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Research of Contact Stresses between Seat Cushion and Human Body

Istraživanje kontaktnih naprezanja između ojastučenja sjedala i korisnikova tijela

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ABSTRACT • *Design optimization of seat cushions is associated with the need to investigate their softness using, for this purpose, various kinds of loading pads. The aim of the investigation was: to determine seat cushion stiffness of a chair selected from a set of dining-room furniture, to determine values and distributions of contact strains on the seat surface caused by loading pad of different hardness, numerical calculation of contact strains between the seat cushion and the loading pad and to verify the results of these calculations with the results of laboratory experiments. The performed tests showed that the assessment of the seat cushion stiffness and the evaluation of contact stresses on their surface should be carried out using an equally stiff loading pad. In numerical calculations, polyurethane foams should be modeled as hyperfoam bodies of* $\sigma=f(\varepsilon)$ *characteristics determined in an axial compression test. Contact stresses between the seat cushion and the user's body should be reduced as a result of application of a frictionless connection of thin layers of polyurethane foams with foam forming the proper elastic layer of the seat.*

Keywords: *seat cushion, human body, contact stresses, numerical analysis*

SAŽETAK • *Optimizacija konstrukcije ojastučenja sjedala povezana je s potrebom istraživanja krutosti s gledišta različitih vrsta podložaka. Svrha opisanog istraživanja bila je odrediti krutost ojastučenja sjedala izabranoga iz asortimana namještaja za objedovanje, odrediti vrijednosti i raspodjelu deformacija površine ojastučenja sjedala s obzirom na podloške različite tvrdoće, numerički izračunati kontaktna naprezanja – deformacije između ojastučenja sjedala i podloška, te provjeriti rezultate dobivene laboratorijskim ispitivanjem. Provedena ispitivanja pokazuju da postizanje krutosti ojastučenja i procjena kontaktnih naprezanja na površini trebaju biti obavljeni korištenjem podložaka istovrsne tvrdoće. U numeričkom proračunu poliuretanske pjene trebaju biti modelirane kao potpuno upjenjena tijela kojima je čvrstoća funkcija naprezanja određena u aksijalnome kompresijskom testu* $\sigma=f(\varepsilon)$*. Kontaktna naprezanja između ojastučenja sjedala i korisnikova tijela trebala bi biti smanjena zbog primjene spojeva koji ne uzrokuju trenje između tankih slojeva poliuretanske pjene i pjene koja tvori odgovarajući elastični sloj sjedala.*

Ključne riječi: *ojastučenje sjedala, ljudsko tijelo, kontaktno naprezanje, numerička analiza*

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1 INTRODUCTION
1. UVOD

Scientific development in the field of analysis of the sitting position and adjusting furniture to the user's physiological features began with Staffel's (1884) statement that "chairs are almost exclusively designed for the eye, for their beautiful form rather than for the back". These investigations showed that factors affecting sitting comfort included: the value of contact stresses between the seat cushion and the user's body, stresses inside soft tissues, period of utilization of a given piece of furniture, anatomic construction of the user's body, size and gender of the user, temperature of the body and seat, predisposition to secrete and absorb sweat, air circulation as well as the way of sitting (Carison, 1995; Defloor and Grypdonck, 1999; Dzięgielewski and Smardzewski, 1995; Gefen, 2005; Guzik, 2001; Kapica, 1993; Kapica and Smardzewski, 2001; Kernozek, 2002; Kokate *et al*, 1995; Krutul, 2004; Linder-Ganz and Gefen, 2004; McCormick, 1957; Nachemson, 1976; Nowak, 1993; Slavikova, 1988; Smardzewski *et al*, 2006; Smardzewski and Wiaderek, 2006; Smardzewski, 2008; Stępowski, 1973; Stinson, 2003; Wang and Lakes, 2002).

Furthermore, the above studies clearly show that compression forces caused by maintaining the sitting position should not lead to constrained circulation in the surface cardiovascular system. Each pressure exceeding 32 mm/Hg may result in closing the vein and next the artery lumen slowing down or even stopping blood circulation leading to localized ischaemia (Krutul, 2004; Stinson, 2003).

The value of stresses between the user and the seat cushion increases proportionally to the user's body weight and is closely related with the stiffness of the used materials. For these reasons, attempts have been made, so far unsuccessful, to find materials with properties similar to the stiffness of the human soft tissue (Smardzewski *et al*, 2006; Linder-Ganz and Gefen, 2004; Wang and Lasek, 2002). That is why more research is necessary to find new ways of optimizing design and certification of anthropo-technical systems such as furniture for sitting.

It is evident from the performed review of the current state of knowledge in the area of cushion modeling of furniture for sitting that so far research has been focussed on: the determination of anthropometric properties of individual Polish and European group populations, determination of elastic properties of the soft tissues of the human body, gels and porous polyurethane foams, property modeling of hyper-elastic bodies and systems made up of traditional cylinder or conical springs as well as modeling of contact phenomena between two hyper-elastic bodies. In addition, basic research is also being conducted in the field of property modeling of auxetic materials and ways of their practical application.

However, in literature on the subject, there is a lack of research results in the area of interactions between: ecology, ergonomics, anthropometry, construction, technology, functionality, mechanics, biomechanics, strength and durability of furniture utilization important for an impeccable design. There is also a lack of research on design optimization of seat cushions, including reasons for testing seat softness, using for this purpose loading pads of various stiffness. It is not quite clear whether the widespread use of hard loading pads instead of soft ones modeled to the shape and anatomically resembling parts of human body is methodologically justified.

The objective of investigations was: to determine seat cushion stiffness of a chair selected from a set of dining-room furniture, to determine values and distributions of contact strains on the seat cushion surface caused by loading pad of different hardness, numerical calculation of contact strains between the seat cushion and the loading pad and to verify the results of these calculations with the results of laboratory experiments.

2 MATERIAL AND METHODS
2. MATERIJALI I METODE

The object of experiments was a chair from a set of dining-room furniture. The seat measuring 400 mm x 400 mm was made of several materials forming four layers, Figure 1. The base layer was a 16 mm particleboard onto which 40 mm thick T4060 polyurethane foam was glued. The seat was covered with upholstery fabric lined with nonwoven fabric in order to ensure minimum friction with the polyurethane foam and desired visual effect.

The seat was loaded using a loading pad with a shape and dimensions corresponding to the appropriate standard (PN-EN 1728:2000). The hard loading pad was made of oak wood, Figure 2a, whereas the soft loading pad was prepared by covering the hard one with 30 mm thick T4060 polyurethane foam, Figure 2b. Bearing in mind the need to represent the contact phenomenon between the two parts, the foam was not glued to wood and, additionally, the chair seat was loaded with a volunteer student, 183 cm tall and weighing 74 kg, corresponding to male anthropometric traits of 50 % of European population.

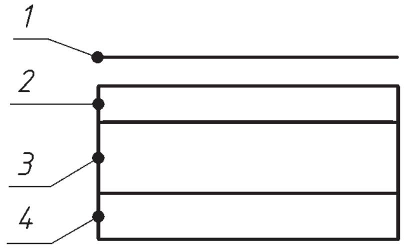


Figure 1 Structure of the seat used in experiments: 1) upholstery fabric (1.5 mm thick), 2) cotton wool 120 g/m^2, 3) T4060 polyurethane foam (40 mm thick), 4) particleboard (16 mm thick)
Slika 1. Konstrukcija (prikaz slojeva) sjedala korištenoga u eksperimentu 1 – tkanina debljine 1,5 mm, 2 – pamučna vuna gustoće 120 g/m^2, 3 – T4060 poliuretanska pjena debljine 40 mm, 4 – iverica debljine 16 mm

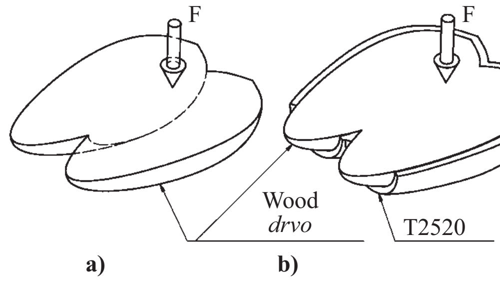


Figure 2 Construction of the sensor used in investigations: a) hard, b) soft with 30 mm thick T4060 polyurethane foam
Slika 2. Konstrukcija podloška upotrijebljena u istraživanju: a) tvrdi, b) meki, obložen s 30 mm debelom T4060 poliuretanskom pjenom

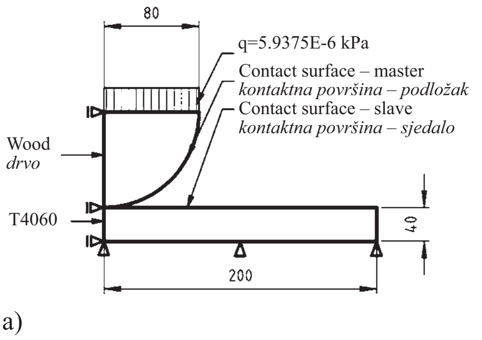
Laboratory experiments were carried out on three different research stands. The first experiment of seat cushion stiffness using a hard loading pad was performed on a special testing machine developed for furniture certification, Figure 3a. As recommended by PN-EN 1728:2000, PN-EN 1729-2:2006 standards, the pressure was exerted with a F force of 1300 N. Consecutive experiments were carried out on the ZWICK 1445 testing machine using both hard and soft loading pads pressed into the seat with the maximum force of 760 N, Figure 3b. The final laboratory test consisted in loading the seat with a volunteer exerting the force of 740 N, Figure 3c. In order to measure contact stresses between the sensor/volunteer and the seat cushion, an FSA sensor mat was used consisting of 32 x 32 sensors arranged in the form of a 900 x 900 mm sheet. The mat guaranteed measurements of stresses in the 0-200 mmHg interval with 3% accuracy. Results of these measurements were collected and collated in the form of a diagram and maps of stress distribution. The seat cushion stiffness was determined on the basis of the measurement results of values of F loads and their corresponding dL displacements illustrating the dependencies on the *F=f (dL)* chart.

Numerical calculations of the contact between the loading pad as the model of a human body and the seat cushion were carried out in the ABAQUS system environment using the finite element method (FEM) algorithm. Three and four-nodal envelope elements in flat state of stress were used for modeling. All component elements of the model were 400 mm thick corresponding to the length of the loading pad and the seat. Calculations were carried out for two static schemes. The first scheme corresponded to driving in the hard loading pad into the T4060 foam with the force of 760 N, Figure 4a. The second scheme represented forcing in the soft loading pad with the same force into the identical foam, Figure 4b. Bearing in mind the seat, loading pad and load symmetry, the calculation model was reduced to the symmetrical, right half of the system. The model was supported in a way that ensured freedom of the vertical play of the loading pad which was loaded with a pressure q of $5.9375 \cdot 10^{-6}$ kPa value corresponding to the force of 760 N. When modeling the contact between two bodies, it was assumed that in the case of the model with the hard loading pad the 'master' and 'slave' type surfaces would occur, respectively, on the surfaces of the loading pad and the T4060 foam, Figure 4a. For the model with the soft loading pad, two pairs of surface were formed. The first pair of the 'master' and 'slave' type surfaces occurred between the hard loading pad and the T2520 foam, while the second pair of surfaces, between the T2530 and T4060 foams, Figure 4b.

When preparing the developed model for numerical calculations, it was necessary to determine elastic properties of the applied materials. The wooden part of the loading pad was assigned elastic properties of oak wood as an isotropic material of the Young modulus of E=15 GPa and Poisson coefficient of 0.3. Polyurethane foams belong to hyper-elastic materials (Smardzewski, 2008; Smardzewski *et al*, 2008) and some of them can even be considered auxetic materials (Leaks, 1986, 1991, 1992, 1993, 1996). That is why their elastic properties were determined in a single axis compression test (Smardzewski, 2008), Figure 5. The obtained characteristics in the form of a dataset $\sigma = f(\varepsilon)$ were fed into the ABAQUS system using a hyperfoam type model for these bodies.

a) b) c)

Figure 3 Stands for seat cushion stiffness tests and contact pressures on their surface: a) a special testing machine developed for furniture certification, b) ZWICK 1445 testing machine, c) volunteer weighing 74 kg
Slika 3. Uzorci za testiranje krutosti sjedala i kontaktnog tlaka na površini: a) specijalni uređaj razvijen za ispitivanje namještaja prema normama, b) ZWICK 1445 uređaj za testiranje, c) ispitanik mase 74 kg



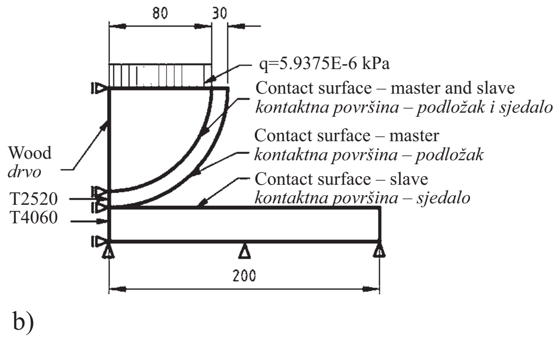
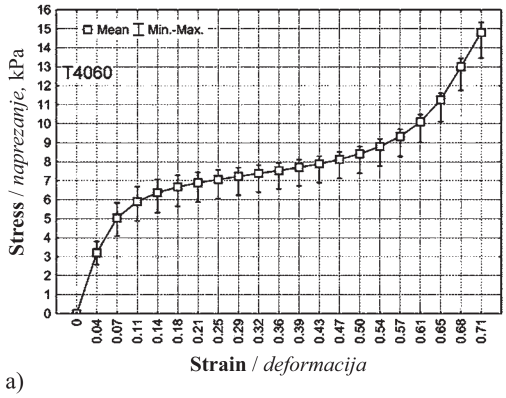


Figure 4 Static load model of the chair seat cushion by: a) hard sensor, b) soft sensor
Slika 4. Model statičkog opterećenja ojastučenog sjedala stolice a) tvrdim podloškom b) mekim podloškom



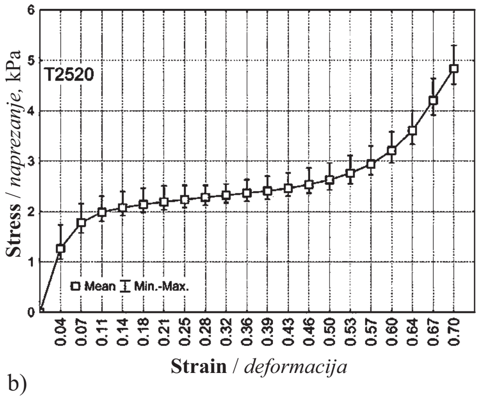


Figure 5 Polyurethane foam stiffness: a) T4060 foam used on the chair seat, b) T2530 foam used as the loading pad cover
Slika 5. Krutost poliuretanske pjene: a) T4060 pjena upotrijebljena za sjedalo stolice, b) T2530 pjena upotrijebljena kao obloga podloška

3 RESULTS
3. REZULTATI

The stiffness of the seat cushion loaded with two types of sensors is presented in Figure 6. It is clear from this Figure that the use of the hard loading pad caused a significantly smaller foam deflection than when the soft loading pad was applied. For example, for the same load of 400 N, the difference in the recorded seat deflection amounted to 20 mm. This can be attributed to the superposition of T2530 and T4060 foams which formed a serial system of elastic materials whose resultant stiffness was smaller than the component stiffnesses.

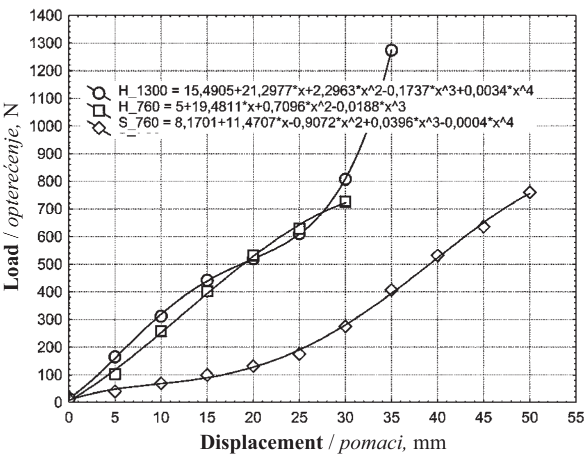


Figure 6 Seat cushion stiffness: H_1300 – hard loading pad loading up to 1300 N, H_760 – hard sensor, loading up to 760 N, S_760 - soft loading pad loading up to 760 N
Slika 6. Krutost ojastučenja sjedala: H_1300 – tvrdi podložak, opterećenje silom do 1300 N, H_760 – tvdi podložak, opterećenje silom do 760 N; S_760 – meki podložak, opterećenje silom do 760 N

Expressing seat cushion stiffness by $k= dF/dL$ quotient, seat stiffness can be calculated on the basis of Figure 6. When the hard loading pad was applied, the mean value of the seat cushion stiffness coefficient k reached 26.6 N/mm, whereas when the soft loading pad was used the stiffness coefficient of the same seat cushion ranged from 6.66 N/mm to 18.40 N/mm. Hence, objective seat cushion stiffness assessment should be carried out exclusively using loading pad of identical hardness.

The impact of loading pad hardness on the distribution of stresses on the seat cushion surface is well illustrated in Figure 7. Using a hard loading pad driven into the seat with the force of 1300 N, the greatest contact surface was achieved as well as the highest stresses reaching values of 120-130 mmHg, Figure 7a. When the value of the pressure force was reduced and the same hard sensor was used, values of contact stresses were reduced proportionally to value changes of the load, Figure 7b. In this case, contact stresses did not exceed 51 mmHg. Additionally, it should be emphasized that chair seats are considered ergonomic and functional when the pressures exerted on the human body do not exceed 32 mmHg. From this viewpoint, the examined seat cushion was too stiff and did not guarantee sufficient level of comfort during long hours of meetin-

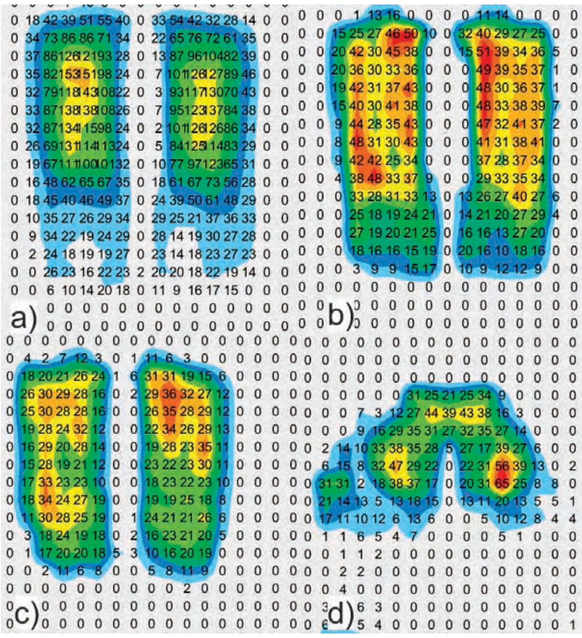


Figure 7 Pressure distribution on the seat cushion surface in mmHg caused by: a) hard loading pad at the load of 1300 N, b) hard loading pad at the load of 760 N, c) soft loading pad at the load of 760 N, d) a volunteer of 74 kg weight

Slika 7. Raspodjela tlaka na površinu sjedala u mmHg prouzročena: a) tvrdim podloškom pri sili od 1300 N, b) tvrdim podloškom pri sili od 760 N, c) mekim podloškom pri 760 N, d) tijelom ispitanika mase 74 kg

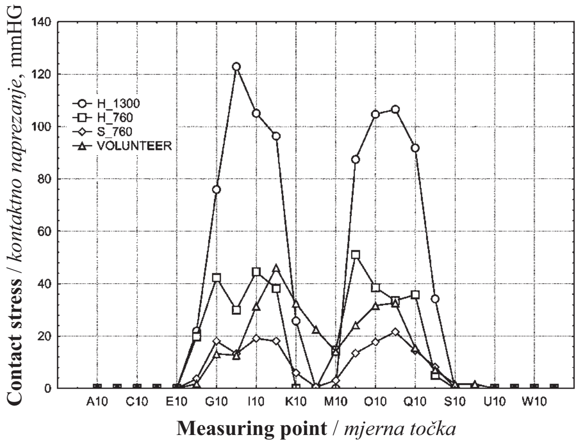


Figure 8 Pressures in selected points of the sensor mat (fourth row from top)

Slika 8. Tlak prikazan u odabranim točkama prostirke (četvrti red odozgo)

gs, talks and meals. However, when the kind of sensor was changed to soft driven into the seat cushion with the force of 760 N, the value of the obtained contact pressure was 36 mmHg, Figure 7c. Loading of the same seat by a volunteer weighing 74 kg resulted in the distribution of contact pressures different from those obtained using loading pad, Figure 7d. Pressure values were also different with their upper value not exceeding 47 mmHg in the place where the sciatic tubers were supported.

In order to better illustrate differences in the distribution of pressures on the seat surface caused by different loading pad as well as by the volunteer, Figure 8 shows the course of pressures in the same, fourth from the top, row of loading pad running along the width of the mat. It is clear from this Figure that the value of contact stresses is significantly dependent on the loading pad hardness. Nevertheless, making the construction of the soft loading pad similar to the structure of the human body failed to guarantee similar stress values. On the other hand, similar stresses were obtained in the case of application of the loading pad with the pressure of 760 N. It can be stated, on the basis of the performed experiments, that the hard loading pad better represents working conditions of the seat cushion under operating load and makes it possible to better assess the stiffness and functionality of the examined chairs.

From the viewpoint of design of furniture for sitting and/or resting, it would be exceptionally advantageous to be able to carry out virtual quality assessment of seats at the stage of their designing or modeling in the CAD system environment. Creating block models, it is relatively easy to subject them to numerical calculations that can verify: construction stiffness as well as the strength of cross sections and connections.

Figure 9 presents distribution of reduced stresses according to Mises caused by loads with the hard and soft loading pad driven into the T4060 foams.

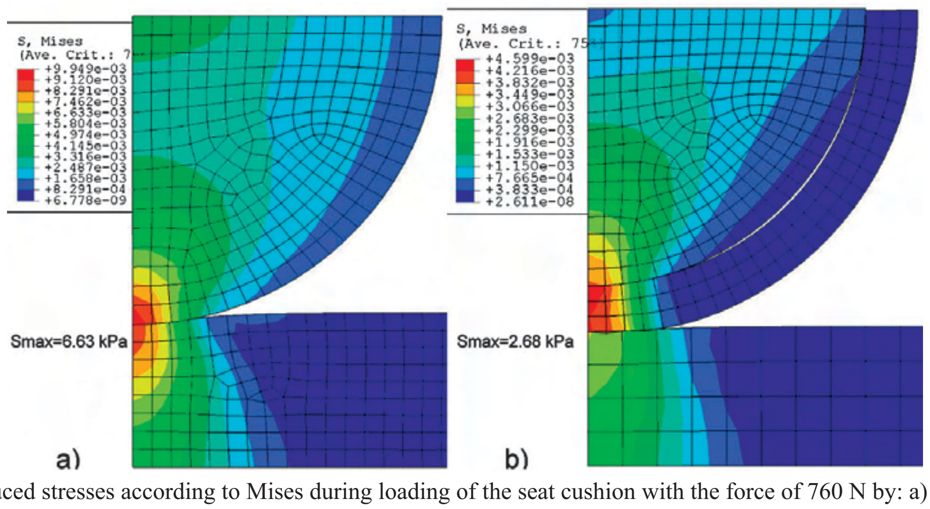


Figure 9 Reduced stresses according to Mises during loading of the seat cushion with the force of 760 N by: a) hard loading pad, b) soft loading pad

Slika 9. Smanjenje naprezanja prema Misesu tijekom trajanja opterećenja na ojastučenje sjedala silom od 760 N i upotrebom: a) tvrdog podloška, b) mekog podloška

Table 1 Contact stresses on the seat surface caused by loading pads of different hardness
Tablica 1. Kontaktna naprezanja na ojastučenje sjedala prouzročena podlošcima različite tvrdoće

Loading pad type *Tip podloška*	**Designation** *Oznaka*	**Contact stress, kPa (mmHg)** *Kontaktno naprezanje, kPa (mmHg)*	
		Sensors mat / *Senzorska prostirka*	Numerical calculations / *Brojčani izračun*
Hard / *tvrdi*	H_1300	13.99 (105)	14.49 (108.7)
Hard / *tvrdi*	H_760	5.99 (45)	6.63 (49.74)
Soft / *meki*	S_760	2.66 (20)	2.68 (20.11)
Volunteer / *ispitanik*	Volunteer / *ispitanik*	4.79 (36)	(-)

It is evident from Figure 9 that the application of an additional layer of soft T2520 polyurethane foam in the construction of the loading pad caused a significant reduction of pressure on the surface of the T4060 foam, Figure 9b. In such situation, the strongest stresses were concentrated in the central layer causing simultaneously maximum stresses of 2.68 kPa on the surface of the seat. In the case of a uniform hard loading pad, contact stresses on the seat surface amounted to 6.63 kPa. The obtained results of numerical calculations were compared with the results of measurements taken using a sensor mat and they are collated in Table 1.

On the basis of this comparison, tt is possible to demonstrate that the results of the performed numerical calculations differ from measurement results in the range of 0.74% to 9.65% and always reach values higher than those obtained in the laboratory. The accuracy of the obtained results was achieved both thanks to the quality of the elaborated numerical model, the quality of the introduced data about material characteristics as well as the calibration error of the sensor mat and standard measurement inaccuracies resulting from technical properties of the sensor mat. However, it should be emphasized that the accuracy is satisfactory and justifies the use of numerical methods for anthropo-technical design and modeling of furniture for work, meal consumption and rest.

4 CONCLUSION
4. ZAKLJUČAK

The following conclusions were drawn on the basis of the analysis of the obtained research results:

1. Seat cushion stiffness assessment should be carried out using the identical loading pads of stiffness selected by the investigator.
2. Contact pressure distribution assessment on the seat cushion surface should be carried out with the assistance of a hard loading pad.
3. In the course of numerical calculations polyurethane foams should be modeled as hyperfoam bodies of $\sigma = f(\varepsilon)$ characteristics determined during the axis compression test.
4. Contact stresses between the seat cushion and the user's body should be decreased as a result of application of a frictionless combination of thin layers of polyurethane foams with foams forming the proper elastic layer of the seat.

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