Auxetic structures in layered furniture panels

Smardzewski, Jerzy*[1]; Prekrat, Silvana[2]
[1] Department of Furniture Design, Faculty of Wood Technology,
Poznan University of Life Sciences, Poznan, Poland
[2] Wood Technology Department, Faculty of Forestry,
University of Zagreb, Zagreb, Croatia
*Corresponding author: jsmardzewski@up.poznan.pl

ABSTRACT

Light honeycomb panels with auxetic cores have found numerous applications in the production of vehicles, boats and aircrafts. There are no such solutions in the furniture industry. It has been proposed to use several new structures of auxetic cores to construct sandwich furniture panels. The purpose of the study was to determine the strength and stiffness of furniture panels with auxetic cores. The Young and Kirchhoff elasticity modules of these panels were determined in the bending and torsion tests. The bending strength and stress distribution in individual layers was also described. The applicability of new wood-based composites in the furniture sector was assessed.

Key words: Auxetic, Core, FEM, Furniture panel, Wood base composite

1. INTRODUCTION

Rational raw material use manifested in the increased utilisation of light materials may ensure economical management of natural resources and reduced greenhouse gas emissions (Feifel *et al.,* 2013). Another important justification for the use of lighter materials is connected with attempts to reduce production costs aiming at increased profitability. For the end user the benefits will always include lower prices, lower weight of the product and easy transport to the intended location. Wood as well as commonly used wood-based materials are used thanks to the efficient utilisation of their capacity to transfer axial, bending and torsional loads. Other reasons for the selection of these materials are connected with their common availability, sustainability, processability, esthetic value and an advantageous weight-to-strength ratio (Nordvik and Broman, 2005; Keenan *et al.,* 2015; Ozyhar *et al.,* 2012). These are the primary reasons why wood and the above-mentioned wood-based materials are commonly used in furniture design. Layered wood-based boards are characterised by highly satisfactory values of Young's modulus and the modulus of elasticity in shear, technologically advantageous isotropy or orthotropy as well as low density (Petras, 1998; Barboutis and Vassiliou, 2005; Smardzewski, 2015; Smardzewski *et al.,* 2017). In this respect layered honeycomb panels prove to be attractive materials. Low weight is their greatest advantage (Librescu and Hause, 2000; Shalbafan *et al.,* 2012), particularly in the manufacture of light furniture for elderly users, disabled users and children (Barboutis and Vassiliou, 2005; Smardzewski *et al.,* 2013; Domljan *et al.,* 2015; Smardzewski, 2012). Essential elements of a sandwich board which determine their stiffness and strength are their facings. The core of the board affects its mass and apparent density. What is particularly interesting is the high strength quality of panels when referred to density (Smardzewski *et al*., 2014, 2015; Petras and Sutchiffe, 1999). In the case of cabinet furniture construction, designers seek light sandwich boards manufactured from wood, wood-based materials and paper, which may be recycled and upcycled. Horizontal shelves and partitions constitute particularly important structural elements of cabinet furniture. Due to their considerable loads, these elements are manufactured from thick fibre boards or MDFs, while thin, less than 25 mm thick sandwich boards with hexagonal cells are avoided. This is mainly associated with their low stiffness and strength (Smardzewski, 2013; Barbutis and Vassiliou, 2005). Experiments regarding these aspects carried out so far resulted in stiffness improvement of sandwich panels thanks to paper impregnation (Sam-Brew *et al.,* 2011), changes in cell dimensions of the core (Smardzewski and Majewski, 2014; Majewski and Smardzewski, 2013; Smardzewski and Prekrat, 2012; Meraghni *et al.,* 1999) and changes in the cell shape of the core (Smardzewski, 2013; Voth and Yamada, 2010). In the presented paper the authors decided to apply a solution consisting in the replacement of the paper core by a wavy structure made of wood fibres.

The aim of this study was to determine the strength and stiffness of furniture panels with auxetic cores. The Young and Kirchhoff elasticity modules of these panels were determined in the bending and torsion tests. The bending strength and stress distribution in individual layers was also described. The applicability of new wood-based composites in the furniture sector was assessed.

2. MATERIALS AND METHODS

2.1. Sandwich panels and cells

It was decided to test 3-layer panels manufactured from HDF and a paper core. Outer facings were made of HDF with thickness t_f = 2.5 mm. The core with thickness t_c = 13 mm were made from recycled paper. The layers were glued using the Folco® LIT D 1932-MOD adhesive. It is a PVAc adhesive with viscosity of 12000 mPas, pH = 3 and density of 1080 kg/m^3. The adhesive was applied onto the HDF surface at 120 g/m^2. The panels were pressed for 10 minutes at a temperature of 70 ˚C at the pressure of 0.4 MPa. After pressing the thickness of honeycomb panel samples was h = 18 mm. Sample dimensions are given in Fig. 1. Elastic properties of wood-based materials and paper are presented in Table 1 based on tests performed by Smardzewski *et al.,* 2017. In this case particleboard was the reference material for the testing results.

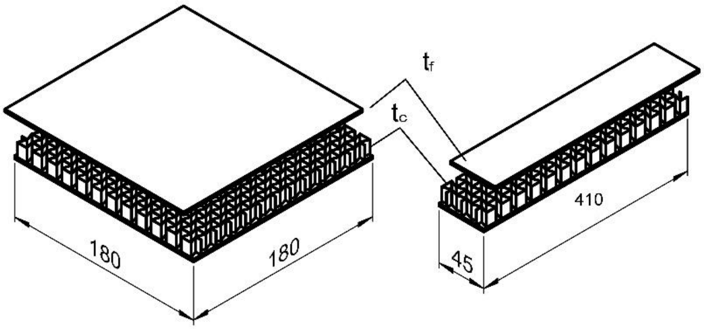

Figure 1. Samples used for testing: torsion and bending test, respectively

Honeycomb panel cores were mane from paper with the thickness t = 0.15 mm. Cell shape was selected to ensure auxetic properties and periodicity in the core structure. For this purpose each elementary core cell was inscribed into a cubicoid with the base dimensions of 15 mm x 15 mm and height of 13 mm. Such a solution made it possible to maintain a comparable specific density of individual cores and to assess the effect of cell shape on mechanical properties of layer boards. Figure 2 presents shapes and dimensions of core cells. Cell B has one axis of symmetry. Cells A and D have two axes of symmetry, while cell C has four axes of symmetry. These properties will have a significant effect on the rigidity of layer boards. In turn, Figure 3 presents relative density of individual cell types. The greatest density was recorded for cell type D (0.0484). Density of the other cells B, C and A is by 7.2%, 6.8% and 2.3% lower.

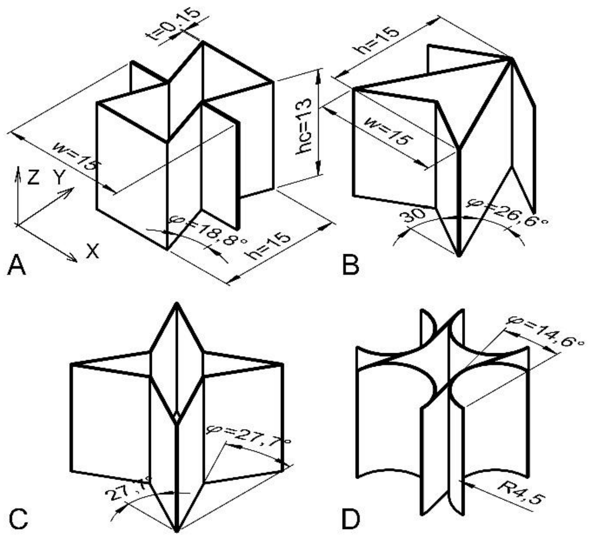

Figure 2. Samples of cells

Table 1. Mechanical properties of materials

Material	Unit	HDF	PB	Paper MD	Paper CD
Thickness	mm	2.5 / 0.02	18.1 / 0.03	0.15 / 0.02	
MC	%	5.6 / 0.23	6.5 / 0.13	4.5 / 0.06	
Density	kg/m^3	879 / 31.4	609 / 9.8		
Paper weight	g/m^2			85	
Tensile					
E_t	MPa	4111 / 102	1939 / 154	4666 / 961	1846 / 291
R_t		27 / 1.4	3.8 / 0.5		
υ		0.3	0.3	0.35 / 0.051	0.43 / 0.059
Bending					
E_b	MPa	5553 / 142	2815 / 226		
R_b		56 / 2.3	13.9 / 1.6		

(mean / Sd)

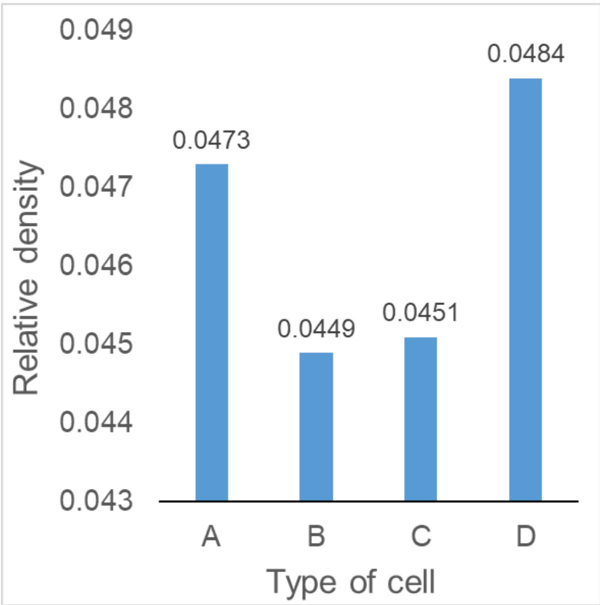

Figure 3. Relative density of cells

2.2. Test

It was decided to perform the tests according to the schemes presented in Fig. 4. During 3-point bending tests constant loading of F = 300 N was applied. For samples subjected to the torsion test loading with F = 150 N was applied. In this case numerical calculations were performed using the Abaqus v.6.16 programme (Dassault Systemes Simulia Corp., Waltham, Ma, USA) in the Poznań Supercomputing and Networking Centre in the Eagle cluster. Geometry of the mesh models is presented in Fig. 5. Elastic properties of modelled materials were described using data given in Table 1. In the model presenting bending, the thrust and support materials were ascribed properties of steel (E = $2*10^5$ MPa, υ = 0.3). Elastic properties of the glue line binding the facings with the core were determined based on literature data (Smardzewski, 2015) (E = 460 MPa, υ = 0.3). Facings were modelled using 8–node rectangular linear elements C3D8R. Cores were modelled using 10–node tetrahedral elements C3D8R. The glue line was described using the Cohesive element COH3D8 with the thickness of 0.1 mm. The surface-to-surface friction-free contact was applied between the thrust, supports and the bottom facing of the composite. In view of the symmetry of the system a half-beam with supports was modelled also applying ½ load value. Numerical calculations produced the maximum value of sample deflection f and reduced stresses according to Mises. Based on the f values the modulus of elasticity was calculated for the beam using the formula:

$$E = \frac{Fl^3}{4wh^3f} \tag{1}$$

where: F – external force, l=360 mm – support spacing, w=45 mm – sample width, h=18 mm – sample thickness, f – deflection calculated numerically. Models of samples subjected to torsion were prepared in an analogous manner as in the case of the bending test. Based on the numerically determined values of deflection f the shear modulus for the panel was calculated using the formula:

$$G = \frac{3Fl^2}{h^3f} \tag{2}$$

where: l=180 mm – support spacing.

A total of eight models were prepared for the purpose of numerical calculations. It was taken into consideration that cells A, B, C and D may be oriented with the Y axis parallel to the longer side of the sample providing models Ay, By, Cy and Dy, or they may be oriented with the X axis parallel to the longer side of the sample providing models Ax, Bx, Cx and Dx, respectively.

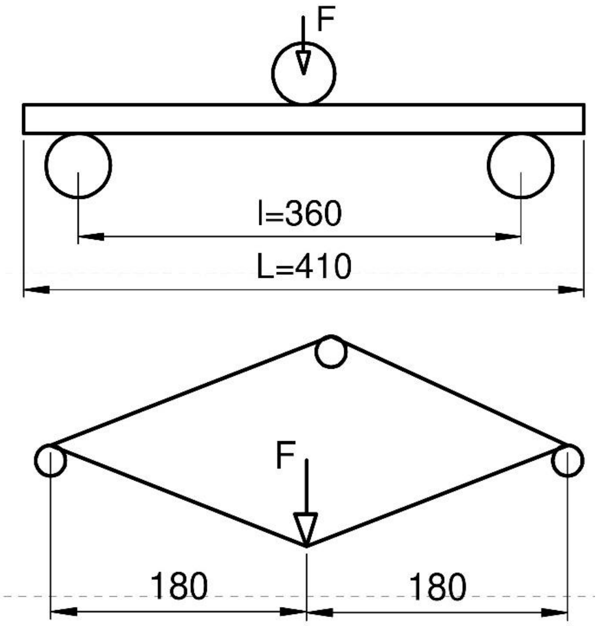

Figure 4. Diagrams of load

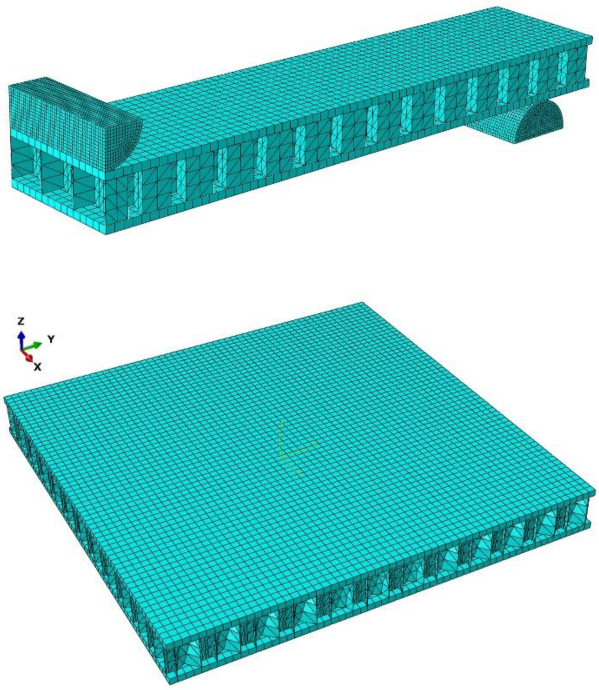

Figure 5. Meshed models

3. RESULTS

Figure 6 presents calculated values of the shear modulus, which were compared with the respective modulus of partcileboard. The shear modulus determines rigidity of furniture items under torsion. For this reason composites with a greater torsional rigidity will considerably increase rigidity of cabinet furniture. It results from Fig. 6 that among the designed layer boards with an auxetic core the highest value of modulus G was recorded for boards type D (523 MPa). Panels C, A and B are characterised by the shear modulus values lower by 56%, 142% and 198%, respectively. It also needs to be stressed here that modulus G of particleboard is 2-fold greater in comparison to the best of the designed honeycomb panels D.

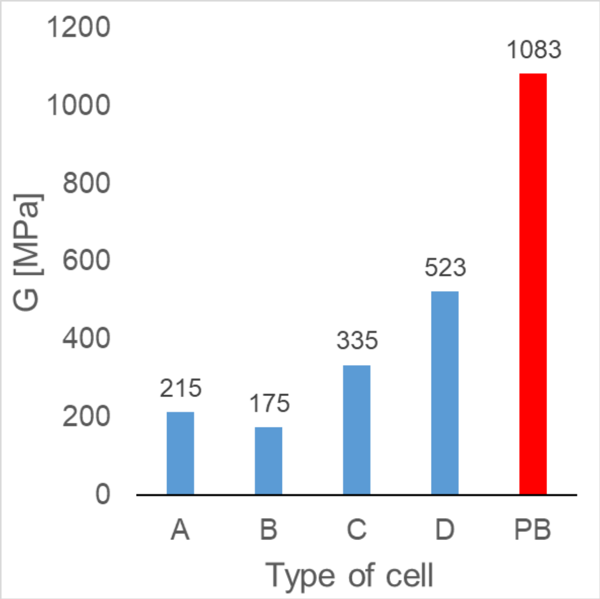

Figure 6. Shear modulus

Values of Young's modulus E for individual board types in the 3-point bending test follow a different trend. It results from Fig. 7 that cell C due to its four axes of symmetry guarantees isotropy of the layer composite and Young's modulus E = 2209 MPa. The other cells provide the boards with orthotropic properties. The highest value of Young's modulus was recorded for panel Dy (2264 MPa). In comparison to this composite the other panels Ax, Ay, Bx, By, Cx=Cy, Dx and Dy have values of modulus E lower by 24.6%, 3.2%, 2.4%, 3.4%, 2.3% and 7.2%, respectively. It is a general rule that boards with cells with a greater relative density (Fig. 1) ensure greater values of Young's modulus. The lowest rigidity was recorded for board Ax (1817 MPa) with cells A with the X axis oriented parallel to the longer axis of the sample. In comparison to the rigidity of the standard particleboard the modulus of elasticity for new layer composites is by 24.3% to 54.9% lower. We also need to stress here that honeycomb panels with auxetic cores have greater moduli of elasticity in comparison to an analogous honeycomb board with hexagonal core cells. For those panels, modulus E amounts to 1512 MPa (Smardzewski, 2013).

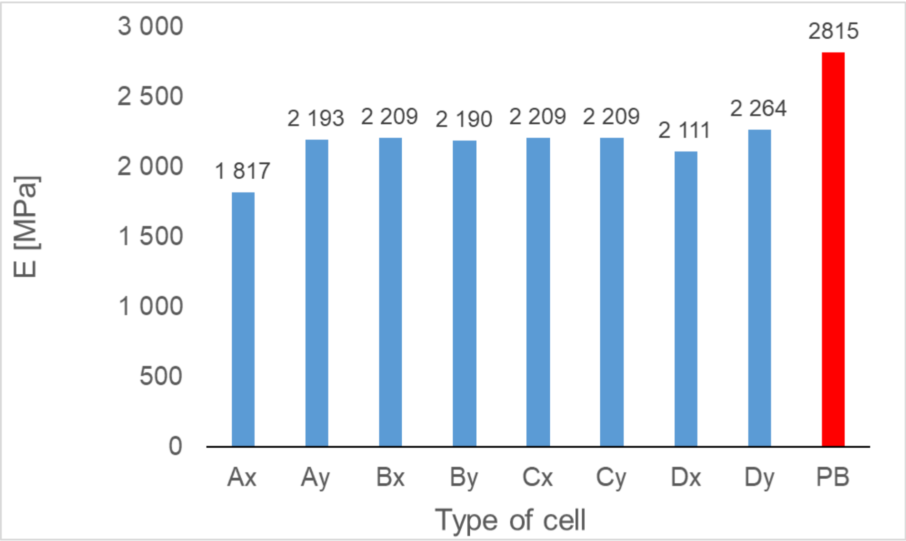

Figure 7. Linear modulus of elasticity

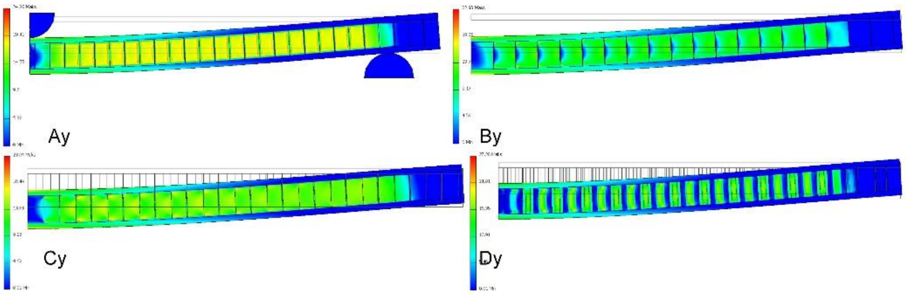

Figure 8. Von Mises stress distribution

Moreover, the distribution of von Mises reduced stresses was determined for panels Ay, By, Cy and Dy (Fig. 8). Values of maximum reduced stresses are presented in Fig. 9. Figure 8 shows that the greatest stresses accumulate in cell walls, causing their compression and shear. The greatest of these stresses is recorded in the core of panel Dy (27.26 MPa). These stresses exceed stresses in the other types of cells Ay, By and Cy by 12.3%, 18.8% and 18.3%, respectively. Also this regularity results from the effect of relative density of cells on panel rigidity.

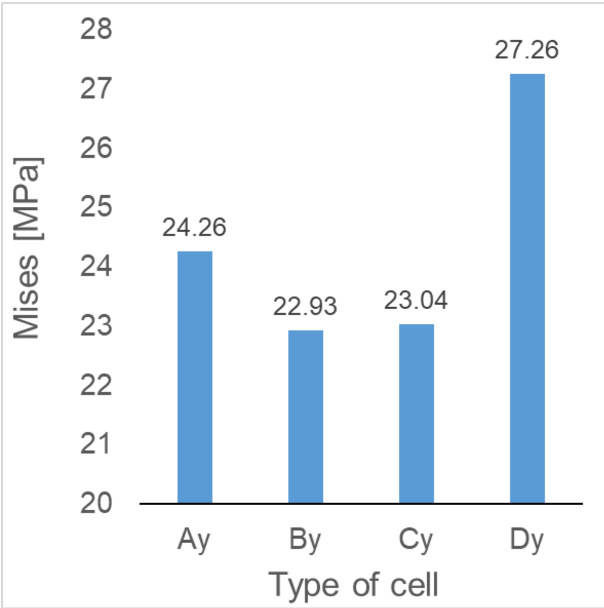

Figure 9. Von Mises stress

Thanks to the low relative density of cells and high values of Young's moduli we may observe advantageous, high values of Young's modulus of layer boards and relatively insufficient values of shear modulus. These properties of composites make it possible to design furniture elements subjected to bending, while they have an adverse effect on the rigidity of cabinets subjected to torsion. An advantage of designed cells is connected with their slight orthotropy. Only cells type Ax and Ay showed considerable differences in the rigidity of beams subjected to bending. Isotropic panels may thus have multiple applications in furniture design.

4. CONCLUSIONS

Based on the analysis of the results of numerical calculations the following conclusions were formulated:

1. Honeycomb boards with auxetic cores are an attractive alternative as a replacement of furniture panels when designing bent furniture elements.

2. Low values of the shear modulus are a constraint in the application of panels with auxetic cores when designing furniture elements subjected to torsion.
3. Most designed panels exhibit properties close to isotropic. This will have an advantageous effect on furniture design.
4. Relative density of cells has a significant effect on their mechanical strength.

Acknowledgements: The authors would like to gratefully acknowledge the National Science Centre (Poland) for financing the present work as part of the research project no. 2016/21/B/ST8/01016.

REFERENCES

Carll, C.; Wiedenhoeft, A.C. (2009): *Moisture-related properties of wood and the effects of moisture on wood and wood products.* Ser. J. Artic.

Barboutis, I. Vassiliou, V. (2005): *Strength Properties of Lightweight Paper Honeycomb Panels for The Furniture*. 10th Int. Sci. Conf. Eng. Des. (Interior Furnit. Des. (2005) 17–18.

Domljan, D.; Smardzewski, J.; Ratković, M.; Lisiecka, N. (2015): *Kindergarten Furniture in Poland and Croatia - User's Opinions, in: Implement.* Wood Sci. Woodwork. Sect. 26th Int. Conf. Wood Sci. Technol. Zagreb 16th Oct. 2015, pp. 67 – 75.

Feifel, S.; Poganietz, W.R.; Schebek, L. (2013): *The utilization of light weight boards for reducing air emissions by the German wood industry – a perspective?.* Environ. Sci. Eur. 25: pp. 1–12.

Keenan, R.J.; Reams, G.A.; Achard, F.; de Freitas, J. V.; Grainger, A.; Lindquist, E. (2015): *Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015*. For. Ecol. Manage. 352: pp. 9–20.

Librescu, L.; Hause, T. (2000): *Recent developments in the modeling and behavior of advanced sandwich constructions: A survey.* Compos. Struct. 48: pp. 1–17.

Majewski, A.; Smardzewski, J. (2013): *Thin purenit honeycomb panels.* Proceedings of the 26th International Conference Research for Furniture Industry. September 19-20th Poznań, Poland : pp. 63-72.

Meraghni, F.; Desrumaux, F.; Benzeggagh, M.L. (1999): *Mechanical behaviour of cellular core for structural sandwich panels.* Composites Part A 30: pp. 767–779.

Nilsson, J.; Ormarsson, S.; Johansson, J. (2017): *Moisture-related distortion and damage of lightweight wood panels — experimental and numerical study.* J. Indian Acad. Wood Sci. 14: pp. 99–109.

Nordvik, E.; Broman, N.O. (2005): *Visualizing wood interiors: a qualitative assessment of what people react to and how they describe it*. For. Prod. J. 55: pp. 81–86.

Ozyhar, T.; Hering, S.; Niemz, P. (2012): *Moisture-dependent elastic and strength anisotropy of European beech wood in tension.* J. Mater. Sci. 47: pp. 6141–6150.

Petras, A. (1998): *Design of Sandwich Structures*. Proc. Est. Acad. Sci. pp. 4–8.

Petras, A.; Sutcliffe, M.P.F. (1999): *Failure mode maps for honeycomb sandwich panels.* Composite structures 44: pp. 237-252,

Shalbafan, A.; Luedtke, J.; Welling, J.; Thoemen, H. (2012): *Comparison of foam core materials in innovative lightweight wood-based panels.* Eur. J. Wood Wood Prod. 70: pp. 287–292.

Sam-Brew, S.; Semple, K.; Smith, G. (2011): *Preliminary experiments on the manufacture of hollow core composite panels.* Forest Products Journal 61: pp. 381-389.

Smardzewski, J. (2015): *Furniture design*. Springer International Publishing, Switzerland.

Smardzewski, J. (2013): *Elastic properties of cellular wood panels with hexagonal and auxetic cores*. Holzforschung 67: pp. 87–92.

Smardzewski, J.; Batko, W.; Kamisiński, T.; Flach, A.; Pilch, A.; Dziurka, D.; Mirski, R.; Roszyk, E.; Majewski, A. (2014): *Experimental study of wood acoustic absorption characteristics*. Holzforschung 68: pp. 467–476.

Smardzewski, J.; Kamisiński, T.; Dziurka, D.; Mirski, R.; Majewski, A.; Flach, A.; Pilch, A. (2015): *Sound absorption of wood-based materials*. Holzforschung 69: pp. 431–439.

Smardzewski, J.; Łabęda, K. (2018): *Mechanical and Hygroscopic Properties of Longitudinally- Laminated Timber (LLT) Panels for the Furniture Industry*. BioResources. 13: pp. 2871–2886.

Smardzewski, J.; Majewski, A. (2014): *Mechanical properties of auxetic honeycomb core with triangular cells*. 25th International scientific conference: New materials and technologies in the function of wooden products. ISBN: 978-953-292-034-5 pp: 103-112. University of Zagreb, Faculty of Forestry. October 17th, 2014, Zagreb, Croatia.

Smardzewski, J.; Majewski, A.; Prekrat, S. (2013): *Effect of cell-wall angle on the uniaxial crushing behaviour of paper hexagonal honeycombs*. In: 24th Int. Sci. Conf. Wood Is Good - User Oriented Mater. Technol. Des. Proc.

Smardzewski, J.; Prekrat, S. (2012): *Modelling of thin paper honeycomb panels for furniture*. International Conference Ambienta, Wood is Good – With Knowledge and Technology to a Competitive Forestry and Wood Technology Sector, Zagreb: pp. 179-186.

Smardzewski, J. Słonina, M.; Maslej, M. (2017) *Stiffness and failure behaviour of wood based honeycomb sandwich corner joints in different climates*. Compos. Struct. 168: pp. 153–163.

Voth, C.; Yamada, V. (2010): *Sustainable Lightweight Wood-Strand Panels for Building Construction*. Proceedings of the International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee. October 11-14, Geneva, Switzerland: pp. 1-7,