Properties of Laminated Strand Lumber Made with European Larch and Norway Spruce: A Preliminary Study

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This study investigated the feasibility of substituting Norway spruce (*Picea abies*) with European larch (*Larix decidua*) in structural applications, specifically in laminated strand lumber (LSL). Four types of experimental LSL panels were manufactured from these species. Two reference panels were produced exclusively from a single species: larch (LSL-L) and spruce (LSL-S). A third variant (LSL-L:S) consisted of a homogeneous mixture of 60% spruce and 40% larch strands. The fourth configuration (LSL-L:S:L) was designed as a mechanically differentiated three-layer structure, with larch strands in the surface layers. The mechanical and physical properties of the panels were evaluated by determining bending strength (MOR), modulus of elasticity (MOE), internal bond strength (IB), compression strength, water absorption (WA), and thickness swelling (TS). Statistically significant differences among panel types were identified for density and IB strength. The LSL-L:S:L configuration exhibited a significantly higher IB value (0.66 MPa) compared with the other variants. No statistically significant differences were observed in bending. Nevertheless, panels manufactured entirely from larch strands (LSL-L) and those containing 40% larch (LSL-L:S) demonstrated higher mean values than the spruce reference panels (LSL-S) in both bending and compression tests. Significant differences were also detected for WA and TS.

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INTRODUCTION

Laminated strand lumber (LSL) is an engineered wood-based composite composed of oriented strands typically 0.5 to 2.0 mm in thickness and less than 300 mm in length. The strands are blended with adhesive and consolidated under heat and pressure to form structural panels (Zhang and Lu 2014). The resulting product can reach thicknesses of up to 90 mm and is widely used in horizontal and vertical framing applications. Because of its favorable mechanical performance, LSL is suitable for various structural and carpentry elements (Stark *et al.* 2010; Wang *et al.* 2015; Hasan *et al.* 2023). The properties of LSL are influenced by several factors, including wood species, adhesive type, panel density, degree of strand orientation, the quality of the raw material, and manufacturing process.

Fast-growing species are commonly utilized in LSL production. Previous studies have investigated the use of alternative species for this purpose. Weyerhaeuser (2014) reported the manufacture of LSL panels from aspen (*Populus Tremula* L.) and southern pine (*Pinus* spp.). Similarly, Özçifçi *et al.* (2010) examined LSL production from aspen (*Populus tremula* L.), while Bayat-Kashkoli (2014) evaluated the applicability of poplar (*Populus deltoides*) and paulownia (*Paulownia fortunei*) for panel manufacturing. Polymeric 4,4′-diphenylmethane diisocyanate (pMDI) is the adhesive most frequently used in LSL production (Papadopoulos *et al.* 2002; Pizzi 2017). Although pMDI may excessively penetrate wood substrates, potentially leading to poor bondline formation (Pizzi 2015), it provides high dry and wet bond strength, strong tolerance to substrate moisture, and rapid curing (Chen and Yan 2018).

In addition to technological considerations, the long-term availability and sustainability of raw materials have become increasingly important factors in engineered wood production. The reliance of LSL manufacturing on specific softwood species, particularly Norway spruce, raises concerns in regions where climatic instability threatens forest productivity and species composition. Consequently, the identification of alternative wood species that are both mechanically suitable and ecologically resilient represents a critical research objective.

Recent climate change–related disturbances, particularly drought, have intensified growth variability and mortality in forest stands due to desiccation and insect damage. Historically, the impacts of climate change on forests were often underestimated (Spiecker 2000). In Central Europe, Norway spruce has shown high vulnerability to extreme climatic events. A potential partial substitute is Douglas fir (*Pseudotsuga menziesii*), which demonstrates better performance at lower altitudes and in areas with reduced precipitation (Podrázský 2015). In the Czech Republic, Norway spruce (*Picea abies* L. Karst) accounts for approximately 50% of forested area and represents the principal commercial species, although its natural occurrence is estimated at only about 11% (Mansfeld 2011). This discrepancy indicates that a substantial proportion of spruce stands are located outside their optimal ecological range. European larch (*Larix decidua*) has considerable economic importance in Europe, and its relevance is expected to increase in response to the projected decline of Norway spruce (Zeidler *et al.* 2022). Larch exhibits high resistance to wind and relatively strong tolerance to air pollution, frost fluctuations, and drought conditions associated with climate change (Vacek *et al.* 2021). As concluded by Reh *et al.* (2024), larch and its bark have significant potential for composite applications. The study shows that larch bark composites can be tested and optimized using experimental methods, achieving excellent performance. Pazio and Boruszewski (2020) investigated the differences in particleboards made from combinations of wood fibers and particles, using plantation-grown larch and pine as reference materials. Larch boards exhibited higher IB values at all fiber-to-particle ratios. Additionally, the thickness swelling of larch boards was lower after 2 and 24 h in four out of five tested cases. However, bending properties were generally superior in pine boards, with larch boards showing better bending only in the boards made entirely from larch fibers.

In response to climate change–induced shifts in forest composition, numerous research initiatives have focused on ensuring a sustainable supply of raw materials and on identifying suitable substitutes for traditionally used wood species in wood-based panel production. Akrami *et al.* (2014) investigated the influence of beech and poplar wood as raw materials for OSB boards. These authors also examined different face/core ratio combinations. Their results indicate that the boards with 40% poplar in the core layer exhibited the best properties for both investigated densities. Pipíška *et al.* (2024) compared nine underutilized wood species in OSB boards, including larch and spruce. Larch boards showed better performance than spruce in terms of thickness swelling, whereas most mechanical properties were superior in spruce boards.

In Europe, a particularly critical issue over recent decades has been the deteriorating condition of Norway spruce stands, especially in Central European regions. This development may lead to shortages of structural timber, despite the continuously growing demand associated with timber-based construction. In addition to the potential deficit in construction lumber, the reduced availability of spruce may also affect the raw material supply for conventional wood-based panel manufacturing. Addressing these interconnected challenges requires the evaluation of alternative species that can simultaneously fulfill structural performance requirements and contribute to long-term resource sustainability. The LSL represents a potential substitute for traditional spruce sawn timber in timber building applications. At the same time, European larch may constitute a more climate-resilient and sustainable raw material for engineered wood products. Therefore, the objective of this study was to compare the physical and mechanical properties of LSL panels manufactured entirely from spruce or larch strands, as well as from their combinations. The presented study provides a more comprehensive analysis of the results measured within the framework of two master's theses, namely Šulák (2023) and Jadrný (2023).

EXPERIMENTAL

Materials and Preparation of Strands

Logs of European larch (*Larix decidua*) and Norway spruce (*Picea abies*) with small diameters of 100 to 150 mm were obtained from the ŠLP Křtiny, a forest enterprise of Mendel University in Brno. The logs were processed within 14 days of harvesting to preserve a high initial moisture content (MC), which facilitates debarking and strand production. Immediately after delivery, the logs were debarked and cross-cut into 300 mm lengths. The mean density of the spruce and larch wood used for the LSL panels was measured as 392 ± 12 and 470 ± 37 kg/m³, respectively. Stranding was performed using a knife-ring flaker MSF/MRZ 1400 SKR60 (Dieffenbacher, Czech Republic).

Fig. 1. Two fractions of strands that were used for LSL productions

To maintain elevated MC levels for improved processing efficiency, all preparatory operations were conducted without delay. The produced strands were subsequently dried at 80 °C to a target MC of 6 to 8%. After drying, the strands were screened into two size fractions (Fig. 1): (i) a coarse fraction retained on a 10 mm screen and (ii) a medium fraction passing through a 10 mm screen but retained on a 5 mm screen. Fine particles (dust fraction) were excluded from LSL manufacturing.

Strand MC was determined prior to panel production using a MA 50/1.R moisture analyzer (RADWAG, Poland). The mean MC of the strands was 7.1%, and this value was used for mat weight calculations. The average strand thickness was 0.74 mm for larch and 0.89 mm for spruce.

Strands were bonded with polymeric 4,4′-diphenylmethane diisocyanate (pMDI) resin (BorsodChem, Hungary) 100% active content (solvent-free) and a viscosity of 170 to 230 mPa·s. Additionally, a water-based paraffin wax emulsion (SVH–60; Dřevozpracující družstvo, Czech Republic) with a solid content of 60 ± 2% and a viscosity of approximately 24 mPa·s was applied.

Manufacturing LSL Panels

Four types of experimental LSL panels were manufactured (Table 1). This table presents the exact weight of strands and other input materials used in the manufacturing process. The stated weights include a small surplus to compensate for potential material losses during mat forming and resin application. The panel designations were defined as follows: LSL-S and LSL-L represented reference (control) panels, where LSL-S consisted of single-layer panels manufactured entirely from spruce strands, and LSL-L consisted of single-layer panels manufactured entirely from larch strands. The LSL-L:S variant comprised single-layer panels produced from a homogeneous mixture of 40% larch and 60% spruce strands. The LSL-L:S:L configuration was designed as a mechanically differentiated three-layer structure, with larch strands in the surface layers and spruce strands in the core layer.

The shelling ratio (surface:core) of the three-layer panels was 40:60. This weighing procedure was selected to maintain the same volume of input strands. Therefore, the strand mass and the target panel density differed depending on the density of the wood species used in each board. This approach was adopted to achieve a comparable level of densification for both raw materials. The densification level was set at approximately 1.6 times the density of the respective solid wood species.

Two strand size fractions were used for panel production: 90% of the furnish consisted of the coarse fraction, and 10% of the small fraction. These two-strand fractions are shown in Fig. 1. Adhesive application was performed in a laboratory drum blender. The pMDI resin was applied at 3% based on oven-dry strand weight, while the wax emulsion was added at 0.5% based on oven-dry strand weight. Strand orientation was achieved using a wooden forming box equipped with aluminum sheets (Fig. 2). The orientation procedure and adhesive application were consistent across all panel variants. The mechanically differentiated variant (LSL-L:S:L) was formed in three separate layers, with each layer individually sprayed and formed prior to assembly.

Table 1. Description of Component Composition for the Manufacture of Panels

LSL Type	Spruce (g)		Larch (g)		pMDI Resin (g)	Wax (g)	Adhesive-coated Strands (g)	Target Density (kg/m³)
	Small Strands	Large Strands	Small Strands	Large Strands				
LSL-S	921	8290			258	86	8948	644
LSL-L			1090	9810	306	102	10588	761
LSL-L:S	593	5339	395	3559	277	92	9604	703
LSL-L:S:L	579	5200	4456	4102	277	92	9604	703

The panels were hot-pressed using a laboratory press HL400 (Strozatech s.r.o., Czech Republic) to a target thickness of 30 mm. The final board dimensions were 800 mm (length) × 500 mm (width). Pressing parameters were as follows: maximum specific pressure of 3.5 MPa, press temperature of 180 °C, and pressing time of 540 s (9 min).

Testing Procedures

Physical properties

The MC of panels was determined gravimetrically in accordance with EN 322 (1993). Measurements were performed on specimens with nominal dimensions of 50 mm × 50 mm. Panel density was determined according to EN 323 (1994). The vertical density profile was measured using a DPX300-LTE densitometer (IMAL, Italy). Density measurements were recorded at increments of 0.05 mm across the entire thickness of the specimen. Specimens used for density profile analysis had dimensions of 50 mm × 50 mm × 30 mm. Based on the obtained density profiles, statistically significant differences in maximum surface density and minimum core density were evaluated among the panel groups. A total of eight specimens per panel type were analyzed for density profile determination.

Fig. 2. Equipment for strands orientation

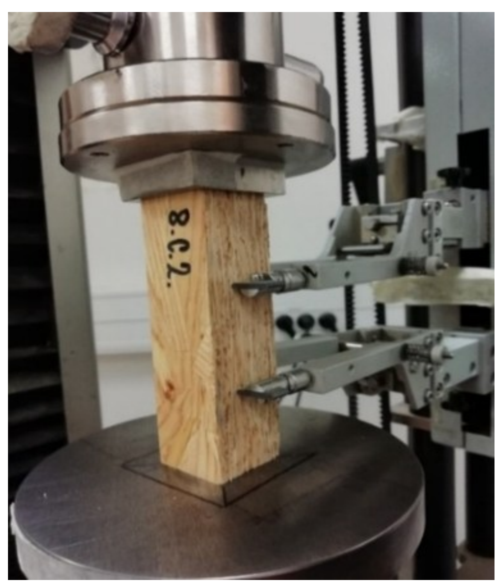

Fig. 3. Testing specimen on compression strength by Zwick Z050

Mechanical properties

After conditioning at 20 °C and 65% relative humidity (RH), the panels were cut into test specimens. Bending strength (MOR) and modulus of elasticity (MOE) were evaluated in both flatwise and edgewise configurations in accordance with EN 310 (1995). Compression strength was determined according to ASTM D1037 (1999) using specimens with dimensions of 30 mm × 30 mm × 105 mm (Fig. 3). Internal bond (IB) strength was measured in accordance with EN 319 (1994) using specimens with nominal dimensions of 50 mm × 50 mm. Mechanical properties were determined using a Zwick Z050 universal testing machine (ZwickRoell, Ulm, Germany). For better comparison, the mechanical properties were normalized by dividing the measured values by the density of the respective specimens. For clearer presentation and comparison of the results, the calculation was performed using density expressed in g/cm^3.

Wood-water relations

Thickness swelling (TS) and water absorption (WA) were determined using specimens with nominal dimensions of 50 mm × 50 mm in accordance with EN 317 (1993). Measurements were conducted after 24 h, 48 h, and 7 days of immersion in water.

Statistical analysis

The experimental data were statistically analyzed using Statistica 12 software (Statistica; StatSoft, Tulsa, OK, USA). One-way analysis of variance (ANOVA) was applied to evaluate differences among panel groups, followed by Tukey's honestly significant difference (HSD) *post-hoc* test for pairwise comparisons. Due to an unequal number of samples in the bending test datasets, non-parametric statistical methods were employed for these properties. Specifically, differences were assessed using the Kruskal–Wallis ANOVA, followed by multiple comparisons based on the Kruskal–Wallis test. The results of the One-way ANOVA and the Kruskal–Wallis ANOVA are summarized in Tables A1 to A3 in the Appendix.

RESULTS AND DISCUSSION

Density, Density Profile, and Moisture Content

The MC of the panels ranged from 7.7% to 7.9%, with no statistically significant differences observed among the panel groups (Table 2). In terms of density, the lowest mean value of 576 kg/m^3 was recorded for the LSL-S panels (manufactured entirely from spruce), and this value differed significantly from those of the other panel types and this value was significantly lower than those of the other panel types. The highest mean density (669 kg/m^3) was observed for the LSL-L panels produced exclusively from larch. The incorporation of larch strands into the panel composition resulted in an increase in panel density, which can be attributed to the inherently higher density of larch wood compared with spruce. These density values are slightly lower than those reported in previous studies; for instance, Moses *et al.* (2003) reported a density of 689 kg/m^3 for aspen LSL, while Denizli (1997) mentioned a value of 685 kg/m^3. Additionally, the technical data for TimberStrand LSL (Weyerhaeuser 2021).

Table 2. Density and MC of Manufactured Panels

LSL Type	Density (kg/m³)	MC (%)
LSL-S	576 (28) B	7.9 (0.7) A
LSL-L	669 (58) A	7.7 (0.6) A
LSL-L:S	631 (33) A	7.8 (0.6) A
LSL-L:S:L	643 (37) A	7.8 (0.8) A
Means with the same letter in the column do not differ statistically by Tukey´s test (α = 0.05). Numbers in parentheses represent the standard deviation.		

The vertical density profiles of the LSL panels are presented in Fig. 4. All panel types exhibited a typical density distribution pattern consistent with that described by Painter *et al.* (2006), characterized by higher densities in the surface layers and lower density in the core layer (Winistorfer *et al.* 2000). The LSL-S panels, manufactured entirely from spruce, showed the lowest overall density profile, corresponding to their lower mean panel density. In contrast, the LSL-L panels produced exclusively from larch exhibited the highest density values throughout the thickness. Notably, in the mixed-species variants (LSL-L:S and LSL-L:S:L), the difference between surface and core densities was more pronounced than in the reference panels. Statistical evaluation using ANOVA followed by Tukey's HSD test. While the ANOVA indicated a significant effect of the group composition on surface density ($p = 0.041$), the subsequent Tukey's HSD post-hoc test revealed no significant differences between the individual groups. However, the core density of the LSL-S panels was significantly lower than that of the other panel types.

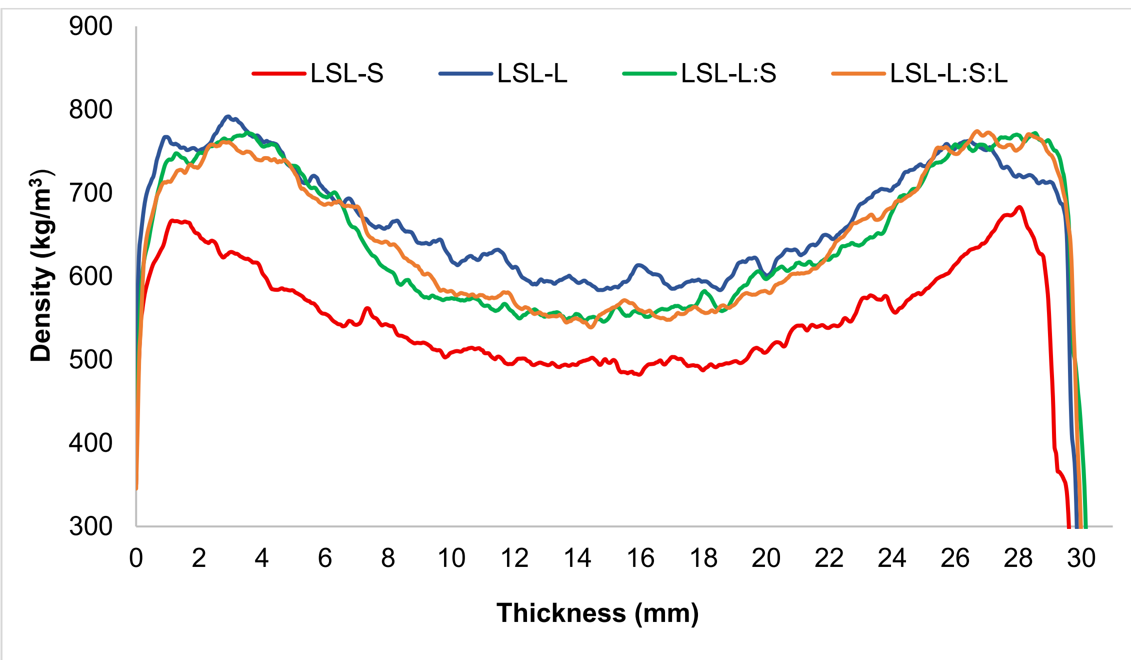

Fig. 4. Density profiles of LSL panels

Mechanical Properties of LSL Specimens

The bending properties are summarized for bending strength (MOR) and MOE in Figs. 5 and 6, respectively. No statistically significant differences ($p > 0.05$) were detected among the panel groups for MOR or MOE, irrespective of testing configuration (edgewise or flatwise). A statistically significant difference was detected only in the case of MOE for the flatwise orientation ($p = 0.045$), however, the subsequent multiple comparisons of mean ranks did not reveal any significant differences between the specific groups. The LSL-L panels, manufactured entirely from larch, exhibited the highest mean MOR and MOE values, which can likely be attributed to their higher average density. In contrast, the lowest MOR and MOE values were recorded for the LSL-S panels produced solely from spruce. These panels also showed small variability in bending properties. When comparing the reference panels with the mixed-species variants, differences between edgewise and flatwise bending behavior were observed. The percentage differences in MOR between LSL-L:S:L and LSL-S were 26% (flatwise) and 23% (edgewise), representing a relatively small difference of 3% between configurations. A similar trend (3%) was observed for MOE. However, when comparing LSL-L with the mixed-species panels (LSL-L:S and LSL-L:S:L), larger discrepancies were found, particularly in edgewise bending. In flatwise MOR, the percentage differences were 1.3% (LSL-L *vs.* LSL-L:S) and 3.2% (LSL-L *vs.* LSL-L:S:L). In contrast, for edgewise MOR, the differences increased substantially to 23.4% (LSL-L *vs.* LSL-L:S) and 19.4% (LSL-L *vs.* LSL-L:S:L). This pattern suggests that heterogeneous species composition may have a greater influence on edgewise bending performance than on flatwise bending. For comparison, Denizli-Tankut *et al.* (2004) reported MOE and MOR values of 11,851 MPa and 47.4 MPa, respectively. Although the MOR values obtained for LSL-L panels in the present study were comparable, direct comparison is limited due to differences in specimen dimensions and testing standards. Following the density-normalization of the data (Table 3), no statistically significant differences were detected among the groups, and the overall trends in the results remained highly consistent. Notably, the difference between the spruce-based LSL-S and the other groups is worth mentioning; the values for LSL-S closely approached those of the variants manufactured from a combination of wood species, although it still exhibited the lowest bending properties. On the other hand, the highest density-normalized values were achieved by LSL-L.

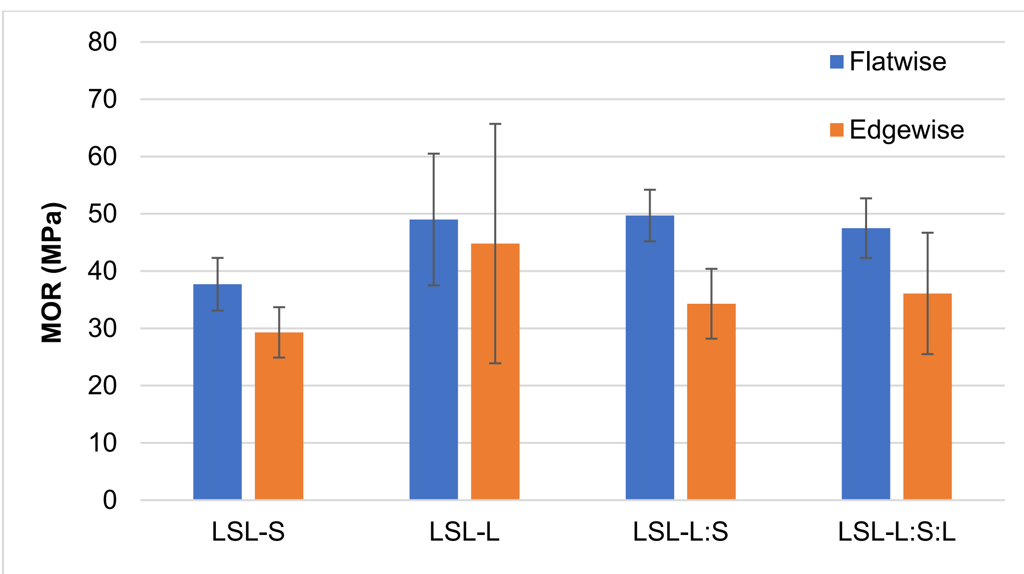

Fig. 5. MOR of LSL panels manufactured from larch and spruce wood (error bars represent standard deviation)

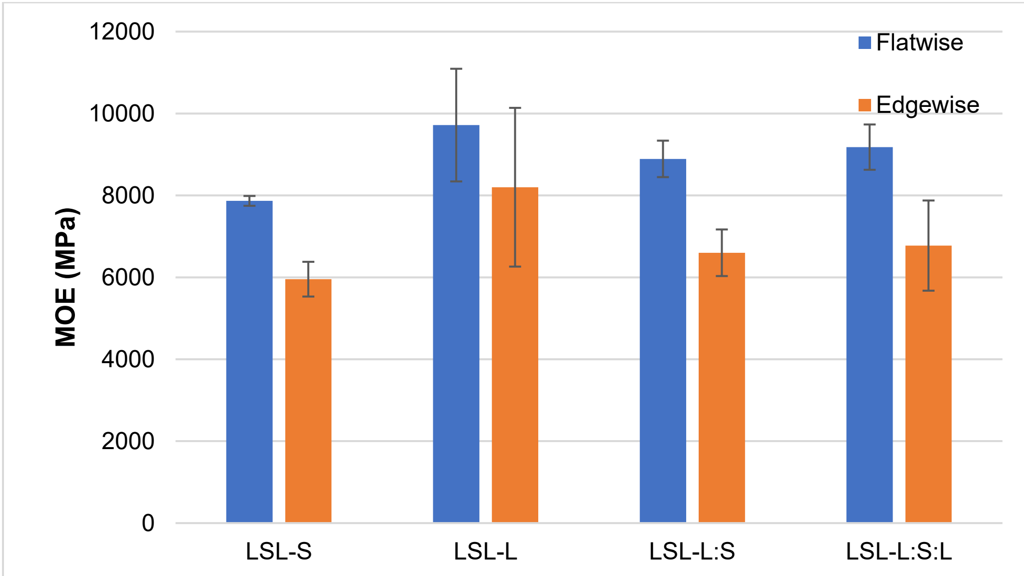

Fig. 6. MOE of LSL panels manufactured from larch and spruce wood (error bars represent standard deviation)

Table 3. Average Values of the Bending Properties Normalized by Density

Type of specimens	Flatwise		Edgewise	
	MOR/ρ [MPa (g/cm³)]	MOE/ρ [MPa (g/cm³)]	MOR/ρ [MPa (g/cm³)]	MOE/ρ [MPa (g/cm³)]
LSL-S	62.9 (7.6) A	13128 (306) A	52.8 (8.3) A	10764 (959) A
LSL-L	71.1 (12.1) A	14166 (1022) A	66.8 (28.0) A	12396 (1832) A
LSL-L:S	76.3 (6.5) A	13657 (481) A	55.7 (8.1) A	10770 (703) A
LSL-L:S:L	70.7 (6.3) A	13687 (548) A	57.8 (14.4) A	10921 (1250) A

Means with the same letter in the column do not differ statistically by the Kruskal-Wallis test (α = 0.05). Then numbers in parentheses represent the standard deviation.

Table 4 presents the mean values of compression strength and compressive modulus. A statistically significant difference was observed in compression strength, with the LSL-L:S:L specimens exhibiting significantly higher strength compared to the pure spruce LSL-S samples ($p = 0.022$). However, this significant difference disappeared when the results were converted to specific values (normalized to density). No significant differences were observed among the specific compression strength values ($p > 0.05$). This suggests that the layer composition with larch face strands enhances the compressive resistance of the composite. The highest average compression strength and compressive modulus were recorded for the LSL-L:S:L panels. In contrast, the LSL-L panels (manufactured entirely from larch) exhibited relatively high variability in compression properties. When expressed as percentage differences relative to the spruce reference panels (LSL-S, produced from spruce), the compression strength of LSL-L increased 8.4%, while the compressive modulus increased only 0.45%. For the LSL-L:S panels, the compressive modulus increased 12.1% and the compression strength by 11.0%. The most pronounced improvement was observed for the LSL-L:S:L configuration, where the compressive modulus increased 14.0%, and the compression strength increased 29.7% compared with the spruce reference.

Table 4. Average Values of the Compression Strength of LSL

LSL Type	Compression Strength (MPa)	Compressive Modulus (MPa)	Compression Strength/ρ [MPa /(g/cm³)]	MOE/ρ [MPa /(g/cm³)]
LSL-S	26.35 (3.98) A	9118 (1609) A	42.38 (3.7) A	14724 (2455) A
LSL-L	28.49 (9.47) A, B	9159 (2384) A	41.07 (9.8) A	13318 (2267) A
LSL-L:S	29.19 (4.05) A, B	10221(1023) A	42.4 (4.5) A	14981 (1281) A
LSL-L:S:L	34.11 (3.74) B	10394 (1702.) A	47.6 (3.2) A	14515 (1965) A
Means with the same letter in the column do not differ statistically by Tukey´s test (α =0.05). Numbers in parentheses represent the standard deviation.				

The mean IB strength values are summarized in Table 5. The LSL-L:S:L panels exhibited significantly higher IB strength compared with the other panel types. This result can be interpreted in conjunction with the vertical density profile (Fig. 4). Although the core layer of the LSL-L:S:L configuration consisted of spruce strands, the core density was significantly higher than that of the LSL-S reference panels. This indicates a higher degree of densification in the middle layer of the LSL-L:S:L panels. This observation is consistent with findings reported by Pizzi *et al.* (2020), who demonstrated that increased core density positively influences IB strength due to improved inter-particle contact and bonding efficiency. In comparison with previously published data, the IB values obtained in the present study were generally lower. Bayatkashkoli and Faegh (2014) reported IB values of 0.98 MPa for LSL panels. According to technical data for the commercial product TimberStrand, the declared IB value is approximately 0.55 MPa. Although most of the measured values in this study were lower than those reported in industrial production, it should be noted that laboratory-scale manufacturing conditions differ substantially from industrial processes. Notably, the IB strength of the LSL-L:S:L panels exceeded the reported value for TimberStrand by approximately 20%. After accounting for density and converting to specific values, the Internal Bond (IB) strength results remained very similar. The highest values were achieved by the LSL-L:S:L specimens, while the lowest IB strength was observed in the LSL-S group. The remaining two groups exhibited mutually similar results, consistent with the standard IB strength findings. Furthermore, the Tukey HSD post-hoc test revealed a significant difference only for the LSL-L:S:L group. Overall, the conversion to specific values did not alter the ranking or the sequence of the IB results.

Table 5. Average Values of the Internal Bond Strength of LSL

Type of LSL	IB (MPa)	IB/ρ [MPa (g/cm³)].
LSL-S	0.31 (0.06) A	0.55 (0.09) A
LSL-L	0.43 (0.15) A	0.64 (0.20) A
LSL-L:S	0.43 (0.12) A	0.67 (0.12) A
LSL-L:S:L	0.66 (0.21) B	1.01 (0.23) B
Means with the same letter in the column do not differ statistically by Tukey´s test (α = 0.05). Numbers in parentheses represent the standard deviation.		

Wood-water Relations Results

The results for TS are presented in Fig. 7. Substantial differences were observed among the panel types, particularly for TS. After 24 h of water immersion, several statistically significant differences in TS were detected. A significant difference was found between the LSL-S panels (manufactured entirely from spruce) and the LSL-L panels (manufactured entirely from larch), with LSL-L exhibiting significantly higher TS values. Significant differences were also observed between LSL-L and LSL-L:S:L, as well as between LSL-L:S and LSL-L:S:L. In both comparisons, the LSL-L:S:L panels demonstrated lower TS. After prolonged immersion (48 h and 7 days), significant differences persisted between LSL-L and LSL-S, as well as between LSL-L and the mixed-species panels (LSL-L:S and LSL-L:S:L). No significant difference was found between the two mixed configurations (LSL-L:S and LSL-L:S:L). Both mixed panel types exhibited significantly lower TS values than the larch reference panels. Overall, an increasing proportion of larch in the panel composition was associated with a significant increase in TS after 48 h and 7 days of immersion.

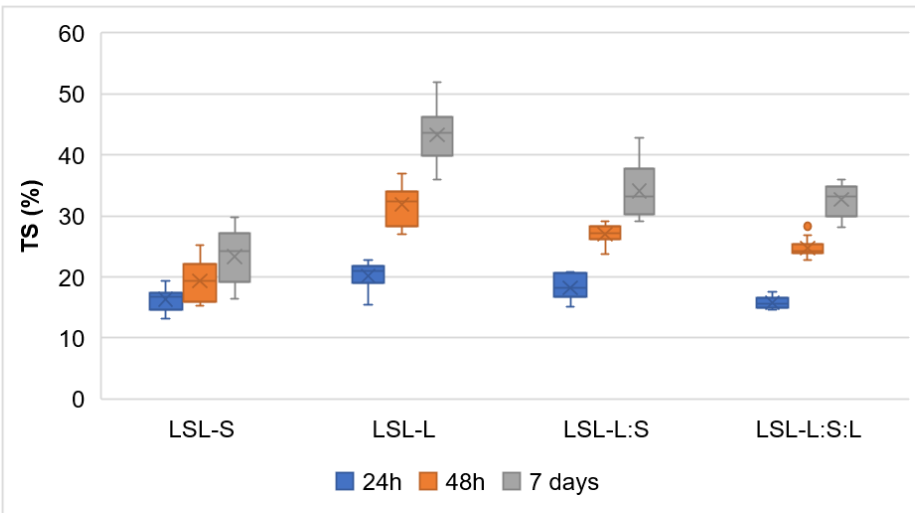

Fig. 7. Thickness swelling of manufactured LSL panels

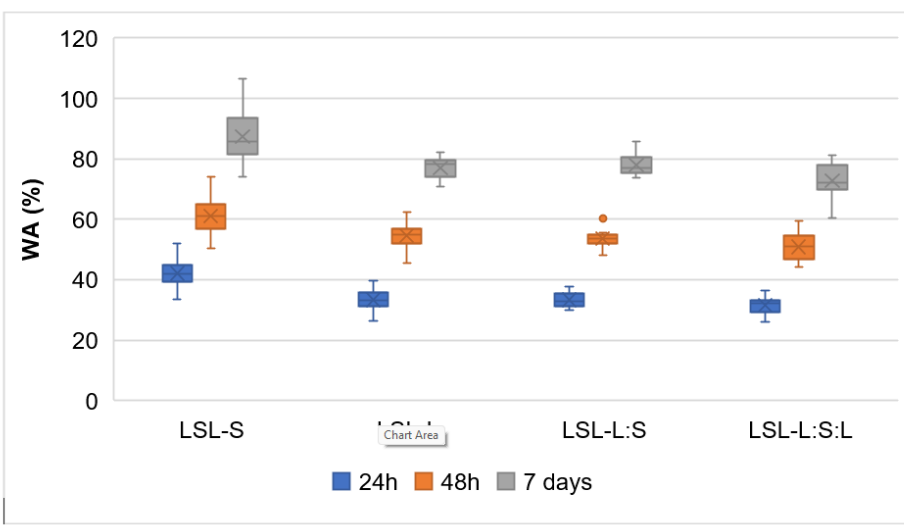

Fig. 8. Water absorption of manufactured LSL panels after 24, 48 hours, and 7 days

Figure 8 shows results of water absorption (WA). Similar trends were observed across all immersion periods. Statistically significant differences were identified only for the spruce reference panels (LSL-S), which exhibited significantly higher WA than the other panel types. No significant differences were found among the remaining groups. These results indicate that the incorporation of larch strands reduced WA. This finding is consistent with the results of Pipíška *et al.* (2024), who reported significantly lower WA values for OSB panels manufactured from larch compared with those produced from spruce after 24 h and 48 h of immersion.

Physical properties, such as TS and WA, are strongly influenced by the density of the raw material and the degree of densification achieved during pressing. Wood species also plays a critical role in dimensional stability (Hsu 2013). According to Bergman (2021), the dimensional change coefficients of larch are higher than those of spruce, which may partly explain the increased TS observed in panels with a higher larch content.

Synthesis of Results

This study has compared spruce and larch strands used in LSL composites. A less traditional approach was adopted by target-dosing the raw material to achieve an identical compression ratio. From an industrial and economic standpoint, this method holds significant merit as it directly compares equivalent amounts of input raw material. On the other hand, from a strictly scientific perspective, this approach introduces challenges because it compares materials with inherently different wood densities. To address this limitation and provide a transparent analysis, the results were also normalized to density, allowing for a more objective evaluation. This density-normalization of the mechanical properties altered the statistical significance only in the case of compressive strength (compression strength), where the previously significant difference among the groups disappeared. Specifically, the p-value for compression strength increased from 0.022 to 0.06 after the conversion. Furthermore, in the case of bending properties, the LSL-S specimens shifted closer to the other groups. From these findings, it can be inferred that the specimen density influenced certain results; for the spruce variant in particular, its lower density resulted in lower mechanical values. On the other hand, in the case of internal bond (IB) strength, the significant differences remained entirely unchanged. Beyond density, the anatomical differences and chemical composition of the utilized wood species—which were not further evaluated in this study—may also influence the final properties. Although both species are conifers, subtle anatomical variations exist, such as the specific presence of parenchyma cells in larch wood. From a bonding perspective, the contrasting resin content is particularly critical. Bergstedt and Lyck (2007) reported a resin content of 4.2% for larch (2.5% in sapwood and 4.6% in heartwood) compared to only 1.7% for Norway spruce. This higher extractive content can affect resin penetration and adhesive curing behaviour during pressing (Dunky 2003). Solt-Rindler *et al*. (2025) attributed a highly positive effect of pine extractives on bond strength. The removal of these substances had a significantly negative impact on the strength of the specimens. On the other hand, a similar collective of authors, Fašalek *et al*. (2025), achieved lower lap-shear strengths for larch bonded with pMDI compared to spruce and pine. This discrepancy suggests that larch extractives may not exert the same positive influence on bond strength development as those found in spruce or pine. It further implies an inherently lower bondability of larch, which could potentially negatively affect the performance. However, this assumption is not supported by the mechanical testing in the present study, as the inclusion of larch strands in the LSL composites did not result in any deterioration of the mechanical properties in virtually any tested configuration.

Another factor that may have contributed to the final results was the difference in strand thickness, which averaged 0.74 mm for larch and 0.89 mm for spruce. Strand thickness is a critical parameter in LSL manufacturing, as thinner strands provide a higher specific surface area for adhesive distribution. This fact could have manifested primarily in the face layers, where intensive densification facilitates excellent inter-strand contact, making the increased specific surface area beneficial. On the other hand, because the panels were manufactured using a target compression ratio approach, this increase in total strand surface area was likely negligible. This contrasts with the more conventional method of pressing to a target density, where the inherently different densities of the raw wood species would cause a pronounced discrepancy in the initial bulk volume of the particles before pressing, and consequently, a major difference in the total surface area available for adhesive application.

In connection with strand thickness, it is worth noting the findings of Jeong *et al.* (2008), who reported that strands with thicknesses of 0.794 mm and 1.91 mm did not differ significantly in terms of tensile MOE and ultimate tensile strength (UTS). Consequently, this implies that the variation in strand thickness within the present study may not have exerted a determining influence on the final mechanical performance of the panels. The issue of strand thickness and the layering of oriented strand boards (OSB) was also investigated by Li *et al.* (2026), who compared poplar strands with thicknesses of 0.3 and 0.5 mm. Regarding bending MOE and MOR, panels made from thinner strands exhibited superior mechanical performance. Conversely, in the case of internal bond (IB) strength, significantly better results were achieved by the variant with 0.5-mm-thick strands. Thickness swelling after 24 hours remained comparable for both thickness variations. The topics of strand thickness and adhesive interaction remain highly compelling and represent a logical continuation for future research, as the data presented in this study do not allow for a comprehensive evaluation of these confounding factors.

CONCLUSIONS

1. The results demonstrate that wood species composition significantly influenced the physical and selected mechanical properties of the laminated strand lumber (LSL) panels. Although moisture content was uniform across all groups, panel density increased with increasing larch content due to the inherently higher density of larch wood. This effect was particularly evident in the core layer, where spruce-only panels exhibited significantly lower density compared with larch-containing configurations. All panel types showed a typical vertical density profile, characterized by densified surface layers and a less dense core.
2. Despite clear differences in density, no statistically significant differences were observed among panel groups in terms of bending (MOR, MOE) or compression properties (MOE). Nevertheless, panels composed entirely of larch exhibited the highest mean bending values, while the LSL with larch:spruce:larch (LSL-L:S:L) configuration demonstrated the highest average compression strength and modulus. The influence of mixed-species composition was more pronounced in edgewise

bending than in flatwise bending, suggesting that heterogeneous strand distribution may affect load transfer mechanisms depending on the loading configuration.

3. Internal bond strength was significantly affected by panel structure. The LSL-L:S:L configuration showed superior internal bond (IB) performance compared with the other panel types, which can be attributed to enhanced core densification and improved inter-particle bonding. This finding highlights the importance of density distribution, particularly in the core layer, for optimizing internal bond performance.
4. Wood–water relations were strongly dependent on species composition. Increasing larch content resulted in significantly higher thickness swelling after prolonged immersion, indicating reduced dimensional stability. In contrast, panels containing larch exhibited lower water absorption compared with spruce-only panels. These results suggest that water absorption and thickness swelling are governed by different mechanisms, with species-specific dimensional characteristics playing a key role in swelling behavior.
5. The density-normalization by density of the results indicates that the lower density of the LSL formed from just spruce strands (LSL-S) potentially influenced the mechanical test outcomes (compressive and bending properties). However, from a statistical standpoint, this effect was only significantly manifested in the case of compressive strength.
6. Overall, the larch wood is an applicable raw material for LSL production and LSL-L:S:L configuration provided the most balanced performance in terms of mechanical properties, internal bond strength, and moisture-related behavior. The findings confirm that strategic species layering and core densification are critical factors in optimizing the performance of mixed-species LSL panels.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of Generative AI

Generative AI tools (ChatGPT, OpenAI, GPT-4/4o and Google Gemini) were used during manuscript preparation exclusively for linguistic revision and stylistic improvement.

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APPENDIX

Table A1. One-way ANOVA for Results Evaluating Significant Differences between the Groups of Specimens

Properties		Statistical Measures				
		SS	Df	MS	F	p-value
Moisture content		0.25	3	0.083	0.193	0.901
Density		28500	3	9504	6.223	0.002*
Density profile (core)		42600	3	14200	7.898	0.001*
Density profile (surface)		126000	3	42000	2.918	0.041*1)
Compression MOE		16600000	3	5530000	1.757	0.169
Compression strength		387.8	3	129.3	3.53	0.022*
Internal Bonding		0.53	3	0.177	8.247	0.001*
Thickness swelling	24 h	118.5	3	39.51	11.59	0.001*
	48h	806.3	3	268.8	38.54	0.001*
	7 days	1994	3	664.7	38.25	0.001*
Water absorption	24 h	687.6	3	229.2	16.85	0.001*
	48h	560.9	3	187	7.63	0.001*
	7 days	1157	3	385.5	10.49	0.001*

Notes: 1) Although the overall One-way ANOVA indicated a statistically significant difference in surface layer density among the groups (p = 0.041), the subsequent Tukey's HSD post-hoc comparison did not detect any significant pairwise differences; (SS — sum of squares; Df — degrees of freedom; MS — variance; F — Fisher's F-test; p — significance level; * - significant)

Table A2. One-way ANOVA for Results Normalized by Density Evaluating Significant Differences between the Groups of Specimens

Specific Properties		Statistical Measures				
		SS	Df	MS	F	p-value
Compression MOE		19500000.00	3.00	6500000.00	1.43	0.25
Compression strength		300.00	3.00	99.99	2.71	0.06
Internal Bonding		0.96	3.00	0.32	9.79	0.001*

Notes: (SS — sum of squares; Df — degrees of freedom; MS — variance; F — Fisher's F-test; p — significance level; * - significant)

Table A3. Kruskal-Wallis ANOVA Results for Evaluating Significant Differences among the Specimen Groups

Bending Properties	Statistical Measures		
	H	Df	p-value
Edgewise orientation			
Bending MOE	4.105	3	0.25
Bending MOR	2	3	0.572
Flatwise orientation			
Bending MOE	8.052	3	0.045*2)
Bending MOR	5.947	3	0.114
Edgewise orientation			
MOE/ρ	2.795	3	0.424
Bending MOR/ρ	0.789	3	0.852
Flatwise orientation			
MOE/ρ	3.076	3	0.38
Bending MOR/ρ	4.666	3	0.197

Notes: 2) Although the global Kruskal-Wallis ANOVA indicated a statistically significant difference among the groups ($p = 0.045$), the subsequent Dunn's post-hoc pairwise comparison did not detect any significant differences between specific pairs; (N — number of observations; Df — degrees of freedom; H — Kruskal-Wallis test statistic; p — significance level; * — statistically significant at $\alpha = 0.05$).