Changes in Some Mechanical Properties Depending on the Orientation of the Laminated Veneer Lumber Layers

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The present study was conducted with the purpose of investigating alterations in mechanical properties resulting from layer orientation used in laminated veneer lumber (LVL) production. The LVL was produced by pressing 12-layer veneer laminates with phenol formaldehyde (PF) adhesive at 130 °C and 1.2 MPa pressure for 20 min. To observe the orientation effect during the production, some layers were rotated 90°. Subsequently, the modulus of elasticity (MOE), modulus of rupture (MOR), impact resistance, static hardness, screw withdrawal, and bonding quality values of the samples produced were determined. It was found that the groups that had undergone orientation exhibited lower volumetric changes after the swelling test. Furthermore, the implementation of orientation led to an enhancing effect on the MOE and screw withdrawal values for edgewise loadings of the tested specimens. However, the MOR, hardness, and impact resistance values of the oriented samples were lower than those of the control group. The results showed that one-sided orientation in the LVL increased stability and the flexural properties under edgewise loading, as well as the screw withdrawal strength. However, hardness and impact strength decreased with layer orientation. Additionally, it was found that MOR could be predicted with a higher correlation (R^2 0.89) using MOE values in flatwise loading, while a lower correlation (R^2 0.40) was found in edgewise loading.

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INTRODUCTION

Wood is one of the most popular materials for furniture and structural applications (Damlayıcı and Arslan 2024). It is easy to recycle, has a warm aesthetic appearance, and has high mechanical properties despite its low specific weight. Wood also has low CO_2 emissions during production and low energy requirements (Davidson and Hanna 2004). However, due to the limited availability of wood as a resource, the efficient use of wood has become increasingly important in recent years. In particular, the use of "engineered wood products" has increased significantly over the past 25 years thanks to reasons such as easy availability, renewability, lower production and processing costs, ease of disassembly and disposal at the end of its service life (Fridley 2002).

The most important advantage of engineered wood products compared to solid wood is that defects in the material can be controlled during production. This ensures the

products are uniform, defect-free, and have consistent physical and mechanical properties (Smulski 1997).

Laminated veneer lumber (LVL) is one of the most commonly used products in engineered wood materials. It is made by stacking wood veneers with parallel grain directions, applying adhesive between them, and compressing the layers under heat and pressure. Compared to solid wood, LVL has very high dimensional stability due to the adhesive used during production (Nelson 1997).

Many researchers investigated LVL production and its performance from various types of wood, such as beech (Çolak *et al*. 2007; Blomqvist *et al*. 2014; Percin and Altunok 2017), poplar (Kilic and Celebi 2006; Boever *et al*. 2007; Kurt 2010; Nazerian and Dahmardeh 2011; De Rahayu *et al*. 2015; El Haouzali *et al*. 2020), eucalyptus (Saviana *et al*. 2009; Palma and Ballarin 2011; Bal and Bektaş 2012a; Bal 2016), birch (Xue and Hu 2013), pine (Kiliç *et al*. 2010; De Souza *et al*. 2011; Wang and Dai 2013), bamboo (Chen *et al*. 2017), paulownia (Arabi *et al*. 2024), ash (Ilçe 2018), oak (Keskin 2004; Purba *et al*. 2019), fir (Wang and Dai 2013; Rahayu *et al*. 2016), and some exotic woods (H'ng *et al*. 2010; Gilbert *et al.* 2018; McGavin *et al*. 2019).

In the literature, some studies have focused on changes in the mechanical properties of LVL using different adhesives (Celebi 2006; Burdurlu *et al*. 2007; Shukla and Kamdem 2009; Bal and Bektaş 2012a, 2012b; Kiliç 2012; El Haouzali *et al*. 2020; Romero and Odenbreit 2023). Additionally, certain studies investigated the effect of press conditions (duration and temperature) on mechanical properties (Shukla and Kamdem 2008; Ido *et al*. 2010). In addition, others have examined the changes of moisture content in veneers on mechanical properties (Wang and Dai 2005; Blomqvist *et al*. 2013). Furthermore, some researchers have analyzed the effect of different layer thickness and number of layer combinations on the mechanical properties of LVL (Özçifçi 2007; Xue and Hu 2013; De Melo and Del Menezzi 2014; Li *et al*. 2023). Moreover, others have examined the effects of different layups (arrangements) on the mechanical properties of hybrid veneers (Keskin 2004; Shukla and Kamdem 2008; H'ng *et al.* 2010; Kiliç *et al*. 2010; Xue and Hu 2012; Chen *et al*. 2017; Ilçe 2018; Arabi *et al*. 2024).

It has been determined that research in the literature regarding the orientation of layers in LVL production is limited (Tenorio *et al*. 2011; Alamsyah *et al*. 2023; Duran and Çavuş 2025). For instance, Alamsyah *et al*. (2023) only changed three layers in the middle (as plywood) of 11-layered LVLs produced from mahoni (*Swietenia macrophylla*), manglid (*Manglietia glauca*), and gmelina (*Gmelina moluccana*) species. On the other hand, Duran and Çavuş (2025) changed only the second and third layers from one surface on the eight-layered LVLs produced from the same species (*Fagus orientalis*) with polyurethane. In the first group (except control), they 90º oriented the second layer. In another group, they 90º oriented the second layer and additionally 45º oriented the third layer. In some cases, for example pressure or tension stresses during bending can significantly affect the LVLs and maximum stresses occur in the outer layers. Consequently, it is imperative to investigate the alterations that will ensue due to layer orientation in a single direction.

The aim of this study is to investigate the physical and mechanical properties of some layer's oriented LVLs. To determine how these properties may be affected by meaning of the orientation of the layers within the pressure zone depending on the direction of the force's action, orientation was performed on the 2nd layer in group Y and the 2nd and 4th layers in group Z, with the bottom and top layers of the plate remaining parallel to each other.

EXPERIMENTAL

Materials

The 2.0-mm-thick beech (*Fagus orientalis* L.) veneer sheets were procured from the Alesta company, which is located in the Düzce region (Turkey). The samples were selected from those exhibiting defect-free, smooth-grained characteristics, with an initial moisture content of 8%, and were subsequently cut into dimensions of 60 cm by 60 cm

Adhesives

A commercial phenol formaldehyde adhesive (46 ± 1% solid) was used from ALFEN 74, which was manufactured by Gentaş Kimya company. The gram weight pick-up was calculated according to procedures described in ASTM D899 (2000). Almost 200 g/m^2 of adhesive was spread manually on the loose side of the veneers.

Production of LVL

To manufacture 12-ply LVLs, adhesives were spread on the veneers [1.6 (t) mm × 600 (w) mm × 600 (l) mm], and they were immediately assembled with the tight side facing out on each veneer. As shown in Fig. 1, the fiber directions of the glued laminates were arranged. X represents (control) groups to which no orientation process has been applied. The second layer from the top of the laminates representing Y is fiber oriented at 90°, and the second and fourth layers from the top of the groups labeled Z are also fiber oriented at 90°.

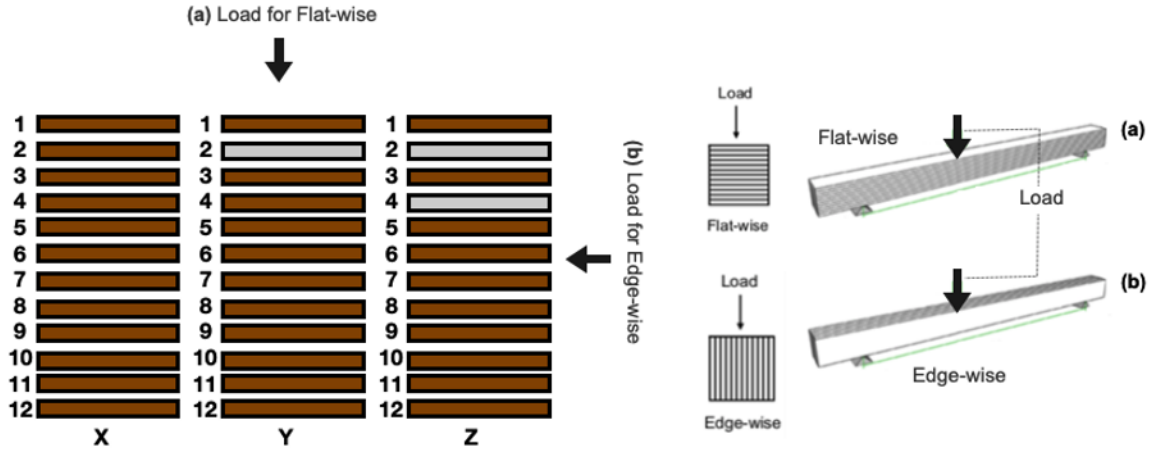


Fig. 1. Preparation of LVL samples (the gray section represents veneer with a 90° orientation applied) and arrangement according to the loading directions (a: flatwise, b: edgewise); *X,Y,Z: Different LVL groups. Numbers were the number of layers. Brown layers parallel-, while gray layers perpendicular to the grain and sample length.

Symmetrical orientation was not applied in this study for investigating one-sided orientation. The adhesives were spread on the veneers' loose side with a gluing machine, ensuring enough adhesive was applied. After that, these laminates were pressed in a hot press at a temperature of 130 °C and pressure of 1.2 MPa for 20 min. The samples were conditioned in a climate cabinet until they reached an equilibrium moisture content of 12%. Then, they were cut according to the dimensions specified in the relevant standards.

Determination of physical properties

The ISO 13061-1 (2021) standard's principles were used to determine the sample moisture content. The ISO 13061-12 (2017) standard's principles were used to determine the sample densities. The tests were conducted in accordance with ISO 13061-4 (2014) to determine volumetric changes. The expansion of air-dried samples was measured after 4, 24, 48, 72, 96 and 168 h. Tests were conducted on samples measuring 20 × 20 × 30 mm, with 10 repetitions.

Mechanical Tests

Modulus of Rupture (MOR)

Static bending strength tests were conducted according to the ISO 13061-3 (2021) standard. For this purpose, 20 mm × 20 mm specimens were prepared. The support span was selected as 15 h. The loading rate was determined to cause failure within the specified range of 0.5 to 5 min. During flatwise tests, the applied load was positioned close to the oriented layers, subjecting the material to compressive forces. In edgewise tests, the load is applied from the midpoint of the surface. Static bending strength was determined using the following equation based on the maximum load obtained,

$$MOR = \frac{3 \times P_{max} \times l}{2 \times b \times h^2} \quad (1)$$

where MOR is defined as the static bending (N/mm^2) P_{max} is defined as the maximum load (N), l is the distance between supports (mm), b is the sample width (mm), and h is the sample thickness (mm).

Flexural modulus of elasticity (MOE)

Flexural modulus tests were conducted according to the ISO 13061-4 (2014) standard. The flexural modulus value was determined using data obtained from the specimen in the static flexural strength test. The calculations were performed using load and deformation amounts corresponding to 10% and 40% of the maximum load, according to the following equation,

$$Flexural\ modulus\ of\ elasticity\ (MOE) = \frac{P \times l^3}{4 \times b \times h^3 \times f} \quad (2)$$

where MOE is the modulus of elasticity (N/mm^2); P is the difference between the upper and lower limit loads (N); l is the span length (mm); b is the specimen width (mm); h is the specimen thickness (mm); and f is the difference in deformation (mm).

Determination of impact resistance

Bending resistance to impact is determined according to ISO 13061-10 (2017). Tests were performed using a pendulum hammer with the characteristics specified in the standard and a support span of 240 mm. The following formula was used to calculate bending resistance to impact,

$$Impact\ resistance\ (A) = \frac{Q}{b \times h} \quad (3)$$

where A is bending resistance (kJ/m^2), Q is energy expended (kJ), b is sample width (m), and h is sample thickness (m).

Static hardness

The ISO 13061-12 (2017) standard was used to determine static hardness for surface, parallel, and perpendicular surfaces. According to the standard, a hemi-spherical test specimen was loaded at a rate of 6 mm/min to a depth of 5.64 mm on its surface and edges, or to a depth of 2.84 mm if separation occurred. The results were calculated using the following equation,

$$Static\ hardness\ (H) = K \times F \quad (4)$$

where H is the static hardness value (N), F is the maximum load (N), and K is the coefficient value according to the test depth (1 for 5.64 mm and 4/3 for 2.84 mm).

Screw withdrawal capacity

The screw withdrawal capacity was determined according to the TS EN 13446 (2005) standard. Tests were performed by drilling a 2-mm-diameter pilot hole through the sample's surface to its thickness and inserting a 4-mm-diameter screw. The samples were sized as 50 mm × 50 mm. The screw withdrawal capacity of the samples were determined using the following formula,

$$Screw\ withdrawal\ (f) = \frac{F_{max}}{d \times l_p} \quad (5)$$

where f is the screw withdrawal capacity (N/mm^2), F_{max} is the maximum pull-out load (N), d is the screw diameter (mm), and l_p is the screw penetration depth (mm).

Bonding quality

The bonding quality was determined according to the TS 3969 EN 314-1 (1998) and TS EN 314-2 (1999) standards. Although standards were prepared for the plywoods, they were referenced due to different layer orientation in some test groups. Twelve-layered LVL panels were tested. Panels were sized to 25 mm width and 100 mm length as test samples. Saw cuts were opened on the samples and 25 mm was the distance between the cuts. The depths were adjusted according to the test group (Fig. 1), and the end of the different oriented layers were referenced. The center of sample for control (X) group, between the 2nd and 3rd layers for group Y and between the 4th and 5th layers for group Z were specified as saw cut depths. Before pretreatment, possible shear-break areas of the samples were measured with an accuracy of 0.1 mm. The standards suggest pretreatment related to usage area. In this study "Class 1: dry interior" class was chosen, and the samples were immersed in the water at 20 °C for 24 h. The shear load was applied parallel to the grain (and longitudinal sample) direction with a constant rate of motion that breaking occurred within 30 (± 10) s. The tension-shear strength was calculated according to the formula,

$$Tension - shear\ strength\ (TSS) = \frac{P_{max}}{w \times l} \quad (6)$$

where TSS is the tension-shear strength (N/mm^2), P_{max} is the maximum break load (N), w is the width of the breaking area (mm), and l is the length of the breaking area (mm).

Statistical analysis

Analysis of variance (ANOVA) was used to determine possible differences among the two or more groups which had normal distribution using IBM SPSS software. The resulting p-value was compared to the tabular p-value at the 95% level of confidence. When

F tests resulted in significant differences ($p < 0.05$), to compare and identify exactly which groups differed from each other by Tukey as a post-hoc test.

RESULTS AND DISCUSSION

Physical Properties

Density and moisture

The moisture contents of the samples were calculated to be 9.92%, 10.64%, and 10.97% for groups X, Y, and Z, respectively. The density values were determined to be 760, 743, and 723 kg/m^3, respectively. Although it was not examined, the veneer densities associated with moisture content or annual ring width changes may have an impact on the observed density variation (Topaloglu *et al*. 2016; Ghorbanian *et al*. 2024).

Similar density results for steamed solid beech wood were noted by Yılgör *et al*. (2001), Burdurlu *et al.* 2007, Çolak *et al*. (2007), and Pruba *et al*. (2019). Conversely, Bal and Bektaş (2012) calculated the density value as 677 kg/m^3 for 7-layer LVL production with phenol formaldehyde (PF) using beech veneers.

A number of studies have indicated that variations in density may be influenced by several factors, including the quantity of adhesive, the fillers and additives contained within the adhesive, and the magnitude of press pressure applied during the manufacturing process (Wang and Dai 2005; Burdurlu *et al*. 2007; Çolak *et al*. 2007; Kurt 2010). The effect of veneer orientation on the density might be related with participation level of early and latewood.

If the oriented (90°) layers had lower latewood (which density is higher than earlywood) participation, it could affect the density decrement. (Barnet and Jeronimidis 2009; Adamopoulos *et al*. 2010; Wang *et al*. 2022; Guo *et al*. 2025).

Dimensional stability

The volumetric change after the water absorption test for the samples is shown in Fig. 2. Based on the results obtained, it was observed that the volumetric changes (swelling) of the samples subjected to fiber orientation (Y and Z) after the water absorption test were lower compared to the control samples (X). The formation of the counter structure between the layers reduced the volume.

After the water absorption test, the Z group samples exhibited the lowest volumetric change. The samples subjected to fiber orientation (Y and Z) showed lower volumetric changes than the control samples (X). The increased counter veneer orientation was found to have a decreasing effect on the volumetric swelling ratio. Furthermore, the side of the layers on the swelling samples exhibited a greater degree of contact with the water. In the samples (X), it was observed that all layers exhibited the potential to absorb water from the cross-section of the veneers.

It has been determined that the orientation of the layers provides dimensional stabilization. This is in line with several results, after 24 h of volume change, in the literature (Shukla and Kamdem 2008; Nazerian and Dahmardeh 2011; Bal 2016; Sulastiningsih *et al*. 2020). It was thought that the density changes directly affected the volumetric change differences.

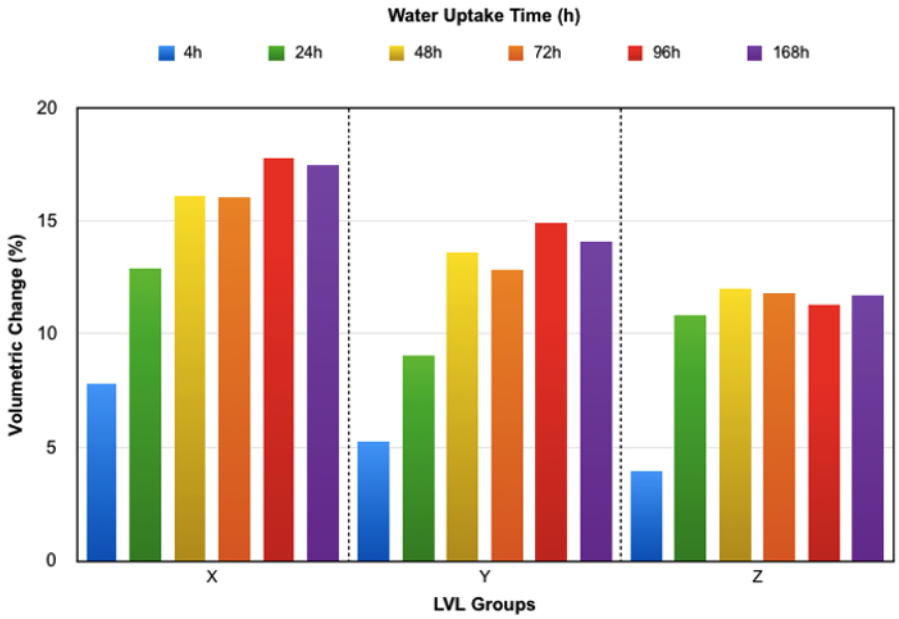


Fig. 2. Volumetric changes (swelling) after water absorption tests on LVL samples;
*LVL groups: X: control, Y: single-layer and Z: double-layer oriented.

As shown in Fig. 3, the area of the oriented layers (plywood area) was more stable than the LVL (not oriented layers) area. It seems that counter fiber orientation decreased the swelling ratio.

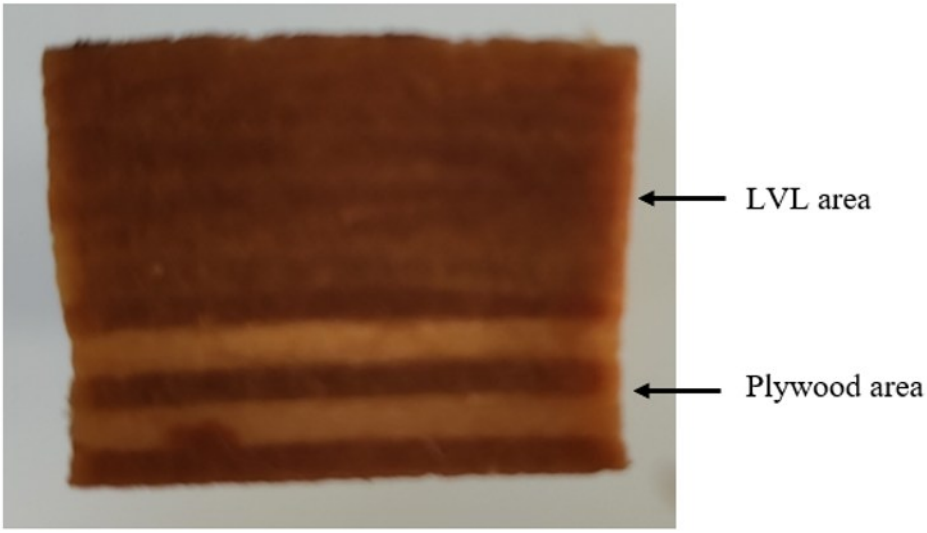


Fig. 3. Different swelling ratios on the same sample (photo from the cross section);
*Plywood area means area had oriented layers

Additionally, the bonding quality decrement on the different oriented groups could have been due to the different swelling ratios. As shown in Fig. 3, the perpendicular to the grain-oriented section (Plywood area) swelled less than the parallel to the grain-oriented section (LVL area). The difference of the swelling ratios could create stress on the bonding line and decrease the strength during the immersion in the water.

Mechanical Properties

MOE and MOR changes

In the majority of structures, such as roof rafters and ceiling joists, wooden beams are bent edgewise. In particular applications, such as scaffold planks, the bending values of MOE and MOR in the flat direction are of crucial importance (Steffen *et al*. 1997; Hou *et al*. 2022). For this reason, experiments were performed on LVL in both edgewise and flatwise directions to determine the MOE, MOR, and impact strength values. The changes in mechanical properties of wood samples are shown in Table 1, Fig. 4, and Fig. 5.

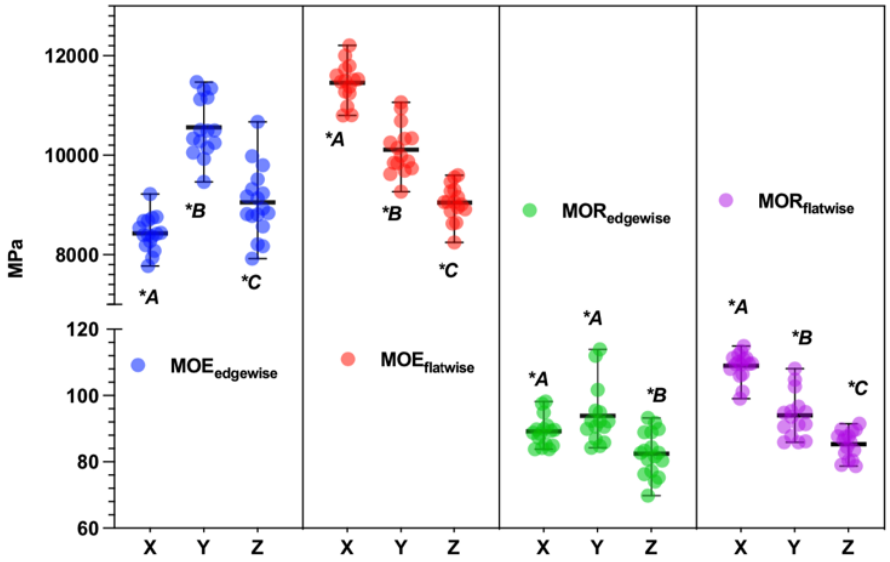


Fig. 4. The MOE and MOR values depend on the loading direction of the specimens (flatwise and edgewise); **LVL groups: X: control, Y: single-layer and Z: double-layer oriented

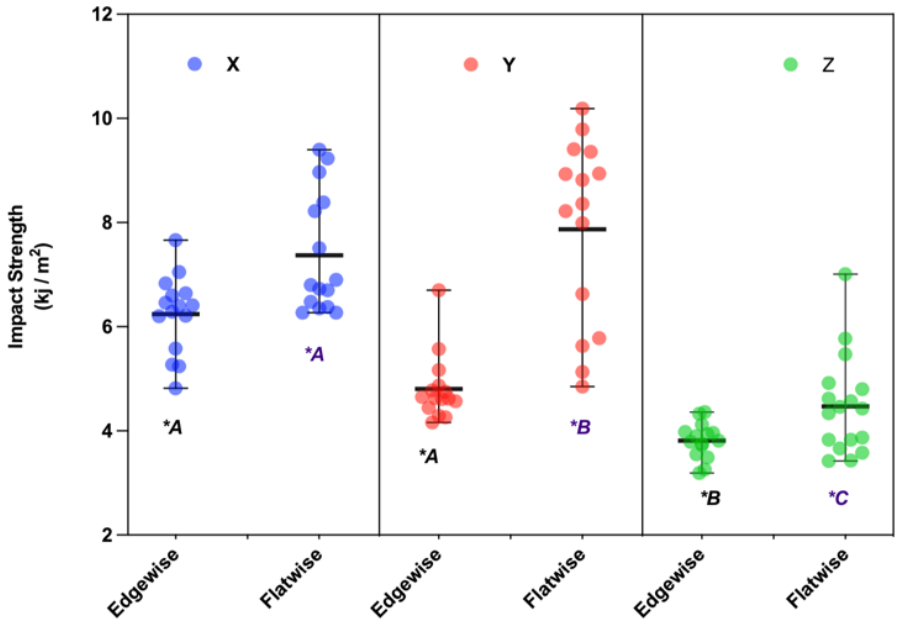


Fig. 5. The impact resistance relies on the loading direction (flatwise and edgewise); *LVL groups: X: control, Y: single-layer and Z: double-layer oriented

Mechanical tests on the samples revealed that flatwise loading resulted in higher values for MOE, MOR, and impact resistance than edgewise loading. For MOE and MOR values, no statistically significant difference was found between flatwise and edgewise loading among groups with 90° layer orientation (Y and Z). However, a statistically significant difference was determined between flatwise and edgewise loading for the control group (X). Additionally, the flatwise loadings of all groups (X, Y, and Z) were found to be statistically significantly higher than the edgewise loadings for impact strength values (Fig. 4.)

Similarly, the literature indicates that LVL samples made from beech, poplar, and eucalyptus wood veneers using PF, MUF, and UF adhesives also had higher MOE and MOR values for flatwise loading than for edgewise loading (Bektaş and Bal 2012b). Furthermore, LVL samples produced with PVAc adhesive from beech and oak veneers exhibited higher flatwise loading compared to edgewise loading (Purba *et al*. 2019). Another study by Wang and Dai (2005) emphasized that LVL samples produced with poplar veneers bonded with phenol-formaldehyde adhesive had higher MOR, MOE, and shear strength in the flatwise direction than in the edgewise direction. Burdurlu *et al*. (2007) also found that flatwise loading was higher in samples produced using PVAc adhesive and seven layers of beech and poplar veneers. Similarly, LVL samples produced with PVAc adhesive and different numbers of *Schizolobium amazonicum* wood veneer layers (8, 9, or 14) were discovered to exhibit higher MOR and MOE values with flatwise loading than with edgewise loading (De Melo and Del Menezzi 2014). In LVL samples produced with poplar wood veneers and urea formaldehyde adhesive, flatwise loading also yielded higher MOR and MOE values than edgewise loading (Nazerian and Ghanenho 2011). Another study demonstrated that flatwise loads exhibited higher values than edgewise loads in MOE and MOR tests on LVL samples produced with 12 layers of MUF adhesive (McGavin *et al*. 2019). Similar results were reported in Bal's (2016) study, which stated that flatwise loading yielded higher MOR, MOE, and shock resistance values than edgewise loading for LVL samples with seven layers of eucalyptus and poplar veneers using phenol formaldehyde adhesive (Bal 2016). Similar decrease ratios (app. 10%) after fiber orientation (Y and 0º to 90º to 0º) in both MOE and MOR were observed in this study as the study of Duran and Çavuş (2025).

In contrast, Li *et al*. (2023) found that LVL samples made with Chinese larch pine wood veneers with formaldehyde adhesive had higher MOR values under edgewise loading than flatwise loading. In another study Wang and Dai (2013), it was noted that edgewise loading led to higher resistance values in MOR tests for LVL samples produced from hem-fir layup veneers. While, flatwise loading showed higher values in MOE tests (Wang and Dai 2013). Additionally, a study by Lara Palma and Ballarin (2011) found that LVL samples produced with eucalyptus veneers using PF adhesive had higher MOR test values under edgewise loading than flatwise loading.

When the flatwise loadings were compared in this study, it was determined that the 90° orientation process (Y and Z) reduced all the MOE, MOR, and impact strength values compared to the control samples (X). This results in a statistically significant decrease. In contrast, the edgewise loadings were assessed independently; it was determined that the MOE value increased for all groups (Y and Z) that underwent a 90° orientation process. This increase was found to be statistically significant. In terms of MOR and impact strength values, it was determined that the groups subjected to a 90° orientation (Y and Z) had a reducing effect. A statistically significant difference was not observed between the control group (X) and the group with a single layer oriented at 90° (Y). However, the group with

multiple layers oriented at 90° (Z) was found to cause a statistically significant decrease in MOR and impact strength.

It is acknowledged that the types of stress that occur are subject to variation depending on the part of the load that is applied (Thelandersson and Larsen 2003). Compressive stresses are observed in the upper portion of the wood samples, while the lower parts are subjected to tensile stresses (Kollmann and Stamm 1968; Kollmann *et al*. 1975). Consequently, it is hypothesized that the counter layers, which are formed as a result of fiber orientation, exhibit a diminished reducing effect on the compressive side during edgewise loading (Zhang *et al*. 1994). The layer orientation application is believed to have an effect that prevents reductions caused by compressive and tensile stresses (Zhang *et al*. 1994; Li *et al*. 2020). In a contrasting study, gmelina (*Gmelina moluccana*), mahogany (*Swietenia macrophylla*), and manglid (*Manglietia glauca*) veneers were utilized to produce an 11-ply LVL with PF adhesive. It was determined that orienting certain veneers within the layers led to a reduction in the MOE values for edgewise loading (Almasyah *et al*. 2023). This difference is thought to stem from the fact that the guidance process in the relevant study (Almasyah *et al*. 2023) was only performed on the middle layer. It has been determined that guidance performed outside of the middle layer results in increased edgewise loading.

Regression relationship (MOR and MOE changes)

Many researchers (Burdurlu *et al.* 2007; De Souza *et al.* 2011; Bal and Bektaş 2012b; Wang and Dai 2013; De Melo and Del Menezzi 2014; McGavin *et al*. 2019; Purba *et al*. 2019; Li *et al*. 2023) have conducted LVL experiments in both the edgewise and flatwise directions. However, the correlation between MOR and MOE has not been examined in these studies. The findings of the present study indicate a higher correlation between MOE and MOR values for flatwise loading compared to edgewise loading. The highest coefficient of determination was 0.89 (flatwise direction) between MOE and MOR. The lowest was 0.40 (edgewise direction) between MOR and MOE (Fig. 6.).

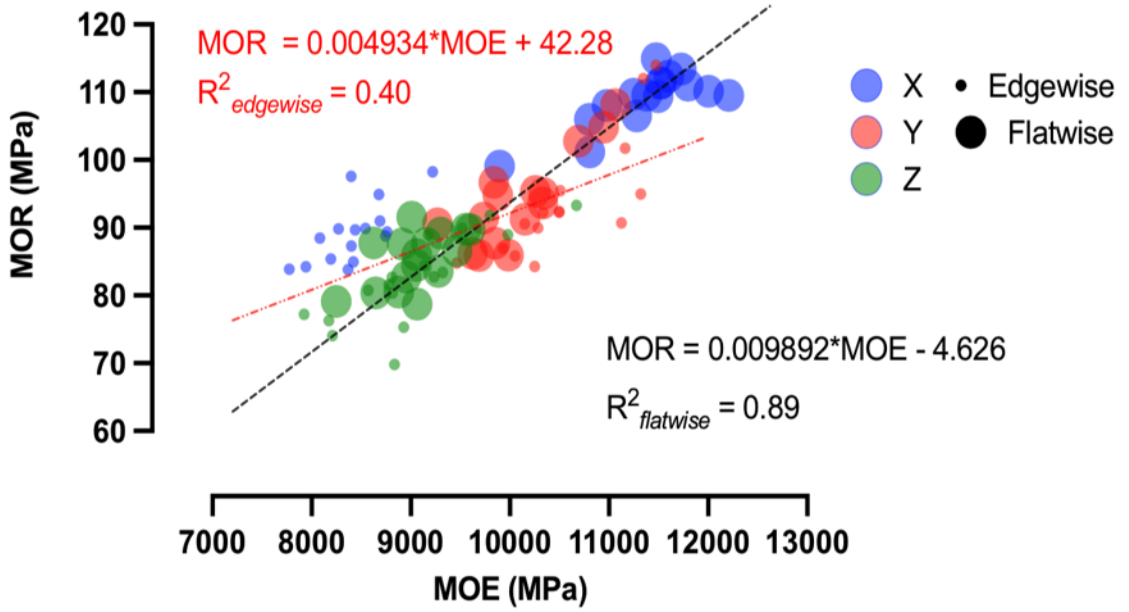


Fig. 6. Regression relationship between MOR and MOE depending on loading direction and layer orientation for LVL; **LVL groups: X: control, Y: single-layer and Z: double-layer oriented

In a similar way, Wang and Dai (2005) identified a correlation of 83% between MOE and MOR in flatwise loading for LVL samples. However, in contrast to the findings in the current study, Bal (2016) demonstrated a higher correlation between MOR and MOE in edgewise loading. In their studies using poplar and eucalyptus veneers, they found a correlation coefficient (R^2) of 0.40 between MOR and MOE for flatwise loading (Bal 2016). There are various reasons to explain why flatwise had higher correlations. Elasticity is related to stresses in the elastic zone, while bending strength is related to breaking point which is the load limit of the material. During the flatwise loading, the material might behave more homogeneously, and stresses might start spreading from top layer to bottom layer. Because each layer can transfer the stress to the other layer through adhesive. On the other hand, during the edgewise loading, the flexural load stress affects each layer, although the adhesive provides integrity. Then, the load limit is more related to the strength of each layer instead of the whole material (Dinwoodie 2000).

Screw withdrawal capacity and bonding quality changes

The changes in mechanical properties (screw withdrawal and bonding quality changes) of samples after layer orientations are shown in Table 1 and Fig. 7.

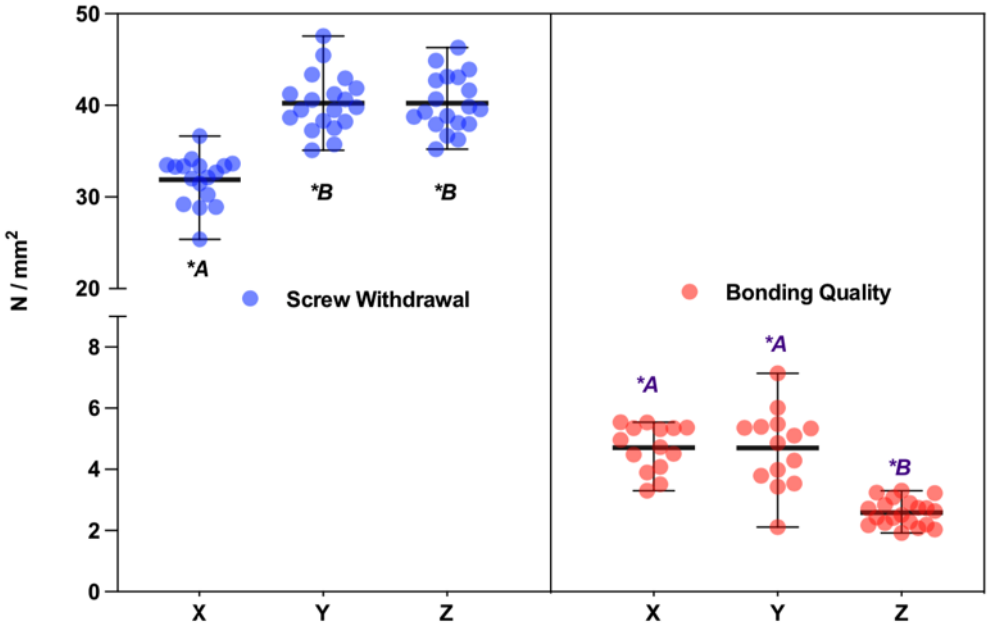


Fig. 7. Screw withdrawal and bonding quality values for the LVL samples; *LVL groups: X: control, Y: single-layer and Z: double-layer oriented

The results of the bonding quality test (shear strength) demonstrate that there was no statistically significant difference ($p > 0.05$) between the group with a single layer oriented at 90° (Y) and the group with no orientation applied (X). However, it was determined that the (Z) samples, which were oriented at 90° in multiple layers, had lower internal bond strength values than both the control and Y groups ($p < 0.05$).

A review of the literature revealed that LVL samples produced with PVAc adhesive from poplar, birch, or maple veneers had similar internal bond values (Shukla and Kamdem 2008). Likewise, compared with LVL samples produced in 7 layers from poplar and eucalyptus veneers using PF adhesive, bonding (tensile shear strength) values were found to range between 2.5 and 4.3 N/mm^2 (Bal 2016). Similarly, bonding quality (shear

strength) was determined for poplar, paulownia, and hornbeam veneers, which exhibited similar values to those of LVL samples produced using a polyurethane adhesive in seven layers (Arabi *et al*. 2024). Additionally, the glueline shear strength values of LVL samples produced using poplar veneers and MUF (Kurt 2010) and PF (Kurt *et al*. 2012) adhesives were similar to the values in this study (bonding quality). In contrast, bonding (shear strength) values of LVL samples produced from poplar and bamboo veneers using seven layers of PF adhesive were found to be between 9 and 22 N/mm^2 (Chen *et al*. 2017).

Examining the screw withdrawal results revealed a statistically significant difference between the groups that underwent the orientation process (Y and Z) and the control samples (X). As a result of the orientation process, the Y and Z groups exhibited increased screw withdrawal performance. Similarly, a study of LVL produced with 11 layers of gmelina, mahogany, and manglid veneers using PF glue observed an increase in screw withdrawal values due to the orientation of some veneers within the layers (Almasyah *et al*. 2023). Likewise, an increase in screw withdrawal was observed after orienting some layers in the production of 5-layer LVL using PF adhesive for *Gmelina arborea* wood veneers (Tenorio *et al*. 2011). In contrast, a study of beech veneers laminated into eight layers using an isocyanate adhesive for LVL production stated that screw pull-out resistance values decreased after fiber orientation (Duran and Çavuş 2025). However, the decrease ratio related to the control group was only 4.2% when considered the 0º to 90º to 0º oriented group which was similar to group Y.

Static hardness

The obtained results indicated that the X group samples, in which force was applied to the surface, exhibited the highest hardness values (Fig. 8.). The lowest hardness value was observed in the Z group samples, in which load was applied perpendicular. There was a statistically significant decrease in hardness values between the LVL control group (X), which underwent no orientation process, and the groups (Y and Z), which underwent an orientation process ($p < 0.05$). However, the hardness values of groups Y and Z were found to be similar ($p > 0.05$).

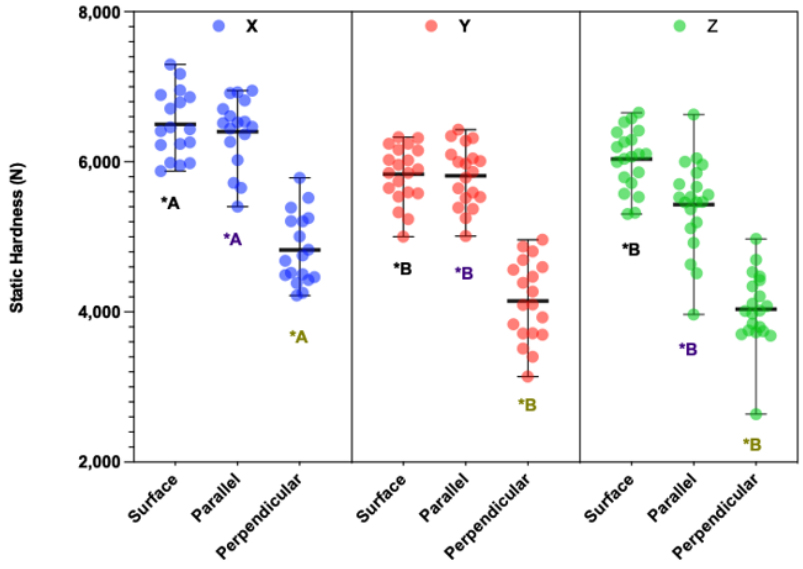


Fig. 8. Results of static hardness tests applied in different directions; *LVL groups: X: control, Y: single-layer and Z: double-layer oriented

Table 1. Overview of Mechanical Properties of the LVL Samples*

	N	Impact Strength (kJ /m²)		Static Modulus of Elasticity (MPa)		Modulus of Rapture (MPa)		Screw Withdrawal (N /mm²)	Bonding Quality (N /mm²)	Hardness (N /mm²)		
		Loading direction		Loading direction		Loading direction		Loading direction		Loading direction		
		Flatwise	***Edgewise***	***Flatwise***	***Edgewise***	***Flatwise***	***Edgewise***	***Surface***	***Tension***	***Surface***	***Parallel***	***Perpendicular***
X	15	7.37 *(1.15)* ***A***	6.24 *(0.74)* ***A***	11455.38 *(400.7)* ***A***	8431.46 *(351.2)* ***A***	109.60 *(3.32)* ***A***	89.18 *(4.53)* ***A***	31.89 *(2.65)* ***A***	4.70 *(0.76)* ***A***	6499.77 *(443.1)* ***A***	6402.17 *(460.1)* ***A***	4827.06 *(469.5)* ***A***
Y	15	7.86 *(1.78)* ***A***	4.80 *(0.63)* ***B***	10558.25 *(595.7)* ***B***	10108.79 *(503.2)* ***B***	93.84 *(8.98)* ***B***	93.99 *(6.87)* ***A***	40.23 *(3.13)* ***B***	4.70 *(1.26)* ***A***	5835.66 *(374.7)* ***B***	5813.81 *(404.8)* ***B***	4145.03 *(536.3)* ***B***
Z	15	4.47 *(0.94)* ***B***	3.81 *(0.33)* ***C***	9051.46 *(356.4)* ***C***	9050.61 *(690.3)* ***C***	85.30 *(4.10)* ***C***	82.41 *(6.63)* ***B***	40.25 *(3.08)* ***B***	2.58 *(0.42)* ***B***	6036.65 *(400.8)* ***B***	5429.01 *(598.6)* ***B***	4037.05 *(490.4)* ***B***

* The different letters in each column shows that the groups were statistically different at the 95% confidence level ($p < 0.05$).

It has been hypothesised that the decline in density value following orientation exerts a reducing effect on hardness (Grekin and Verkasalo 2013; Peng *et al*. 2016). The hardness of the oriented groups (Y and Z) decreased because the proportion of latewood per unit area after orientation was lower compared to the control group (X). Besides, the number of ray cells per unit area has also been demonstrated to have a significant impact on hardness (Dinwoodie 2000). A similar phenomenon was observed in a study that found a decrease in Janka hardness values with the orientation of layers of LVL samples produced using beech wood (Duran and Çavuş 2025). However, another study demonstrated that the production of 11-layer LVL using PF glue with exotic wood veneers of gmelina, mahogany, and manglid enhanced the hardness value of the LVL layers following orientation (Alamsyah *et al*. 2023).

CONCLUSIONS

1. In comparison with the control samples (X), a reduced volume change was observed in the groups subjected to layer orientation (Y and Z). These groups were found to demonstrate enhanced stability.
2. With regard to mechanical properties, it has been observed that the modulus of rupture (MOR), modulus of elasticity (MOE), and impact strength values for flatwise loadings generally exceed those for edgewise loadings in control samples (X). However, in groups subjected to layer orientation (Y and Z), a decrease in the resistance difference between flatwise and edgewise loading was found. In other words, it has been determined that edgewise loading increases following layer orientation. In particular, it has been shown that an increase in edgewise loads is observed following layer orientation for the MOE value.
3. Upon thorough examination of the screw withdrawal values, it was exhibited that layer orientation was responsible for an increase, while it was also found to cause a decrease in hardness and impact resistance values.
4. Additionally, it has been demonstrated that this is a superior predictor of the structural properties of laminated veneer lumber (LVL) by means of flatwise loading for the MOE/MOR relation.

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