polymers, auxetic structures and auxetic composites. On a macro scale, we can use NPR structures to obtain effects similar to micro-mechanical effects. Auxetics change contact pressure distribution and can be useful for reducing peak contact pressure. The behaviour of NPR materials has been examined in the context of the contact problem before the idea of its application in the design of office seats [5]. Literature on the application of auxetic skeleton structures in office chairs has been written by Smardzewski, Jasińska, Janus-Michalska [6–9]. Negative Poisson ratio materials have been also investigated with regard to quasi-static and dynamic indentation compliances [2, 3], and also to indentation resilience [2]. It has been shown that indentation and impact compliances are significantly affected when Poisson's ratio of the material assumes negative values [2]. Indentation resilience of auxetic materials are strongly strain dependent according to a study presented by Alderson et al [2]. It was found that the auxetic material was more difficult to indent than the other materials at low loads.

Seating comfort is an important factor used to distinguish competitive products in the furniture industry. The literature attempting to correlate seat comfort with interface mechanical measures is not extensive. Some indications of optimal seat modelling for achieving seating comfort are described by Verver et al [15]. The relationship of comfort with interface pressure is described by Looze [10]. Experimental investigation of the interaction between driver and seat and numerical analyses of pressure distribution have been carried out by Montmayeur et al. and Xiaoming et al [16]. Attempts at identifying relationships between seat pressure and comfort were described by Oudenhuijzen [11]. For furniture seats, as opposed to car seats, similar analyses were carried out by Smardzewski J., Prekrat S. [12], Smardzewski et al. Jasińska et al. [13].

This paper presents a numerical study of pressure distribution with respect to comfort for two different seat structures. The first is a typical structure made of foam and the second is comprised of auxetic springs with foam upholstery. These examples have been previously studied in the context of the application of auxetic elastic media to the contact problem [9].

The current study is devoted to comfort analysis. Comfort requirement is not only important for the maximal load for which the structure is designed, but also for intermediate stages. The study concerns quasi-static loading or loads not reaching the maximal value. The designed seats should be comfortable for users with a wide range of weight and duration of sitting. Several steps of quasi-static loads are chosen for comfort analysis in order to assess the dependence of measures of comfort on the mechanical properties of the applied structural solutions. Clear differences are identified between the foam seat and the seat with an auxetic skeleton with respect to comfort.

## 2. Mechanical measure of comfort

Stress distribution induced by load is complex due to the occurrence of non-uniform pressure, pinch shear and horizontal shear stress. Shear stresses of both kinds cause discomfort. To measure discomfort caused by nonuniformity of contact pressure, the seat pressure distribution coefficient SPD is defined as follows [13]:

$$SPD = \frac{\sum_{i=1}^n (p_i - p_m)^2}{4n p_m^2} \cdot 100\%. \quad (1)$$

where:

- $p_i$  – contact stress in point  $i$ ,
- $p_m$  – mean contact stress for  $n$  points,
- $n$  – number of points of registered or calculated contact pressure.

The latest mechanical measure of sitting discomfort based on the analysis of contact stress and verified experimentally was proposed in work by Smardzewski et al [13]. It is defined as scalar  $D$  given according to the following formula:

$$D = \frac{p_m}{A} \cdot SPD \quad (2)$$

where:

- $A$  – contact area

In the ideal situation, the uniform distribution of contact stress SPD coefficient equals zero and the seat is at its most comfortable on the condition that the mean contact pressure is not higher than the critical value. A near uniform pressure distribution also reduces shear. To reduce discomfort, it is recommended to make contact surfaces with a low friction coefficient. The contact area should be as maximal as possible.

## 3. Two types of seat structures

A foam seat and a seat with an auxetic skeleton are considered in this study. The first seat (seat  $A$ ) is of a typical design and is made of components described in Fig. 1. A cross-section of the seat is presented in the figure.

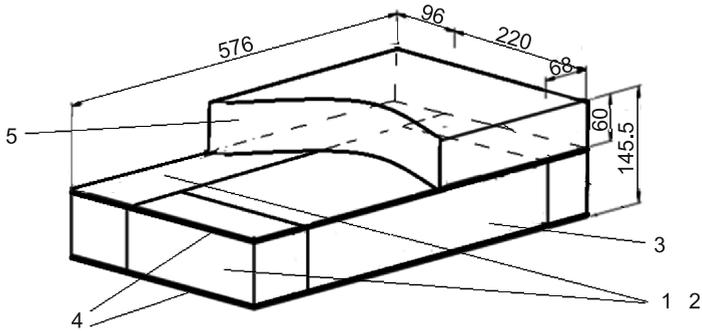


Fig. 1. Cross-section of the foam seat (seat A). Seat components: 1, 2 – frames, 3 – foam filling, 4 – upper and bottom layers of felt, 5 – seat upholstery (dimensions [mm])

The main load bearing section of the second seat is a set of springs arranged as a skeleton spatial framed structure. For the purpose of contact stress distribution, the skeleton is chosen as it is a structure with an auxetic. The shape of the auxetic spring is shown in Fig. 2.

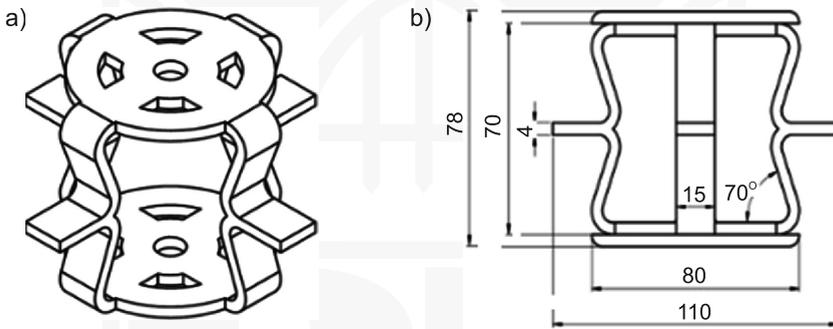


Fig. 2. Auxetic spring: a) spring shape, b) spring (dimensions [mm])

The components of the seat with the skeleton (seat B) are shown in Fig. 3.

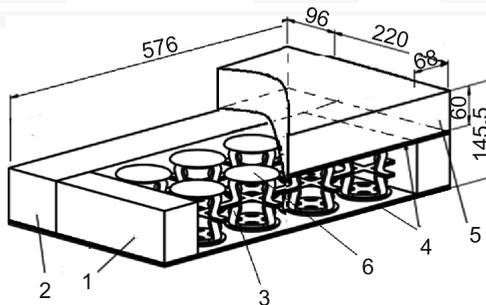


Fig. 3. Seat structure (seat B): 1, 2 – seat frame; 3 – spring, 4 – felt, 5 – foam upholstery, 6 – cover of spring (dimensions [mm])

#### 4. Mechanical properties of seats' structural components

The chosen materials for both seats have properties as described in Table 1.

Table 1

**Mechanical properties of the materials of the seats' structural elements**

Structural element	Material	Elastic properties
Foam filling (seat A)	Foam T3037	Nonlinear characteristic Fig. 4
Spring (seat B)	Silicon Shore's 75	Mooney-Rivlin hyper-elastic model $E = 9.32$ MPa, $K_0 = 77.7$ MPa, $C_{10} = 1.05$ , $C_{01} = 0.30$
spring cover (seat B)	Rubber Shore's 95	Mooney Rivlin hyper-elastic model $E = 21.80$ MPa, $K_0 = 18.16$ MPa, $C_{10} = 16.91$ , $C_{01} = 55.35$
Seat frame	Foam T3546	Nonlinear characteristic Fig. 4
Seat upholstery	Foam T3037	Nonlinear characteristic Fig. 4
Aligning layer	Felt	Linear elastic $E = 2.58$ kPa, $\nu = 0.3$

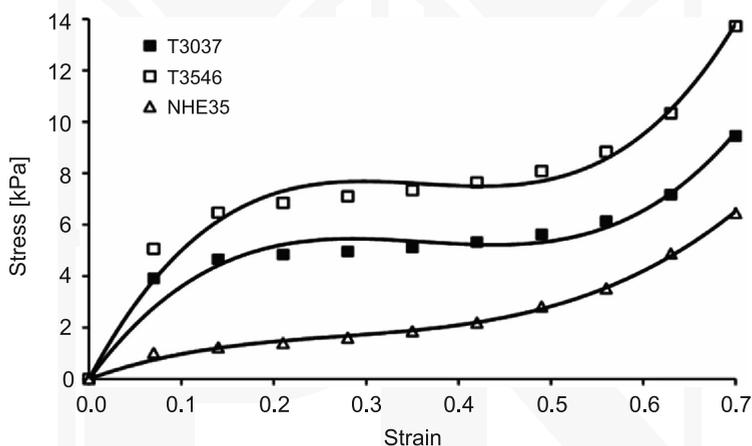


Fig. 4. Seat foam and seat upholstery foam characteristics obtained from experiment

Foam stiffness has been established in compression test according to standard PN-EN ISO 3386-1:2000/A1:2010E [17].

Spring elements are modelled as hyper-elastic materials with strain energy given by formula (3):

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{K_0}{2}(J_{el} - 1)^2 \quad (3)$$

where:

- $C_{10}$ ,  $C_{01}$ ,  $K_0$  – material parameters for silicon [9, 13],
- $I_1$ ,  $I_2$ ,  $J_{el}$  – deviatoric strain first and second invariant and elastic volume ratio.

The human body is modelled by timber oak indenter used in experiments [13]. The elastic material data are:  $E = 12 \text{ GPa}$ ,  $\nu = 0.3$ .

## 5. Numerical simulation and finite element model

Numerical simulation of the indentation test is carried out by means of ABAQUS FEA [19]. A static incremental load was applied to the rigid indenter up to a load of 790 N representing the weight of a human body. A nonlinear analysis involving material and geometric nonlinearity with the contact problem is performed. As a result of the analysis, seat characteristics and maps of contact stress distribution in subsequent stages are obtained. This allows for the calculation of discomfort coefficient. For this purpose, author FORTRAN codes were developed.

The described spatial models are imported into the ABAQUS FE analysis software package. Due to symmetry, it was only necessary to analyse half of the structure. The following discretisation was applied:

Seat type *A*:

56000 8-node linear brick elements with reduced integration, modelling aligning foam and frame foam, 2400 3-node triangular facet rigid elements for model of indenter.

Seat type *B*:

spring skeleton – 94000 10-node quadratic tetrahedron elements, frame and aligning foam – 82200 8-node linear brick elements, felt – 5100 4-node quadrilateral membrane elements, indenter– 2400 3-node triangular facet rigid elements,

Boundary conditions:

elements stuck together: frame parts, frame and felt, spring and disc, parts of seat frame.

Contact conditions:

contact of the indenter with the seat is frictionless.

## 6. Results

The stiffness characteristics of the two analysed structures are shown in Fig. 6. The structures are chosen in such a way that load – displacement curves are very similar. It allows comparing the discomfort of seats with similar indentation resistance.

For both seats, comfort analysis is carried out in the chosen four stages with loads of the following values: 200 N, 400 N, 600 N, 790 N.

The author's program in Fortran code is applied to calculate the following comfort parameters: mean contact stress, contact area, seat pressure distribution coefficient and discomfort coefficient.

Maps of normal stresses in subsequent stages of quasi-static load for the foam seat and for the auxetic seat are shown in Fig. 6. and 7. Comfort parameters are given below the maps of stresses.

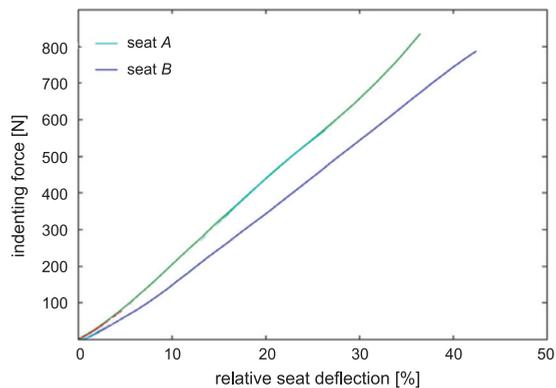


Fig. 5. Seat stiffness characteristics

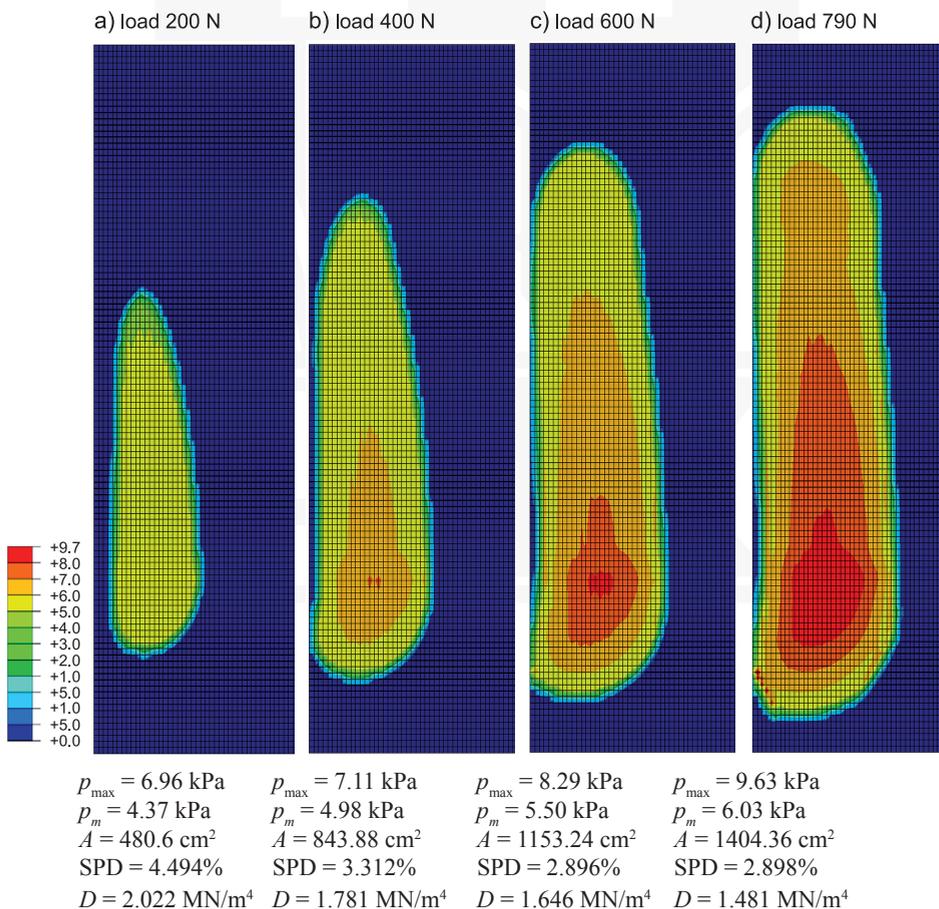


Fig. 6. Contact pressure maps for foam seat [kPa] and comfort parameters

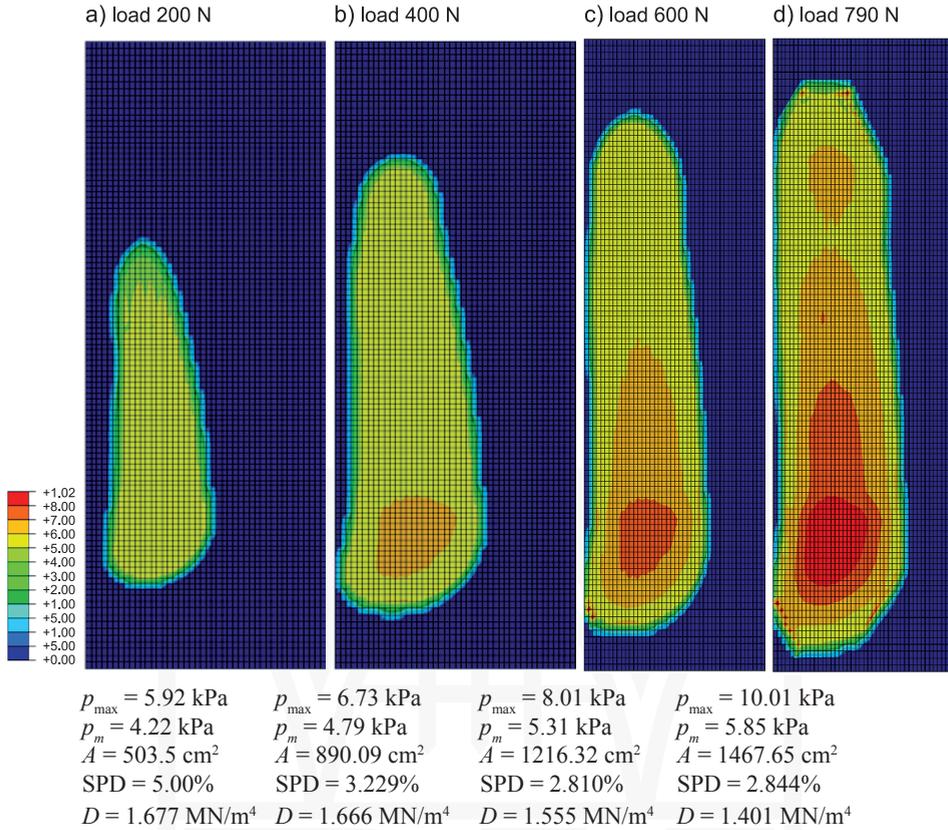


Fig. 7. Contact pressure maps for auxetic seat [kPa] and comfort parameters

A detailed analysis of all maps of normal stresses and comfort parameters leads to the general observation that the auxetic seat provides similar levels of comfort across the full range of loads. For all stages, the difference between  $p_{\max}$  and  $p_m$  is smaller than for the foam seat – this means that the distribution of contact stress is more uniform. Moreover contact area for auxetic seat is greater. Both of these two factors increase the comfort of the auxetic seat and as a result, make it more comfortable than the foam seat. Auxeticity has an influence on indentation resistance, so we expect comfort dependence on the negative of Poisson's ratio of applied auxetic materials or structures.

The foam seat becomes more comfortable with greater loads. Since majority of usual materials have a similar positive Poisson's ratio, smaller comfort properties are expected in the first stages of loading.

## 7. Conclusions

Quasi-static contact problems involving the interaction of the human body with the seat structure is of significant practical interest because of the need to consider comfort in the design of seats.

On the basis of the conducted calculations and the determination of the discomfort coefficient, the following conclusions can be made:

- auxetic structures can be more comfortable across the full range of load, especially in the first stages of loading,
- a software based prototype proposed to simulate pressure distribution on the seat is a tool which allows tracing the comfort properties of the final product,
- the model can be improved by changing structural elements,
- the auxetic skeleton presents a novel solution which can be applied in the construction of comfortable seats.

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