Mechanical and Hygroscopic Properties of Longitudinally-Laminated Timber (LLT) Panels for the Furniture Industry

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One likely reason why cross-laminated timber (CLT) panels are not applied in furniture designing is their unaesthetic appearance, with a crosswise arrangement of layers visible on narrow surfaces of furniture panels. The objective of this investigation was to manufacture and determine physic-mechanical properties of solid and cell Longitudinally-Laminated Timber (LLT) panels. The cognitive goal of the performed experiments was to determine orthotropy, linear elasticity moduli, and bending strength of LLTs. It was also decided to ascertain swelling coefficients of composites caused by changes in air humidity. Advantageous MOE and MOR values of LLTs were determined in relation to similar solid panels. In addition, it was demonstrated that, for furniture panel designing, it was rational to employ facings from beech wood as well as cores from beech wood free from anatomical defects.

Keywords: Furniture; LLT (Longitudinally-Laminated Timber); Stiffness; Strength; Swelling

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INTRODUCTION

In recent years, the importance of optimal wood utilisation has become increasingly vital, and attempts are being made continuously to find novel light-layered composites, which could replace traditional solid wood or equalise its properties in mutually perpendicular directions. Therefore, much attention has been focused on the analysis of cross-laminated timber (CLT) panels. Saavedra Flores *et al.* (2015) determined mechanical properties of CLT derived from radiata pine wood. Samples were subjected to bending, shearing, and compression. Numerical models were also developed based on homogenising the properties of this composite. In later experiments, a more accurate numerical model of homogenisation of the CLT panel was described by taking into account grain arrangement as well as timber annual ring orientation in individual layers of the composite (Saavedra Flores *et al.* 2016). Brandner *et al.* (2017) described the mechanics of CLT composite failure subjected to shear and, at the same time, compared mathematical models with the results of empirical studies. Similar experiments were conducted by Buka-Vaivadea *et al.* (2017). They described a calculation procedure for the determination of mechanical properties of simple elements manufactured from CLT, which was verified in laboratory experiments. In their paper, Christovasilis *et al.* (2016) described mechanical properties of CLT beams subjected to four-point bending. They also presented suitability of application, for this purpose, of a simple theory of strength of materials and utilisation appropriateness of the results in the theory of construction reliability. Sharifnia and Hindman (2017) published results of technological parameter optimisation, which made it possible to achieve the most advantageous CLT panel structures from pine wood. Buck *et al.* (2015) compared different methods of CLT combination from the point of view of manufacturing costs of new building objects. Still other investigations were concerned with the assessment of metal screw and dowel joints found in elements of construction made from CLT (Hassanieh *et al.* 2016). Numerical models were also elaborated allowing evaluation of vibration properties of floors made from CLT panels (Ussher *et al.* 2017a,b). Many studies were devoted to research on the application of novel materials and new systems suitable for CLT panels. Stanic *et al.* (2016) presented results of optimisation of CLT panel design strengthened with ribs, employing for this purpose the finite elements method. Experiments were also carried out aiming at testing bending and shear resistance of hybrid cross-laminated timber (CLT) panels made from Spruce-Pine-Fir (South) (SPFs) and laminated strand lumber (LSL) (Davids *et al.* 2017). Hybrid cross-laminated timber (HCLT) panels were made by employing lumber and/or laminated strand lumber (LSL) (Wang *et al.* 2015). In that study, mechanical properties were determined of novel composites, including linear elasticity moduli as well as bending strength. Liao *et al.* (2017) determined mechanical properties of CLT panels made from fast-growing eucalyptus species. The authors compared results obtained in static and dynamic tests. The objective of experiments conducted by Castro *et al.* (2010) was property optimisation of light honeycomb panels with a cork core dedicated to the construction of flying objects. Models were also made of CLT panels with a cork core together with the application of veneer. Mechanical experiments included the analysis of panel failure in the course of bending, compression, and tension (Lakreb *et al.* 2015).

From a review of the literature, it can be concluded that the CLT panels are suitable for building objects but are not presently used in the furniture industry. The main reason why CLT panels are not used in furniture design may be their unaesthetic crosswise arrangement of layers visible on narrow surfaces of furniture panels. It is widely expected that grain in glued furniture elements should run uniformly in all layers. Therefore, timber layers should be glued longitudinally when they are to be used in the furniture industry. In addition, it is expected that the composite formed in this way, in relation to solid wood, should exhibit such features as: lower density, similar strength and stiffness, and more advantageous, hence, lower values of swelling coefficients resulting from increases in air humidity.

The aim of this study was to make solid and cell (hollow) LLT (Longitudinally-Laminated Timber) panels and to determine their physic-mechanical properties. The cognitive objective of experiments was to determine orthotropy, linear elasticity moduli, and bending strength of LLT panels. It was also decided to determine composite swelling coefficients resulting from changes in air humidity.

EXPERIMENTAL

Description of Sample Preparation

Beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L.) wood were selected for experiments. Following timber drying to approximately 6% moisture content, samples measuring 5 mm x 50 mm x 150 mm and 20 mm x 20 mm x 400 mm were prepared from each species. They were used to determine mechanical and elastic properties of the raw material intended to manufacture LLT panels. Timber that was to be used for external layers was free of any defects and samples derived from this timber were designated with symbols as in Table 1. Timber intended for the core was divided into two groups – without defects and with such defects as: knots (including decayed knots), failures, twisted grains, presence of bark, sapwood, and false heartwood. Taking into account two timber species, four sample types were obtained and their designations are shown in Table 1. Each sample comprised 10 items (total of 60).

Multilayer composites from beech (*Fagus sylvatica* L.) and oak (*Quercus robur* L.) wood were prepared in two main construction variants (Fig. 2). Variant F was a composite cell panel with a core consisting of separated slats with empty spaces between them (Fig. 1a). Variant C – reference panels – comprised composites with cores made of slats glued together (Fig. 1b).

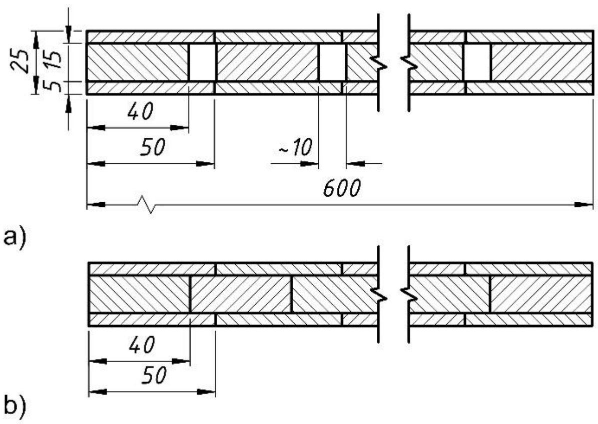

Fig. 1. LLT panels, core slats: a) separated, b) glued

Table 1. Designation of Wood Samples

Code	Description	Dimensions of samples [mm]
External LLT layers		
B-ND	Beech without defects	5 x 50 x 150
O-ND	Oak without defects	
Internal LLT layers		
B-ND	Beech without defects	20 x 20 x 400
B-WD	Beech with defects	
O-ND	Oak without defects	
O-WD	Oak with defects	

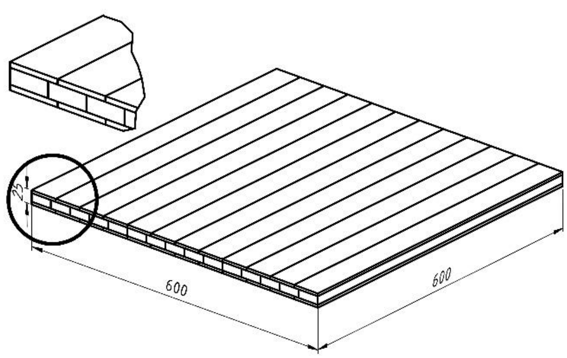

Fig. 2. Shape and dimensions of timber components

Composite facings were obtained by gluing together rails measuring 50 mm x 200 mm x 600 mm into blocks and then cutting them into sheets measuring 5 mm x 600 mm x

600 mm. Rails were glued together using water-thinned glue PVAc. Core slats were obtained from rails with 15 mm x 40 mm cross section dimensions. F variant composites were obtained by applying the amount of 140 g/m^2 of PVAc glue onto wide surfaces of two facings. Wider surfaces of slats were placed on the bottom facing, leaving spaces of about 10 mm between them. Composites from variant C were made in the same way as described above but, additionally, core slats were glued with one another by their narrow surfaces using the PVAc glue. Once the top facing was put in place, the composites were cold-pressed under a pressure of 1.2 MPa. The manufactured composites were cut into panels measuring 25 mm x 600 mm x 600 mm (Fig. 2). In individual combinations, cores were made from beech wood and facings from beech wood or oak wood as well as cores from oak wood and facings from beech or oak wood. Ten samples were prepared for each type of composite (40 samples in total).

Using the construction of composites collated in Table 2, additionally, samples measuring 25 mm x 170 mm x 600 mm were made (Fig. 3). The arrangement of layers corresponded to the order presented in Table 2 and Fig. 2. In addition, samples were characterised by a crosswise (P) (Fig. 3a) as well as lengthwise (L) (Fig. 3b) grain arrangement in relation to the longer edge of the sample. Ten samples each were prepared for each composite type and grain arrangement (160 samples in all).

Table 2. Layer Arrangement in Individual Wood Composites

Code	Description		
	Core	Facing	Method of core gluing
BB-C	Beech	Beech	Among themselves and with facings
BB-F	Beech	Beech	With facings
BO-C	Beech	Oak	Among themselves and with facings
BO-F	Beech	Oak	With facings
OB-C	Oak	Beech	Among themselves and with facings
OB-F	Oak	Beech	With facings
OO-C	Oak	Oak	Among themselves and with facings
OO-F	Oak	Oak	With facings

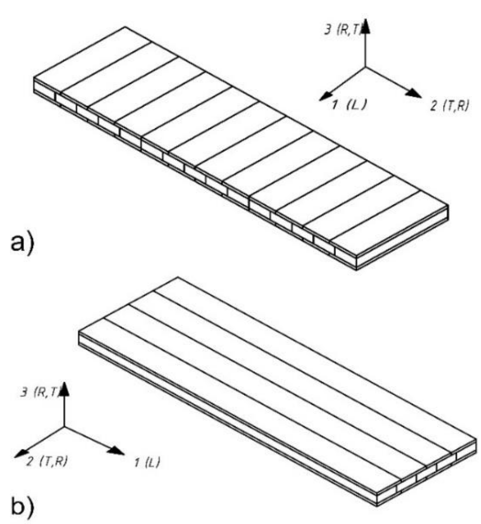

Fig. 3. LLT panels, arrangement: a) crosswise (P), b) longitudinal (L)

Method of Examination of Physical-chemical Properties of Timber and LLT

Timber, as well as composite water content and density, were determined in accordance with PN-D-04100 (1977) and PN-D-04101 (1977), respectively. Mechanical examinations were carried out on a universal testing machine ZWICK 1445 (Zwick, Germany). Physic-mechanical properties of oak and beech wood intended for composite panel facings were designated in accordance with EN 310 (1993) standard. In the case of core slats, their mechanical properties were determined according to PN-D-04103 (1977). In both cases, sample deflection on the testing machine was determined with 0.01 mm accuracy, while loading – with the accuracy of up to 0.01 N. Experiments were terminated at the moment of sample destruction or when the value dropped by 50 N. The velocity with which the sample was loaded amounted to 10 mm/min. In both cases, bending strength along grains MOR was calculated according to the following equation,

$$MOR = \frac{3P_{max}L}{2bh^3}\ \text{[MPa]} \tag{1}$$

where P_{max} is the maximal destruction force [N], L is the distance between supports (20·h (110 [mm], 500 [mm]) or 240 [mm]), b is the sample width [mm], and h is the sample thickness h [mm].

Results of measurements from the area of linear elasticity of this material were used to determine timber elasticity modulus along grain. These forces equalled $0.4{\cdot}P_{\max}$, $0.1{\cdot}P_{\max}$ and the corresponding beam deflections - $f_{0.4\ \mathrm{Pmax}}$, $f_{0.1\ \mathrm{Pmax}}$. Timber linear elasticity modulus MOE was calculated with the assistance of the equation,

$$MOE = \frac{(P_{0.4}-P_{0.1})L^3}{4(f_{0.4}-f_{0.1})bh^3}\ \text{[MPa]} \tag{2}$$

where $P_{0.4}$ is 0.4 $P_{\max}$ [N], $P_{0.1}$ is 0.1 $P_{\max}$ [N], $f_{0.4}$ is the beam deflection corresponding to the force of 0.4 $P_{\max}$ [mm], and $f_{0.1}$ is the beam deflection corresponding to the force of 0.1 $P_{\max}$ [mm].

Before the strength test, each sample was measured with electronic calliper 150 mm DIGI-MET (Helios-Preisser, Poland) with up to 0.01 mm accuracy and weighed on a laboratory balance SKX Scout Ohaus (Ohaus, Poland) with 0.01 g accuracy. On this basis, the density of each sample, the mean values, as well as basic statistical characteristics were calculated. Following strength tests, samples were subjected to drying in a laboratory drier Zalmed SML 30/250 (Zalmed, Poland) at the temperature of 103˚C ±2˚C to absolute dry state and weighed again. On the basis of the obtained data, sample absolute moisture content at the moment of tests was calculated.

In the case of LLT, the following physic-mechanical properties were determined: bending strength and linear elasticity modulus in accordance with EN 310 (1993), density according to PN-D-04103 (1977), and moisture content according to EN 322 (1993). Because of strong orthotropy of timber and manufactured composite panels, their elastic properties were determined for two main orthotropy directions: along grains $MOR_{(L)}$, $MOE_{(L)}$ as well as across grains $MOR_{(P)}$, $MOE_{(P)}$ (Fig. 3). It is worth emphasising here that direction (P), depending on the placement of core slats, comprised tangential (T) and radial (R) directions. Samples were subjected to three-point bending on ZWICK 1445 testing machine (Zwick, Germany). In the course of the performed experiments, sample deflection was measured with up to 0.01 mm accuracy and their loading - with up to 0.01 N accuracy. Experiments were terminated at the moment of sample destruction or when the value dropped by 50 N. The velocity with which the sample was loaded amounted to 10 mm/min. Bending strength was calculated from Eq. 1.

Results of measurements from the area of linear elasticity of this material were used to determine elasticity modulus of composites. These forces equalled $0.4 \cdot P_{max}$, $0.1 \cdot P_{max}$ and beam deflections corresponding to them - $f_{0.4\ Pmax}$, $f_{0.1\ Pmax}$. Using this method, composite linear elasticity modulus MOE was calculated with the assistance of Eq. 2. Prior to the strength test, each sample was measured with a calliper with up to 0.01 mm accuracy and weighed on a laboratory balance with 0.01 g accuracy. On this basis, density of each sample was calculated. Following strength tests, samples were subjected to drying at the temperature of 103˚C ±2˚C to absolute dry state and weighed again. On the basis of the obtained data, sample absolute moisture content at the moment of tests was calculated.

Method of the Swelling Coefficient Determination for LLT

Trials included determination of the impact of changes in relative air humidity on dimensional stability of LLT panels. Laboratory measurements were carried out on samples with shapes and dimensions as in Fig. 2 in the following order. Following the determination of sample moisture content at the moment of examination, sample reference width and length dimensions were determined. For this purpose, a research station as shown in Fig. 4 was designed. The sample was placed in the facility in such a way that timber grains ran parallel to the frame horizontal edge, whereas the right top corner of the panel sheet was situated in the right top corner of the frame. Change of dimensions was recorded with 0.01 mm accuracy half through the panel thickness using a depth gauge at points marked with numbers 1, 2, 3, and 4.

The first measurement in points 1, 2, 3, and 4 was taken under laboratory conditions at the temperature of 21˚C ±2˚C and relative humidity of 43% ± 3%. Next, panel sheets were subjected to wetting in order to increase their absolute moisture content to about 15%. Current moisture content of the moistened composites was monitored using a control sample whose mass and absolute moisture content were established earlier and which corresponded to the equilibrium moisture content for the climatic conditions of the laboratory facility. Sample mass gain gradient, which should characterise panels in the moistening process to the assumed absolute moisture content of about 15% was also calculated.

The moistening process was conducted on the research stand as shown in Fig. 5 (Laboratory of Department of Furniture Design, Poznan University of Life Sciences). Piles of 20 panel sheets, each separated by 20 mm thick wooden spacers, were placed in a climatic chamber into which moist air was pumped produced with the assistance of a Durahealth type ultrasound humidifier (Durahealth, China) of 3.5 kg water/h capacity. Air humidity and temperature in the climatic chamber were controlled with, respectively, 0.1% and 0.1˚C accuracy using a Hiar/Royco 5250A type controller and a Laser Particle Counter (Merazet, Poland). Every 24 hours the control sample was weighed with 0.01 g accuracy on a laboratory balance and moisture content of panel sheets was monitored. Once the assumed moisture content of panel sheets was achieved, humidity and temperature inside the climatic chamber were recorded and written down.

After wetting, each panel sheet was placed in the research stand (Fig. 4) and its measurements in points 1, 2, 3 and 4 were taken. Appropriate swelling coefficients of the examined panels along (L) and across (R/T) grain were calculated from the equations given below,

$$S_L = \frac{(S_1' + S_2') - (S_1 + S_2)}{2 \cdot 600} \frac{FSP}{\Delta W} 100 \ [\%] \tag{3}$$

$$S_{R/T} = \frac{(S_3' + S_4') - (S_3 + S_4)}{2 \cdot 600} \frac{FSP}{\Delta W} 100 \ [\%] \tag{4}$$

where S_L is swelling along grains, $S_{R/T}$ is swelling across grains, $S_1{}'$ is sheet measurement following wetting established in point 1, along grains, $S_2{}'$ is sheet measurement following wetting established in point 2, along grains, S_1 is sheet measurement before wetting established in point 1, along grains, S_2 is sheet measurement before wetting established in point 2, along grains, $S_3{}'$ is sheet measurement following wetting established in point 3, across grains, $S_4{}'$ is sheet measurement following wetting established in point 3, across grains, S_3 is sheet measurement before wetting established in point 4, across grains, S_4 is sheet measurement before wetting established in point 4, across grains, FSP is moisture content at the Fibre Saturation Point of Wood (30%), ΔW is the difference of wood moisture content (ΔW=15%-6%=9%), and 600 is the dimension of panel before wetting.

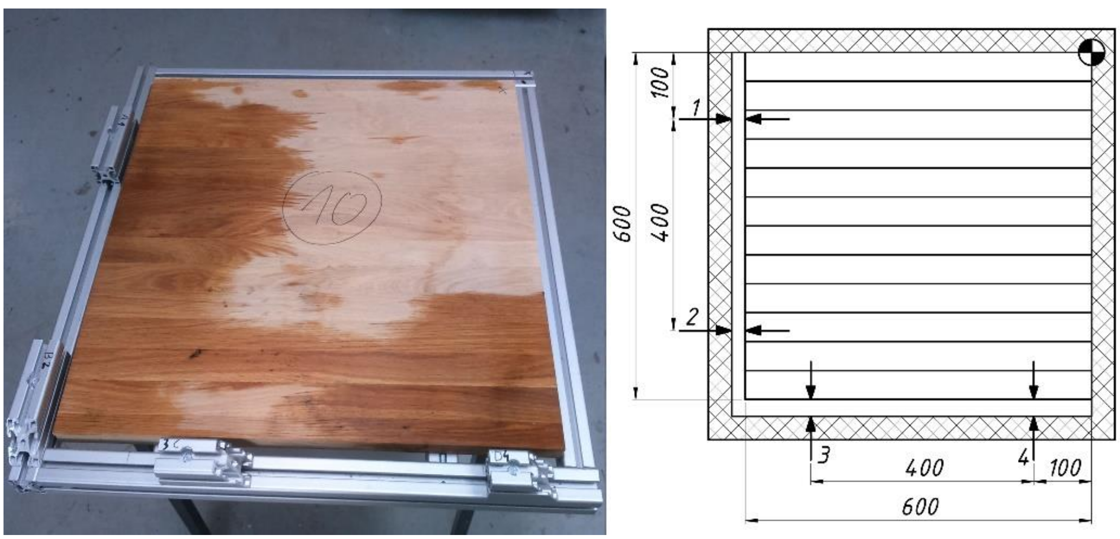

Fig. 4. Stand for measurements of swelling of LLT panels

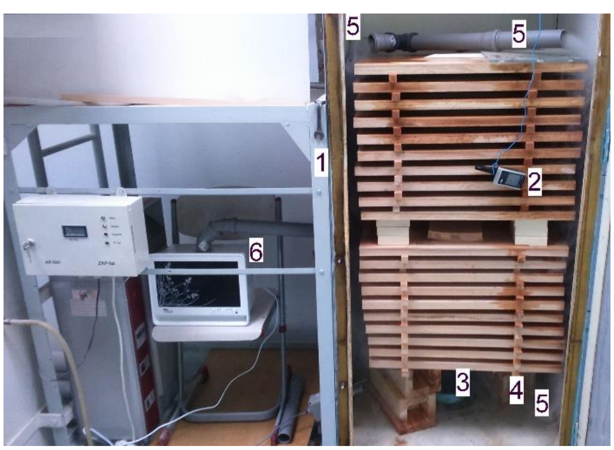

Fig. 5. Climatic chamber together with control facilities: 1 – chamber, 2 – electronic probe for measurements of air humidity and temperature, 3 – LLT panels, 4 – separators, 5 – inlet of moist air, 6 – generator of moist air

RESULTS AND DISCUSSION

Wood Physical-Mechanical Properties

Table 3 presents physical-mechanical properties of wood without defects designated for facings of composite panels. It is clear from this Table that beech wood exhibited considerable greater density than oak wood, 751 kg/m^3 and 685 kg/m^3, respectively. In addition, beech wood was characterised by a higher linear elasticity modulus along grains (13746 MPa) in comparison with the employed oak wood (10601 MPa), and this difference amounted to 29.7%. A similar relationship was found in the case of the bending strength of the examined timbers. Beech wood was characterised by 184 MPa bending strength, while oak by 127 MPa. In this case, the difference reached 44.9%.

Table 3. Properties of Wood Used to Manufacture LLT Panels

Type of material	Statistics	Thickness	MC	Density	MOE	MOR
		[mm]	[%]	[kg/m³]	[MPa]	
B-ND	AV	5.1	6.2	751	13746	184
	SD	0.02	0.45	20	731	6
O-ND	AV	5.0	6.3	685	10601	127
	SD	0.02	0.46	36	2091	27
B-ND	AV	20.4	6.1	728	13234	138
	SD	0.65	0.45	52	1644	24
B-WD	AV	20.3	6.2	742	11161	112
	SD	0.21	0.45	46	1645	23
O-ND	AV	20.2	6.3	714	12095	126
	SD	0.19	0.46	39	838	19
O-WD	AV	20.2	6.2	787	8595	78
	SD	0.17	0.45	57	2951	38

Taking into consideration the above data, it was more advantageous for stiffness of three-layer panels to prepare facings from beech wood. Table 3 also presents physic-mechanical properties of wood with and without defects intended for cores of composite panels. Similarly to the previous case, for wood without defects, beech wood exhibited considerably higher density than oak wood, 728 kg/m^3 and 714 kg/m^3, respectively. Moreover, beech wood was characterised by a higher linear elasticity modulus value along grains (13234 MPa) in comparison with oak wood (12095 MPa) and this difference amounted to 9.4%. A similar relationship occurred in the case of bending strength of this wood. Beech wood showed bending strength at the level of 138 MPa and oak – of 126 MPa. This time, the difference was 9.5%. Bearing the above in mind, it was more advantageous for stiffness of three-layer panels to use beech wood without anatomical defects as their cores.

In the case of wood with defects, its physical-mechanical properties deteriorated quite considerably, although in this situation, beech wood density reached 742 kg/m^3 and that of oak 787 kg/m^3. These values exceeded densities of the examined wood without defects. This can be attributed to the fact that the presence of numerous knots increased sample mass but exerted a negative influence on stiffness and strength of the material. It is evident from Table 3 that beech wood with defects was characterised by linear elasticity modulus along grains of 11160 MPa, whereas oak wood – of 8595 MPa and the difference amounted to 29.9%. A similar relationship can be found in the case of bending stress of this wood. Beech wood was characterised by bending strength of 112 MPa, while oak wood – 78 MPa. In this case, the difference amounted to 43.6%. Taking the above into consideration, it is advantageous for stiffness of tree-layer panels to apply beech wood without anatomical defects as their cores.

Physical-mechanical Properties of Composites

Due to structural differences between timber layered composites, successive figures and tables present results characterising orthotropic properties of solid and cell LLT panels. Table 4 and Figs. 6, 7, and 8 collate determined physic-mechanical properties of composites characterised by grains running crosswise (P) in relation to the sample axis.

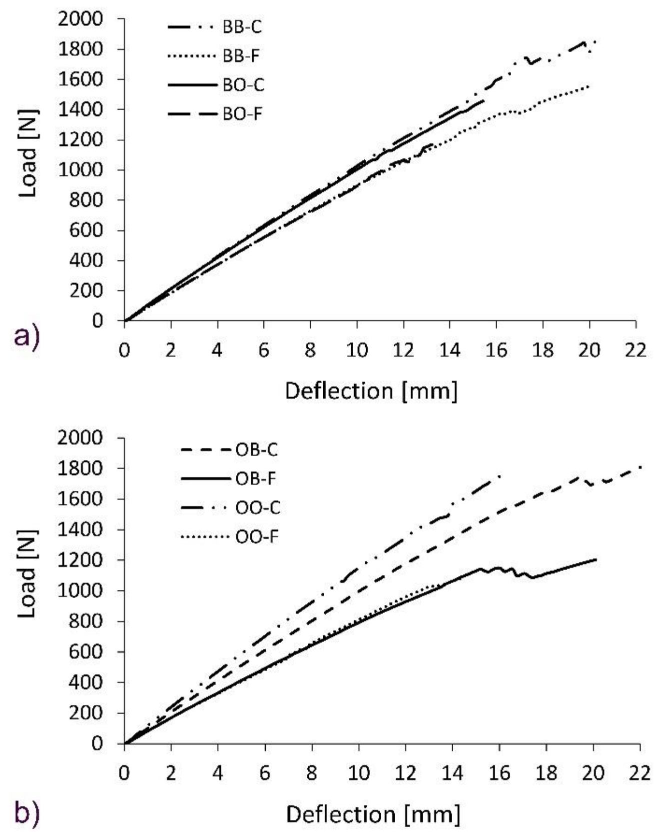

Fig. 6. Stiffness of cell and solid panels with facings of: a) beech wood BB-F, BO-F BB-C, BO-C, b) oak wood OB-F, OO-F, OB-C, OO-C, in (P) direction.

It is evident from Table 4 that the highest densities were determined in solid panels: BO-C, BB-C, OB-C, OO-C; 733, 726, 723, and 718 kg/m^3, respectively, whereas cell panels BO-F, BB-F, OB-F, and OO-F were found to have the lowest densities of 670, 667, 643, and 660 kg/m^3, respectively. Differences in densities between solid and channel panels ranged from 15.3% to 8.8% with greater differences observed in the case of panels with beech cores. Also in this case, this regularity exerted a significant impact on mechanical properties of these composites. Figure 6 shows dependence of beam bending force on its deflection. It can be noticed that composites with facings made from beech wood were characterised by a considerably greater stiffness.

Table 4. Properties of Cell Panels: BB-F, BO-F, OB-F, OO-F and Solid Panels: BB-C, BO-C, OB-C, OO-C

		(P) direction			(L) direction		
Type of material	Stat.	Thickness	MC	Density	Thickness	MC	Density
		[mm]	[%]	[kg/m³]	[mm]	[%]	[kg/m³]
BB-C	AV	26.1	15.2	726	26.1	15.1	723
	SD	0.14	1.24	8	0.12	1.10	23
BB-F	AV	26.1	15.3	667	26.1	15.2	681
	SD	0.10	1.25	14	0.10	1.11	14
BO-C	AV	26.1	15.1	733	26.1	15.1	723
	SD	0.10	1.23	11	0.16	1.10	16
BO-F	AV	26.0	15.2	670	26.1	15.3	667
	SD	0.13	1.24	12	0.10	1.12	17
OB-C	AV	25.8	15.8	723	26.0	15.6	708
	SD	1.00	1.29	40	0.22	1.13	18
OB-F	AV	26.0	15.6	643	26.0	15.6	671
	SD	0.09	1.27	6	0.10	1.13	16
OO-C	AV	26.1	15.8	718	26.1	15.8	713
	SD	0.10	1.19	8	0.15	1.15	16
OO-F	AV	26.0	15.7	660	26.1	15.7	655
	SD	0.06	1.28	8	0.10	1.14	33

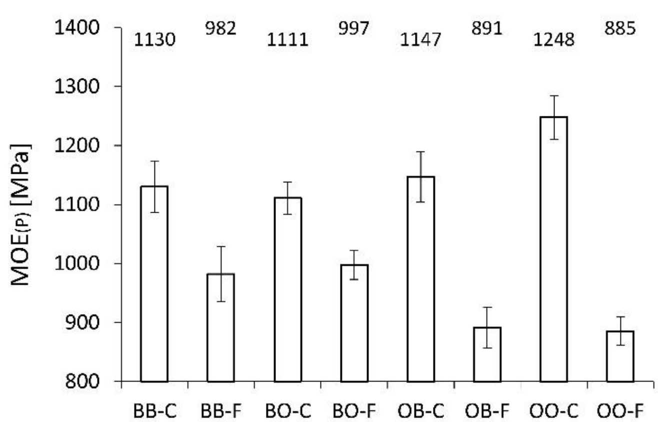

Fig. 7. Linear elasticity modulus of cell panels: BB-F, BO-F, OB-F, OO-F, and solid panels: BB-C, BO-C, OB-C, OO-C in (P) direction

Numerically, these differences are presented in Fig. 7, from which it is evident that solid panels: OO-C, OB-C, BB-C, and BO-C of respectively 1248, 1147, 1130, and 1111 MPa were characterised by the highest $MOE_{(P)}$ value. On the other hand, the lowest $MOE_{(P)}$ values amounting to respectively 885, 891, 982, and 997 MPa were determined in cell panels: OO-F, OB-F, BB-F, BO-F. Differences in rigidity of solid and cell panels ranged from 11.4% to 41% with greater differences occurring in the case of panels with oak cores. This indicates beech wood as a better material not only for cores but also for facings of cell panels. This remark is further strengthened by the analysis of bending strength.

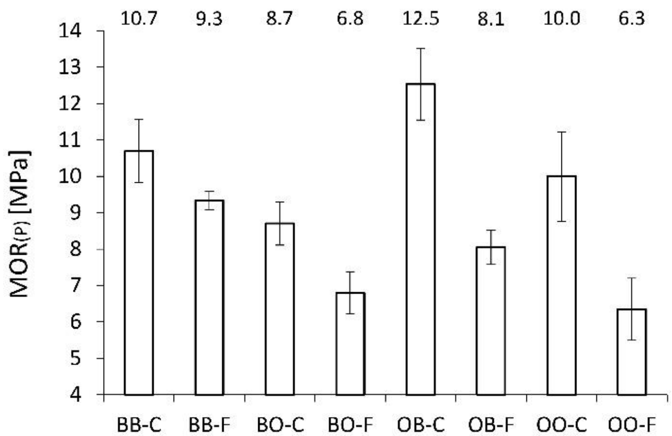

Fig. 8. Bending strength of cell panels: BB-F, BO-F, OB-F, OO-F and solid panels: BB-C, BO-C, OB-C, OO-C in (P) direction

Pertinent relationships are presented in Fig. 8. The data found here show that solid panels: OB-C, BB-C, OO-C, and BO-C were characterised by the highest bending strength $MOR_{(P)}$ of respectively 12.5, 10.7, 10.0, and 8.7 MPa. The lowest $MOR_{(P)}$ values of, respectively 6.3, 6.8, 8.1, and 9.3 MPa were determined in cell panels OO-F, BO-F, OB-F, and BB-F. Strength differences between solid and channel panels ranged from 28.6% to 44.4% with greater differences observed in the case of panels with oak cores.

Further on, in Table 4 and Figs. 9, 10, and 11, the authors collated physic-mechanical properties of composites characterised by grains running longitudinally (L) in relation to the sample axis. It is evident from Table 4 that solid panels: BB-C, BO-C, OB-C, and OO-C were characterised by the highest densities of, respectively, 723, 723, 708, and 713 kg/m^3. The lowest densities of 681, 667, 671, and 655 kg/m^3, respectively were determined in channel panels BB-F, BO-F, OB-F, and OO-F. Differences in densities between solid and cell panels ranged from 5.5% to 6.2%. Greater differences could be observed in panels with beech cores. In this case, this regularity exerted a significant influence on mechanical properties of these composites.

Figure 9 shows the dependence of the beam bending force on its deflection. It can be noticed that composites whose facings were made from beech wood were characterised by a slightly greater stiffness. Numerically, these relationships are presented on Fig. 10, where it can be seen that the linear elasticity modulus $MOE_{(L)}$ of BB-C, OB-C, OO-C, and BO-C panels had values of, respectively 9625, 9399, 9114, and 8949 MPa. On the other hand, values of $MOE_{(L)}$ moduli for cell panels BB-F, OB-F, OO-F, and BO-F amounted to 9231, 9473, 8264 and 7979 MPa, respectively. Hence, stiffness differences between solid and cell panels ranged from 4.3% to 12.1% to the disadvantage of cell panels.

Smaller differences could be observed in the case of panels with an oak or beech core and beech facings. This shows that beech wood can be utilised not only for cores but also for facings of cell panels. Appropriate relationships of panel bending strength along grains (L) are shown in Fig. 11. Data from this figure indicate that all panels were characterised by a relatively similar strength. It can be attributed to the fact that each of layer panels with longitudinal arrangement of grains carried maximal forces of similar value.

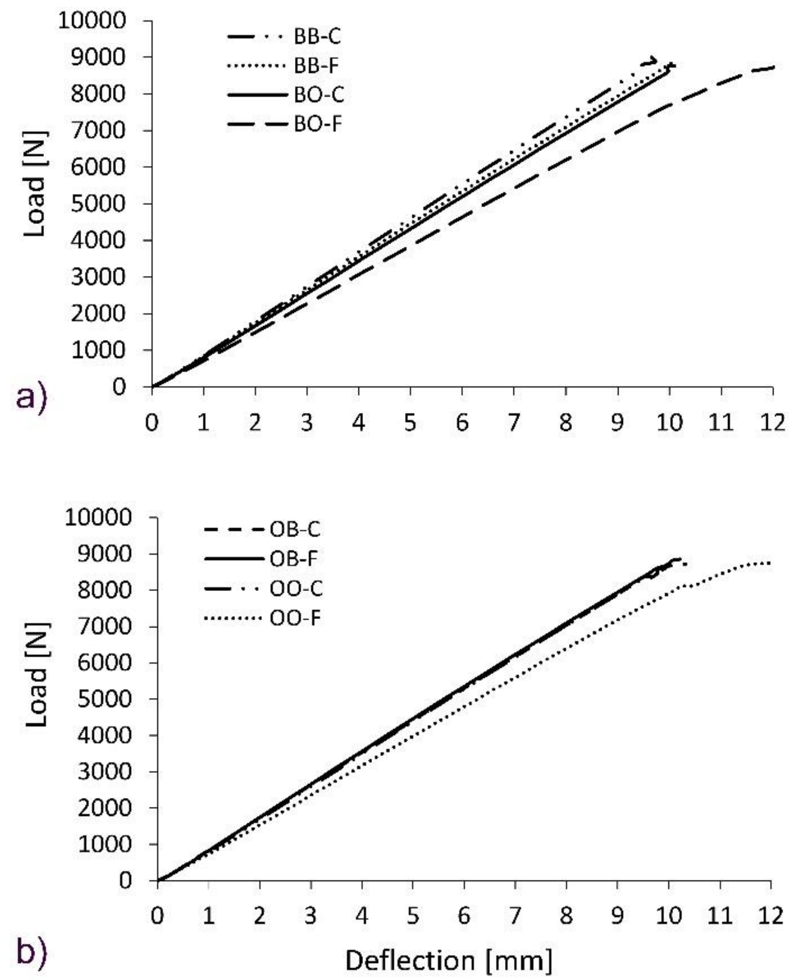

Fig. 9. Stiffness of cell panels and solid panels with facings of: a) beech wood BB-F, BO-F BB-C, BO-C, b) oak wood OB-F, OO-F, OB-C, OO-C, in (L) direction.

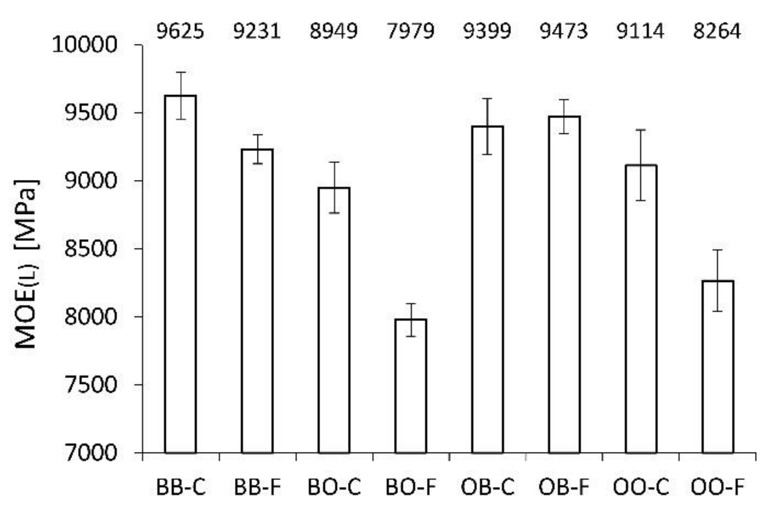

Fig. 10. Elasticity modulus of cell panels: BB-F, BO-F, OB-F, OO-F and solid panels: BB-C, BO-C, OB-C, OO-C, in (L) direction

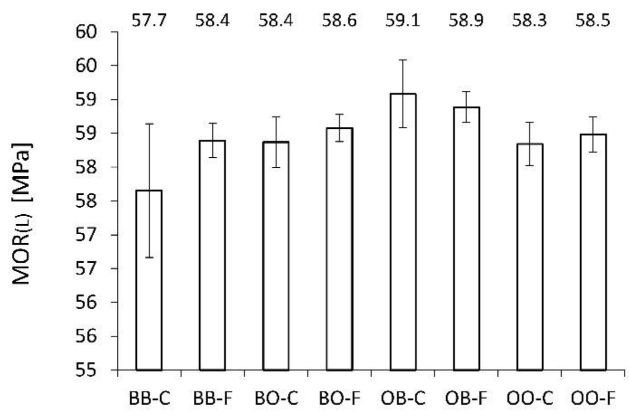

Fig. 11. Bending strength of cell panels: BB-F, BO-F, OB-F, OO-F and solid panels: BB-C, BO-C, OB-C, OO-C, in (L) direction.

Dimensional stability of three-layer panels

Conditions of high air relative humidity of 98.9% and temperature of 20.7ºC prevailed in the climatic chamber. Sample initial moisture content was approximately 6%, while their final moisture content after a 21-day period of wetting was about 15% (Table 4). On the basis of changes in panel dimension in (L) and (R/T) directions, swelling coefficients for individual LLT panels and anatomical directions were determined (Table 5).

Table 5. Swelling Coefficients of LLT Panels and Solid Panels

Panel type	Symbol	S_L/(SD) [%]	$S_{R/T}$/(SD) [%]
Solid	BB-C	0.10/(0.0010)	3.16/(0.0015)
	BO-C	0.07/(0.0008)	1.90/(0.0015)
	OB-C	0.10/(0.0011)	2.23/(0.0012)
	OO-C	0.10/(0.0012)	1.23/(0.0011)
Cell	BB-F	0.07/(0.0009)	6.43/(0.0018)
	BO-F	0.20/(0.0010)	4.00/(0.0016)
	OB-F	0.31/(0.0012)	5.00/(0.0013)
	OO-F	0.07/(0.0009)	3.23/(0.0014)

It is clear from data presented in Table 5 that the swelling of solid and cell panels in the direction along grains (L) was small and did not exceed 0.3%. This indicates that this value is advantageous in comparison with the value of the swelling coefficient along grains of beech or oak wood. According to Kollmann and Cote (1968), the value of this coefficient for the full range of wood hygroscopicity is contained between 0.1% to 0.8%. For the direction across grains (R/T), cell panels exhibited greater swelling in comparison with solid panels, from 3.13% to 6.43% and from 1.83% to 3.16%, respectively. Generally speaking, this difference amounts to about 100%. This kind of regularity can be attributed to air pockets between core slats and lack of mutual pressures between them. Nevertheless, is should be stressed that this kind of swelling did not exceed 6.5%. According to Kollmann and Cote (1968), the value of the swelling coefficient across grain for full range of wood hygroscopicity ranges from 3% to 6% and from 6% to 13% for the radial and tangential direction, respectively.

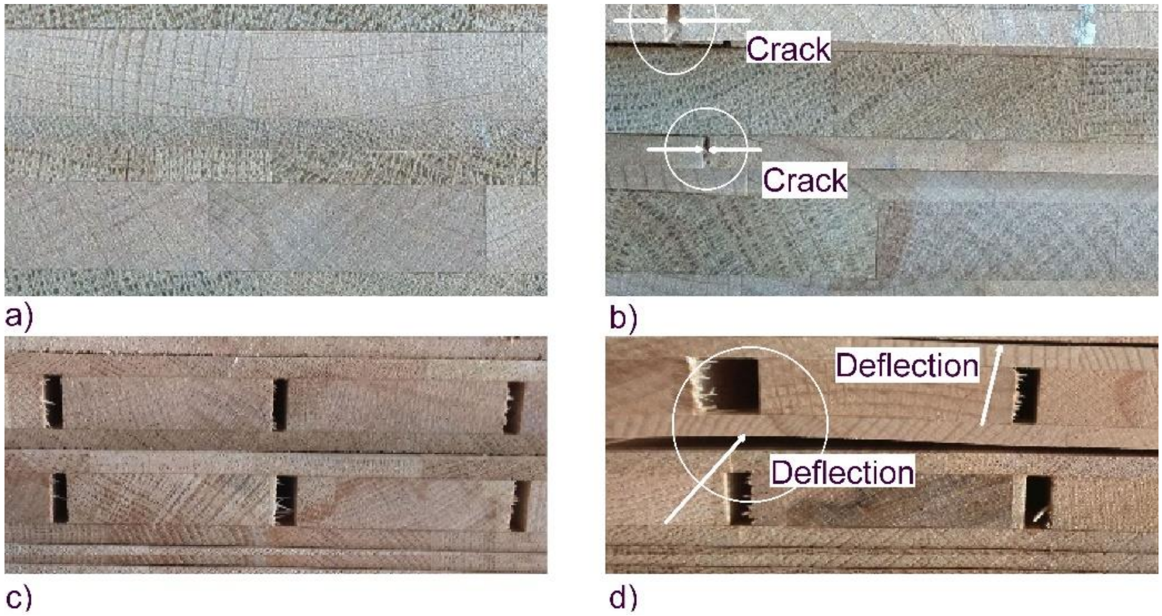

Fig. 12. Shape of LLT panels before wetting: a, c) and after wetting b, d)

Another regularity can also be inferred from Table 5, namely that the smallest swelling was observed in panels containing oak wood, especially panels manufactured exclusively from this wood species. When analysing the shape of panel deformations before and after wetting (Fig. 12), it is evident that solid panels underwent smaller deformations in the direction normal to the wide plane in comparison with cell panels. In the case of solid panels, a few cracks were observed in the place of the vertical glue line occurrence (Fig. 12b). Such cracks were not found in cell panels. On the other hand, significant corrugation of wide surfaces was observed, which affected aesthetic value of these panels (Fig, 12d).

CONCLUSIONS

Based on the result analysis of the performed experiments, advantageous MOE and MOR values were demonstrated of cell panels in comparison with similar solid panels. The value of the linear elasticity modulus along grain of cell panels ranged from 7979 to 9473 MPa, whereas that of solid panels – from 8949 to 9625 MPa. For these reasons, LLT cell panels constitute a competitive composite in relation to solid panels for production of furniture from solid wood. From the aesthetic point of view, this is possible by using in the core layer an edge bars with a fibre pattern in accordance with the fibres of the facing layers. In addition, application of beech wood facings as well as cores made of beech wood free of anatomical defects can be used rationally for designing furniture panels. Moreover, low value of the swelling coefficient across grain of cell panels encourages for their utilisation in furniture industry. It should be mentioned that solid panels undergo smaller deformation in the direction normal to the wide plane in comparison with deformations of cell panels. It was also demonstrated that solid panels were characterised by the highest density of about 720 kg/m^3. Density of cell panels reached about 650 kg/m^3.

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Article submitted: December 12, 2016; Peer review completed: February 17, 2018; Revised version received: February 21, 2018; Accepted: February 24, 2018; Published: February 28, 2018.
DOI: 10.15376/biores.13.2.2871-2886