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Determination of Bending Resistance and Modulus of Elasticity in CLT, Wood Materials and Wood Laminated Materials

Određivanje čvrstoće na savijanje i modula elastičnosti CLT-a, drvnih materijala i drvnih lameliranih materijala

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ABSTRACT • *In this study, test samples were prepared from CLT, wooden materials and wooden laminated materials, and bending strength and elasticity modulus values were determined. All samples were prepared using Scots pine (Pinus sylvestris L.) timber as the wood species and PVAc glue as the adhesive. Four-point bending test was applied to the test samples in two different directions, vertical and parallel to the glue line. Flexural and elastic modulus values were examined. The highest bending strength and elasticity modulus values were found in wood laminated material and the lowest in solid wood material. The average values of bending strength and modulus of elasticity were found to be higher in the direction parallel to the glue line than in the direction vertical to the glue line. As a result of the study, it can be said that CLT and wooden laminated materials can be used as an alternative to solid materials, which are frequently used as building and frame construction furniture materials.*

KEYWORDS: *CLT; wood laminate; wood material; bending resistance; elastic modulus*

SAŽETAK • *U ovom istraživanju ispitni su uzorci pripremljeni od CLT-a, masivnog drva i drvnih lameliranih materijala te su određeni čvrstoća na savijanje i modul elastičnosti. Svi uzorci pripremljeni su od drva običnog bora (Pinus sylvestris L.) i PVAc ljepila. Ispitni uzorci savijani su u četiri točke u dva različita smjera, okomito i paralelno s lijepljenim spojem. Ispitane su vrijednosti modula savijanja i modula elastičnosti. Utvrđeno je da drvni lamelirani materijali imaju najviše, a masivno drvo najniže vrijednosti čvrstoće na savijanje i modula elastičnosti. Prosječne vrijednosti čvrstoće na savijanje i modula elastičnosti bile su veće u smjeru paralelnom s lijepljenim spojem nego u smjeru okomitom na taj spoj. Kao rezultat istraživanja može se reći da se CLT i drvni lamelirani materijali mogu upotrebljavati kao alternativa materijalima od masivnog drva, koji se često rabe u graditeljstvu i izradi okvira namještaja.*

KLJUČNE RIJEČI: *CLT; drvni lamelirani materijal; masivno drvo; čvrstoća na savijanje; modul elastičnosti*

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1 INTRODUCTION
1. UVOD

Wood has been one of humanity's oldest and most indispensable materials throughout history. This valuable resource provided by nature is used in many different fields for both aesthetic and functional purposes. Modern processing techniques, particularly laminated wood and cross-laminated timber (CLT), have further expanded the use of wood and established a significant place among construction materials.

In recent years, the use of CLT and laminated wood materials as alternatives to solid materials has become increasingly widespread. Numerous studies have been conducted on the use of CLT materials in regions with high seismic risk. (Asiz and Smith, 2009; Ceccotti *et al*., 2013; Dujic and Zarnic, 2005; Gavric, 2013)

Laminated wood is created by combining multiple layers of wood to produce durable and aesthetically pleasing products. These products are commonly used in furniture, across all areas of the construction industry, as well as in interior cladding and flooring. On the other hand, cross-laminated timber (CLT) has revolutionized the construction sector with its structural advantages, finding applications in large buildings, bridges, and prefabricated structures. The potential of these materials to offer sustainable building solutions presents a significant opportunity in today's environmentally friendly construction practices.

CLT has emerged as a versatile prefabricated material for flooring, roofing, and wall systems, gaining traction in construction across Austria, Germany, and North America (Fredriksson *et al*., 2015; Karacabeyli and Douglas, 2013). This innovative panel system traces its roots back to the 1990s in the Swiss cities of Lausanne and Zurich. However, it was not until 1996 that a significant industrial-academic collaboration in Austria led to its advancement and wider adoption (Schickhofer *et al*., 2009; Espinoza *et al.*, 2016).

CLT is an innovative engineered wood product that typically comprises three to nine layers of dimensioned lumber, arranged perpendicular to one another, similar to the layers of veneer in plywood. This unique configuration enhances its structural integrity and stability. CLT has gained traction in prefabricated construction, serving as effective wall, floor, and roofing elements across residential, commercial, and non-residential buildings. Its potential is particularly noteworthy in the realm of tall timber structures, offering a sustainable and efficient alternative in modern architecture (Mohammed *et al*., 2012).

In Europe, the predominant raw materials for constructing CLT are structural C24-grade spruce and pine, with densities ranging from 420 kg/m³ to 500 kg/m³ at 12 % moisture content. In contrast, U.S. standards set by ANSI restrict the use of lumber for CLT to species with a minimum density of 350 kg/m³. As CLT continues to gain traction in industry, it is crucial to explore the potential of alternative and lower-density wood species that are not specified in ANSI/APA PRG 320. Investigating these materials could expand the versatility and sustainability of CLT panels, allowing for innovative applications in construction.

CLT is an engineered wood panel composed of layers of lumber, typically ranging from 20 to 60 mm in thickness, that are laminated orthogonally to the grain direction. This configuration enhances its strength and stability, allowing it to effectively support loads in various directions (Schmidt and Griffin, 2009).

Recently, CLT has gained significant traction in Europe as a preferred material for both interior and exterior applications, particularly in high-rise construction, due to its versatility and sustainability (Gagnon and Pirvu, 2011). CLT panels serve as essential load-bearing components in walls, floors, and roofs, contributing to the overall structural integrity of buildings (Popovski *et al*., 2012).

CLT serves as a fundamental component in constructing heavy timber structures for mid- to high-rise buildings. Its benefits as a building material encompass factory prefabrication, ease of installation, lightweight nature, exceptional strength, solid structural integrity, superior thermal insulation, and long-lasting durability (Que *et al*., 2017; Wang *et al*., 2017)

In CLT production, adhesives are selected and applied based on the specific requirements of the intended use and the environmental conditions. For example, polyurethane (PU) adhesives are used for moist environments and high durability, phenolic adhesives for moisture and high temperatures, EPI (Emulsion Polymer Isocyanate) adhesives for moisture and high durability, and MDA (Melamine Diisocyanate) adhesives. Polyvinyl Acetate (PVA) adhesives are used for low-cost, non-toxic, and easy application. This composition exhibits remarkable stiffness and strength in all directions, making it highly durable. The primary raw materials for producing this panel are sourced from the Pinus genus, combined with phenol-resorcinol-formaldehyde adhesive (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013; Buck *et al*., 2016).

Recent research has focused on key properties such as bending strength, shear strength (Okabe *et al*., 2014; Fredriksson *et al*., 2015; Espinoza *et al*., 2016; Lu *et al*., 2018), and elastic limit (Gsell *et al*., 2007; Gulzow *et al*., 2011), highlighting their significance in enhancing performance and application potential.

In this study, solid wood, laminated wood, and CLT were produced from the same tree species. The decision to conduct such a test was made to better understand the performance of CLT in different usage scenarios. While CLT is typically used for walls, floors, and other structural elements, this test aimed to examine its different load-bearing capacities and properties. Additionally, the test was carried out to provide data for future potential applications of CLT, contribute to product development and innovation processes, and gain a deeper understanding of its mechanical properties.

This study aimed to investigate the effects of forces applied on wooden materials, specifically CLT and laminated wooden materials, commonly used in the construction and furniture industries. We compared the bending strength and modulus of elasticity of these materials under different force applications – both perpendicular and parallel to the glue line. The objective was to assess how these variables, including the type of material and the direction of the applied forces, influence bending and elastic modulus values. By understanding these relationships, we can select materials that are best suited for specific applications, optimize their use based on the expected force directions, and ultimately enhance the durability and longevity of the products.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wooden material
2.1. Drvni materijal

All test samples were made from Scots pine (*Pinus sylvestris* L.), sourced from commercial suppliers (Bag Kerestecilik, Karabuk, Turkey). The average density of the wood was measured at 0.45 g/cm³. Scots pine, a common choice in the wooden construction industry, was specifically selected for this study due to its availability from the Eastern Black Sea region in Turkey. The test specimens were chosen based on the TS 2470 (1976) standard. Selection criteria included uniformity of natural color, smooth fiber texture, absence of knots, heartwood consistency, and lack of reaction wood, as well as the absence of fungal and insect damage. This careful selection ensured the suitability of the specimens for further processing.

2.2 Polyvinyl acetate D4 (PVA D4) adhesive
2.2. Polivinilacetatno D4 (PVA D4) ljepilo

PVA D4 is an odorless, nonflammable adhesive ideal for a wide range of wood bonding applications, including veneering and laminating. Manufactured to meet BS EN204 category D4 and DIN 68602 standards, it is suitable for both internal and external uses. This adhesive performs well in cold temperatures and cures quickly, ensuring ease of application without damaging cutting tools. For optimal results, the adhesive must be applied to only one surface, using a recommended amount of 150–200 g/m². The application process follows the TS 3891 standard, ensuring consistent quality. PVA D4 has a density of 1.1 g/cm³, a viscosity of 13–18 Pa·s, and a pH value between 2.0 and 3. For jointing, a pressing time of 30 minutes is advised for cold processes, while hot pressing at 60 °C should last 5 minutes, maintaining a humidity level of 6–15 %. After hot pressing, materials should be kept until they reach normal temperature for optimal bonding results.

2.3 Preparation of test samples
2.3. Priprema ispitnih uzoraka

The solid material used for control test samples was made from Scots pine (*Pinus sylvestris* L.) wood. The wood was cut to dimensions of 1900 mm × 100 mm × 100 mm and stored at a temperature of (20 ± 2) °C and a humidity of (65 ± 5) % until it reached a constant weight. The average moisture content (MC) of the first control sample was determined to be (12 ± 0.5) % according to TS 2471 (2005) standard.

The length of the laminations used in the production of CLT and laminated wood samples was 2000 mm, and their thickness was prepared to be 14 mm. In the laminated wood preparation, the lamination layers were glued parallel to each other, while the CLT lamination layers were bonded to each other at a 90-degree angle. The samples were laminated using PVAc adhesive, in accordance with the TS EN 408+A1 (2015) standard, to create a 5-layer laminated wood element. Finally, the resulting structural laminated wood elements were cut to dimensions of 1900 mm × 100 mm × 100 mm.

2.4 Density
2.4. Gustoća

The density of the Solid, Cross-Laminated Timber (CLT), and Wood Laminate samples was determined in accordance with the TS EN 408+A1 (2015) standard. The air-dried density (δ) was calculated using the following Eq. 1:

$$\rho = M / V \text{ (g/cm}^3\text{)} \quad (1)$$

Where, M is the air-dried mass (g) and V is the air-dried volume (cm³).

2.5 Bending test method
2.5. Metoda ispitivanja savijanjem

The bending strength test applied a 4-point load method on specimens aligned both parallel and vertical to the glue line. This test was conducted in the Karabük University Safranbolu Vocational School Laboratory using a SHIMADZU universal testing device, such as a SHIMADZU AGS-X series model, with a measuring capacity generally ranging from 0.1 N to 50 kN. According to TS EN 408+A1 (2015), bending strength and modulus of elasticity were measured. A total of 60 test specimens, each measuring 100 mm × 100 mm ×

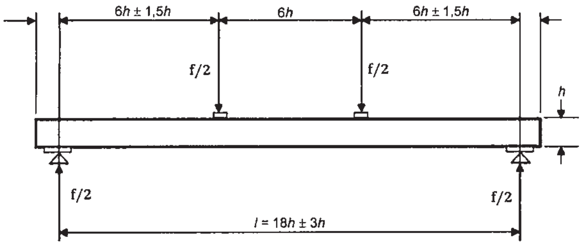

Figure 1 Bending strength and elasticity module test assembly
Slika 1. Postav ispitivanja čvrstoće na savijanje i modula elastičnosti

Figure 2 Four-point bending test setup
Slika 2. Postavljanje ispitivanja savijanja u četiri točke

1900 mm, were prepared – 30 for each loading direction and laminated type. The support distance was set to 18 times the specimen height, as illustrated in Figure 1, while Figure 2 depicts the experimental setup.

The 4-point bending test is an experiment used to determine a material bending strength and modulus of elasticity. The sample is fixed on two parallel supports, equipped with two symmetrical loading points. The deformation of the material is measured as a result of the applied loads. This test is commonly used in materials science and engineering to examine the durability of structural materials. The test setup is shown in Figure 2.

The average value of the deformation of two displacement transducers was used for the analysis of the results. The *MOE* and *MOR* were determined by substituting the test results into equarions 2 and 3, respectively.

$$MOR = \frac{3 \cdot P_{max} \cdot (L - S)}{2 \cdot b \cdot h^2} \qquad (2)$$

Where, *MOR* is the bending strength (N/mm²), P_{max} is the maximum applied load (N); *L* is the span of the CLT (mm); *S* is the distance between the loading points (mm); *b* is the width (mm); *h* is the thickness of CLT (mm)

$$MOE = \frac{\lambda^3 \cdot (F_2 - F_1)}{b_1 \cdot h_1^3 \cdot (W_2 - W_1)} \cdot \left[\left(\frac{3a}{4\lambda} \right) - \left(\frac{a}{\lambda} \right)^3 \right] \qquad (3)$$

In bending tests, the modulus of elasticity in bending (*MOE*) is calculated using the following parameters: *MOE* (N/mm²) – modulus of elasticity in bending; *l* (mm) – span length between supports; b_1 (cm) – width of the cross section being tested; h_1 (cm) – depth of the cross section being tested; *a* (mm) – distance from the loading position to the nearest support; ΔF (N) – change in load between two points on the regression line, where the correlation coefficient is 0.99 or better (i.e., $F_2 - F_1$); ΔW (mm) – change in deformation corresponding to the change in load (i.e., $W_2 - W_1$) and λ – represents the elastic modulus constant.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Flexural strength
3.1. Čvrstoća na savijanje

Statistical evaluation of the results regarding the bending strength of CLT and laminated wood materials and solid wood materials is given in Table 1, and the results of multiple variance analysis are given in Table 2.

According to Table 1, the results of the four-point bending strength tests indicate clear differences in the average values of laminated wood, CLT and solid wood materials. This test was conducted to determine the bending strength of each material, and the results allow for a comparison of the mechanical properties of these three materials.

First, the test results for laminated wood materials generally show high strength, while the strength of CLT is also at a noteworthy level. In contrast, solid wood materials typically have lower average values compared to laminated and CLT. It is believed that these differences are related to the manufacturing techniques and structural properties of the materials. To assess whether the differences between the groups are statistically significant, a multiple variance analysis (ANOVA) was performed (Table 2).

According to the results of the variance analysis, the material type and the interaction between material type and load application direction were found to be statistically significant. However, the direction of load application (to the adhesive line) was found to be insignificant.

Deformation types are presented in Figures 4 and 5. Under the load applied perpendicular to the adhesive line, the deformation of the prepared laminate is first observed in the bottom lamella. In contrast, when the load is applied parallel to the adhesive line, deformation is observed simultaneously across all the lamellae that make up the laminate. The Duncan test was conducted to determine the significance level between groups (Table 3). The results of the Duncan test indicate that the differences between the groups are statistically significant.

3.2 Flexural modulus of elasticity
3.2. Modul elastičnosti pri savijanju

The comprehensive statistical evaluation of the results regarding the bending modulus of elasticity of CLT and laminated wood materials, as well as solid

Table 1 Four-point bending strength results of the test samples (N/mm²)
Tablica 1. Rezultati čvrstoće na savijanje u četiri točke (N/mm²)

Force direction *Smjer sile*	**Material type** *Vrsta materijala*	**Xmin.**	**Xort.**	**Xmax**	**Std.**
Parallel to the glue line *paralelno s lijepljenim spojem*	Solid wood materials (no glue) / *masivno drvo (bez ljepila)*	75.10	77.50	79.90	3.028
	CLT	76.50	78.90	81.30	4.229
	Wood laminated / *lamelirano drvo*	88.50	90.90	93.30	3.143
Vertical to the glue line *okomito na lijepljeni spoj*	CLT	77.20	79.60	82.00	4.926
	Wood laminated / *lamelirano drvo*	79.60	82.00	84.40	3.916

Table 2 Four-point bending strength results of test samples (N/mm²)
Tablica 2. Rezultati čvrstoće na savijanje u četiri točke (N/mm²)

Sources of variance *Izvori varijance*	**S.D**	**Total of squares** *Ukupno kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	***F* Value** *F-vrijednost*	**Chance of error P<0.05** *Vjerojatnost pogreške P<0,05*
Material type *vrsta materijala*	2	900.033	450.017	31.511	.000
Force direction *smjer sile*	1	112.067	112.067	7.847	.007
M.T. × F.D.	2	286.433	143.217	10.028	.000
Error / *greška*	54	771.200	14.281		
Total / *ukupno*	60	396378.000			

wood materials, is presented in Table 4. Additionally, the results of the multiple variance analysis conducted to examine the differences among these materials are provided in Table 5.

According to Table 4, the results obtained from the four-point bending tests aimed at determining the modulus of elasticity reveal significant average differences among laminated wood, CLT and solid wood materials. This test serves as an important method for establishing the modulus of elasticity for each type of material, facilitating a comprehensive comparison of their mechanical properties.

First, the results indicate that laminated wood materials generally exhibit high strength, which can be attributed to their engineered nature and the advantages of their layered structures. Similarly, CLT also demonstrates a remarkable level of strength, which can be said to arise from its cross-laminated structure that enhances stability and load-bearing capacity. In contrast, the average modulus of elasticity values for solid wood materials tend to be lower compared to both laminated wood and CLT. This difference may stem from the inherent characteristics of solid wood, such as natural variations in density and grain structure.

The observed discrepancies in mechanical properties are believed to be influenced by the distinct manufacturing techniques and structural attributes of each material. Laminated wood is typically produced by bonding layers of wood together, which enhances its mechanical performance. CLT, on the other hand, increases durability through the cross-lamination of its layers. To determine whether the differences among the groups are statistically significant, a multiple variance analysis (ANOVA) has been conducted (Table 5).

Table 3 Duncan results regarding the effects of material type on bending strength (N/mm²)
Tablica 3. Duncanovi rezultati utjecaja vrste materijala na čvrstoću na savijanje (N/mm²)

Material type / *Vrsta materijala*	**Xort.**	**H.G**
Solid wood materials / *masivno drvo*	77.50	A
CLT	79.25	B
Wood laminated / *lamelirano drvo*	86.45	B

The results of the variance analysis conducted to determine the bending modulus of elasticity indicate that both the material type and the interaction between material type and load application direction are statistically significant (p<0.05). However, it was found that the direction of load application (relative to the adhesive line) is not significant (p<0.05). To further investigate the differences among the groups, a Duncan test was conducted, which determined the significance levels between the groups (Table 6). The results of the Duncan test indicate that there are statistically significant differences between the groups.

3.3 Fracture types
3.3. Vrste loma

The wood (control), laminated wood, and cross-laminated timber materials exhibited different types of fractures under loading. The test samples fractured between both load arms and support points. These fractures indicate that the prepared samples were appropriately designed for the purpose of the experiment and that the obtained values are valid. The type of fracture observed in the wood material samples is presented in Figure 3; the fracture type observed in the laminated wood material is shown in Figure 4; and the fracture

Table 4 Results of modulus of elasticity of test samples in four-point bending (N/mm²)
Tablica 4. Rezultati modula elastičnosti ispitnih uzoraka pri savijanju u četiri točke (N/mm²)

Force direction *Smjer sile*	**Material type** *Vrsta materijala*	***X*min.**	***X*ort.**	***X*max**	**Std.**
Parallel to the glue line *paralelno s lijepljenim spojem*	Solid wood materials (No glue) *masivno drvo (bez ljepila)*	10676.66	10919.90	11163.14	268.921
	CLT	11268.86	11512.10	11755.34	270.451
	Wood laminated / *lamelirano drvo*	12248.36	12491.60	12734.84	545.978
Vertical to the glue line *okomito na lijepljeni spoj*	CLT	11479.06	11722.30	11965.54	466.022
	Wood laminated / *lamelirano drvo*	11528.36	11771.60	12014.84	387.458

Table 5 Results of variance analysis regarding the effects of material type and force direction on bending modulus of elasticity values
Tablica 5. Rezultati analize varijance utjecaja vrste materijala i smjera sile savijanja na modul elastičnosti

Sources of variance *Izvori varijance*	***S.D***	**Total of squares** *Ukupno kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	***F* Value**	**Chance of error P<0.05** *Vjerojatnost pogreške P<0,05*
Material type *vrsta materijala*	2	14,793,676.933	7,396,838.467	50.252	.000
Force direction / *smjer sile*	1	433,160.067	433,160.067	2.943	.092
M.T. × F.D.	2	2,379,760.133	1,189,880.067	8.084	.001
Error / *pogreška*	54	7,948,549.600	147,195.363		
Total / *ukupno*	60	8,038,346,878.0			

Table 6 Results of Duncan test regarding the effects of material type on elasticity modulus in bending (N/mm²)
Tablica 6. Rezultati Duncanova testa utjecaja vrste materijala na modul elastičnosti pri savijanju (N/mm²)

Material type / *Vrsta materijala*	***X*ort.**	**H.G**
Solid wood materials / *masivno drvo*	10919.90	A
CLT	11617.20	B
Wood laminated / *lamelirano drvo*	12131.60	C

type observed in the cross-laminated timber material is illustrated in Figure 5.

In the examples of wooden materials, it was observed that the effects of force initiated capillary action from the midpoint of both supports and progressed inward. During the initial phase of the test, the displacement increased linearly with the applied force. However, at the point of fracture (at maximum loading), while the displacement continued to increase, the force exhibited a decline.

In laminated wood samples subjected to forces, distinct differences have been observed between the fracture characterization under perpendicular forces to the adhesive line and that under parallel forces. In samples perpendicular to the adhesive line, wide-angle fractures occur, while narrow-angle fractures are ob-

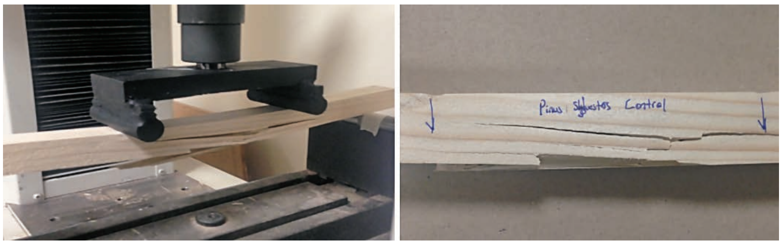

Figure 3 Type of fracture observed in wood material
Slika 3. Vrsta loma uočena na masivnom drvu

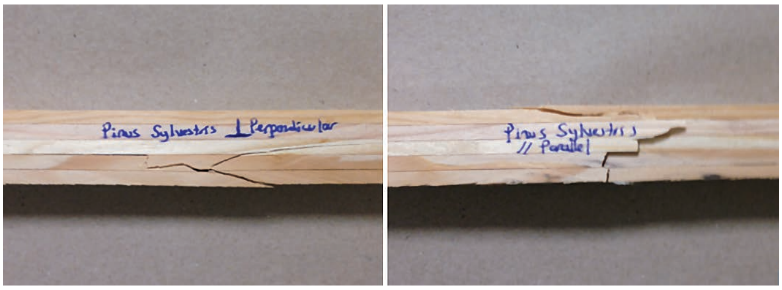

Figure 4 Type of fracture observed in laminated wood material
Slika 4. Vrsta loma uočena na lameliranom drvu

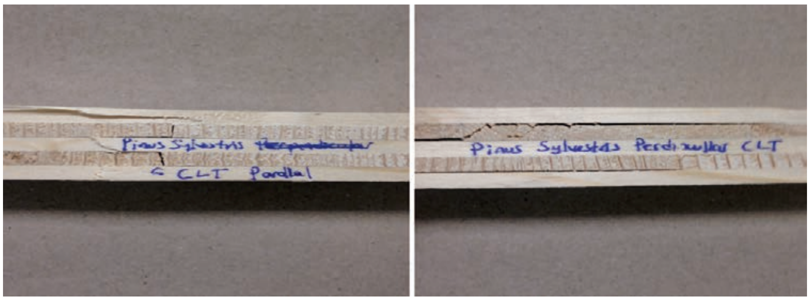

Figure 5 Type of fracture observed in CLT
Slika 5. Vrsta loma uočena na CLT-u

served in samples parallel to the adhesive line. In the samples subjected to perpendicular forces, it has been determined that the fracture starts from the lower layer and progresses towards the inner sections, meaning that the initial fracture occurs in the bottom laminate. In the parallel samples, the fracture occurs between the wood laminates and the adhesive layers.

In cross-laminated timber materials, failure primarily occurs as the annual rings of the laminates in the middle layer separate from one another. The fracture angle has been observed to be wide in samples parallel to the glue line, while it is narrow in samples perpendicular to the glue line.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, solid wood materials, cross-laminated timber (CLT), and laminated wood materials, which are frequently used in the construction and furniture industries, were compared in terms of their bending strength and elastic modulus values. Four-point bending tests were applied to the test samples, with forces applied in two different directions: perpendicular and parallel to the glue line. The results obtained from the experimental work led to the following conclusions:

When examining the results of the four-point bending tests, it was observed that the highest value was obtained for the laminated wood material in the direction parallel to the glue line. This can be attributed to the alignment of the laminates in the same direction and the resistance of the adhesive layer against bending. The lowest bending resistance was observed in solid wood. It was also noted that the adhesive and laminates used in CLT and laminated wood materials enhanced their resistance to bending.

According to the results of the Duncan test, higher values were obtained in the direction parallel to the glue line when considering the applied force direction. This finding suggests that when the material is used as a structural or furniture skeleton component, the forces it will be subjected to, will be independent of the point of application and parallel to the glue line, which would yield better results.

It was observed that the adhesive and laminates bonding the layers of CLT and laminated wood materials provided high bending strength, and there were no issues with the adhesive bonding area.

Average values for bending strength and elastic modulus were found to be higher in the direction parallel to the glue line compared to the direction perpendicular to the glue line. In conclusion, it can be stated that CLT and laminated wood materials can be used as alternatives to solid wood materials, which are frequently used in construction and as furniture materials in framed structures.

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