

EFFECT OF WOOD VENEER LAMINATION ON THE BENDING PERFORMANCE OF 3D PRINTED WOOD-FILLED PLA COMPOSITES

Yasemin Öztürk¹

<https://orcid.org/0000-0003-2292-2447>

Haldun Ender Erdem²

<https://orcid.org/0000-0001-5395-6629>

Hilal Ulaşan^{1,*}

<https://orcid.org/0000-0003-3734-2904>



ABSTRACT

The integration of additive manufacturing and wood-based reinforcement systems has created new opportunities for the development of sustainable hybrid composite materials. This study investigated the effects of wood veneer lamination on the bending behavior of 3D-printed wood-filled PLA composites produced with different infill ratios. Specimens were manufactured using fused filament fabrication (FFF) with 50 % and 100 % infill configurations and subsequently laminated with 0,5 mm thick pine and oak veneers on both surfaces. For comparative evaluation, medium-density fiberboard (MDF) and particleboard specimens were also included in the study. A total of 120 specimens were subjected to three-point bending tests in order to determine bending strength and modulus of elasticity (MOE) values. In addition, representative load–extension behavior, fracture characteristics, and qualitative finite element method (FEM) observations were evaluated. The experimental results demonstrated that veneer lamination affected the mechanical performance of the tested materials differently depending on substrate structure and internal continuity characteristics. The highest bending strength values were obtained from the uncoated specimens printed at 100 % infill. In these groups, veneer lamination increased stiffness behavior but did not improve ultimate bending strength. In contrast, veneer application significantly improved both bending strength and stiffness performance in particleboard specimens and moderately enhanced the performance of MDF specimens. Fracture observations indicated that veneer lamination altered crack propagation behavior and interfacial response during bending, particularly in the laminated 3D-printed groups. Qualitative FEM observations supported the experimental findings by showing reduced displacement behavior and localized stress regions in veneer-laminated specimens, although the numerical simulations were interpreted qualitatively due to simplified modeling assumptions. These findings provide new insight into the reinforcing effect of wood veneer lamination on 3D-printed wood-filled PLA composites and demonstrate its potential as an effective strategy for improving the flexural performance of bio-based additively manufactured structures. The study contributes to the development of sustainable hybrid wood-polymer composites by clarifying the relationship between veneer reinforcement, infill density, and bending behavior.

Keywords: Additive manufacturing, Wood-filled PLA, Wood veneer lamination, Hybrid composites, Bio-based composite, Flexural behavior.

¹Gazi University. Technology Faculty. Wood Products Industrial Engineering. Ankara, Türkiye.

²Kırıkkale University. Kırıkkale Vocational School. Furniture and Decoration Program. Kırıkkale, Türkiye.

*Corresponding author: hilalulasan@gazi.edu.tr

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INTRODUCTION

Wood-based materials are widely recognized as renewable and sustainable engineering materials that play an essential role in the transition toward environmentally responsible manufacturing and construction. However, increasing environmental pressures, climate change, and the growing demand for raw materials have intensified the need to utilize wood resources more efficiently while maintaining structural performance (Çiğdem and Perçin 2022). Consequently, considerable research efforts have focused on developing high-value wood-based products and hybrid bio-based composites capable of combining sustainability with improved mechanical properties. Among the available manufacturing strategies, lamination has become one of the most widely adopted approaches because it enables the efficient utilization of low-grade wood resources while enhancing strength, dimensional stability, and surface quality (Falk and Colling 1995, Ashter 2013, Çiğdem and Perçin 2022, Sikora *et al.* 2021, Fico *et al.* 2022). Laminated wood products are therefore extensively employed in structural and industrial applications, including furniture, transportation, bridge construction, and housing systems.

In parallel with developments in wood lamination, additive manufacturing has emerged as a promising production technology for sustainable material systems. Among additive manufacturing techniques, fused filament fabrication (FFF) has attracted considerable attention because of its ability to fabricate complex geometries with minimal material waste while allowing precise control over internal architecture (Gibson *et al.* 2015). Recent developments in wood-filled PLA filaments have further expanded the application potential of FFF by incorporating wood flour and lignocellulosic residues into thermoplastic matrices, thereby supporting circular economy principles and creating environmentally friendly alternatives to conventional wood-based products (Fico *et al.* 2022, Huang *et al.* 2021, Palaniyappan *et al.* 2023, Lohar *et al.* 2022, Estakhrianhaghighi *et al.* 2020, Romani *et al.* 2023). The combination of renewable raw materials with digitally controlled manufacturing has therefore positioned additive manufacturing as an increasingly important platform for the development of next-generation hybrid bio-based composites.

Although both veneer lamination and fused filament fabrication have independently demonstrated considerable potential for improving the performance and sustainability of wood-based materials, predicting the mechanical response of hybrid structures produced by combining these two technologies remains a significant scientific challenge. In laminated additively manufactured composites, the overall flexural response is governed not only by the intrinsic properties of the constituent materials but also by complex interactions between the printed internal architecture, the veneer-core interface, adhesive bonding characteristics, and stress transfer mechanisms during loading. Consequently, the effectiveness of veneer reinforcement cannot be evaluated solely based on the individual performance of either laminated wood products or FFF-printed composites, as the interaction between these components introduces additional structural complexities that remain insufficiently understood.

Wood lamination has long been recognized as an effective strategy for enhancing the structural performance of wood-based materials. Depending on the selected adhesive system and product configuration, laminated wood products such as laminated veneer lumber (LVL) and plywood provide improved dimensional stability, mechanical strength, and defect distribution compared with solid wood (Acosta *et al.* 2023). Furthermore, previous studies have demonstrated that laminating densified wood lamellae using polyvinyl acetate (PVAc) adhesive can significantly improve bending resistance, particularly at relatively low densification ratios (Sikora *et al.* 2021). More recently, different reinforcement materials, including carbon fiber fabrics, bamboo veneers, and steel wire mesh, have also been incorporated into laminated structures to further improve stiffness and strength (Ulaşan and Söğütü 2024, Novosel *et al.* 2023). Although these reinforcement strategies have generally improved mechanical performance, they often increase manufacturing complexity and production cost, thereby limiting their broader industrial application.

Similarly, extensive research has demonstrated that the mechanical performance of FFF-manufactured components is strongly influenced by the internal architecture of the printed structure. Parameters such as infill density, raster arrangement, and internal porosity directly affect stiffness, load-bearing capacity, deformation behavior, and failure mechanisms. In particular, increasing infill density generally improves the flexural performance of PLA- and wood-filled PLA-based composites by reducing internal voids and increasing structural continuity (Sultana *et al.* 2024). Likewise, previous investigations have shown that the internal void architecture substantially influences stress propagation and crack development during bending (Faizaan *et al.* 2025). These findings clearly demonstrate that the internal architecture of additively manufactured components plays a fundamental role in determining their structural behavior.

Despite these advances, an important scientific uncertainty remains unresolved. Previous investigations have primarily examined veneer lamination and fused filament fabrication as independent approaches for improving material performance. Consequently, the interaction between natural wood veneer reinforcement and different internal architectures of wood-filled FFF composites remains insufficiently understood. In particular, it is still unclear how veneer reinforcement modifies stress transfer, stiffness development, deformation characteristics, and crack propagation in printed structures with different infill densities. Because these mechanisms govern the overall flexural response of hybrid laminated composites, the absence of this knowledge limits the rational design and optimization of structurally efficient bio-based materials for engineering applications.

This knowledge gap is further emphasized by the increasing interest in integrating conventional wood-processing techniques with additive manufacturing technologies. A recent comprehensive review by Krapež and Kariž (2022) highlighted the growing demand for wood-based materials in additive manufacturing and identified the integration of wood-filled filaments with structural wood laminates as an important future research direction. However, experimental evidence describing the mechanical interaction between veneer reinforcement and printed wood-filled PLA substrates remains limited, particularly with respect to flexural stiffness, bending resistance, deformation behavior, and failure mechanisms. Therefore, additional experimental investigations are required to clarify these interactions and provide a scientific basis for the development of structurally efficient hybrid wood-polymer composites.

To address this scientific uncertainty, an experimental approach capable of simultaneously evaluating global flexural performance and the underlying deformation mechanisms is required. Three-point bending testing provides quantitative information regarding bending strength and stiffness while enabling direct observation of failure characteristics under flexural loading. However, experimental observations alone do not fully explain how veneer reinforcement influences stress distribution within hybrid laminated structures. Therefore, qualitative finite element analysis (FEM) was employed as a complementary tool to support the interpretation of stress transfer, deformation behavior, and the mechanical interaction between the veneer layers and the printed wood-filled PLA core. The combination of experimental testing and qualitative numerical analysis therefore provides complementary evidence for understanding the flexural behavior of veneer-reinforced additively manufactured composites and contributes to a more comprehensive interpretation of the observed mechanical responses.

Therefore, the objective of this study was to investigate the flexural behavior of wood-filled PLA composites manufactured by fused filament fabrication (FFF) and reinforced with natural pine and oak veneers. The influence of veneer lamination on bending strength, modulus of elasticity, deformation characteristics, and failure behavior was experimentally evaluated through three-point bending tests, while qualitative finite element analysis was performed to support the interpretation of stress distribution and deformation mechanisms. By clarifying the interaction between veneer reinforcement and different infill densities, this study provides new insight into the design of sustainable hybrid wood-polymer composites for structural applications.

MATERIALS AND METHODS

Material

In this study, biocomposite specimens were produced using wood-filled PLA filaments with two different infill ratios: 50 % and 100 %. Filaments (1,75 mm diameter) were supplied by ABG, a filament manufacturing company operating in Türkiye, and were used to form the intermediate core layer of the laminated structure using the fused filament fabrication (FFF) method. In addition to 3D printed samples, medium-density fiberboard (MDF) and particleboard panels were also included for comparison.

For surface lamination, natural pine and oak veneers with a thickness of 0,5 mm were obtained from suppliers located in the Siteler region of Ankara, Türkiye. The lamination of the top and bottom surfaces was performed using a one-component moisture-curing polyurethane (PU) adhesive, selected for its strong bonding performance and compatibility with both wood and thermoplastic substrates. The polyurethane adhesive was applied to the core surface at an approximate spread rate of 150–180 g/m² prior to lamination. Since a one-component moisture-curing PU adhesive was used, distilled water was lightly sprayed onto the veneer surface at an approximate rate of 20–30 g/m² in order to promote curing through activation of the isocyanate groups.

The MDF and particleboard panels used in the study were commercially manufactured wood-based panels commonly used in furniture applications. Prior to specimen preparation, the average air-dry densities of MDF

and particleboard were determined as approximately 0,77 g/cm³ and 0,64 g/cm³, respectively. The specimens were conditioned at 20 ± 2 °C and 65 ± 5 % relative humidity until reaching equilibrium moisture content before lamination and testing procedures.

The pine and oak veneers used for lamination had a nominal thickness of 0,5 mm and were applied with their fiber direction oriented parallel to the longitudinal axis of the test specimens in order to ensure consistency during bending tests. The veneer sheets were conditioned under the same environmental conditions prior to bonding. Based on air-dry measurements, the average density values of the pine and oak veneers were approximately 0,48 g/cm³ and 0,72 g/cm³, respectively.

Method

Preparation of samples

The fabrication of the test specimens was carried out using a “Makerbot Replicator 2” 3D printer. Wood-filled PLA filaments were printed at two infill ratios: 50 % and 100 %. All 3D printed specimens were prepared in dimensions of 10 mm × 10 mm × 180 mm, consistent with the requirements of bending tests.

The specimens were printed in the vertical orientation due to the build volume and working area limitations of the printer used in the study. This orientation enabled the specimens to be manufactured within the available printing space. Since all specimens were produced under identical printing orientation conditions, consistency was maintained throughout the comparative evaluations.

G-code generation was performed using the MPrint software. During specimen production, a layer height of 0.20 mm, a shell/perimeter value of 2, a printing speed of 50 mm/s, a nozzle temperature of 210 °C, a bed temperature of 60 °C, and a nozzle diameter of 0.4 mm were used for all specimen groups. Within the printing process, the infill ratio (50% and 100%) was the only variable parameter, whereas all remaining user-accessible printing settings were kept constant. All other user-accessible printing parameters were kept constant throughout the study. However, the MPrint software provides only limited reporting of slicing parameters, and detailed information regarding the infill pattern, raster orientation, top and bottom solid layer configuration, and other internal infill generation settings was not available in the software output used for this study. Consequently, these parameters could not be reported and should be considered a limitation for the exact reproduction of the internal printing architecture.

The selected infill ratios were intended to represent two distinct internal structural conditions: a relatively dense structure (100 % infill) and a partially hollow structure containing internal voids (50 % infill). The primary objective of the study was not to optimize lightweight lattice geometries, but rather to comparatively evaluate the influence of veneer lamination on substrate structures with different internal continuity characteristics under bending loads.

In addition to the 3D-printed samples, MDF and particleboard specimens were also prepared in the same dimensions for comparative analysis. These reference materials were cut from commercially available panels. The experimental design consisted of 12 experimental groups, representing four substrate types (wood-filled PLA printed at 50% and 100% infill, MDF, and particleboard) and three veneer conditions (control, pine veneer, and oak veneer), with 10 replicate specimens (n=10) per group, resulting in a total of 120 fabricated specimens. A visual of the 3D printing process is provided in Figure 1.



Figure 1: Printing of wood added filaments.

Lamination process

After cutting and printing were completed, all test specimens were conditioned in a climate-controlled chamber at $20 \pm 2\text{ }^{\circ}\text{C}$ temperature and $65 \pm 5\text{ }\%$ relative humidity until they reached air-dry equilibrium moisture content.

Following the conditioning, natural pine and oak veneers were adhered to the upper and lower surfaces of the 3D printed specimens using polyurethane (PU) adhesive. The lamination process was carried out using cold pressing under a uniform pressure of $1,2\text{ N/mm}^2$ for 8 hours (Figure 2).



Figure 2: Lamination process. (a): Gluing the intermediate layers and placing them in the mold; (b): Placement of veneers; (c): Pressing process.

Following the pressing stage, the laminated specimens were trimmed to final dimensions ($10 \times 10 \times 180\text{ mm}$) and the edge surfaces were cleaned to remove excess glue or misalignment. The trimmed samples were then re-conditioned in the same climate chamber until reaching a constant weight prior to testing.

No lamination or additional processing was applied to the control group specimens.

Air-dry density determination

The air-dry density values of the specimens were determined in accordance with the TS EN 323 (1999) standard. Prior to testing, the specimens were conditioned under laboratory conditions until reaching air-dry moisture content. The dimensions of the specimens, including width (b_1 , b_2) and thickness (t), were measured using a digital caliper with $0,01\text{ mm}$ precision, while the mass (m) values were determined using an analytical balance with $0,01\text{ g}$ sensitivity. The air-dry density values were calculated according to Equation 1.

$$d = \frac{m}{b_1 \times b_2 \times t} \times 10^4 \quad (1)$$

Bending strength and modulus of elasticity

The bending strength of the prepared specimens was determined using a universal testing machine (Instron) under a static three-point bending configuration, in accordance with the TS ISO 13061-3 (2021) standard for small clear wood specimens (Figure 3). The modulus of elasticity (MOE) values were determined based on the load–deflection relationship obtained during the bending tests, in accordance with the TS ISO 13061-4 (2021) standard.

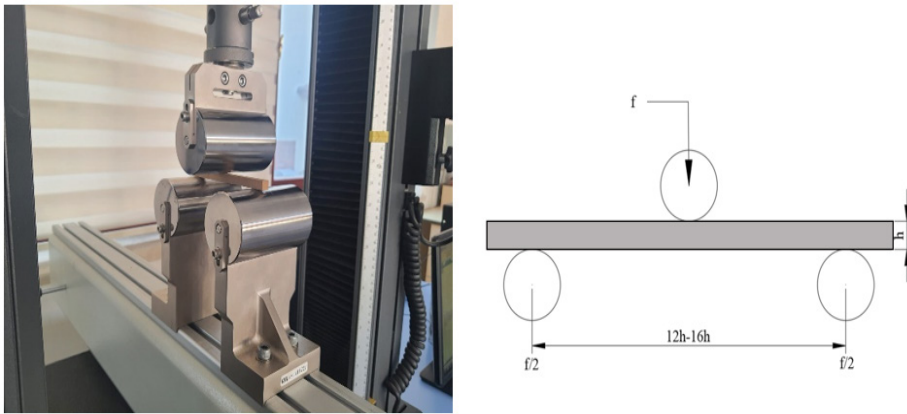


Figure 3: Performing the bending strength test.

During testing, each specimen was placed on two supports with a span length of 150 mm, and a downward load was applied at the midpoint of the span until failure. The loading speed and test configuration were adjusted in accordance with the relevant standard requirements. The maximum load values obtained during the tests were used to calculate the bending strength according to Equation 2, while the modulus of elasticity (MOE) values were calculated from the load–deflection relationship within the elastic deformation region according to Equation 3.

$$\sigma_{b,w} = \frac{3P_{max}l}{2bh^2} \quad (2)$$

Were;

P_{max} = Maximum load (N),

l = Distance between supports (mm),

b = Width of the test sample (mm),

h = Height of the test sample (mm).

$$E_w = \frac{Pl^3}{4bh^3f} \quad (3)$$

P= Load difference between the upper and lower proportional limits (N),

l = Distance between supports (mm),

b = Width of the test specimen (mm),

h = Thickness (height) of the test specimen (mm),

f = Deflection difference corresponding to the upper and lower load limits (mm)

Evaluation of data

The obtained data were statistically analyzed using the MSTAT-C 1.2 software package. A one-way analysis of variance (ANOVA) was performed to evaluate the effects of material type and veneer type on bending strength.

When significant differences were detected at the $p \leq 0,05$ significance level, mean comparisons were conducted using the Duncan's multiple range test based on the least significant difference (LSD) criterion. Groupings based on statistical homogeneity were identified to interpret the influence of each variable on mechanical performance.

Numerical analysis

In addition to experimental testing, numerical simulations were conducted using the Stress Analysis environment of Autodesk Inventor Professional to qualitatively evaluate the stress distribution and deformation behavior of the specimens under three-point bending. The simulations were intended to complement the experimental observations and provide qualitative insight into the structural response of the investigated configurations.

Three separate finite element models were developed for the 100% infill groups: (1) uncoated control, (2) pine-veneered, and (3) oak-veneered specimens. All models were created using the same geometry as the experimental specimens ($10 \times 10 \times 180$ mm) with a support span of 150 mm. The veneer layers were modeled as 0.5 mm thick laminates bonded to the top and bottom surfaces of the PLA core.

Material properties were assigned directly from the Autodesk Inventor standard material library without manual modification. Accordingly, the predefined material properties available for wood-filled PLA, pine veneer, and oak veneer were adopted in the simulations. All materials were assumed to exhibit linear-elastic behavior throughout the analysis.

A static load of 1500 N was applied at the midspan, while both supports were defined as frictionless constraints to reproduce the experimental loading configuration. Meshing was performed using the automatic mesh generation function available in Autodesk Inventor, and no manual mesh refinement or element size adjustment was applied. A perfectly bonded interface was assumed between the PLA core and veneer layers, with no interfacial slip or delamination. As the numerical simulations were intended to provide qualitative support for the experimental observations, a formal mesh convergence analysis was not performed. Accordingly, the numerical results were interpreted qualitatively to support the experimental findings rather than as a quantitative validation of structural performance.

Results and discussion

Air-dry density

Table 1: Air-dry density values of the tested specimens.

Material Type	Veneer Type	Density (kg/m ³)				
		Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation (%)
Filament Printed at 100 % Infill	Control Group	1120	1160	1140	10	1,09
	Pine Veneer	1120	1170	1150	20	1,85
	Oak Veneer	1140	1160	1150	10	0,45
Filament Printed at 50 % Infill	Control Group	680	710	700	10	1,14
	Pine Veneer	740	760	750	10	0,79
	Oak Veneer	710	770	740	20	3,05
MDF (Medium Density Fiberboard)	Control Group	760	790	770	10	1,18
	Pine Veneer	770	810	790	10	1,29
	Oak Veneer	760	780	780	10	0,75
Particleboard	Control Group	610	680	640	20	2,99
	Pine Veneer	710	750	740	10	1,93
	Oak Veneer	700	750	720	20	3,02

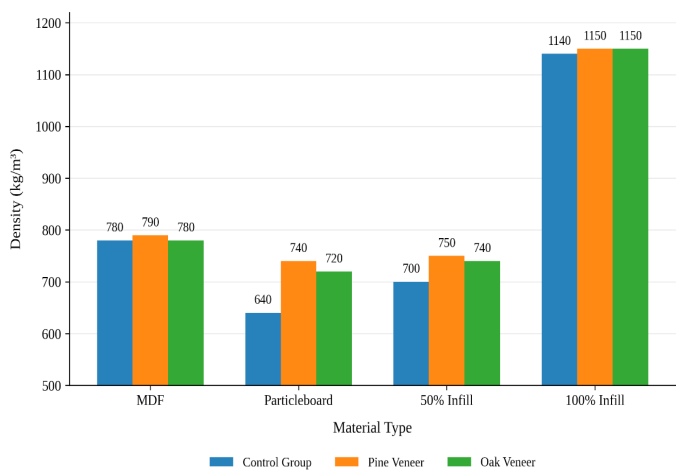


Figure 4: Mean air-dry density values of the tested specimen groups.

The air-dry density values of the tested specimen groups are presented in Table 1, while the mean density values are illustrated in Figure 4. According to the results, the highest density values were obtained from the filament specimens printed at 100 % infill ratio, with mean values ranging between 1140 and 1150 kg/m³. In contrast, the lowest density value was determined in the particleboard control group with a mean density of 640 kg/m³. Veneer lamination generally increased the density values in all material groups compared to the control specimens. Among the veneer types, pine veneer specimens exhibited slightly higher density values than oak veneer specimens in most groups.

The higher density values observed in the 100 % infill filament groups can be attributed to the reduction of internal voids and the increased structural continuity resulting from the fully filled printing structure. In contrast, the 50 % infill specimens contained internal gaps due to the partial filling pattern, leading to lower density values. The increase in density after veneer application was associated with the additional veneer layer and the adhesive material introduced into the composite structure. Furthermore, adhesive penetration into the porous structure of the substrate materials may have contributed to the increase in overall density values. Similar findings have been reported in previous studies, indicating that veneer lamination and adhesive incorporation generally increase the density of wood-based composite structures.

Table 2: Analysis of variance (ANOVA) results for the effects of material type and veneer type on air-dry density.

Source	Degrees of Freedom	Mean Squares	F Value	p≤0,05
Material Type (A)	3	1,154	1362,23	0,0000*
Veneer Type (B)	2	0,21	322316,84	0,0000*
Material Type x Veneer Type (AB)	6	0,05	4897,36	0,0000*
Error	96	0,000		
Total	108			

Table 3: Material type for Duncan test (kg/m³).

Material Type	Density (kg/m³)	
	Arithmetic Mean	Homogeneity Group
Filament printed at 100 % infill	1140	A
Filament printed at 50 % infill	780	B
MDF	730	C
Particleboard	700	D
LSD: 27		

Table 4: Veneer type for Duncan test (kg/m³).

Veneer Type	Density (kg/m³)	
	Arithmetic Mean	Homogeneity Group
Pine Veneer	860	A
Oak Veneer	850	B
Control Group	810	C
LSD: 0,4		

Table 5: Duncan test at material type–veneer type level (kg/m³).

Material Type	Veneer Type					
	Pine Veneer		Oak Veneer		Control Group	
	–	HG	–	HG	–	HG
Filament printed at 100 % infill	1150	A*	1150	A	1140	A
Filament printed at 50 % infill	750	D	740	D	700	E
MDF	790	B	780	B	780	B
Particleboard	740	D	720	E	640	F**
LSD: 3						

–:Arithmetic mean HG:Homogeneity group *: Highest bending strength **:Lowest bending strength.

Variance analysis results presented in Table 2 showed that material type, veneer type, and the interaction between these factors had statistically significant effects on density values ($p\leq0,05$). According to the Duncan test results given in Table 3, Table 4, Table 5 the filament specimens printed at 100 % infill formed a distinct homogeneity group with the highest density values, whereas the particleboard control specimens exhibited the lowest density values. Although veneer lamination increased density values in almost all groups, this increase did not always correspond to proportional improvements in bending strength. This result suggests that the mechanical performance of laminated composite structures is influenced not only by density, but also by factors such as interfacial compatibility, stress transfer efficiency, and bonding behavior between the veneer and substrate material.

Bending strength

The bending strength values obtained from the tested specimen groups are presented in Table 6. The results indicate that both material type and veneer application significantly influenced the flexural performance of the specimens. Among all groups, the highest bending strength was obtained from the uncoated filament specimens printed at 100 % infill, with a mean value of 86,47 MPa, whereas the lowest value was recorded in the uncoated particleboard group with a mean value of 8,69 MPa. In general, the 3D-printed filament specimens exhibited substantially higher bending strength values than the conventional wood-based panel materials.

Table 6: Bending strength values of the tested specimens.

Material Type	Veneer Type	Bending Strength (MPa)				
		Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation (%)
Filament Printed at 100 % Infill	Control Group	82,27	88,75	86,47	2,18	2,52
	Pine Veneer	47,82	78,12	70,08	8,14	11,61
	Oak Veneer	65,84	75,66	69,89	2,67	3,81
Filament Printed at 50 % Infill	Control Group	38,70	45,13	41,48	2,27	5,47
	Pine Veneer	32,82	69,51	43,75	10,80	24,69
	Oak Veneer	35,37	53,64	42,99	6,11	14,22
Particleboard	Control Group	6,33	13,02	8,69	1,84	21,22
	Pine Veneer	25,49	38,96	32,11	4,13	12,87
	Oak Veneer	27,96	40,26	35,48	3,73	10,52
MDF (Medium Density Fiberboard)	Control Group	38,60	49,13	46,03	3,17	6,88
	Pine Veneer	36,64	51,19	42,68	4,34	10,16
	Oak Veneer	42,74	58,60	48,69	5,23	10,74

The results further demonstrated that veneer lamination produced different effects depending on the substrate material. In the filament specimens printed at 100 % infill, both pine and oak veneer applications reduced the bending strength values to 70,08 MPa and 69,89 MPa, respectively. Similarly, slight changes were observed in the 50 % infill groups, where the pine- and oak-laminated specimens exhibited mean bending strength values of 43,75 MPa and 42,99 MPa, respectively, compared to 41,48 MPa for the uncoated control specimens. In contrast, veneer application significantly improved the bending strength of particleboard specimens. The mean bending strength increased from 8,69 MPa in the control group to 32,11 MPa and 35,48 MPa in the pine- and oak-veneered groups, respectively. Oak veneer also improved the bending strength of MDF specimens, increasing the mean value from 46,03 MPa to 48,69 MPa.

The reduction in bending strength observed in the densely printed PLA-based specimens after veneer lamination may be associated with differences in stiffness and stress transfer behavior between the veneer layer, adhesive layer, and printed core structure. In highly dense printed specimens, the compact internal architecture may have limited the ability of the veneer layer to redistribute tensile stresses effectively, leading to localized stress concentrations at the veneer–core interface. In contrast, the veneer layers acted as an effective reinforcement element in low-strength wood-based panels, particularly particleboard, where the veneer contributed to improved load distribution during bending. Similar improvements in the flexural performance of veneer-laminated wood products have previously been reported by Sikora *et al.* (2021) and Ulaşan and Söğütü (2024), who attributed the enhancement to the reinforcing effect of laminated surface

layers. Likewise, Sultana et al. (2024) and Faizaan et al. (2025) demonstrated that the mechanical response of additively manufactured wood-filled composites is strongly governed by internal architecture, with infill density influencing stress distribution and crack propagation. However, unlike previous studies reporting consistent improvements after veneer reinforcement, the present study showed that veneer lamination did not enhance the bending strength of specimens printed at 100% infill. This difference is likely related to the combined influence of the dense printed architecture, the adhesive-mediated veneer–core interface, and the resulting stress-transfer mechanisms during bending. Therefore, the present findings demonstrate that the effectiveness of veneer reinforcement is highly substrate-dependent and controlled by the interaction between infill architecture and veneer–core compatibility. This study extends the current understanding of veneer-reinforced wood-filled PLA composites by showing that veneer lamination is more effective in improving the flexural performance of relatively compliant substrates than densely printed structures.

The coefficient of variation (CV) values generally indicated acceptable experimental consistency among the tested groups. However, relatively high variation was observed in the pine-veneered filament specimens printed at 50 % infill (24,69 %), which may be associated with the heterogeneous internal structure of partially filled printed specimens and local differences occurring at the veneer–core interface.

Table 7: Analysis of variance (ANOVA) results for the effects of material type and veneer type on bending strength.

Source	Degrees of Freedom	Mean Squares	F Value	p≤0,05
Material Type (A)	3	12953,62	426,74	0,0000*
Veneer Type (B)	2	130,64	4,30	0,0000*
Material Type x Veneer Type (AB)	6	1002,86	33,04	0,0000*
Error	108	30,36		
Total	120			

*: Difference is significant according to 0,05

The results of the two-way ANOVA presented in Table 7 revealed that material type (A), veneer type (B), and their interaction (A × B) had statistically significant effects on bending strength values (p≤0,05). Among these factors, material type exhibited the highest F-value, indicating that the inherent mechanical properties of the substrate materials had the strongest influence on flexural performance.

Table 8: Material type for Duncan test (MPa).

Material Type	Bending Strength	
	Mean	Homogeneity Group
Filament printed at 100 % infill	75,48	A
Filament printed at 50 % infill	42,74	C
Particleboard	25,43	D
MDF	45,80	B
LSD: 2,79		

Table 9: Veneer type for Duncan test (MPa).

Veneer Type	Bending Strength	
	Mean	Homogeneity Group
Oak Veneer	49,26	A
Pine Veneer	47,15	AB
Control Group	45,67	B
LSD :2,41		

Table 10: Duncan test at material type–veneer type level (MPa).

Material Type	Veneer Type					
	Pine Veneer		Oak Veneer		Control Group	
	–	HG	–	HG	–	HG
Filament printed at 100 % infill	70,08	B	69,89	B	86,47	A*
Filament printed at 50 % infill	43,75	DE	42,99	E	41,48	E
Particleboard	32,11	F	35,48	F	8,69	G**
MDF	42,68	E	48,69	D	46,03	DE
LSD: 4,83						

–:Arithmetic mean HG:Homogeneity group *: Highest bending strength **:Lowest bending strength.

According to the Duncan multiple comparison test results presented in Table 8, Table 9 and Table 10, all material groups formed statistically distinct homogeneity groups. The filament specimens printed at 100 % infill exhibited the highest overall bending strength performance, while the particleboard control specimens formed the lowest homogeneity group. The interaction-level Duncan analysis further confirmed that veneer application did not produce identical effects across different material types. While veneer lamination significantly enhanced the flexural performance of particleboard and moderately improved MDF performance, it did not provide additional bending strength benefits for the densely printed PLA-based composites.

Öztürk and Burdurlu (2021) reported that veneer lamination using PVAc adhesive improved the bending strength of 3D-printed materials. A similar reinforcing effect was observed in the present study for particleboard and, to a lesser extent, MDF specimens. However, unlike the findings of Öztürk and Burdurlu (2021), veneer lamination did not improve the bending strength of the specimens printed at 100% infill. This difference is likely associated with differences in substrate architecture, infill configuration, adhesive system, and stress-transfer behavior at the veneer–core interface. These findings indicate that the reinforcing efficiency of veneer lamination is substrate-dependent and highlight the critical role of internal infill architecture in determining the flexural performance of veneer-reinforced wood-filled PLA composites.

Modulus of elasticity

The modulus of elasticity (MOE) values obtained from the tested specimen groups are presented in Table 11. The results demonstrated that both material type and veneer application significantly affected the stiffness behavior of the specimens. Among all groups, the highest MOE values were obtained from the MDF specimens laminated with oak veneer and pine veneer, with mean values of 5659,57 MPa and 5567,57 MPa, respectively. In contrast, the lowest MOE value was recorded in the uncoated particleboard group with a mean value of 1686,43 MPa.

Table 11: Modulus of elasticity values of the tested specimens.

Material Type	Veneer Type	Modulus of elasticity (MPa)				
		Minimum	Maximum	Mean	Standard Deviation	Coefficient of Variation (%)
Filament Printed at 100 % Infill	Control Group	2917,81	3410,85	3313,53	134,74	4,07
	Pine Veneer	3993,47	4621,84	4289,11	200,64	4,68
	Oak Veneer	3743,88	4600,50	4156,11	278,68	6,70
Filament Printed at 50 % Infill	Control Group	1932,74	2091,37	2012,91	68,10	3,38
	Pine Veneer	2911,44	3271,06	3118,50	93,56	3,00
	Oak Veneer	1983,08	3252,79	2802,87	406,62	14,51
Particleboard	Control Group	1065,22	2110,18	1686,43	265,43	15,75
	Pine Veneer	3253,81	4029,90	3613,17	231,42	6,40
	Oak Veneer	3260,98	4061,17	3596,59	221,08	6,15
MDF (Medium Density Fiberboard)	Control Group	2883,94	3899,41	3420,11	302,22	8,84
	Pine Veneer	4507,46	6496,89	5567,57	687,86	12,35
	Oak Veneer	4745,11	6185,12	5659,57	372,51	6,58

In general, veneer lamination substantially increased the modulus of elasticity values in all material groups compared to the corresponding control specimens. This increase was particularly pronounced in particleboard and MDF specimens. In particleboard, the MOE values increased from 1686,43 MPa in the control group to 3613,17 MPa and 3596,59 MPa for pine- and oak-veneered specimens, respectively. Similarly, in MDF specimens, veneer lamination increased the stiffness values from 3420,11 MPa to above 5500 MPa. These results indicate that veneer layers significantly contributed to the stiffness behavior of conventional wood-based panels.

A similar trend was also observed in the 3D-printed filament specimens. In the filament specimens printed at 100 % infill, the MOE increased from 3313,53 MPa in the control group to 4289,11 MPa and 4156,11 MPa after pine and oak veneer lamination, respectively. Likewise, the 50 % infill specimens exhibited increased stiffness values after veneer application. These findings indicate that veneer lamination generally improved the rigidity of the composite structure, even in cases where bending strength did not increase proportionally.

The difference between bending strength and modulus of elasticity behavior is particularly noteworthy. Although some laminated groups exhibited reduced bending strength values, their stiffness values increased significantly after veneer application. This result suggests that veneer lamination increased the rigidity of the composite structure while potentially reducing its ability to dissipate stress during bending. Such behavior may be associated with changes in stress transfer mechanisms and deformation behavior occurring at the veneer–core interface.

The coefficient of variation (CV) values generally indicated acceptable experimental consistency among the test groups. However, relatively higher variation was observed in the oak-veneered filament specimens printed at 50 % infill (14,51 %) and in the MDF specimens laminated with pine veneer (12,35 %), which may be related to local differences in bonding quality and structural heterogeneity.

Table 12: Analysis of variance (ANOVA) results for the effects of material type and veneer type on modulus of elasticity.

Source	Degrees of Freedom	Mean Squares	F Value	$p \leq 0,05$
Material Type (A)	3	30618939,28	277,66	0,0000*
Veneer Type (B)	2	29775460,47	270,01	0,0000*
Material Type x Veneer Type (AB)	6	1531456,80	13,89	0,0000*
Error	108	110275,45		
Total	120			

The two-way ANOVA results presented in Table 12 revealed that material type (A), veneer type (B), and their interaction ($A \times B$) had statistically significant effects on modulus of elasticity values ($p \leq 0,05$). Both material type and veneer type exhibited high F-values, indicating that the stiffness behavior of the specimens was strongly dependent on both the substrate material and veneer reinforcement.

Table 13: Material type for Duncan test (MPa).

Material Type	Modulus of elasticity	
	Mean	Homogeneity Group
Filament printed at 100 % infill	3919,58	B
Filament printed at 50 % infill	2644,76	D
Particleboard	2965,40	C
MDF	4882,42	A
LSD: 168,41		

Table 14: Veneer type for Duncan test (MPa).

Veneer Type	Modulus of elasticity	
	Mean	Homogeneity Group
Pine Veneer	4147,09	A
Oak Veneer	4053,78	A
Control Group	2608,25	B
LSD: 145,85		

Table 15: Duncan test at material type–veneer type level (MPa).

Material Type	Veneer Type					
	Pine Veneer		Oak Veneer		Control Group	
	—	HG	—	HG	—	HG
Filament printed at 100 % infill	4289,11	B	4156,11	B	3313,53	DE
Filament printed at 50 % infill	3118,50	E	2802,87	F	2012,91	F
Particleboard	3613,17	C	3596,59	C	1686,43	G**
MDF	5567,57	A*	5659,57	A*	3420,11	DE
LSD: 291,70						

—:Arithmetic mean HG:Homogeneity group *: Highest bending strength **:Lowest bending strength.

According to the Duncan multiple comparison test results presented in Table 13, Table 14, Table 15, MDF specimens formed the highest homogeneity group in terms of modulus of elasticity, whereas the uncoated particleboard specimens formed the lowest group. Veneer-laminated MDF specimens exhibited the highest overall stiffness performance among all tested groups. The interaction-level Duncan analysis further confirmed that veneer application significantly improved stiffness behavior regardless of the substrate type, although the magnitude of improvement varied among materials.

Overall, the MOE results demonstrated that veneer lamination was more effective in increasing stiffness than in improving bending strength. This finding suggests that veneer reinforcement may contribute primarily to rigidity enhancement rather than to ultimate load-carrying capacity, particularly in densely printed PLA-based composites.

Load–extension behavior

Representative load–extension curves obtained from the three-point bending tests are presented in Figure 5 and Figure 6 in order to comparatively evaluate the deformation behavior, stiffness characteristics, and fracture responses of the tested specimen groups. The curves revealed substantial differences in mechanical behavior depending on substrate material, infill ratio, and veneer configuration.

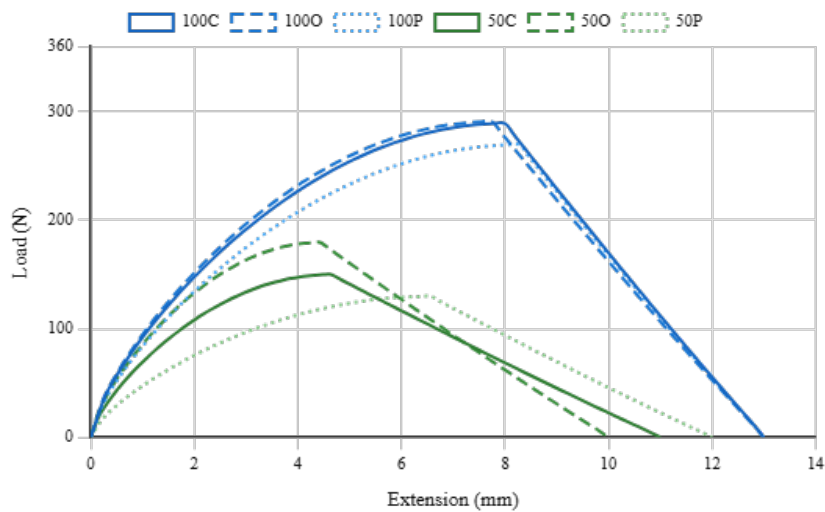


Figure 5: Representative load–extension curves obtained from 3D-printed specimens with different infill ratios and veneer configurations during three-point bending tests.
100C: 100 % infill control; 100O: 100 % infill oak veneer; 100P: 100 % infill pine veneer; 50C: 50 % infill control; 50O: 50 % infill oak veneer; 50P: 50 % infill pine veneer.

The 3D-printed specimens exhibited noticeably higher extension capacities compared to the conventional wood-based panel groups (Figure 5). In particular, the specimens printed at 100 % infill demonstrated the highest load-carrying capacity and deformation behavior among all tested groups. These specimens exhibited relatively smooth and progressive load increases prior to failure, indicating more stable stress distribution during bending. Veneer-laminated specimens within the 100 % infill groups generally showed steeper initial slopes compared to the uncoated control group, suggesting increased structural rigidity after lamination. However, despite the increased stiffness behavior, some laminated groups exhibited earlier load reduction tendencies following the maximum load point.

The 50 % infill groups demonstrated lower load-carrying capacities and lower initial stiffness values compared to the fully filled specimens. In addition, the broader deformation regions observed in these curves indicate a more gradual failure behavior, which may be associated with the presence of internal voids and reduced structural continuity resulting from the lower infill ratio. Among these groups, veneer application altered the deformation behavior and changed the post-peak load response characteristics during bending.

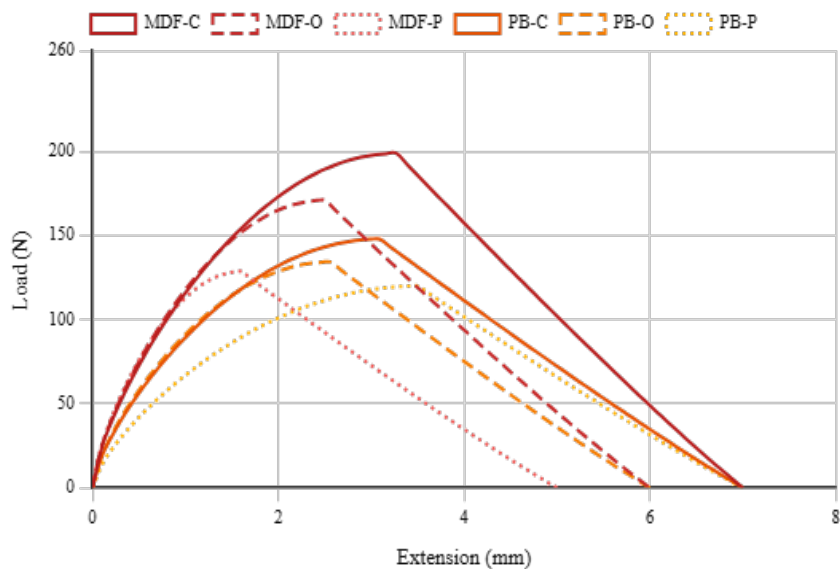


Figure 6: Representative load–extension curves obtained from MDF and particleboard specimens with different veneer configurations during three-point bending tests.

MDF-C: MDF control; MDF-O: MDF with oak veneer; MDF-P: MDF with pine veneer; PB-C: particleboard control; PB-O: particleboard with oak veneer; PB-P: particleboard with pine veneer.

The MDF and particleboard groups exhibited comparatively lower extension capacities and more abrupt load drops after reaching maximum load values (Figure 6). This behavior indicates a more brittle fracture tendency compared to the 3D-printed groups. MDF specimens generally exhibited higher initial stiffness values than particleboard specimens, whereas particleboard groups showed more progressive post-peak load reductions. Veneer application modified the load–extension behavior of both wood-based panel groups and generally contributed to increased rigidity during the initial loading stage.

Overall, the load–extension curves demonstrated that veneer lamination significantly influenced not only the maximum bending performance of the specimens but also their deformation characteristics and fracture progression behavior. These observations are consistent with the modulus of elasticity results and the fracture analyses discussed in the following sections.

Failure mode analysis

Representative fracture surfaces obtained after the three-point bending tests are presented in Figure 7 in order to qualitatively evaluate crack propagation behavior and interfacial response in laminated and uncoated specimens. The fracture patterns revealed noticeable differences depending on material type, infill ratio, and veneer application.

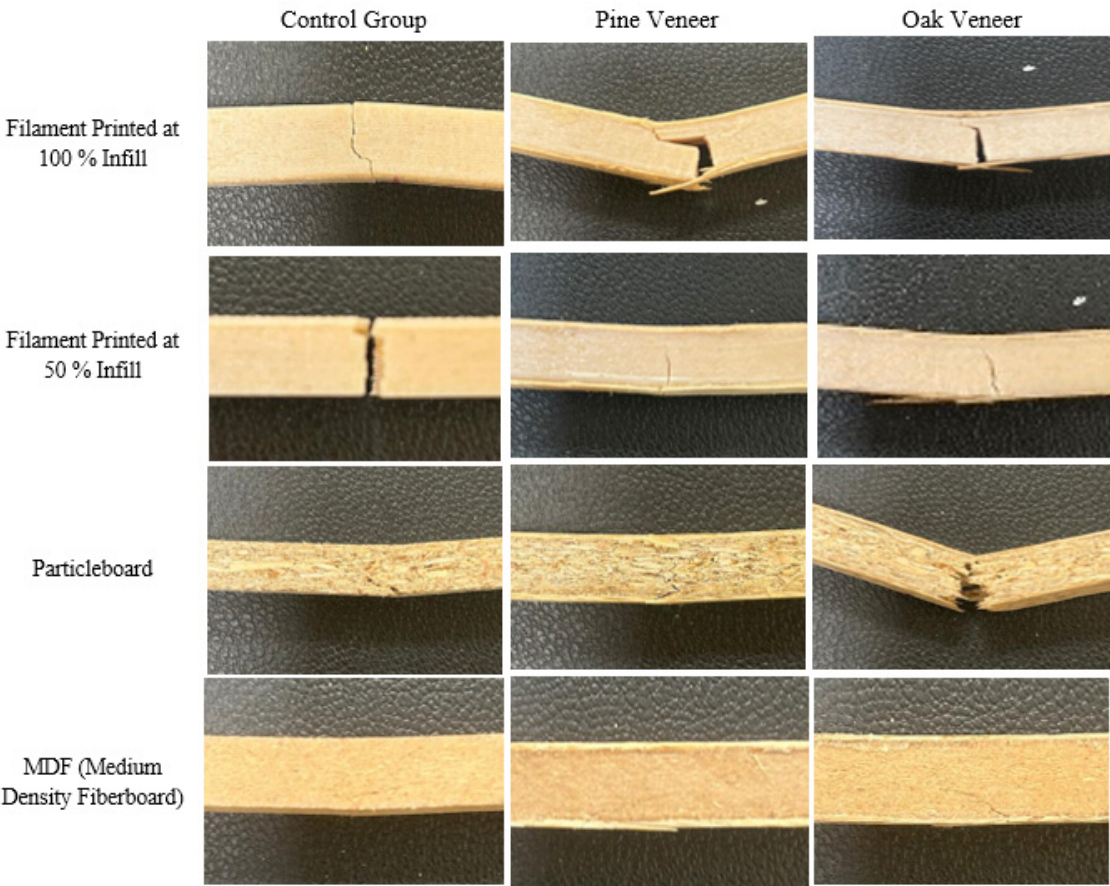


Figure 7: Representative failure modes observed after three-point bending tests for control and veneer-laminated specimens produced from 3D printed wood-filled PLA composites, particleboard, and MDF.

The uncoated filament specimens printed at 100 % infill exhibited relatively localized and brittle fracture behavior, characterized by a concentrated crack region at the tensile side of the specimen. In most laminated 3D-printed specimens, crack initiation was observed primarily in the tensile region at the lower surface during bending, followed by localized propagation toward the veneer–core interface. Following veneer lamination, the fracture behavior changed noticeably, and crack propagation appeared to extend along the veneer–core interface in some specimens. This behavior may be associated with differences in stiffness and deformation compatibility between the veneer layer and the densely printed PLA-based core structure.

Due to the vertical printing orientation used during specimen production, the bending behavior of the printed structures may also have been partially influenced by interlayer tensile and shear-related mechanisms associated with the layer-by-layer manufacturing process. Fracture observations indicated that crack propagation did not follow a completely uniform path and, in several specimens, appeared to interact both with the printing layer orientation and the veneer–core interface regions during bending.

In the filament specimens printed at 50 % infill, fracture behavior appeared more distributed compared to the fully filled specimens. The presence of internal voids resulting from the lower infill ratio may have

contributed to gradual crack propagation and less localized fracture formation. Veneer-laminated specimens in this group generally exhibited partial crack arrest behavior, although local interfacial separation tendencies were also observed in certain regions. The veneer layers generally exhibited localized cracking and partial interfacial separation rather than complete brittle fragmentation.

The particleboard specimens exhibited the most noticeable improvement in fracture behavior after veneer lamination. While the uncoated particleboard specimens showed severe brittle fracture and structural separation during bending, the veneered specimens maintained greater structural integrity after failure. This observation supports the bending strength results, where veneer application significantly improved the flexural performance of particleboard specimens.

Compared to particleboard, MDF specimens exhibited more stable and uniform deformation behavior during bending. Veneer application did not cause pronounced fracture localization in MDF specimens, and the laminated structure generally remained intact after testing. This behavior may indicate a more compatible stress transfer mechanism between the veneer layer and the MDF substrate.

The vertically printed specimens exhibited visible layer structures and surface irregularities associated with the additive manufacturing process. These surface characteristics may have affected the bonding quality and stress transfer behavior between the printed substrate and veneer layers during cold pressing. In addition, the expansion behavior of the one-component polyurethane adhesive may have partially contributed to filling localized surface irregularities during curing. However, no direct surface roughness measurements or microscopic interfacial analyses were performed within the scope of the present study. Therefore, the interaction between printed surface morphology and adhesive penetration behavior could only be qualitatively evaluated based on the observed mechanical responses and fracture characteristics.

Overall, the fracture observations demonstrated that veneer lamination altered the crack propagation behavior and deformation characteristics of the tested materials. The effectiveness of veneer reinforcement appeared to depend strongly on the compatibility between the substrate material, adhesive layer, and veneer structure. These qualitative observations are consistent with the bending strength and modulus of elasticity results presented in the previous sections.

Qualitative finite element analysis of bending behavior

To complement the experimental observations, simplified finite element method (FEM) simulations were conducted using Autodesk Inventor Professional in order to qualitatively evaluate stress distribution and deformation behavior in the laminated and uncoated specimens. Three-dimensional models were created for the filament specimens printed at 100 % infill with dimensions of $10 \times 10 \times 180$ mm and a support span of 150 mm. The analyzed groups included uncoated control specimens, pine-veneered specimens, and oak-veneered specimens.

Only the specimens printed at 100 % infill were selected for FEM analysis in order to minimize uncertainties associated with internal porosity and irregular infill geometry. Lower infill ratios may produce heterogeneous internal structures that are difficult to represent using simplified solid-body modeling approaches. Therefore, the fully filled specimens were considered more suitable for comparative numerical evaluation.

In the simulations, all materials were modeled as homogeneous solid bodies using the material properties available in the software library. The veneer layers were modeled as 0,5 mm thick outer surfaces bonded to the PLA-based core structure. A static central load of 1500 N was applied under simplified three-point bending conditions. In the numerical model, the bond between the veneer layers and printed core structure was defined using an ideal bonded interface assumption. Therefore, the layers were modeled as fully connected without relative sliding, interfacial separation, or delamination behavior during loading. The FEM model was primarily intended to provide qualitative insight into stress propagation and displacement tendencies rather than exact quantitative prediction of experimental values.

In the FEM simulations, simplified homogeneous material properties available in the Autodesk Inventor material library were used for the numerical evaluations. The elastic modulus values assigned to the pine and oak veneer layers were based on standard isotropic material definitions available within the software environment. Similarly, the PLA-based printed structure was modeled using simplified bulk material assumptions rather than anisotropic layer-based printing behavior.

It should be noted that the printed specimens were manufactured in the vertical direction, which may introduce anisotropic mechanical behavior associated with layer orientation and interlayer adhesion characteristics. However, such anisotropic printing effects and localized interfacial damage mechanisms were not directly incorporated into the simplified FEM model. Therefore, the numerical simulations were intended primarily for qualitative evaluation of stress distribution and deformation tendencies rather than exact quantitative prediction of experimental behavior.

Table 16: FEM at maximum von Mises stresses and displacements.

Group	Max. Stress (MPa)	Displacement (mm)
Control	28,13	0,333
Pine veneer	77,21	0,231
Oak veneer	71,26	0,241

The FEM results obtained for the analyzed groups are summarized in Table 16. The laminated specimens exhibited lower displacement values compared to the uncoated control specimen, indicating increased structural rigidity after veneer application. The control specimen exhibited the highest displacement value (0,333 mm), whereas the pine- and oak-veneered specimens showed reduced displacement values of 0,231 mm and 0,241 mm, respectively.

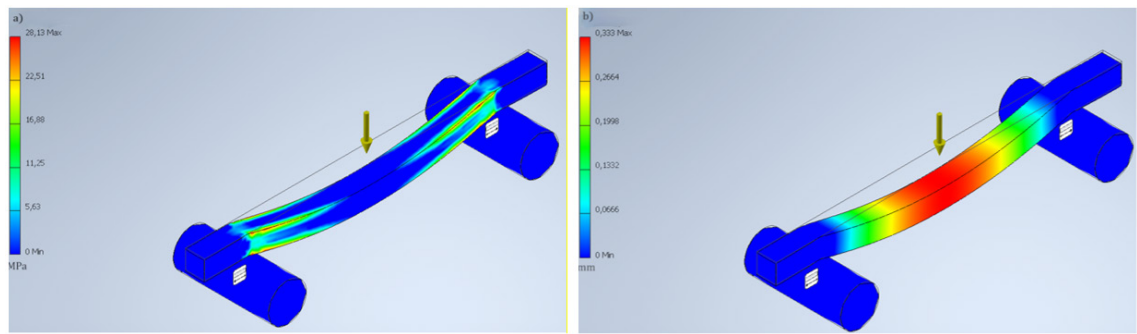


Figure 8: FEM results for the uncoated specimen printed at 100 % infill under a 1500 N load: (a) von Mises stress distribution; (b) displacement distribution.

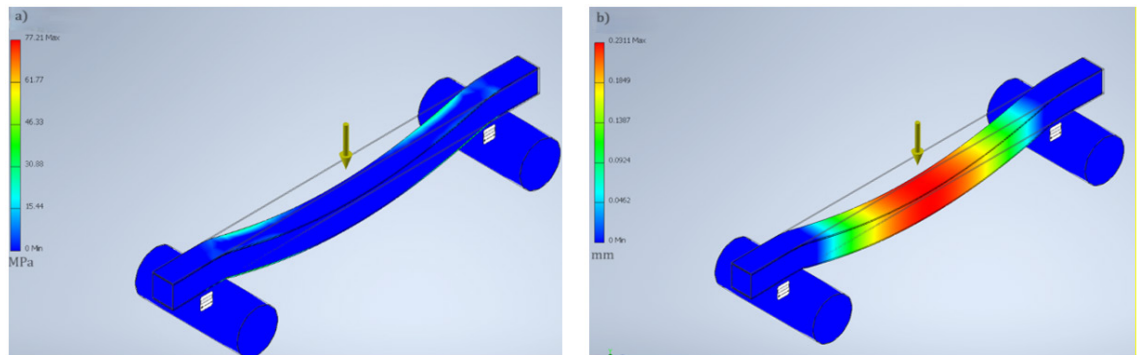


Figure 9: FEM results for the pine-veneered specimen printed at 100 % infill under a 1500 N load: (a) von Mises stress distribution; (b) displacement distribution.

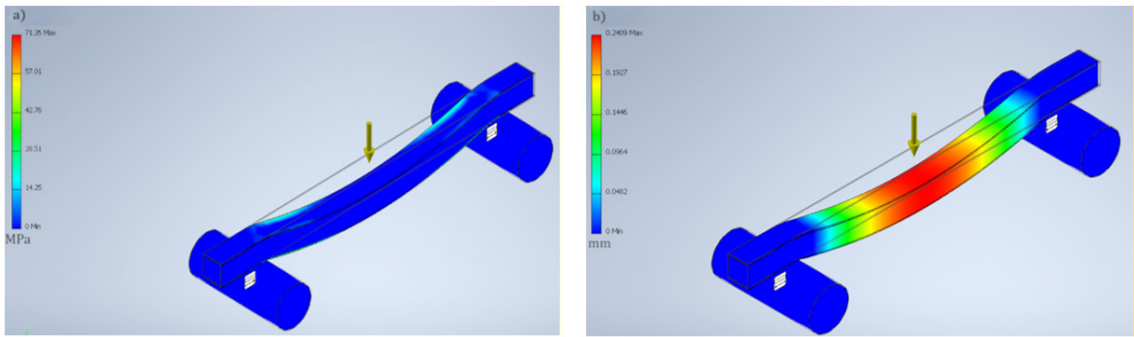


Figure 10: FEM results for the oak-veneered specimen printed at 100 % infill under a 1500 N load: (a) von Mises stress distribution; (b) displacement distribution.

The stress distribution patterns obtained from the simulations are illustrated in Figure 8, Figure 9, Figure 10. The uncoated specimen exhibited a relatively more uniform stress distribution beneath the loading point, whereas the laminated specimens showed more localized stress regions near the veneer–core transition zones. This behavior qualitatively corresponds with the experimental observations, where veneer lamination increased stiffness while altering fracture behavior and crack propagation characteristics.

The pine- and oak-veneered models exhibited higher localized stress values compared to the uncoated specimen. However, these stress values should be interpreted qualitatively due to the simplified modeling assumptions, including ideal bonding conditions, isotropic material behavior, and the absence of interfacial damage or delamination modeling. The simplified support constraints used in the numerical model may also have affected the deformation behavior and localized stress regions observed in the simulations. In particular, rotational behavior at the support regions was not fully represented as in an ideal experimental three-point bending configuration. Therefore, localized stress concentrations appeared not only in the central bending region but also near certain support-contact areas. For this reason, the FEM stress distributions were interpreted qualitatively rather than as exact quantitative stress prediction results. Consequently, the FEM analysis was used primarily as a supportive visualization tool for understanding deformation trends and stress localization behavior within the laminated composite structures.

The simplified support constraints used in the numerical model may also have affected the deformation behavior and localized stress regions observed in the simulations. In particular, rotational behavior at the support regions was not fully represented as in an ideal experimental three-point bending configuration. Therefore, localized stress concentrations appeared not only in the central bending region but also near certain support-contact areas. In addition, the deformation profile near the specimen ends did not fully reproduce the curvature behavior expected under ideal experimental three-point bending conditions, which may also have contributed to the differences observed between the numerical and experimental displacement responses. For this reason, the FEM stress distributions were interpreted qualitatively rather than as exact quantitative stress prediction results.

Overall, the FEM observations suggest that veneer lamination modifies stress transfer behavior within the composite structure and contributes to changes in rigidity under bending loads. These observations were generally consistent with the modulus of elasticity results and the fracture characteristics presented in the previous sections.

Qualitative comparison of experimental and numerical observations

The experimental bending test results and FEM observations were compared in order to qualitatively evaluate the relationship between the physical behavior of the specimens and the numerical stress–deformation tendencies obtained from the simulations. The comparison was limited to the 100 % infill groups, which were also selected for FEM analysis due to their relatively homogeneous internal structure (Table 17).

Table 17: Qualitative comparison of experimental bending results and FEM stress–displacement observations for 100 % infill specimens.

Group	Experimental Stress (MPa)	FEM Stress (MPa)	Experimental Displacement (mm)	FEM Displacement (mm)
Control	87,11	28,13	8,28	0,333
Pine Veneer	72,12	77,21	7,75	0,231
Oak Veneer	69,79	71,26	7,34	0,241

Table 17 presents the experimental bending strength values together with the corresponding FEM stress and displacement results. Although noticeable differences were observed between the experimental and numerical stress magnitudes, particularly for the uncoated control specimen, the simulations generally reflected similar deformation tendencies among the tested groups.

The experimental results showed that the uncoated control specimens exhibited the highest bending strength values, whereas veneer-laminated specimens demonstrated reduced displacement behavior and increased rigidity in the FEM simulations. This trend was also consistent with the modulus of elasticity results, where veneer application increased stiffness values despite not always improving ultimate bending strength.

The differences between the experimental and FEM stress values may be associated with the simplified assumptions used in the numerical model. In the FEM analysis, materials were modeled as homogeneous isotropic bodies under ideal bonding conditions, whereas the experimental specimens contained more complex structural features, including layer interfaces, adhesive effects, and localized deformation behavior. In addition, the numerical model did not include interfacial damage evolution or delamination mechanisms that may occur during physical testing.

Noticeable differences were also observed between the experimentally measured deformation behavior and the displacement values predicted by the FEM simulations. These differences may be attributed to the simplified isotropic material assumptions, ideal bonded interface conditions, and the absence of interlayer anisotropy and localized damage evolution mechanisms in the numerical model. In addition, the vertically printed structures likely exhibited deformation behavior associated with layer-by-layer interfacial characteristics that could not be fully represented within the simplified FEM approach.

Therefore, the FEM analysis should be interpreted primarily as a qualitative visualization tool for understanding stress localization and deformation behavior rather than as an exact quantitative predictor of experimental bending performance. Despite the numerical differences, the FEM observations provided supportive insight into the influence of veneer lamination on rigidity and stress distribution characteristics within the composite structure.

CONCLUSIONS

This study investigated the effects of veneer lamination on the bending behavior of 3D-printed wood-filled PLA composites produced with different infill ratios. In addition, the mechanical responses of laminated particleboard and MDF specimens were evaluated in order to comparatively assess the influence of veneer reinforcement on different substrate materials.

The experimental results demonstrated that veneer lamination affected the bending performance of the tested materials differently depending on the substrate structure. The highest bending strength values were obtained from the uncoated filament specimens printed at 100 % infill. In these specimens, veneer lamination did not improve the ultimate bending strength and, in some cases, resulted in reduced flexural performance. In contrast, veneer application significantly improved the bending strength and stiffness behavior of particleboard specimens and moderately enhanced the performance of MDF specimens.

The modulus of elasticity results showed that veneer lamination substantially increased the stiffness of almost all tested groups, including the 3D-printed specimens. This finding indicates that veneer reinforcement was more effective in increasing rigidity than in improving ultimate load-carrying capacity. The combined evaluation of bending strength, stiffness behavior, and fracture observations suggests that the mechanical

response of laminated structures is strongly influenced by interfacial compatibility and stress transfer behavior between the veneer layer and the substrate material.

Qualitative FEM observations supported the experimental findings by demonstrating reduced displacement behavior and localized stress regions in veneer-laminated specimens. However, the numerical analysis was primarily used as a supportive visualization approach due to the simplified modeling assumptions employed in the simulations.

Overall, the results indicate that veneer lamination may provide mechanical advantages for conventional wood-based panels and partially filled structures, whereas its effectiveness in densely printed PLA-based composites depends strongly on the compatibility between the adhesive layer, veneer structure, and printed core material. Future studies should focus on alternative adhesive systems, different veneer configurations, interfacial characterization methods, and advanced numerical modeling approaches in order to improve the mechanical compatibility of laminated hybrid composite structures.

The present study provides new experimental evidence regarding the interaction between veneer reinforcement and the internal architecture of wood-filled PLA composites manufactured by fused filament fabrication. The results demonstrate that the effectiveness of veneer lamination depends not only on the presence of the veneer itself, but also on its interaction with infill density, substrate stiffness, and the veneer–adhesive–core interface. These findings improve the current understanding of the mechanical response of veneer-reinforced additively manufactured wood-filled composites and provide a scientific basis for the design and optimization of structurally efficient hybrid wood–polymer composites for sustainable engineering applications.

Authorship contributions

H.U.: Conceptualization, investigation, methodology, formal analysis, writing – original draft. H.E.E.: Supervision, conceptualization, writing – review & editing. Y.Ö.: Formal analysis, writing – review & editing. All authors reviewed and approved the final version of the manuscript.

Declaration of conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

REFERENCES

- Acosta, A.P.; da Silva, A.A.X.; de Avila Delucis, R.; Amico, S.C. 2023.** Wood and wood-jute laminates manufactured by vacuum infusion. *Journal of Building Engineering* 64. e105619. <https://doi.org/10.1016/j.jobe.2022.105619>
- Ashter, S.A. 2013.** *Thermoforming of Single and Multilayer Laminates: Plastic Films Technologies, Testing, and Applications*. Oxford, UK: William Andrew (Elsevier). ISBN 978-1-4557-3172-5. 352 p. <https://doi.org/10.1016/C2012-0-02821-9>
- Çiğdem, E.; Perçin, O. 2023.** Some physical and mechanical properties of thermally modified laminated veneer lumbers (LVL) reinforced with carbon fiber and glass fiber. *Journal of the Faculty of Engineering and Architecture of Gazi University* 38(2): 653–664. <https://doi.org/10.17341/gazimmfd.984248>
- Gibson, I.; Rosen, D. W.; Stucker, B. (2015)** Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. *Johnson Matthey Technology Review* 59(3): 193-198 <https://doi.org/10.1595/205651315X688406>
- Estakhrianhaghighi, E.; Mirabolghasemi, A.; Zhang, Y.; Lessard, L.; Akbarzadeh, A. 2020.** 3D-printed wood-fiber reinforced architected cellular composites. *Advanced Engineering Materials* 22(11). e2000565. <https://doi.org/10.1002/adem.202000565>

- Falk, R.H.; Colling, F. 1995.** Laminating effects in glued-laminated timber beams. *Journal of Structural Engineering* 121(12): 1857–1863. [https://doi.org/10.1061/\(ASCE\)0733-9445\(1995\)121:12\(1857](https://doi.org/10.1061/(ASCE)0733-9445(1995)121:12(1857)
- Fico, D.; Rizzo, D.; De Carolis, V.; Montagna, F.; Palumbo, E.; Corcione, C.E. 2022.** Development and characterization of sustainable PLA/Olive wood waste composites for rehabilitation applications using Fused Filament Fabrication (FFF). *Journal of Building Engineering* 56. e104673. <https://doi.org/10.1016/j.job.2022.104673>
- Faizaan, M.; Shenoy, B.S.; Nunna, S.; Mallya, R.; Rao Udupi, S.; Ramanath, K.C.; Creighton, C. 2025.** A study on the overall variance and void architecture on mex-pla tensile properties through printing parameter optimisation. *Scientific Reports* 15(1). e3103. <https://doi.org/10.1038/s41598-025-87348-2>
- Huang, Y.; Löschke, S.; Proust, G. 2021.** In the mix: The effect of wood composition on the 3D printability and mechanical performance of wood-plastic composites. *Composites Part C: Open Access* 5. e100140. <https://doi.org/10.1016/j.jcom.2021.100140>
- Krapež Tomec, D.; Kariž, M. 2022.** Use of Wood in Additive Manufacturing: Review and Future Prospects. *Polymers* 14(6): 1174. <https://doi.org/10.3390/polym14061174>
- Lohar, D.V.; Nikalje, A.M.; Damle, P.G. 2022.** Development and testing of hybrid green polymer composite (HGPC) filaments of PLA reinforced with waste bio fillers. *Materials Today: Proceedings* 62: 818–824. <https://doi.org/10.1016/j.matpr.2022.04.023>
- Novosel, A.; Sedlar, T.; Čizmar, D.; Turkulin, H.; Živković, V. 2023.** Improvement of mechanical properties of oak-wood by bi-directional laminations—Efficacy of standard and pre-stressed glass fibre implants. *Composite Structures* 304. e116465. <https://doi.org/10.1016/j.compstruct.2022.116465>
- Öztürk, Y.; Burdurlu, E. 2021.** Effect of wood veneer lamination on the bending resistance of 3D-printed material. *Bartın Journal of Forestry Faculty* 23(3): 885–891. <https://doi.org/10.24011/barofd.963190>
- Palaniyappan, S.; Annamalai, G.; Kumar, S.N.; Muthu, P. 2023.** Development of functional gradient multi-material composites using Poly Lactic Acid and walnut shell reinforced Poly Lactic Acid filaments by fused filament fabrication technology. *Journal of Building Engineering* 65. e105746. <https://doi.org/10.1016/j.job.2022.105746>
- Romani, A.; Suriano, R.; Levi, M. 2023.** Biomass waste materials through extrusion-based additive manufacturing: A systematic literature review. *Journal of Cleaner Production* 386. e135779. <https://doi.org/10.1016/j.jclepro.2022.135779>
- Sikora, A.; Gaff, M.; Sethy, A.K.; Fantuzzi, N.; Horáček, P. 2021.** Bending work of laminated materials based on densified wood and reinforcing components. *Composite Structures* 274. e114319. <https://doi.org/10.1016/j.compstruct.2021.114319>
- Sultana, J.; Rahman, M.M.; Wang, Y.; Ahmed, A.; Cao, X. 2024.** Influences of 3D printing parameters on the mechanical properties of wood PLA filament: an experimental analysis by Taguchi method. *Progress in Additive Manufacturing* 9(4): 1239–1251 <https://doi.org/10.1007/s40964-023-00516-6>
- Turkish Standards Institute 2021.** Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 3: Determination of ultimate strength in static bending. TS ISO 13061-3. Turkish Standards Institute: Ankara, Türkiye.
- Turkish Standards Institute 2021.** Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 4: Determination of modulus of elasticity in static bending. TS ISO 13061-4. Turkish Standards Institute: Ankara, Türkiye.
- Turkish Standards Institute 1999.** Wood-Based panels- Determination of density. TS EN 323. Turkish Standards Institute: Ankara, Türkiye.
- Ulaşan, H.; Söğütlü, C. 2024.** The Effect of Support Layer Material and Adhesive Type on Compressive Dynamic Bending and Shear Strength in Laminated Wood. *Wood Research* 69(3): 402–416. <https://doi.org/10.37763/wr.1336-4561/69.3.402416>