Modus of elasticity and flexural behavior of glulam beams reinforced with steel mesh in different mesh openings

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Keywords

wood material
lamination
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Abstract

This study determined the modulus of elasticity and flexural strength properties of laminated wood elements reinforced with steel mesh with different mesh openings. Following the purpose of the study, 3- and 5-layer laminated elements were produced from scotch pine (*Pinus sylvestris* L.) wood material, which is widely used in the wood construction industry in Turkey. The 50, 70, and 90 mesh steel mesh used as the support layer is placed between each lamella and pressed with polyvinylacetate (PVAc-D_4) and polyurethane (PUR-D_4) adhesives. After the prepared test samples were kept for 3 weeks at 20°C temperature and 60 ±5% relative humidity for 3 weeks. Flexural strength and modulus of elasticity in flexural were determined according to the TS EN 408: 2010+A1 standard of the prepared test samples. Determined under static load from 4 points on the Zwick tester. Multiple analysis of variance (MANOVA) was carried out using the MSTAT-C software to determine the effect of the modulus of elasticity and flexural strength in the obtained flexural properties, the mesh opening of the support layer, and the adhesive type. When the differences within or between groups were significant with 0.05 margin of error; Achievement rankings were made using the Duncan test on the basis of the least significant difference.
As a result, in cases where flexural modulus and flexural strength properties are important, a lamination combination with a high level of success has been tried to be obtained.

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Introduction

Wood is an engineering material widely used in interior and exterior decoration applications due to its superior properties such as ease of processing, paintability, low energy consumption during processing, availability in various colors and patterns, low sound and heat permeability (Laboratory, 1974; Kopač and Šali, 2003; Aydın and Çolakoğlu, 2005; Söğütlü et al., 2016). Wood, in addition to its many superior

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properties, also has some disadvantages, such as being hygroscopic and heterogeneous and size limitation.

Today's technology has increased the durability of wood material and paved the way for the production of many new wood materials such as plywood, particleboard and other panel products. Wood material has been preferred as raw material in construction elements for the last 40 years and although it is used frequently, it is mostly in the form of timber obtained from tree trunks or wood pieces. Especially evergreen, coniferous, mature trees are seen as a source of structural timber. As with various other construction materials, wood material is available in different qualities (grades) and in many standardized features and sizes (Issa and Kmeid, 2005).

Elimination of the disadvantages of wood material such as heterogeneous structure, limited size possibilities and improvement of mechanical resistance properties can be reduced by lamination technology (Glulam = glue-laminated wood). Layered timber has been used since the 1800s. Research on this material started in the USA in the 1930s in Forest Products Laboratories (Dagher et al., 1996). Under prolonged load, wood will undergo viscoelastic creep, which requires a constant load that varies over time. When the load applied to the reinforced glulam beam changes over time, both the strength and stiffness of the beam will decrease. Once the prestress is applied, the distortion will become even more significant. Therefore, it is of great theoretical and engineering importance to understand the long-term mechanical performance of reinforced glulam beams and to clarify the effect of creep (Guo et al., 2021).

Reinforcement in glulam beams is a technique that provides greater advantages in both increased stiffness and strength, with structural members having higher mechanical performance. Reinforcement can be achieved using natural fibers or polymeric (artificial) fibers, which are usually bonded internally or externally to the laminate of the stretched region of the beams. It has been observed that reinforcement with metal elements, which can be applied to both the stretched and compressed regions of the glulam parts, is effective in reducing deflection and increasing the loading capacity (Luca and Marano, 2012). Metal material has been one of the most widely used materials for reinforcement since the 1960s. Steel bar, steel strip, steel or aluminum sheets, and steel knitted wire mesh are the best examples. Reinforcing wooden structures with steel material is both effective and cost-effective (Yang et al., 2016). The steel reinforced beams show that the behavior of reinforced beams is completely different from the non-reinforced one. The strengthening process changed the failure mode to dullly from fragile and increased the load carrying capacity of the beams (Issa and Kmeid, 2005). It has been determined that for simply reinforced beams, stiffness increased by 25.9%, the ultimate load increased by 48.1% and ductility increased by 43.8%. For reinforced and prestressed beams, stiffness increased by 37.9%, the ultimate load increased by 40.2% and ductility increased by 79.1% (Luca and Marano, 2012).

In a study that proposed that close-mounted steel rods could be used to reinforce glulam bamboo beams, a total of five glulam bamboo beams, one unreinforced and four reinforced, were constructed and tested to break under a four-point loading system, and the bending behavior was examined by comparing the differences. Experimental results showed that the load-bearing capacity and cross-sectional stiffness of the reinforced beams increased significantly compared to the unreinforced beam. It has also been found that steel bars mounted close to the surface can share the tensile stress of bamboo beams and work effectively during the loading process. Also, the plane section assumption of the cross-sectional stress distribution along the height is verified and an analytical model is proposed to predict the section stiffness of reinforced bamboo beams (Wei et al., 2015).

Load-displacement responses, ultimate capacities, ductility ratios, initial stiffness, energy dissipation capacities and fracture mechanisms of glued laminated beams were compared with the properties of solid beams. The use of reinforcing mesh on the laminated surfaces increased the ultimate load capacities of the tested beams. It was determined that the highest ultimate load capacities were observed in the tests of adhesive laminated beams, which were reinforced with polyurethane adhesive using steel wire reinforcement nets and produced using five laminated layers in the direction perpendicular to the lamination surface (Uzel et al., 2018).

The results of the study, which used one precast concrete, one post-tensioned concrete, one porous steel and one solid timber, were intriguing in the construction of four one-way parking garages. The resulting comparison shows that there is little difference in the energy of the structural systems used for car parks under material best practices. While solid timber is more suitable even in the worst-case scenario, it has been observed that it loses its advantageous position against its cement equivalent and high recycled content steel (Zeitz et al., 2019).

40 mm × 80 mm cross-section and 4.8 m span reinforced with bars made of steel reinforcement, rational zones for the location of reinforcement were determined in the stretched and compressed regions of the beams. It has been experimentally verified that the fracture of wood composite beams has a plastic structure and occurs only along normal sections. This excluded the possibility of brittle fracture from shear

stresses and ensured the operational reliability of the structures as a whole. It has been shown that the proposed rational reinforcement of wooden beams increases their bearing capacity by 175% and reduces bearing deformation by 85%. The study revealed the high efficiency of the application of the strengthening method in the roof beams and floors of the buildings (Lukin et al., 2021).

Compared to the unreinforced glulam beam, the long-term deflection of the reinforced glulam beam was even smaller. Under the constant loading level condition, the total stress value of the steel bars decreased by 17.5%, 13.6%, and 9.1%, and the ratio of long-term deflection of the beam mid-span to the total deflection was 26.9%. With the increase of the strengthening ratio, the stress loss of the steel bars decreased and the long-term deflection rate also decreased. When other conditions remained constant and the prestress level of the steel bars was 0 MPa, 30 MPa and 60 MPa, the total stress value of the steel bars decreased by 9.1%, 9.4% and 10.2%, respectively. The long-term deviation in the total deviation was determined as 20.6%, 26.1% and 64.9%, respectively. With the increase in the prestress value, the stress loss of the steel bars increased and the long-term deflection rate also increased (Guo et al., 2021).

As can be seen in the literature studies summarized above, wood is used for different purposes in different conditions. In order to achieve high success with smaller sized sections, wood is subjected to various processes and reinforced with different materials. The aim of this study is to determine the bending strength properties and elasticity properties in bending of glulam beams produced as 3 and 5 layers by placing a steel wire mesh with 50, 70 and 90 mesh pore openings between the layers obtained from Scotch pine (*Pinus sylvestris* L.).

Methods and materials

Materials

Wood

Scotch pine (*Pinus sylvestris* L.) used in the preparation of the test samples was selected according to criteria such as natural color uniformity, smoothness of fibers, absence of knots, absence of reaction wood, and the absence of fungal and insect damage.

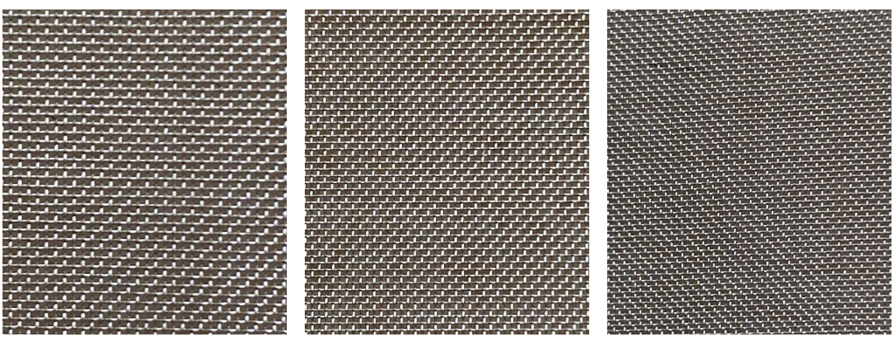
Test samples formed into 7 and 4.2 mm lamellas, respectively, according to the 3 and 5-layered state, by wood saw and planer machines. The wood material, which became lamellae, was stacked and kept at 20 ±2°C temperature and 65 ±5% relative humidity until the equilibrium moisture content about 12%.

Stainless Steel Wire Mesh

Stainless steel wire meshes are used as braided in various places due to the continuity of their mechanical properties, their ability to preserve the aesthetic appearance and brightness on their surfaces for a long time, and they are not deformed even at high temperatures. They are preferred because they have a long life, do not require maintenance and have high mechanical resistance In this study, steel wires with 50, 70, and 90 mesh pore openings were used. The wire diameters are 0.18 mm, 0.12 mm, and 0.10 mm, respectively, and the pore spacing is 330 µm, 242 µm, and 180 µm (Fig. 1).

Table 1. Experimental plan

Adhesive type	Number of layers	Reinforcement
PUR-D_4	3	non-reinforcement
		50 mesh
		70 mesh
		90 mesh
	5	non-reinforcement
		50 mesh
		70 mesh
		90 mesh
PVAc-D_4	3	non-reinforcement
		50 mesh
		70 mesh
		90 mesh
	5	non-reinforcement
		50 mesh
		70 mesh
		90 mesh



50 mesh 70 mesh 90 mesh

Fig. 1. Stainless steel wire mesh samples with different pore openings

Adhesives

The recommendations of the manufacturer (Klebreit) were followed for the application of polyvinylacetate (PVAc-D_4) and polyurethane (PUR-D_4) glue with the addition of hardener in the bonding of the layers. PVAc; viscosity at 20°C 13.000 ±2,000 mPas, color white, application amount 120–200 g/m^2, open time 6–10 min, press pressure 0.1–1 N/mm^2. PUR; viscosity of 8.000 ±1,000 MPa at 20°C, color yellowish brown, application amount of 100–200 g/m^2, open time 20–25 minutes, press pressure at least 0.6 N/mm^2 (Söğütlü, 2004).

Preparation of samples

The test samples were prepared with dimensions of 21 mm × 30 mm × 400 mm according to the TS EN 408: 2010+A1 standard. Polyvinylacetate adhesive (PVAc-D_4) and polyurethane adhesive (PUR-D_4) were applied to the 7 and 4.2 mm thick lamellas prepared by air-dried Scots pine (*Pinus sylvestris* L.) and reinforced with 50, 70 and 90 mesh steel wire mesh reinforcement and non-reinforced (control) experimental groups were formed.

Fig. 2. Preparation of the test samples

Two types of specimens were prepared, with and without reinforcement layer. Steel with 3 different mesh properties (50, 70, 90) was used between each layer of the samples consisting of 3 and 5 lamellas reinforced with the support layer. For each variable, 10 samples were prepared from both reinforced and non-reinforced experimental groups. While gluing the samples, 180–200 g/m^2 adhesive was applied with a brush on both surfaces of the lamellas and pressed under 1.2 N/mm^2 pressure. After waiting for at least 24 hours in the press, the samples were cut with a saw in dimensions of 21 mm × 30 mm × 400 mm (Fig. 3).

Fig. 3. Test samples after sizing

Conduct of experiments

Flexural strength and modulus of elasticity in flexural were determined according to the TS EN 408: 2010+A1 standard of the prepared test samples. Determined under static load from 4 points on the Zwick tester. The experimental setup is given in Fig. 4.

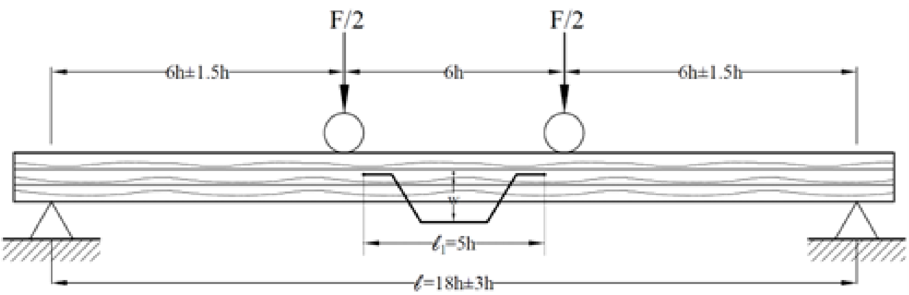


Fig. 4. The experimental setup

$$f_m = \frac{3F_{\max} l_2}{bt^2}$$

f_m – flexural strength (N/mm²)
F_{max} – maximum load (N)
l_2 – 16 times the thickness (mm)
b – width (mm)
h – thickness (mm)

$$E_{m,g} = \frac{l^3 (F_2 - F_1)}{b_1 . h_1^3 (w_2 - w_1)} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right]$$

E_m – modulus of elasticity (N/mm²)
l – length (mm)
b_1 – width (mm)
h_1 – thickness (mm)
a – distance between loading point and nearest support (mm)

$F_2 - F_1$ – increase in the load ratio on the right part of the load deformation curve (N)
$w_2 - w_1$ – the increase in deformation corresponding to $F_2 - F_1$ (mm).

The 4-point flexural strength (f_m) and modulus of elasticity ($E_{m,g}$) of the test specimens placed (Fig. 5) at a distance of 366 mm between the supports were calculated using the following equations.

Fig. 5. Performing flexural strength and modulus of elasticity test

Statistical analysis

The multiple analysis of variance (MANOVA) was carried out using the MSTAT-C package software to determine the effect of the modulus of elasticity and flexural strength in the obtained flexural properties, the mesh opening of the support layer, and the adhesive type. When the differences within or between groups were significant with 0.05 margin of error; achievement rankings were made using the Duncan test on the basis of the least significant difference (LSD). As a result, in cases where the modulus of elasticity and flexural strength properties are important, a lamination combination with a high level of success has been tried to be obtained.

Results and discussion

Flexural strength

Statistical values regarding the modulus of elasticity and flexural strength of non-reinforced beams made of 3 layers of lamellas of 7 mm thickness and reinforced beams made of 5 layers of 4.2 mm thick lamellas are given in Table 2.

Table 2. Modulus of elasticity, flexural strength, and standard deviation values (N/mm^2)

Adhesive type	Number of layers	Reinforcement type	Number of samples	Flexural strength (N/mm^2)	Modulus of elasticity (N/mm^2)
PUR-D_4	3	non-reinforcement	10	103.2 ±4.8	19 629.5 ±1 862.0
		50 mesh	10	120.3 ±2.9	26 804.1 ±1 793.0
		70 mesh	10	107.6 ±1.8	22 310.4 ±1 823,6
		90 mesh	10	101.7 ±5.9	20 195.0 ±1 915.5
	5	non-reinforcement	10	79.6 ±9.0	15 359.9 ±1 041.2
		50 mesh	10	103.1 ±5.4	23 386.9 ±2 170.0
		70 mesh	10	104.7 ±2.0	19 367.1 ±1 729.4
		90 mesh	10	110.0 ±6.9	22 443.9 ±1 208.1
PVAc-D_4	3	non-reinforcement	10	96.0 ±2.7	18 730.2 ±1 900.5
		50 mesh	10	90.1 ±7.2	20 267.4 ±1 257.4
		70 mesh	10	107.9 ±8.0	22 310.4 ±1 823.6
		90 mesh	10	87.7 ±4.3	20 195.0 ±1 915.5
	5	non-reinforcement	10	93.6 ±5.6	16 178.3 ±1 071.1
		50 mesh	10	93.5 ±4.6	18 778.8 ±750.5
		70 mesh	10	95.3 ±3.0	19 367.1 ±1 729.4
		90 mesh	10	94.5 ±4.3	22 443.9 ±1 208.1

When the flexural strength values given in Table 3 are examined, it can be seen that there are differences according to the adhesive type, the number of layers and the characteristics of the reinforcement material. The results of the analysis of variance to determine the factor affecting the flexural strength are given in Table 3.

The difference between the groups in terms of the effects of the sources of variance on the flexural strength properties; adhesive types, numbers of layer, reinforcement type, adhesive types-numbers of layer, adhesive types-reinforcement type numbers of layer-pore openings binary interactions and adhesive types-numbers of layer- reinforcement type triple interaction level were statistically significant ($P \leq 0.05$).

Triple interaction Duncan results of adhesive type-number of layer-reinforcement type on flexural strength are given in Table 4.

Table 3. Analysis of variance results on flexural strength

Source of variance	Degrees of freedom	Sum of squares	Mean square	F value	$P \leq 0.05$
Adhesive type (A)	1	3 220.230	3 220.230	113.238	0.0000*
Number of layers (B)	1	1 014.049	1 014.049	35.659	0.0000*
Interaction (AB)	1	588.289	588.289	20.687	0.0000*
Reinforcement type (C)	3	2 652.834	884.278	31.095	0.0000*
Interaction (AC)	3	3 260.366	1 086.789	38.217	0.0000*
Interaction (BC)	3	2 320.004	773.335	27.194	0.0000*
Interaction (ABC)	3	1 833.480	611.160	21.491	0.0000*
Error	144	4 095.016	28.438		
Total	159	18 984.268			

*The difference is a significant level of 0.05.

Table 4. Triple interaction Duncan results of adhesive type-number of layers-reinforcement type on flexural strength (N/mm^2)

Reinforcement type	$PUR\text{-}D_4$				$PVAc\text{-}D_4$			
	3 layers		5 layers		3 layers		5 layers	
	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG
Non-reinforcement	103.20	CD	77.88	H**	95.96	E	93.56	EF
50 mesh	120.30	A*	103.10	CD	90.08	FG	93.45	EF
70 mesh	107.60	BC	104.70	CD	107.90	BC	95.28	EF
90 mesh	101.70	D	110.00	B	87.67	G	94.48	EF

LSD ±5.339
$\bar{x}$ – arithmetic mean; HG – homogeneity group.
*The highest flexural strength. **The lowest flexural strength.

According to the results of the homogeneity test carried out to determine the importance of the triple interaction of adhesive types-number of layers-pore openings on the flexural strength properties. While the highest flexural strength (120.30 N/mm^2) was obtained in 50 mesh steel mesh reinforced beams with polyurethane adhesive, the lowest flexural strength (77.88 N/mm^2) was obtained in non-reinforced with polyurethane adhesive, produced as 5 layers. There is no statistical difference between 5-layer glued laminated wood beams bonded with $PVAc\text{-}D_4$. Additionally, there is no difference between the 3-layer non-reinforcement material bonded with $PUR\text{-}D_4$ and the 5-layer 50 mesh and 70 mesh reinforcement material (LSD ±5.34).

Modulus of elasticity

The results of the analysis of variance to determine the factor affecting the modulus of elasticity are given in Table 5.

Table 5. Analysis of variance results on modulus of elasticity

Source of variance	Degrees of freedom	Sum of squares	Mean square	F value	$P \leq 0.05$
Adhesive types (A)	1	204 453 427.879	204 453 427.879	82.9513	0.0000*
Number of layers (B)	1	200 843 606.456	200 843 606.456	81.4867	0.0000*
Interaction (AB)	1	846 327.390	846 327.390	0.3434	NS
Reinforcement type (C)	3	494 272 240.381	164 757 413.460	66.8457	0.0000*
Interaction (AC)	3	212 314 096.749	70 771 365.583	28.7135	0.0000*
Interaction (BC)	3	241 519 382.965	80 506 460.898	32.6633	0.0000*
Interaction (ABC)	3	54 665 131.811	18 221 710.604	7.3930	0.0001*
Error	144	354 922 737.069	2 464 741.230		
Total	159	1 763 836 950.430			

*The difference is a significant level of 0.05.

The difference between the groups in terms of the effects of the sources of variance on the flexural elasticity modulus; adhesive types, the number of layers, pore openings, adhesive types- reinforcement type number of layers-reinforcement type binary interaction levels were statistically significant ($P \leq 0.05$). However, adhesive types-number of layers' binary interaction levels were not statistically significant. Due to the anisotropic nature of the wood material, the difference between fiber length and wood elasticity modulus values; significantly affects the measured forces (Smardzewski et al., 2022).

Triple interaction Duncan results for adhesive types-number of layers-reinforcement types on the modulus of elasticity are given in Table 6.

Table 6. Homogeneity for the interaction of adhesive types-number of layers-reinforcement types on the modulus of elasticity (N/mm^2)

Reinforcement types	PUR-D_4				PVAc-D_4			
	3 layers		5 layers		3 layers		5 layers	
	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG	$\bar{x}$	HG
Non-reinforcement	19 630	D	15 360	G**	18 730	DE	16 180	FG
50 mesh	26 800	A*	23 390	BC	20 270	D	18 780	DE
70 mesh	22 310	C	19 370	D	24 040	B	17 280	EF
90 mesh	20 190	D	22 440	C	17 440	EF	18 690	DE

LSD ±1387
$\bar{x}$ – arithmetic mean, HG – homogeneity group.
*The highest flexural strength.
**The lowest flexural strength.

According to the results of the homogeneity test carried out to determine the importance of the triple interaction of adhesive types-number of layers-reinforcement types on the modulus of elasticity; While the highest flexural strength (26800 N/mm^2) was obtained in 50 mesh steel mesh reinforced beams with polyurethane adhesive produced as 3 layers, the lowest flexural strength (15360 N/mm^2) was obtained in non-reinforced with polyurethane adhesive, produced as 5 layers (LSD ±1387).

The use of steel wire mesh between layers in the production of reinforced beams increases the flexural strength and modulus of elasticity in flexuring. In the use of 90 mesh steel-knitted wire mesh, 5-layer beams suffered more breakage than the 3-layer beams, regardless of the adhesive type. Additionally, it should be noted here that the glue line, which has a significant effect on the deformation of the beam between the layers, is damaged during bending (Smardzewski, 2019).

In terms of the effect on the flexural elasticity modulus, there is an increase of 60% in the reinforcements made with 50 steel mesh and polyurethane adhesive. There was a 31% increase in flexural strength of the same combination.

Conclusions

It is aimed to obtain glulam beams that will give high strength properties in terms of performance in the place of use by using steel wire mesh in different pore openings, different types of adhesives and different number of layers. For this purpose, between the layers of glulam beams, 50, 70, and 90 mesh steel wire mesh, which is considered more cost-effective, was used as reinforcement. Additionally, the lamella thicknesses of 4.2 mm (for 5 layers) and 7 mm (for 3 layers) were produced with the same final thickness of the glulam beams. The flexural strength and modulus of the elasticity properties of the reinforced glulam beams were determined. The obtained data were compared with beams produced non-reinforcement. Because of the experiment, non-reinforced glulam beams and reinforced glulam beams were evaluated statistically according to adhesive type, number of layers and pore openings.

In terms of adhesive type, the highest flexural strength value was obtained from polyurethane (PUR-D_4) glue, and the lowest flexural strength value was obtained from polyvinylacetate (PVAc-D_4) glue. Moreover, in terms of adhesive type, the highest modulus of elasticity properties was obtained from PUR-D_4 glue and the lowest modulus of elasticity properties was obtained from PVAc-D_4 glue.

In terms of adhesive type, PUR-D_4 glue gave high results for the highest flexural strength and modulus of elasticity, while PVAc-D_4 glue gave low results. This result can be interpreted as that polyurethane glue establishes a stronger chemical bond between the lamellae compared to polyvinylacetate glue.

The highest flexural strength and modulus of elasticity values were obtained from 3 layers, and the lowest flexural strength value was obtained from 5 layers.

In terms of pore openings, the highest flexural strength value was obtained from 70 mesh, and the lowest flexural strength value was obtained from non-reinforcement glulam beam. Again, in terms of pore openings, the highest modulus of elasticity properties was obtained from 50 mesh, and the lowest modulus of elasticity was obtained from non-reinforcement glulam beam. In line with the data obtained, it can be interpreted that as the pore opening increases, the flexural strength decreases. Here, it can be interpreted that porous reinforcement materials may be preferred instead of plate-shaped reinforcement material to be used between layers. Simultaneously, the use of 90 mesh can be recommended in cases where elasticity is desired, while the use of 50 mesh can be recommended in applications that require rigidity.

As a result, it is predicted that satisfying results can be obtained by diversifying adhesives with different wood species in the construction sector, and by experimenting with different reinforcements, variable number of layers and sequences. Additionally, the preliminary idea was been formulated that materials with a porous structure as reinforcement will increase the healing effect more.

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