Annals of Warsaw University of Life Sciences – SGGW
Forestry and Wood Technology № 125. 2024: 23-37
(Ann. WULS - SGGW, For. and Wood Technol. 124, 2023: 23-37)
Received: 19.02.24 / Accepted: 22.03.24 / Published: 31.03.24

Parallel strand lumber made from pine veneer

PAWEŁ BĄCZEK[1], PIOTR BORYSIUK[2]

[1]Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW
[2]Department of Technology and Entrepreneurship in Wood Industry, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences – SGGW

Abstract: *Parallel strand lumber made from pine veneer*. In the study, 12 beams were produced in 3 different veneer width variants, each 3mm thick, using polyurethane adhesive. The veneer was used in the form of full sheets (LVL) with a width of 120 mm and in the form of veneer strips (PSL) with widths of 1/2" (12.5 mm) and 1" (25 mm). The manufacturing method and parameters were identical for each variant. An analysis was conducted to evaluate the impact of different veneer widths on selected mechanical and physical properties of the obtained parallel-strand lumber: density and density profile, modulus of elasticity (MOE), static bending strength (MOR), shear strength, water absorption (WA), and thickness swelling (TS). It was indicated that the material made from full veneer sheets (LVL) has the most favorable mechanical and physical properties. Reducing the width of the raw material leads to a decrease in the strength properties of PSL materials. Generally, this decrease is statistically significant compared to LVL only for the raw material with a width of 12.5 mm. The type of raw material has a statistically significant impact on the tested properties, although the percentage level of this impact is generally lower than the influence of other factors not analyzed during the study.

Keywords: LVL, PSL, pine veneer, mechanical properties, physical properties

INTRODUCTION

Wood has been an excellent building material since the dawn of time. One of its major advantages as a construction material is its high density-to-strength ratio (Chybiński and Polus 2021). Its growing popularity led to more thoughtful harvesting and utilization practices. This includes everything from proper forest management to using wood that, without appropriate processing, would not be suitable as a building material. The actions taken by the wood industry in this direction aimed to maximize the use of this valuable resource, which takes a long time to regrow. Currently, to reduce the felling of structural lumber from massive logs, wood of various diameters and shapes is used to produce engineered wood products (EWPs) (Vladimirova and Gong 2021).

Solid wood, due to its structure, has certain characteristics (knots, cracks, grain twist) that can significantly reduce its strength properties (Bal 2014). When using wood to produce wood-based materials, it is possible to eliminate defects during the technological process that often exclude solid wood as a building material. Generally speaking, wood-based materials used in construction can be classified based on the wood processing method, the degree of its fragmentation, and the internal structure characterized by the specific arrangement of fibers in the joined wood elements (Kram 2015). Properly prepared raw material and the technological process allow for the production of material with excellent strength properties, free from the defects of solid wood.

Laminated veneer lumber (LVL) is a structural material created by gluing veneers primarily in a parallel arrangement, although there are variants with cross-grain layers.

According to the PN-EN 14279 standard, there are three service classes of LVL, ranging from dry conditions to exterior conditions. LVL can be used in the form of beams (all layers parallel) or panels (selected layers arranged perpendicularly). Unlike plywood, panel LVL only has 2 to 5 symmetrically placed cross-grain layers. This arrangement provides sufficient rigidity when used in panel form (Borysiuk et al. 2023). The main applications of LVL are in wooden constructions, where it is used as floor beams, beam reinforcements, rafters, main girders, supports, sills, headers, and much more (Stepinac et al. 2016). Compared to solid wood used for similar applications, LVL is more durable and stronger (Baldwin 1995, Aydin et al. 2004, Çolak et al. 2007). Additionally, it is more predictable (Ghani et al. 2022). This is mainly due to its layered structure, which ensures even distribution of wood defects (e.g., knots, grain disturbances) both in cross-section and lengthwise (Youngquist 1978). The construction of LVL with or without cross layers affects the variability of its strength parameters (Burdurlu et al. 2007). During the formation of LVL, it is advantageous to place veneers with more defects in the middle of the set (Wang and Dai 2013, Gilbert et al. 2017), allowing the production of material with the same properties as LVL made solely from high-quality veneer (Kimmel and Janowiak 1995; Shupe et al. 1997; Pu and Tang 1997, Byczek and Borysiuk 2017). Sasaki and Abdullahi (2016) indicated that overlap scarf joints are beneficial for lengthwise veneer joints. The strength properties of LVL are directly related to its density and, consequently, to the raw material from which it is made (Kawai et al. 1993, Bednarek et al. 2010, Wang and Dai 2013, Alamsyah et al. 2023). Higher density materials also exhibit higher strength parameters. Li et al. (2023) and Li et al. (2024) indicated, among other things, that LVL exhibits bending strength comparable to or even higher than conventional glued laminated wood. Considering technological parameters, the combined action of pressure and pressing temperature significantly affects LVL properties (Zang et al. 1994). The thickness of the veneers and the amount of adhesive used also influence LVL strength and dimensional stability (Kawai et al. 1993; Chui et al. 1994). Darmawan et al. (2015) also point out the negative impact of longitudinal cracks in the veneers caused by peeling on the strength properties of LVL. Meanwhile, Chybiński et al. (2021) showed that LVL, compared to solid wood, also has a lower thermal conductivity coefficient.

Parallam PSL (parallel strand lumber) is a structural wood material, produced similarly to LVL from veneers. However, unlike LVL, PSL uses veneer strips approximately 25mm wide instead of whole sheets (Ehart et al. 1998, Busta and Honesty 2013). The strips are arranged parallel to each other. As with LVL, the veneer thickness is around 3 mm. Due to its specific structure, PSL is an intermediate material between laminated and particleboard products (Borysiuk 2016). Currently, PSL is not very popular in the European or Polish markets. Its main area of use is in the United States and Canada. The locations of factories producing Parallam are often coordinated with construction markets utilizing this material (Opacic 2016).

The production process of PSL essentially consists of four main stages (Hrázský and Král 2010). The first stage is obtaining veneer through rotary cutting. Next, the veneer is divided into sheets, which are then dried. Production can also utilize by-products from plywood and LVL manufacturing (Stark et al. 2010). The prepared veneer is cut into strips approximately 25mm wide. Defective (too short) strips are sorted out to minimize material weakening. The next stage involves the continuous forming and pressing of the beam. Finally, the PSL beam is cut into the desired elements and finished (sanded). The most commonly used wood species for PSL production are pine, poplar, and Douglas fir, while phenolic adhesives are used for bonding the veneer strips. The finished PSL is available in beams with widths ranging from 40 to 280mm and heights from 44 to 483mm. If necessary, Parallam beams can be glued together to achieve larger, non-standard dimensions.

The properties of Parallam depend on both the raw materials used, including the width of the veneer strips and the type and concentration of adhesive, as well as the pressing parameters (Massijaya and Nugroho 2018, Moradpour et al. 2019, Oh 2022, Zhou et al. 2022, Çavuş and Ersin 2023). The organized structure of PSL often results in better properties than traditional lumber or glued wood (Kram 2011, Oh 2022, Çavuş and Ersin 2023). However, it's worth noting that the strength parameters of the material decrease with an increase in the angle between the fibers and the longitudinal axis of the material (Qiu et al. 2020b). This indicates the anisotropic structure of the material related to the arrangement of the veneer strips (Qiu et al. 2020a, Qiu et al. 2020b, Zhou et al. 2021). There is no clear indication in the literature regarding the optimal required width of veneer strips. According to Szełemeja and Tomusiak (1995) and Nicewicz et al. (2003), the width of the veneer strips is 12 mm, while Ehart et al. (1998), Hoadley (2000), and Ozelton and Baird (2002) suggest a value of 13 mm in this range. On the other hand, according to Rammer and Zaan (1997), the width of the strips for Parallam production is 16 mm, while White (2000) and Bao (2002) point to a value of 19 mm. The arrangement of the veneer strips also affects the presence of voids within the material. Excessive voids in the material structure may result in a decrease in the strength properties of Parallam. However, small voids can facilitate PSL impregnation (Ellis et al. 2007).

Figure 1. The manufactured wood materials: a - LVL, b - PSL 1", c - PSL 0.5"

Parallel strand lumber has found application as structural elements in construction. This material is mainly used in the form of beams and columns, both in the construction of single-family homes and public buildings, as well as large-scale structures (Stark et al. 2010). With proper impregnation, this material can also be used for bridge construction (Borysiuk et al. 2023).

Both LVL and PSL offer interesting alternatives to solid lumber in construction. The use of veneer strips in the case of PSL allows for increased raw material efficiency in the manufacturing process compared to LVL. However, there are no clear indications regarding the recommended width of veneer strips for PSL production. It is also worth noting that unlike LVL, PSL is not yet produced in Europe. Therefore, research into the properties of this material, obtained based on domestic raw materials, is recommended.

MATERIALS AND METHODS

Preparation of materials

For research purposes, three types of wood-based materials were produced (Fig. 1) with nominal dimensions of 18x120x400mm, made from 3mm thick pine veneer:

a) LVL - a 6-layer material produced from veneer sheets bonded in a parallel arrangement;
b) PSL 1" - a material made from veneer strips with a nominal width of 25 mm bonded in a parallel arrangement;
c) PSL 0.5" - a material made from veneer strips with a nominal width of 12.5 mm bonded in a parallel arrangement.

The materials were cold-pressed into forms with dimensions of 18x125x400mm using a hydraulic press. The assumed density of the materials was 650 kg/m3. Three repetitions were performed for each type of board. To produce the materials, a solvent-free, single-component polyurethane adhesive D4 Chemolan B45 (Interchemol sp. z o.o., Oborniki Śląskie, Poland) was used. The bonding level was set at 15%. The adhesive for the veneers was manually applied using a brush. A workstation was prepared for this process, allowing for the free distribution of veneer strips to ensure thorough coverage with adhesive. The bonded material was placed in a form protected with anti-adhesive film. Pressing was conducted at room temperature (approximately 20°C) for 40 minutes. The pressing pressure was adjusted each time to ensure complete closure of the mold. After pressing, the materials were conditioned under laboratory conditions (t = 20°C, φ = 65%) for 7 days. The finished materials, after conditioning, had an average thickness of 19mm.

Density profile and density test

The density of the materials was tested according to the PN-EN 323:1999 standard. Samples measuring 19x50x50mm were prepared for testing, with 10 samples for each type of material. Density profile testing was conducted using an X-ray density profiler from GreCon (Fig. 2). Samples measuring 19x50x50mm were used for the tests, with 3 samples for each type of material. The measurement speed range was from 0.05 mm/s. Density measurement was carried out with a resolution of 0.02mm.

Figure 2. Density profiler X-ray by GreCon

MOR and MOE test

The tests were conducted according to the PN-EN 310:1994 standard. Samples measuring 19x50x400mm were prepared for testing, with 6 samples for each type of material. The tests were carried out using a strength testing machine (OBRPPD, Czarna Woda). The support span during the test was 360mm (Fig. 3), and the loading rate was 10 mm/min.


Figure 3. Sample during MOR and MOE testing

Shear strength test

The shear strength test was conducted on samples measuring 19x20x50mm (with a length of 50mm along the fibers), with 20 samples for each type of material. The method of securing the sample in the strength testing machine is shown in Fig. 4. The sample was sheared in a vertical plane (along the fibers), coinciding with the width of the sample.

The shear strength of the joints was calculated using the formula (with an accuracy of 0.1 N/mm^2):

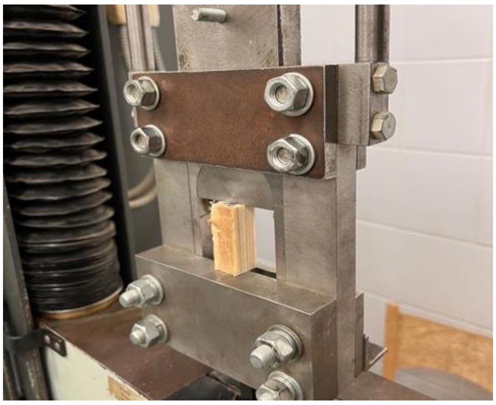
Figure 4. The specimen is clamped during the shear strength test

$$f_v = \frac{F}{lxb}\ [N/mm^2]$$

where*:*
f_v – shear strength [N/mm^2],
F – destructive force [N],
l – the length of the cutting plane [mm],
b – the width of the cutting plane equals the thickness of the sample [mm].

Thickness swelling (TS) and water absorption (WA) test

The test was conducted according to the PN-EN 317:1999 standard. Samples measuring 19x50x50mm were used for the test, with 10 samples for each type of material. Measurements were taken after soaking the samples in water for 2 hours and 24 hours (Fig. 5).

Water absorption was calculated using the formula:

$$N_{(2,24)} = \frac{m_{2(2,24)} - m_1}{m_1} \times 100\ [\%]$$

where:
$N_{(2,24)}$- water absorption after 2 or 24h soaking in water [%],
$m_{2(2,24)}$- mass of the sample after 2 or 24h soaking in water [g],
m_1- mass of the sample before immersion in water [g].

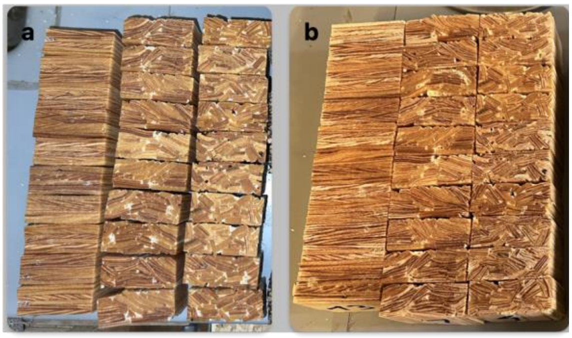

Figure 5. Samples during testing after 2 hours (a) and 24 hours (b) of immersion in water

Statistical analysis

Statistical analysis of the results was carried out in Statistica version 13 (TIBCO Software Inc., CA, USA). Analysis of variance (ANOVA) were used to test (α=0.05) for significant differences between factors. A comparison of the means was performed by Tukey test, with α=0.05.

RESULTS

The results of the density test of the produced materials are presented in Fig. 6. The variant PSL 0.5" showed the lowest average density of 572kg/m^3. On the other hand, the material with the highest density turned out to be LVL, with an average density of 608 kg/m^3. It is worth noting that the recorded difference between the density values of these variants, although small - 36 kg/m^3, is statistically significant (different homogeneous groups A and B). The higher density of LVL compared to PSL results from a more compact structure of the material and lower porosity. However, the differences in average density between the PSL 1" and PSL 0.5" variants are statistically insignificant (the same homogeneous group A). The density of both LVL and PSL depends mainly on the raw material used and the type and amount of adhesive introduced (Arabi et al. 2024). Ehart et al. (1998) found that the density of parallam is about 15% higher compared to the species from which it was produced. Generally, it can be stated that the obtained density values correlate with the data found in the literature (Cai and Ross 2010, Borysiuk et al. 2023). The conducted analysis of variance (Table 1) showed that the type of raw material (sheets, strips) statistically significantly affects the density value (p<0.05). However, it should be noted that the percentage impact of this factor was only 27.7%. The decisive influence on the density of the materials was exerted by factors not analyzed in these studies, with an Error = 72.3% (Table 1).

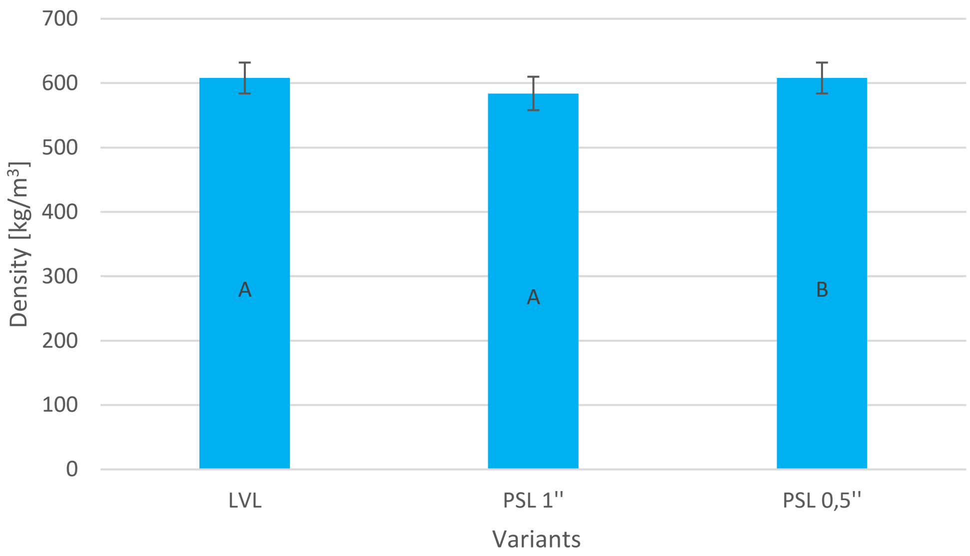

Figure 4. Density of the tested materials; A, B - homogeneous groups based on Tukey's test

The results of the density profile analysis are presented in Fig. 7. The observed densities measured across the entire width of the samples ranged from 440kg/m^3 to over 900kg/m^3. The PSL samples, both in the PSL 1" and PSL 0.5" variants, exhibited a relatively uniform density distribution. In the case of LVL, the significant variation in density was due to the presence of continuous joints depicted as five "peaks" in the density profile. For parallam, the joints did not form continuous parallel layers (Fig. 1). Their influence on the density profile was averaged out.

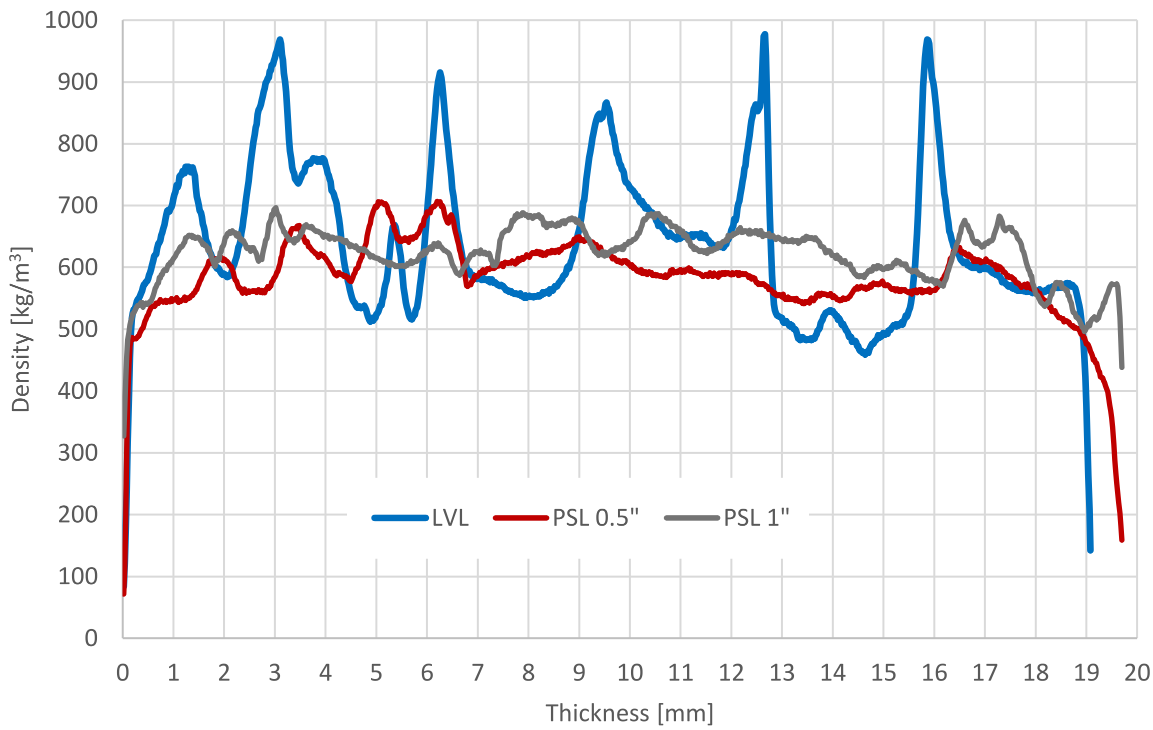

Figure 5. Density profiles of the tested samples

The results of the MOR tests conducted on the produced materials are presented in Fig. 8. The highest strength value, reaching 85.9 N/mm^2, was characteristic of the LVL material. However, it is worth noting that the difference in MOR values between the LVL and PSL 1" variants, although visible (7.8 N/mm^2), is practically statistically insignificant (the same homogeneous group B). Similarly, no statistically significant difference in strength was observed between the PSL 1" and PSL 0.5" variants (the same homogeneous group A). However, it should be pointed out that the differences in MOR values between the LVL and PSL 0.5" variants are statistically significant (different homogeneous groups A and B). The obtained MOR values for LVL and PSL align with the data found in the literature (Hakkarainen 2020, Oh 2022). Overall, it can be stated that the type of material variant statistically significantly influenced the MOR values (Table 1). However, it is worth adding that similar to density, the percentage impact of the type of raw material (36.8%) was lower than the influence of factors not analyzed in the conducted research (Error = 63.2%).

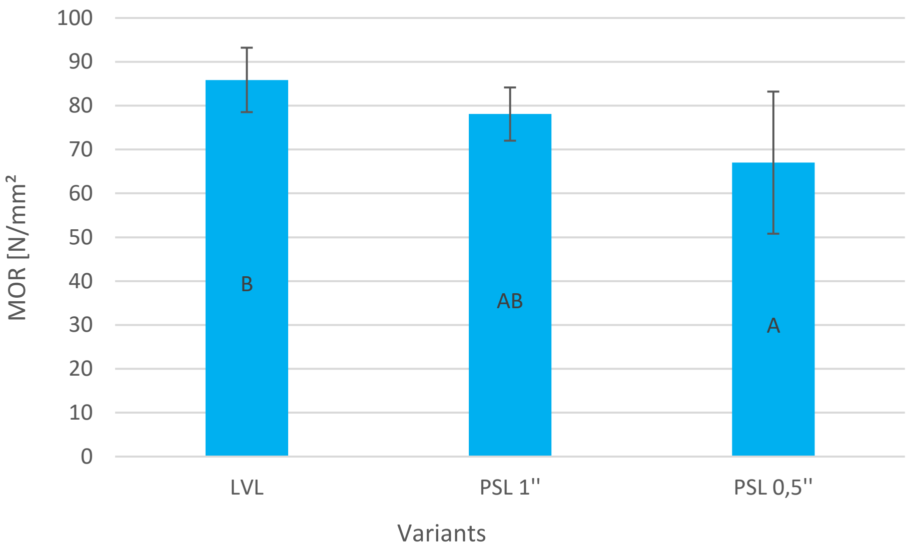

Figure 6. Values of MOR of the tested materials; A, B - homogeneous groups based on Tukey's test

The results of the MOE test are presented in Fig. 9. Similar to the MOR, the highest MOE value - 11898 N/mm^2 was recorded for the LVL variant. Also, in this case, the difference in MOE values between the LVL and PSL 1" variants, although visible, was statistically insignificant (the same homogeneous group B). However, unlike the MOR test, the differences in MOE values between the PSL 1" and PSL 0.5" variants are statistically significant (different homogeneous groups A, B). The PSL 0.5" variant had the lowest MOE value - 8143 N/mm^2. However, it should be noted that the obtained MOE values for the tested variants correspond to the data found in the literature (Hakkarainen 2020, Oh 2022). The analysis of variance (Table 1) also showed that the type of raw material (sheets, strips) significantly affects the MOE value ($p < 0.05$). The percentage impact of this factor was decisive and amounted to 60.8%. The influence of factors not analyzed in this study was lower, amounting to Error = 39.2% (Table 1).

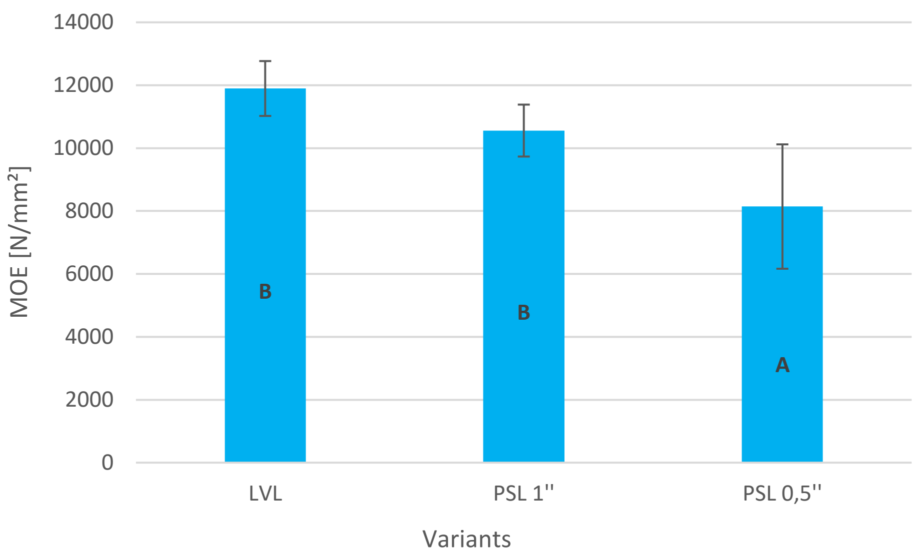

Figure 7. Values of MOE of the tested materials; A, B - homogeneous groups based on Tukey's test

The results of the shear strength test for the tested materials are presented in Fig. 10. Similar to the other cases, the LVL variant showed the highest strength value (7.94 N/mm^2). This value was over 16% higher than the shear strength values obtained for the PSL 1" and PSL 0.5" variants. The observed differences were statistically significant (different homogeneous groups A, B). However, the difference in shear strength values between the PSL 1" and PSL 0.5" variants was statistically insignificant (the same homogeneous group A) and amounted to only 7.4%. Also in this test, it can be noted that the type of raw material (sheets, strips) significantly affected the shear strength values (Table 1). In this case as well, the percentage impact of the material type (19.4%) was significantly lower than the impact of factors not analyzed in this study (Error = 80.6%).

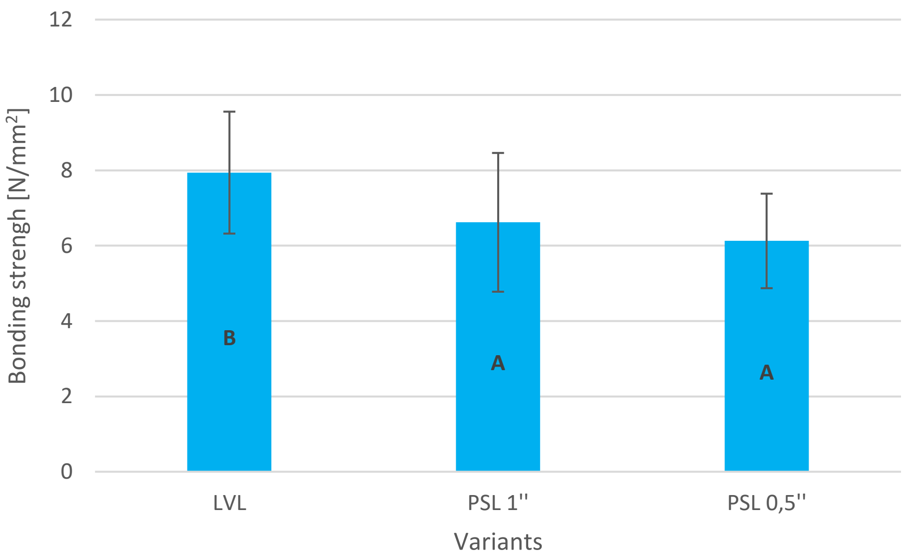

Figure 8. Values of shear strength of the tested materials; A, B - homogeneous groups based on Tukey's test

Table 1. Analysis of variance of the results of strength tests of the manufactured materials

factor	Density		MOR		MOE		Shear strength	
	p	X	p	X	p	X	p	X
type of raw material	0.000097	27.7	0.040476	36.8	0.001414	60.8	0.002651	19.4
Error		72.3		63.2		39.2		80.6

p – significant with α=0.05; X – percentage of contribution

Analyzing the strength properties of the tested materials, it can be generally concluded that they are related to their internal structure. LVL, with its uniform and homogeneous layered construction, exhibits the most favorable strength parameters compared to the other variants. Replacing veneer sheets with strips (PSL 1” and PSL 0.5” variants) disrupted the layered arrangement (Fig. 1, Fig. 11, 12, 13), resulting in a decrease in strength values.

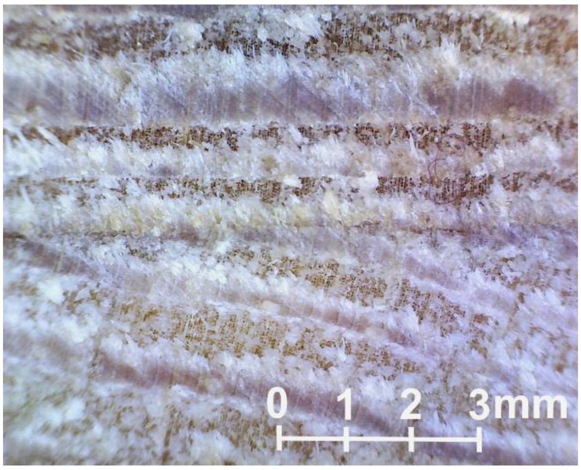

Figure 1. Cross-section of the LVL variant (40x magnification)

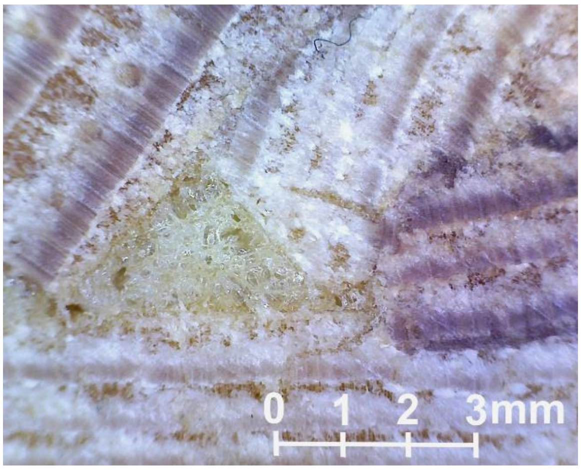

Figure 2. Cross-section of the PSL 1” variant (40x magnification)

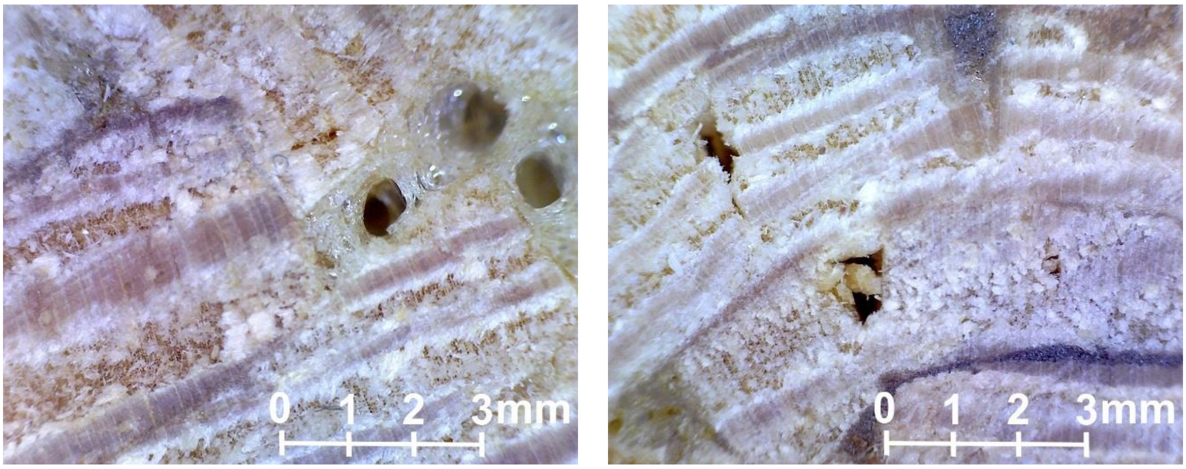

Figure 3. Cross-sections of the PSL 0.5” variant (40x magnification)

The decrease was greater in the case of the variant made from narrower strips (PSL 0.5”), which may indicate an increase in the angle between the fibers and the longitudinal axis of the material. The negative impact of such a arrangement of raw material in the material on strength properties was also indicated by Qiu et al. (2020b). In the case of the PSL 0.5” variant, cross-sectional material reveals voids and cracks (Fig. 13), which may also have contributed to the decrease in strength parameters, as confirmed by literature data (Ellis et al. 2007).

The results of the thickness swelling test for the layered materials after 2 hours and 24 hours are presented in Fig. 14. The highest swelling after 2 hours and 24 hours was recorded for the PSL 0.5” variant, reaching 8.11% and 9.83%, respectively. Conversely, the lowest swelling value was observed for the LVL variant, which was 3.95% after 2 hours and 5.06% after 24 hours. The noted differences between these variants were statistically significant (different homogeneous groups A and B).

It is also worth noting that the PSL 1” variant, both after 2 hours and 24 hours of soaking, exhibited higher swelling values than LVL, but the observed differences were not statistically significant (the same homogeneous group A). The higher swelling values of the PSL 0.5” variant are associated, on one hand, with the presence of voids in the material structure, which facilitated water penetration, and on the other hand, with the varied arrangement of veneer strips. Some of them, due to their width (tangential direction), were more oriented towards the narrow plane of the sample (thickness).

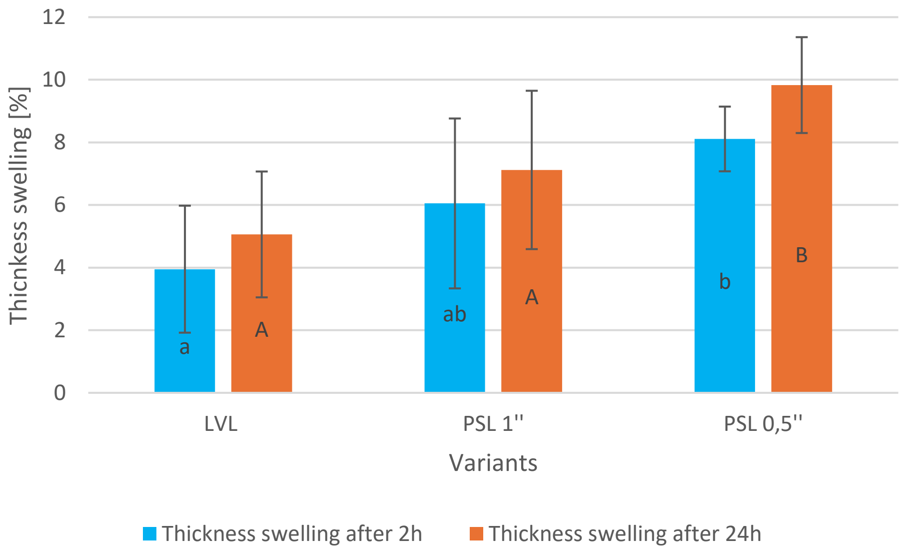

Figure 9. Values of thickness swelling after 2h and 24h of soaking in water of the tested materials; a,b, A, B - homogeneous groups based on Tukey's test

The results of the water absorption test after 2 hours and 24 hours of soaking are presented in Fig. 15. Similar to the thickness swelling, the PSL 0.5” variant exhibited the highest water absorption values, reaching 42.27% after 2 hours and 50.93% after 24 hours of soaking. Conversely, the lowest water absorption values, 32.90% after 2 hours and 46.58% after 24 hours, were observed for the LVL variant. However, it is worth noting that statistically significant differences in water absorption values between the LVL and PSL 0.5” variants were only noted after 2 hours of soaking (homogeneous groups A and B). After 24 hours of soaking, all variants (LVL, PSL 1”, PSL 0.5”) exhibited similar water absorption values (the same homogeneous group - no statistically significant differences).

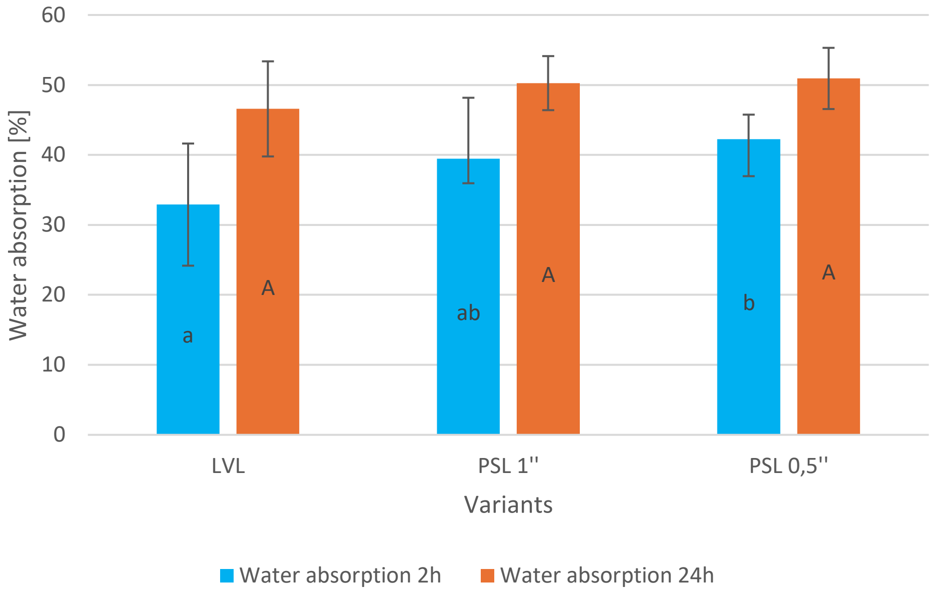

Figure 10. Values of water absorption after 2h and 24h of soaking in water of the tested materials; a, b, A, B - homogeneous groups based on Tukey's test

Overall, it should be noted that the obtained values of thickness swelling and water absorption of the materials are comparable to the data cited in the literature (Moradpour et al. 2019). The authors state that the type of adhesive used plays a significant role.

Table 2. Analysis of variance of the results of physical properties testing of the produced materials

factor	Thickness swelling				Water absorption			
	2h		24h		2h		24h	
	p	X	p	X	p	X	p	X
type of raw material	0.000461	43.4	0.000090	49.8	0.007220	30.6	0.147900	13.2
Error		56.6		50.2		69.4		86.8

p – significant with α=0.05; X – percentage of contribution

The conducted analysis of variance (Table 2) showed that the type of material (veneers, strands) generally statistically significantly affects the materials' resistance to water exposure ($p < 0.05$). Only in the case of water absorption after 24 hours of immersion, there was no statistically significant influence of the material type ($p > 0.05$). In each of the examined characteristics, the percentage impact of the material type was lower than the impact of factors not analyzed in the present study (Error = 50.2% - 86.8%) (Table 2).

CONCLUSIONS

Based on the conducted research on LVL, PSL 1”, and PSL 0.5” materials, differentiated in terms of the form of raw material from which they were produced, the following conclusions can be drawn:

1. LVL manufactured from veneer sheets exhibits more favorable strength (MOR, MOE, shear strength) and physical properties (TS, WA) compared to PSL materials produced from veneer strands, although differences between materials are generally statistically insignificant in the case of 25 mm strands.

2. Decreasing the width of veneer strands from 25 mm (PSL 1”) to 12.5 mm (PSL 0.5”) generally leads to a deterioration in strength and physical properties, with statistically significant effects observed only in the case of modulus of elasticity (MOE).
3. Compared to LVL, PSL 1” and PSL 0.5” materials exhibit a more uniform density profile on the cross-section.
4. The type of raw material, whether in the form of veneer sheets or wide (25 mm) and narrow (12.5 mm) veneer strands, has a statistically significant impact on the investigated properties, although the percentage level of this influence is generally lower than the influence of other factors not analyzed during the research.

REFERENCES

1. ALAMSYAH E.M., DARWIS A., SUHAYA Y., SUTRISNO, MUNAWAR S.S., MALIK J., SUMARDI I., 2023: Modified grain orientation of laminated veneer lumber characteristics of three fast-growing tropical wood species. BioResources, 18 (3), 6132 - 6141
2. ARABI M., HAZRATI M., ROSTAMPOUR-HAFTKHANI A., 2024: Performance of Laminated Veneer Lumber Panels from Fast-Growing Species with Different Layering Arrangements. BioResources 19(2), 2546-2561.
3. AYDIN I., ÇOLAK S., ÇOLAKOĞLU G., SALIH E., 2004: A comparative study on some physical and mechanical properties of Laminated Veneer Lumber (LVL) produced from Beech (Fagus orientalis Lipsky) and Eucalyptus (Eucalyptus camaldulensis Dehn.) veneers. Holz Roh Werkst 62, 218-220
4. BAL B.C., 2014: Some physical and mechanical properties of reinforced laminated veneer lumber. *Construction and Building Materials*, *68*, 120-126.
5. BALDWIN R. F., 1995: Plywood and veneer-based products, manufacturing practices, (Wood technology books ser). Miller Freeman, San Francisco
6. BAO Z., 2002: Structural composite lumber. In: APA engineered wood handbook, ed. Williamson T.G., MacGraw-Hill, Nowy Jork, USA.
7. BEDNAREK Z., PIENIAK P., OGRODNIK P., 2010: Wytrzymałość na zginanie i niezawodność kompozytu drewnianego LVL w warunkach podwyższonych temperatur. Zeszyty Naukowe SGSP, Szkoła Główna Służby Pożarniczej, (40), 5-17.
8. BORYSIUK P., 2016: Nowoczesne tworzywa drzewne materiałem budowlanym przyszłości. Biuletyn Informacyjny Ośrodka Badawczo-Rozwojowego Przemysłu Płyt Drewnopochodnych w Czarnej Wodzie, 57(3-4).
9. BORYSIUK P., KOZAKIEWICZ P., KRZOSEK S., 2023: Drzewne materiały konstrukcyjne. Wydawnictwo SGGW, Warszawa.
10. BURDURLU E., KILIC M., ILCE A. C., UZUNKAVAK O., 2007: The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech *(Fagus orientalis* L.) and lombardy poplar *(Populus nigra* L.). Construction and Building Materials, 21, 1720-1725
11. BUSTA H., HONESTY L., 2013: How It’s Made: Laminated Veneer Lumber and Parallel Strand Lumber. https://www.architectmagazine.com/technology/products/how-its-made-laminated-veneer-lumber-and-parallel-strand-lumber_o (access: 23.05.2024 r.)
12. BYCZEK M., BORYSIUK P., 2017: Impact of the veneer quality on the properties of the LVL. Annals of Warsaw University of Life Sciences - SGGW. Forestry and Wood Technology, 99/2017, 132-142
13. CAI Z., ROSS R.J., 2010: Mechanical Properties of Wood-Based Composite Materials. In: Wood Handbook, Wood as an Engineering Material. General Technical Report FPL–GTR–190, Forest Products Laboratory, United States Department of Agriculture Forest Service, Madison, Wisconsin

14. ÇAVUŞ V., ERSIN İ., 2023: Determination of Some Physical and Mechanical Properties of Parallel-strand Lumber Manufactured with Bamboo (Phyllostachys bambusoides). BioResources, 18 (4), 6802 – 6814.
15. CHUI Y., SCHNEIDER M., ZHANG H., 1994: Effects of resin impregnation and process parameters on some properties of poplar LVL. Forest Products Journal, 44 (7-8), s. 74-78
16. CHYBIŃSKI M., POLUS Ł., 2021: Experimental and numerical investigations of laminated veneer lumber panels. Archives of Civil Engineering, 67(3).
17. CHYBIŃSKI M., POLUS Ł., SZYMKUĆ W., 2021: Zastosowanie drewna klejonego warstwowo z fornirów LVL w budownictwie. Przegląd Budowlany, 92(5-6), 44-50.
18. ÇOLAK S., ÇOLAKOĞLU G., AYDIN I., 2007: Effects of logs steaming, veneer drying and aging on the mechanical properties of laminated veneer lumber (LVL). Building and Environment, 42, 93-98
19. DARMAWAN W., NANDIKA D., MASSIJAYA Y., KABE A., RAHAYU I., DENAUD L., OZARSKA B., 2015: Lathe check characteristics of fast growing sengon veneers and their effect on LVL glue-bond and bending strength. Journal of Materials Processing Technology, 215, 181-188
20. EHART R.J.A., STANZL-TSCHEGG S.E., TSCHEGG E.K., 1998: Fracture characteristics of PARALLAM® PSL in comparison to solid wood and particleboard. Wood science and technology, 32, 43-55.
21. ELLIS S., DUBOIS J., AVRAMIDIS S., 2007: Determination of Parallam® macroporosity by two optical techniques. Wood and fiber science, 27, 70-77.
22. GHANI A., LEE S.H., SABARUDDIN F.A., SAIFULAZRY S.O.A., PARIDAH M.T., 2022: Laminated veneer lumber from oil palm trunk. Oil Palm Biomass for Composite Panels: Fundamentals, Processing, and Applications, 241 – 251
23. GILBERT B. P., BAILLERES H., ZHANG H., MCGAVIN R. L., 2017: Strength modelling of Laminated Veneer Lumber (LVL) beams. Construction and Building Materials, 149, 763-777
24. HAKKARAINEN J., 2020: LVL Handbook. Federation of the Finnish Woodworking Industries, Finland, https://woodworkingindustries.fi/
25. HOADLEY R.B., 2000: Understanding wood. A craftsman's guide to wood technology. The Taunton Press, Inc., USA.
26. HRÁZSKÝ J., KRÁL P., 2010: Analysis of selected mechanical properties of construction wood KVH and Parallam 2.0 E. Wood Industry/Drvna Industrija, 61(1).
27. KAWAI S., WANG Q., SASAKI H., TANAHASHI M., OHOTA C., 1993: Properties of compressed Laminated Veneer Lumber produced by steam pressing. Mokuzai-Gakkaishi (Journal of the Japan Wood Research Society), 39 (5), s. 550-554, Japonia
28. Kawai, S., Wang, Q., Sasaki, H., Tanahashi, M., & Ohota, C. (1993). Properties of compressed laminated veneer lumber produced by steam pressing.
29. KIMMEL J., JANOWIAK J., 1995: Red maple and yellow-poplar LVL from ultrasonically rated veneer. Forest Products Journal, 45 (7-8), s. 54-58
30. KRAM D., 2011: Drewno naturalnym surowcem współczesnego budownictwa. Czasopismo techniczne. Wydawnictwo Politechniki Krakowskiej.
31. KRAM D., 2015: Materiały budowlane na bazie drewna–obecny stan wiedzy i możliwości stosowania. Przegląd budowlany, 86.
32. Li M., He M., Li Z., 2023: Size effects on the bending strength of Chinese larch pine laminated veneer lumber. European Journal of Wood and Wood Products, 81 (5), 1211 - 1222
33. Li M., He M., Li Z., Yun X., 2024: Flexural behavior of LVL made from Australian radiata pine. Structures, 61, 106014

34. MASSIJAYA M.Y., NUGROHO S.S., 2018: Basic properties of parallel strand lumber from oil palm trunk wastes (Elaeis guineensis Jacq.) bonded by isocyanate adhesive. IOP Conference Series: Earth and Environmental Science, 196 (1), 012026.
35. MORADPOUR P., BEHNIA M., PIRAYESH H., SHIRMOHAMMADLI Y., 2019: The effect of resin type and strand thickness on applied properties of poplar parallel strand lumber made from underutilized species. European Journal of Wood and Wood Products, 77 (5), 811 – 819.
36. NICEWICZ D., BORYSIUK P., PAWLICKI J., 2003: Tworzywa drzewne specjalnego przeznaczenia, Wydawnictwo SGGW, Warszawa
37. OH S., 2022: Experimental Study of Bending and Bearing Strength of Parallel Strand Lumber (PSL) from Japanese Larch Veneer Strand. Journal of the Korean Wood Science and Technology, 50 (4), 237 - 245.
38. OPACIC L., 2016: Developing simulation models to improve the production process of a parallam mill. Doctoral dissertation, University of British Columbia.
39. OZELTON E.C., BAIRD J.A., 2002: Timber designers' manual. Blackwell Science Ltd. A Blackwell Publishing Company, UK
40. PN-EN 14279+A1:2009 Drewno klejone warstwowo z fornirów (LVL) -- Definicje, klasyfikacja i wymagania
41. PN-EN 310:1994 Płyty drewnopochodne -- Oznaczanie modułu sprężystości przy zginaniu i wytrzymałości na zginanie.
42. PN-EN 317:1999 Płyty wiórowe i płyty pilśniowe -- Oznaczanie spęcznienia na grubość po moczeniu w wodzie.
43. PN-EN 323:1999 Płyty drewnopochodne - Oznaczanie gęstości.
44. PU J., TANG R. C., 1997: Nondestructive evaluation of modulus of elasticity of southern pine LVL: effect of veneer grade and relative humidity. Wood and Fiber Science, 29 (3), s. 249-263.
45. QIU Z., WANG J., FAN H., LI T., 2020a: Anisotropic mechanical properties and composite model of parallel bamboo strand lumbers. Materials Today Communications, 24, 101250.
46. QIU Z., WANG J., HE H., FAN H., 2020b: First-order anisotropic beam model and failure criterion for flexural parallel bamboo strand lumbers. Construction and Building Materials, 263, 120125.
47. RAMMER D.R., ZAHN J.J., 1997: Determination of Ylinen's parameter for Parallel-Strand Lumber. Journal of Structural Engineering, 10 (123), s. 1409.
48. SASAKI H., ABDULLAHI A. A., 2016: Lumber: Laminated Veneer. In book: Reference Module in Materials Science and Materials Engineering
49. SHUPE T. F., HSE C. Y., GROOM L. H., CHOONG E. T., 1997: Effect of silvicultural practice and veneer grade lay-up on some mechanical properties of loblolly pine LVL. Forest Products Journal, 47 (9), s. 63-69.
50. STARK N.M., CAI Z., CARLL C., 2010: Wood-based composite materials panel products, glued-laminated timber, structural composite lumber, and wood–nonwood composite materials. Wood handbook: wood as an engineering material, 1, 11-20.
51. STEPINAC M., RAJČIĆ V., HUNGER F., VAN DE KUILEN J.W.G., 2016: Glued-in rods in beech laminated veneer lumber. European Journal of Wood and Wood Products, 74 (3), 463 - 466
52. SZEŁEMEJ Z., TOMUSIAK A., 1995: Metoda wytwarzania, właściwości i zastosowanie materiału Parallam PSL. 9 Konferencja Naukowa WTD SGGW „Technologie wyrobów z drewna i materiałów drewnopochodnych dla budownictwa". Warszawa 14.11.1995 r.
53. VLADIMIROVA E., GONG M., 2022: Veneer-based engineered wood products in construction. Engineered Wood Products for Construction. IntechOpen.

54. WANG B. J., DAI CH., 2013: Development of structural laminated veneer lumber from stress graded short-rotation hem-fir veneer. Construction and Building Materials, 47, 902-909
55. WHITE R.H., 2000: Charring rate of Composite Timber Products. In: The proceedings of Wood and Fire Safety 2000 (part one), ed. Osvald A., Technical University of Zvolen, Slovakia.
56. YOUNGQUIST J. A., 1978: Production and marketing opportunities for parallel – laminated veneer products. Reprint from Proceedings of the sixth Plywood Clinic, Portland Oregon, March 1978
57. ZANG H., CHUI Y., SCHNEIDER M., 1994: Compression control and its significance in the manufacture and effects on properties of poplar LVL. Wood Science and Technology, 4, s. 285 – 290
58. ZHOU K., LI H., HONG C., ASHRAF M., SAYED U., LORENZO R., CORBI I., CORBI O., YANG D., ZUO Y., 2021: Mechanical properties of large-scale parallel bamboo strand lumber under local compression. Construction and Building Materials, 271, 121572.
59. ZHOU K., REN Z., SHUOSUN C., NA B., 2022: The study on glue-applying methods and hot-pressing technology of parallel strand lumber. Wood Research, 67 (4), 661 – 670.
60. MORADPOUR P., BEHNIA M., PIRAYESH H., SHIRMOHAMMADLI Y., 2019: The efect of resin type and strand thickness on applied properties of poplar parallel strand lumber made from underutilized species. European Journal of Wood and Wood Products (2019) 77:811–819

Streszczenie: *Tworzywa równoległowłókniste wykonane z forniru sosnowego.* W ramach badań wytworzono 12 belek w 3 różnych wariantach szerokości fornirów o gr. 3mm przy zastosowaniu kleju poliuretanowego. Wykorzystano fornir w postaci pełnych arkuszy (LVL) o szerokości 120 mm oraz w postaci pasm fornirów (PSL) o szerokości 1/2" (12.5 mm) i 1" (25 mm). Sposób i parametry wytwarzania były jednakowe dla każdego wariantu. Przeprowadzono analizę wpływu różnych szerokości forniru na wybrane właściwości mechaniczne i fizyczne otrzymanych materiałów równoległówłóknistych: gęstość i profil gęstości, moduł sprężystości (MOE), wytrzymałość na zginanie statyczne (MOR), wytrzymałość na ścinanie, nasiąkliwość (WA) oraz spęcznienie na grubość (TS). Wskazano, ze najkorzystniejszymi parametrami wytrzymałościowymi i fizycznymi charakteryzuje się materiał wytworzony z pełnych arkuszy forniru (LVL). Zmniejszenie szerokości surowca wpływa na spadek właściwości wytrzymałościowych materiałów PSL, przy czym na ogół spadek ten, w porównaniu do LVL, jest statystycznie istotny jedynie w przypadku surowca o szerokości 12.5 mm. Rodzaj surowca wykazuje statystycznie istotny wpływ na badane właściwości, przy czym procentowy poziom tego wpływu jest na ogół niższy niż wpływ innych czynników nie analizowanych w trakcie badań.

Słowa kluczowe: LVL, PSL, fornir sosnowy, właściwości wytrzymałościowe, właściwości fizyczne

Corresponding author:

Paweł Bączek,
ul. Nowoursynowska 159, budynek 34
02-787 Warszawa, Poland
email: s201803@sggw.edu.pl