Determination of the Modulus of Elasticity of Wooden Construction Elements Reinforced with Fiberglass Wire Mesh and Aluminum Wire Mesh

Abdullah Togay,[a] Nihat Döngel,[b] Cevdet Söğütlü,[b] Emre Ergin,[b] Murat Uzel,[c] and Serkan Güneş [a]

Laminated composite wooden construction elements were produced with 7 layers of Scots pine (*Pinus sylvestris* L.). Fiberglass wire mesh and aluminum wire mesh, which were used as reinforcement materials, were pressed with polyvinyl acetate (PVAc) and polyurethane-type adhesives between each Scots pine layer. The highest bonding strength values were obtained from laminated control specimens produced with polyurethane adhesive without using support materials (4.98 N/mm^2) and laminated control specimens made with polyurethane adhesive without using support materials (4.39 N/mm^2), respectively. The modulus of elasticity in bending perpendicular to the glue line values of all the specimens except the laminated control specimens produced with polyurethane adhesive without using support materials (14800 N/mm^2) were lower than solid wood (6720 N/mm^2). In contrast, in the experiments for the modulus of elasticity parallel to the glue line, the variables (adhesive, intermediary layer materials) used for all experiments and specimens were effective factors. Although the modulus of elasticity in bending parallel to the glue line values of all samples were higher than solid wood (6720 N/mm^2), the maximum value was obtained in the laminated control specimens produced with polyurethane adhesive without using support materials (17800 N/mm^2).

Keywords: Wooden material; Composite; Reinforcement; Bonding

*Contact information: a: Gazi University, Faculty of Architecture, Department of Industrial Design, 06570 Ankara, Turkey; b: Gazi University, Technology Faculty, Department of Wood Products Industrial Engineering, 06500 Ankara, Turkey; c: Hacettepe University, Hacettepe ASO 1. OSB Vocational School, 06935, Ankara, Turkey; *Corresponding author: muratu@hacettepe.edu.tr*

INTRODUCTION

The need for wooden materials and their usage areas is constantly increasing because of their properties, such as exhibiting easy machinability, heat and sound insulation, high resistance and being lightweight (Özalp 2003). Solid wooden materials in the form of single pieces are not very appropriate economically and technically for use on curved surfaces and in large dimensions. With curved surfaces, the use of solid wood increases the ratio of wastage, and the strength properties are negatively affected as a result of a diagonal cut of the fibers. Laminated wooden materials resolve these drawbacks and are produced by gluing the veneers fibers in parallel. Therefore, laminated wooden materials are widely used in the forest products industry (Keskin and Togay 2003; Karayılmazlar *et al.* 2008).

Structurally glued laminated lumber (glulam) is one of the oldest glued wooden engineering products (Moody *et al.* 1999). Engineered wood products that meet the design requirements are manufactured *via* advancing technology (Cowan 1991). In recent studies related to reinforced wood, adding non-woody materials using appropriate adhesives effectively reinforces the lamination.

Mechanical properties of the wood are affected by the adhesive formulation, ambient conditions, sample preparation, and the use of various testing methods (Stoeckel *et al.* 2013). Moreover, the bonding strength depends not only on adhesive type but also on the FRP type (Raftery *et al.* 2009). The steel rods with metric threads M12, M16, and M20 were bonded in glulam made of Norway spruce lamellas perpendicular to the grain by an epoxy-type adhesive (Widmann *et al.* 2007). It has been observed that the layered rectangular beams manufactured with a concrete layer that was bearing in a notched shear key, on a lumber layer has medium to high degrees of composite action (Gutkowski *et al.* 2008). Timber-concrete composite T beams and the connection system were produced by steel hooks and by perforated steel plates, both glued with epoxy adhesive (Miotto and Dias 2011). In the past 20 years, the use of fiber-reinforced polymers for reinforcing structural elements has been effective, both economically and for structural performances (Taheri *et al.* 2009; Kureli *et al.* 2013). In recent years, studies related to the reinforcement of wooden construction materials by non-FRP materials such as concrete, glass, steel, and FRP materials that are produced from glass, carbon, boron, and aramid fibres, increased (Motlagh *et al.* 2008; Nowak *et al.* 2013). GFRP and CFRP are used intensively from these materials. Because carbon fibre reinforced polymers (CFRPs) have higher mechanical properties, they are used in the applications that need higher strength (Meier 1995; Nowak *et al.* 2013). The flexural behaviors of wood beams reinforced with pre-stressed carbon/epoxy fiber-reinforced plastic (FRP) sheets have superior performance in terms of favorable strength, stiffness, and ductility (Triantafillou and Deskovic 1992).

The use of materials other than wood in wood lamination applications has increased; further research is needed to develop economic products that increase the technical properties of wood in lamination (Ergin 2011; Togay and Ergin 2014). An analytical solution has been presented for the estimate of the development of a fine FRP layer in laminated wooden beams with existing twisting damage and under bending (Kim *et al.* 1997). The short carbon fibers were used as reinforcement material in wooden veneer composites for examining the effect of the fiber length and fiber orientation on the flexibility of plywood (Xu *et al.* 1998). Douglas fir glulam beams, with full or partial length fiber-reinforced polymer (FRP), have sufficient fatigue resistance for use as bridge girders (Davids *et al.* 2005). Adding reinforcement is a widespread application for increasing the load-bearing capacities of glulam beams. Guan *et al.* (2005) recently showed that due to the harmony of the two materials and low pre-tension losses of the pultruded glass-reinforced plastic (GRP) beams, it provided a suitable alternative.

Textile reinforcement is embedded within a matrix and connected to the wood in timber constructions; it also enables improvement in load-bearing behavior (Putzger and Haller 2006). High-performance fibers are being diversely studied for repairs and renovations in civil engineering field. The potential benefits, liabilities, and architectural evaluations are being treated in the reinforcement of wooden beams (Corradi and Borri 2007). The effect of the material's compositions on the mechanical properties of wood-plastic composites (WPC) produced with molded injection were examined (Kuo *et al.* 2009). The flexibility performance of wooden beams that were improved with the use of carbon fiber-reinforced plastic (CFRP) composite layers was investigated (Li *et al.* 2009).

The four-point bending test results show that the glass fiber-reinforced plastic (GFRP) rods and the carbon fiber reinforced plastic (CFRP) composite materials increased the bending strength of the wood beams (Li *et al.* 2014). The failure modes, bearing capacities, and deformation characteristics of the composite beams are related with the flange thickness of the bamboo plywood, the thickness of the cold-formed steel channel, and the whole sectional dimensions that form the composite beams (Li *et al.* 2015). Recent studies demonstrated that wood and wood-based materials reinforced with FRP composites in construction applications, especially for structural elements, are promising for the future. However, there are concerns about the long-term performance of CFRP-wood hybrid materials, such as the endurance of the carbon fiber reinforcements when they are subjected to environmental factors and wood preservatives, and the CFRP-wood interface sensitivity to damage (Pirvu *et al.* 2004). It is determined that although the effect of the carbon fiber reinforced polymers on the strength was not clear, increasing the ratio of its increased the rigidity (Nguyen Trung *et al.* 2015).

This study determined the modulus of elasticity of the layered composite wooden construction elements obtained from the lamination of solid wood reinforced with woven structure fiberglass mesh. New criteria for the use of these materials as effective products in the sector are proposed.

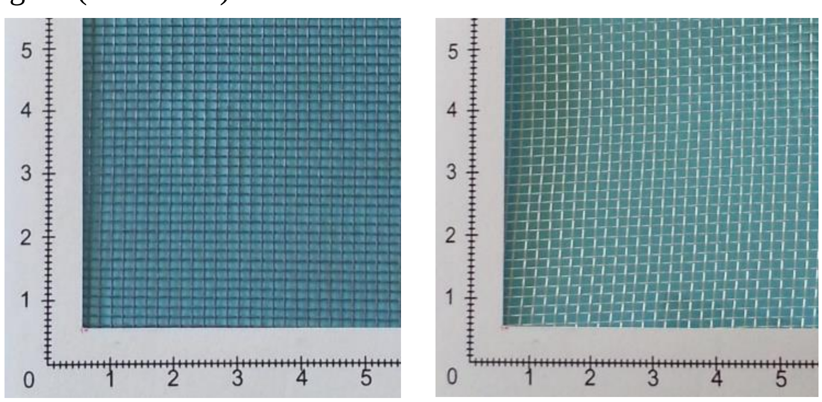
EXPERIMENTAL

Materials

Scots pine (*Pinus sylvestris* (L.)) is used extensively in the wood construction sector and was used as the wooden material for these experiments. Scots pine wood was obtained from the Eastern Black Sea region in Turkey for this study. The test specimens were selected according to the TS 2470 (1976) standard, and criteria such as natural color uniformity, smoothness of fibers, absence of knots, heart uniformity, absence of reaction wood, and absence of fungal and insect damage were used to identify the specimens for further processing.

The fiberglass wire mesh (SGT, İzmir, Turkey) used as an intermediary layer material had an interocular distance of 18 mm × 16 mm, wire thickness of 0.28 mm, and a minimum weight of 125 g/m². It contained 35% fiber and 65% plastic, was black, and had a wire mesh structure (Fig. 1). The fiberglass wire mesh was purchased with a width of 1 m and a length of 30 m and was dimensioned according to the test samples (SGT 2016).

Aluminum wire mesh (SGT, İzmir, Turkey) (Fig. 1) was used also as an intermediary layer material. It was a spiral-type material with a diamond-shaped mesh, in the dimensions of 1 mm × 15 mm × 15mm, a width of 100 cm, a length of 30 m, and a weight of 1 kg/m² (SGT 2016).



a. Fiberglass wire mesh   b. Aluminum wire mesh

Fig. 1. Fiberglass and aluminum wire mesh (dimensions in cm)

The single-component polyvinyl acetate (PVAc) adhesive Kleiberit 303 manufactured by the German Kleiberit Company (Weingarten, Germany) was used in this study. According to BS EN 204 (2001) standards, the technical properties of the adhesive were as follows: density of ~1.12 g/cm^3, viscosity of 13000 mPas ± 2000 mPas at 20 °C, white in color, usage amount of 120 g/m^2 to 200 g/m^2, an open time of 6 min to 10 min, pressing pressure of 0.1 N/mm^2 to 1 N/mm^2, duration of pressing 15 min at 20 °C, and a 7 day duration for complete hardening (Söğütlü and Döngel 2007).

Polyurethane (PU; Kleiberit, Weingarten, Germany) is a single component polyurethane-based adhesive. The technical properties of the adhesive are as follows: density of 1.13 g/cm^3 ± 0.02 g/cm^3 at 20 °C, viscosity of 3300 cps to 4000 cps at 25 °C, hardening in 30 min at a temperature of 20 °C, and a relative humidity of 65%. The material is spread on surfaces that have a high absorption, at packaging viscosity, and to slightly moisten dried surfaces (Söğütlü and Döngel 2007; Kleiberit 2016).

Preparation of the Test Specimens

Solid control specimens were cut to the dimensions of 1900 mm × 100 mm × 100 mm from the solid lumber and stored at 20 °C ± 2 °C and 65% ± 5% relative humidity until they reached a constant weight. The average moisture content (MC) was 12% ± 0.5% in the 10 pre-control specimens, as determined by TS 2471 (2005). The lamellas, which were used in the production of wooden construction elements, were prepared in a length of 2000 mm and a thickness of 14 mm. The control specimens, which did not have an intermediary layer, were subjected to the lamination procedure in accordance with TS EN 408+A1 (2015) standards with PVAc or polyurethane adhesives to make 7 layer laminated wooden elements. As shown in Fig. 2, reinforced laminated wooden elements were produced by placing the fiberglass wire mesh or aluminum wire mesh between each layer with the objective of increasing the resistance. The laminated wooden construction elements obtained were cut to the dimensions of 1900 mm × 100 mm × 100 mm.

Fig. 2. Layer structures of the laminated wooden construction elements

Test Methods

Density

The density of the samples was determined according to the standard TS EN 408+A1 (2015). A total of 14 of each specimen were prepared from 7 different test patterns with two of each from every type of specimen, including the solid specimens for the lamination produced from different adhesives and the composite lamination specimens. These were obtained by using different adhesives and intermediary layer materials. Accordingly, the air-dried density (δ) was calculated with Eq. 1,

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

where M is the air-dried mass (g) and V is the air-dried volume (cm^3).

Bonding strength

The BS EN 204 (2001) and BS EN 205 (2003) standards were complied with for the bonding strength tests. A total of 60 of each test specimen were prepared with 10 each in the dimensions of 28 mm × 20 mm × 150 mm from every type produced from the laminated wooden materials. A test mechanism was prepared in accordance with the standards determined for the test specimens prepared (Fig. 3). The bonding strength (σ) was calculated by Eq. 2,

$$\sigma = F_{\gamma} / A = F_{\gamma} / (b_2 \times l_1) \quad (2)$$

where σ is the bonding strength (N/mm^2), F_{γ} is the force at break (N), b_2 is the width of bonding surface (mm), and l_1 is the length of bonding surface (mm).

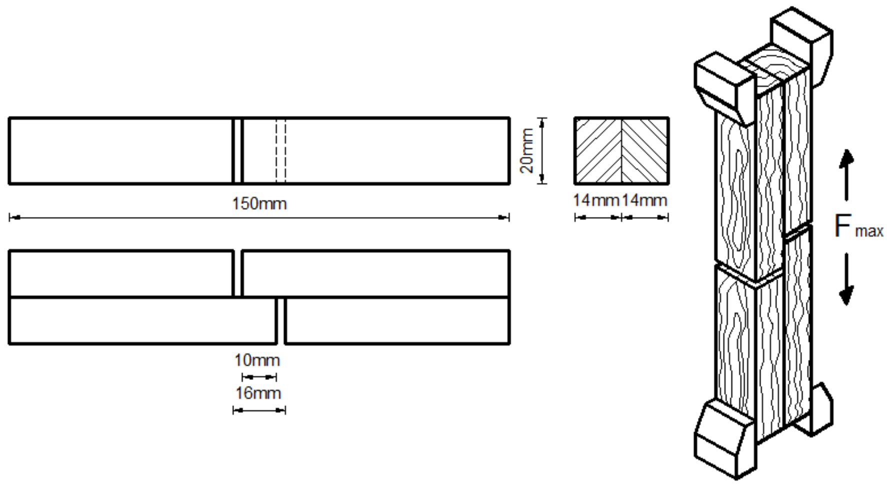


Fig. 3. Test sample of bonding strength and testing apparatus

Modulus of elasticity in bending

The modulus of elasticity in bending was determined by complying with the TS EN 408+A1 (2015) standard. There were 36 of each of the two-way test specimens prepared for every one of the adhesive and intermediary layer materials specified in the dimensions of 100 mm × 100 mm × 1900 mm for perpendicular to the glue line, as shown in Fig. 4. A total of 39 test specimens were prepared, and three of them were solid wood specimens. Figure 4 shows that the distance between supports was arranged so that it would be 18-fold of the height. The greatest load applied did not exceed a maximum of 0.4 F. The moduli of elasticity in bending were calculated with Eq. 3,

$$E_{mg} = \frac{l^3 \, (F_2 - F_1)}{b_1 \, . \, {h_1}^3 \, (W_2 - W_1)} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right] \quad (3)$$

where $E_{m,g}$ is the modulus of elasticity in bending (N/mm^2), l is the span in bending (mm), b_1 is the width of the cross section in a bending test (cm), h_1 is the depth of the cross section in a bending test (cm), a is the distance between a loading position and the nearest support in a bending test (mm), F_2-F_1 is the change of the load on the regression line with a correlation coefficient of 0.99 or better (N), and W_2-W_1 is the change of the deformation corresponding to F_2-F_1 (mm).

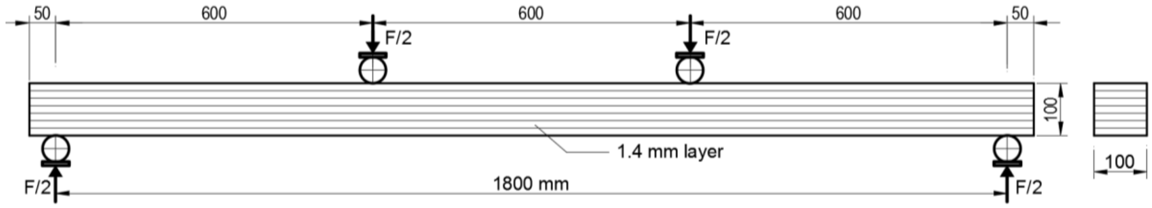


Fig. 4. Test arrangement for measuring modulus of elasticity (mm)

Evaluation of the data

To determine the effects of the support material type, adhesive type in bonding strength and modulus of elasticity in bending, multiple analyses of variance (MANOVA) were conducted using the MSTAT-C, a computer-based statistical package developed by Michigan State University, USA. When the differences emerged as statistically significant according to $p \leq 0.05$, the importance was determined amongst groups with the least significant difference Duncan test.

RESULTS AND DISCUSSION

Density

The average values for the air-dried densities of the laminated wooden materials, laminated layered composite materials, and solid wooden materials are given in Table 1.

Table 1. Average Values for Air-Dried Densities of the Samples (g/cm^3)

Support material	Density (g/cm^3)	
	PVAc	Polyurethane
Control group	0.470	0.495
Fiberglass wire mesh	0.455	0.490
Aluminum wire mesh	0.480	0.490

Bonding strength

The bonding strength arithmetic means, standard deviations, and the analysis of variance results (to determine the effect on the bonding strength in terms of support material type and adhesive type) are given in Table 2.

Table 2. Bonding Strength Arithmetic Means, Standard Deviations, and Analysis of Variance

Adhesive type	Support material type-Bonding strength (N/mm^2)		
	Control group	Aluminum wire mesh	Fiberglass wire mesh
PVAc	4.386 ± 0.183	3.748 ± 0.133	4.057 ± 0.218
Polyurethane	4.976 ± 0.218	4.018 ± 0.231	4.379 ± 0.198
Analysis of Variance (P-value)			
Support Material (SM): 0.000*, Adhesive (A); 0.000*, Interaction of the SM x A: 0.018*			

Note: * indicates a significant difference with 0.95 confidence

Support material type, adhesive type, and the interaction of the support material type-adhesive type had a significant effect ($p \leq 0.05$) on the bonding strength. The results of the Duncan tests for the interactions of the support material type and the adhesive type with the bonding strength values are given in Table 3.

Table 3. Results of the Duncan Tests for the Support Material and Adhesive Type

Bonding strength (N/mm^2)				
Support material type			**Adhesive type**	
Control	**Aluminum**	**Fiberglass**	**PVAc**	**Polyurethane**
4.681^A	3.883^C	4.223^B	4.062^B	4.458^A

Note: Number followed by the different letter indicates significant differences with 0.95 confidence

The highest bonding strength was obtained in the laminated control specimens produced without using support materials, whereas the lowest bonding strength was obtained in the laminated layered composite specimens produced by using an aluminum wire mesh. When the homogeneity groups were examined in terms of the adhesive types, the highest bonding strength was obtained in the polyurethane adhesive, whereas the lowest bonding strength was obtained in the polyvinyl acetate adhesive. As Custódio *et al.* (2009) has reported; true chemical bonds are the strongest links that can be obtained when a chemical reaction occurs between the cellulose and the adhesive molecules one of them is polyurethane.

The results for the interactions of the support material type-adhesive type value differences are given in Fig. 5.

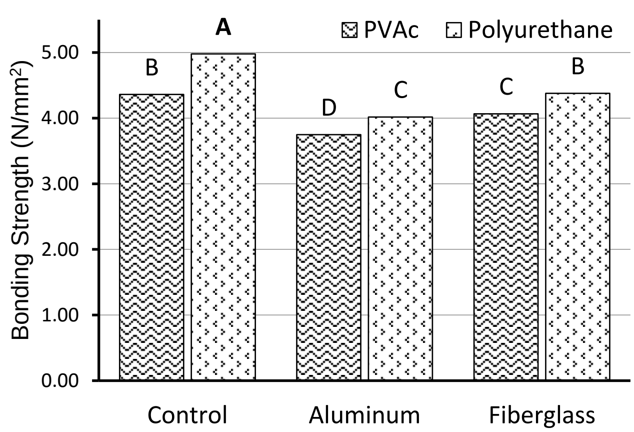


Fig. 5. The interactions of support material type-adhesive type

The highest bonding strength was obtained in the laminated control specimens produced with polyurethane adhesive without using support materials (4.979 N/mm^2). The lowest bonding strength was obtained in the layered laminated composite material supported with an aluminum wire mesh and glued with PVAc (3.748 N/mm^2). Polyurethane adhesive has been reported to have a higher penetration (Bastani *et al.* 2016). This could be due to the fact that the polyurethane adhesive provided a better adaptation with the support materials used between the layers and the wooden materials and that it established a stronger chemical bond.

Modulus of elasticity in bending perpendicular to the glue line

The modulus of elasticity perpendicular to the glue line for the laminated wooden materials, laminated layered composite materials, and the solid wooden materials and the analysis of variance are given in Table 4.

Table 4. Modulus of Elasticity in Bending Perpendicular to the Glue Line Arithmetic Means, Standard Deviations, and Analysis of Variance

Adhesive type	Support material type- Modulus of elasticity in bending perpendicular to the glue line (N/mm^2)			
	Control	Aluminum	Fiberglass	Solid Wood
PVAc	10743.97±982.95	7167.40±232.60	8071.60±1086.30	11568.50±2117.90
Polyurethane	14753.67±247.95	7452.57±243.15	6896.77±281.75	
Analysis of Variance (P-value)				
Support Material (SM): 0.000*, Adhesive (A); 0.000*, Interaction of the SM x A: 0.000*				

Note: * indicates a significant difference with 0.95 confidence

Support material type, adhesive type, and the interaction of support material type-adhesive type had a significant effect ($p \leq 0.05$) on the modulus of elasticity. The results of the Duncan tests for the interactions of the support material type, adhesive type, and solid wood are given in Table 5. The highest value for the modulus of elasticity in bending perpendicular to the glue line was in the solid specimens, and the lowest value was in the specimens produced with the polyvinyl acetate adhesive.

Table 5. Duncan Tests for the Support Material, Adhesive Type, and Solid Wood

Modulus of elasticity in bending perpendicular to the glue line (N/mm^2)					
Support material type			Solid wood	Adhesive type	
Control	Aluminum	Fiberglass		PVAc	Polyurethane
12748.81^A	7300.98^C	7484.18^B	11568.50^A	8660.99^B	9709.58^A

Note: Number followed by the different letter indicates significant differences with 0.95 confidence

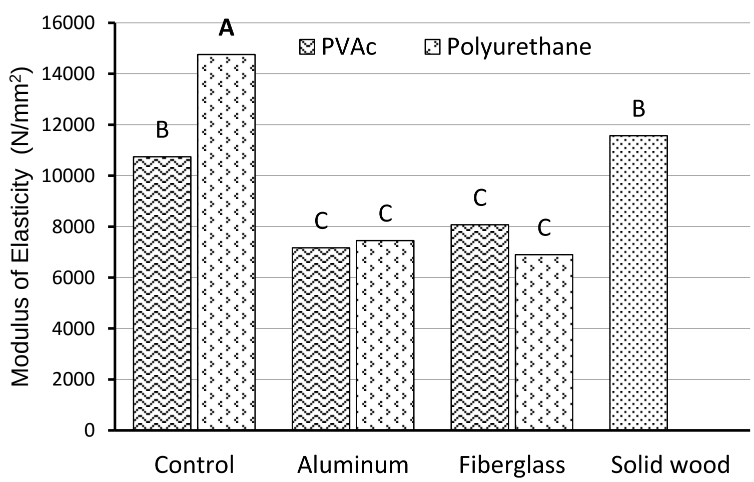


Fig. 6. The interactions of support material type-adhesive type-solid wood

The values for the modulus of elasticity in bending perpendicular to the glue line for the support material type, adhesive type, and solid wood are given Fig. 6. The highest value for the modulus of elasticity in bending perpendicular to the glue line was in the control group produced with the polyurethane adhesive. The control group specimens produced by using polyvinyl acetate and the solid specimens showed similar properties for the modulus of elasticity perpendicular to the glue line. The more successful results of the polyurethane adhesive in the elasticity modulus tests may be due to its elastic structure and in the drying process in addition to bonding based on adhesion due to the mechanical bond which was established by the penetration to the pores of the wood material by means of the tendency of the adhesive in volume expansion. This study showed results similar to the literature (Knorz *et al.* 2015).

Modulus of elasticity in bending parallel to the glue line

The modulus of elasticity parallel to the glue line for the laminated wooden materials, laminated layered composite materials, and the solid wooden materials arithmetic means and standard deviations, and the analysis of variance results is given in Table 6.

Table 6. Modulus of Elasticity in Bending Parallel to the Glue Line Arithmetic Means, Standard Deviations, and Analysis of Variance

Adhesive type	**Support material type- Modulus of elasticity in bending parallel to the glue line (N/mm²)**			
	Control	**Aluminum**	**Fiberglass**	**Solid wood**
PVAc	9364.60 ± 219.50	9512.05 ± 538.45	8642.40 ± 565.70	6721.27 ± 163.95
Polyurethane	17776.35 ± 2011.05	8888.80 ± 626.80	7272.20 ± 560.60	
Analysis of Variance (P-value)				
Support Material (SM): 0.000*, Adhesive (A); 0.000*, Interaction of the SM x A: 0.000*				

Note: * indicates a significant difference with 0.95 confidence

Support material type, adhesive type, and interaction of support material type-adhesive type had a significant effect ($p \leq 0.05$) on the modulus of elasticity. The results of the Duncan tests for the interactions of support material type, adhesive type, and solid wood are given in Table 7. The highest value for the modulus of elasticity parallel to the glue line was determined in the control groups, whereas, the lowest value was obtained in the solid specimens. The lowest value for the modulus of elasticity in bending parallel to the glue line was determined in the solid specimens, whereas, the highest value was in the specimens produced with the polyurethane adhesive.

Table 7. Duncan Tests for the Support Material, Adhesive Type, and Solid Wood

Modulus of elasticity in bending parallel to the glue line (N/mm²)					
Support material type			**Solid wood**	**Adhesive type**	
Control	**Aluminum**	**Fiberglass**		**PVAc**	**Polyurethane**
13570.48^{A}	9200.43^{B}	7957.30^{C}	6721.27^{D}	9173.02^{B}	11312.45^{A}

Note: Number followed by the different letter indicates significant differences with 0.95 confidence

The values for the differences on the modulus of elasticity in bending parallel to the glue line for the support material type, adhesive type, and solid wood are given in Fig. 7. The highest value for the modulus of elasticity in bending perpendicular to the glue line was in the control group produced with the polyurethane adhesive, whereas the lowest value for the modulus of elasticity in bending parallel to the glue line was observed in the solid specimens.

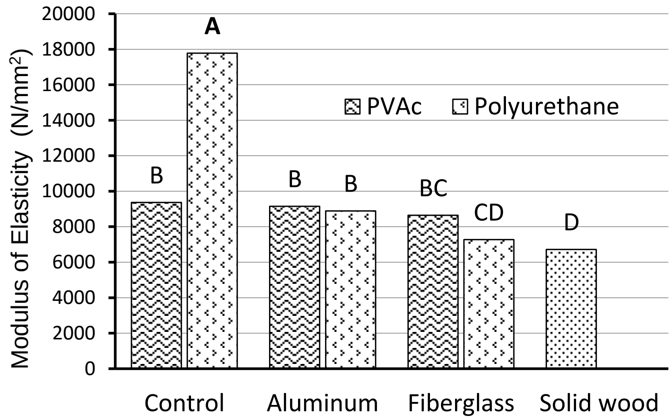


Fig. 7. The interactions of support material type-adhesive type-solid wood

According to the comparative test results of the dual interaction for support material type and adhesive type, it was determined that the modulus of elasticity in bending parallel to the glue line was the lowest in the solid specimens at 6720 N/mm^2, whereas, the highest was in the laminated control group specimens without support materials produced with the polyurethane adhesive at 17800 N/mm^2 and the modulus of elasticity in the bending parallel to the glue line increased ~2.6-fold.

CONCLUSIONS

1. Polyurethane adhesive increased the bonding strength approximately 10% compared to the PVAc adhesive.
2. The highest bonding strength value was in the laminated control group without support materials. It was observed that the intermediary support materials negatively affected bonding, even if only slightly. However, despite the fact that the fiberglass wire woven wooden construction elements combined with the polyurethane adhesive for bonding strength showed similar properties to the control specimens without support materials that were combined with the PVAc adhesive, it was higher even if only very slightly.
3. When the modulus of elasticity in bending perpendicular to the glue line was examined for the support materials, aluminum wire mesh significantly increased the elasticity of the wooden construction elements. When it was evaluated for the adhesive type, it was determined that the modulus of elasticity of the wooden construction elements produced with the lamination method was lower compared to the solid specimens, and the lowest value was obtained in the specimens produced with the PVAc adhesive.
4. In terms of the modulus of elasticity in bending parallel to the glue line, the use of solid materials would be more appropriate, but it was observed that layered composite materials supported with fiberglass wire mesh and combined with polyurethane adhesive could also provide advantages compared to the lamination without support materials.

5. While the use of support materials between the layers is the cause of a decrease in the bonding strength, it is also the cause of a decrease, especially in the modulus of elasticity in bending parallel to the glue line. When it was evaluated for the adhesive type, the polyurethane adhesive provided a 10% increase in the bonding strength compared to the PVAc adhesive, whereas, the modulus of elasticity in bending perpendicular to the glue line and parallel to the glue line was lower in the PVAc adhesive and it provided for obtaining a more elastic material.
6. Although the adhesion strength increased when polyurethane adhesive was used, the polyurethane adhesive showed a raising effect on the modulus of elasticity values of the laminated composite wooden construction elements, compared to PVAc.

ACKNOWLEDGMENTS

This study was funded by the Gazi University Scientific Research Unit (Project number: 25/2010-04). This study is part of an MSc thesis submitted to Gazi University.

REFERENCES

Bastani, A., Adamopoulos, S., Koddenberg, T., and Militz, H. (2016). "Study of adhesive bondlines in modified wood with fluorescence microscopy and X-ray micro-computed tomography," *International Journal of Adhesion and Adhesives* 68, 351-358. DOI: 10.1016/j.ijadhadh.2016.04.006

BS EN 204 (2001). "Classification of thermoplastic wood adhesives for non-structural applications," British Standards Institution, London, United Kingdom.

BS EN 205 (2003). "Adhesives. Wood adhesives for non-structural applications. Determination of tensile shear strength of lap joints," British Standards Institution, London, United Kingdom.

Corradi, M., and Borri, A. (2007). "Fir and chestnut timber beams reinforced with GFRP pultruded elements," *Composites Part B: Engineering* 38(2), 172-181. DOI: 10.1016/j.compositesb.2006.07.003

Cowan, H. J. (1991). *Handbook of Architectural Technology*, Van Nostrand Reinhold, New York, USA.

Custódio, J., Broughton, J., and Cruz, H. (2009). "A review of factors influencing the durability of structural bonded timber joints," *International Journal of Adhesion and Adhesives* 29(2), 173-185. DOI: 10.1016/j.ijadhadh.2008.03.002

Davids, W. G., Richie, M., and Gamache, C. (2005). "Fatigue of glulam beams with fiber-reinforced polymer tension reinforcing," *Forest Products Journal* 55(1), 93-101.

Ergin, E. (2011). Strengthened wood construction materials design and determination of some technical properties, Master's Thesis, Gazi University, Ankara, Turkey.

Guan, Z. W., Rodd, P. D., and Pope, D. J. (2005). "Study of glulam beams pre-stressed with pultruded GRP," *Computers and Structures* 83(28), 2476-2487. DOI: 10.1016/j.compstruc.2005.03.021

Gutkowski, R., Brown, K., Shigidi, A., and Natterer, J. (2008). "Laboratory tests of composite wood–concrete beams," *Construction and Building Materials* 22(6), 1059-1066. DOI:10.1016/j.conbuildmat.2007.03.013

Karayılmazlar, S., Çabuk, Y., Tümen, I., and Atmaca, A. (2008). "Use of laminated wood beams in various structures," *Journal of Bartin Faculty of Forestry* 10(14), 13-21.

Keskin, H., and Togay, A. (2003). "Physical and mechanical properties of laminated wood materials made up with the combination of oriental beech wood and poplar wood," *Turkish Journal of Forestry* A(2), 101-114

Kim, Y., Davalos, J. F., and Barbero, E. J. (1997). "Delamination buckling of FRP layer in laminated wood beams," *Composite Structures* 37(3), 311-320. DOI: 10.1016/S0263-8223(98)80002-0

Kleiberit (2016). "Adhesive groups," *Kleiberit Adhesives/Coatings*, (https://www.kleiberit.com/en/adhesive-groups.html), 20.10.2016.

Knorz, M., Neuhaeuser, E., Torno, S., and van de Kuilen, J. W. (2015). "Influence of surface preparation methods on moisture-related performance of structural hardwood–adhesive bonds," *International Journal of Adhesion and Adhesives* 57, 40-48. DOI: 10.1016/j.ijadhadh.2014.10.003

Kuo, P. Y., Wang, S. Y., Chen, J. H., Hsueh, H. C., and Tsai, M. J. (2009). "Effects of material compositions on the mechanical properties of wood-plastic composites manufactured by injection molding," *Materials and Design* 30(9), 3489-3496. DOI: 10.1016/j.matdes.2009.03.012

Kureli, I., Altinok, M., and Percin, O. (2013). "Experimental investigation of some technological properties of thermo modified and impregnated wood samples," *Wood Research* 58(3), 369-380.

Li, Y. F., Tsai, M. J., Wei, T. F., and Wang, W. C. (2014). "A study on wood beams strengthened by FRP composite materials," *Construction and Building Materials* 62, 118-125. DOI: 10.1016/j.conbuildmat.2014.03.036

Li, Y. F., Xie, Y. M., and Tsai, M. J. (2009). "Enhancement of the flexural performance of retrofitted wood beams using CFRP composite sheets," *Construction and Building Materials* 23(1), 411-422. DOI: 10.1016/j.conbuildmat.2007.11.005

Li, Y., Shan, W., Shen, H., Zhang, Z. W., and Liu, J. (2015). "Bending resistance of I-section bamboo-steel composite beams utilizing adhesive bonding," *Thin-Walled Structures* 89, 17-24. DOI: 10.1016/j.tws.2014.12.007

Meier, U. (1995). "Strengthening of structures using carbon fibre/epoxy composites," *Construction and Building Materials* 9(6), 341-351. DOI: 10.1016/0950-0618(95)00071-2

Miotto, J. L., and Dias, A. A. (2011). "Glulam-concrete composites: Experimental investigation into the connection system," *Materials Research-Ibero-American Journal of Materials* 14(1), 53-59. DOI: 10.1590/S1516-14392011005000002

Moody, R. C., Hernandez, R., and Liu, J. Y. (1999). "Glued structural members," in: *Wood Handbook: Wood as an Engineering Material*, U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI, USA, pp. 11-25.

Motlagh, Y. B., Gholipour, Y., Ebrahimi, Gh., and Hosseinalibeygi, M. (2008). "Experimental and analytical investigations on flexural strengthening of old wood members in historical buildings with GFRP," *Journal of Applied Sciences* 8(21), 3887-3894. DOI: 10.3923/jas.2008.3887.3894

Nguyen Trung, V. A., Leroy, R., and Caron, J.-F. (2015). "Multi-reinforcement of timber beams with composite materials: Experiments and fracture modeling," *Composite Structures* 123, 233-245. DOI: 10.1016/j.compstruct.2014.12.004

Nowak, T. P., Jasienko, J., and Czepizak, D. (2013). "Experimental tests and numerical analysis of historic bent timber elements reinforced with CFRP strips," *Construction and Building Materials* 40, 197-206.

Özalp, M. (2003). *Investigation of physical, mechanical, and chemical characteristics change of water repellent and preservative-treated pine specimens and their use in water cooling towers*, MSc Thesis, Zonguldak Karaelmas University, Zonguldak, Turkey.
Pirvu, A., Gardner, D. J., and Lopez-Anido, R. (2004). "Carbon fiber-vinyl ester composite reinforcement of wood using the VARTM/SCRIMP fabrication process," *Composites Part A- Applied Science and Manufacturing* 35(11), 1257-1265. DOI: 10.1016/j.compositesa.2004.04.003
Putzger, R., and Haller, P. (2006). "Fracture energy in mode I and mode II of textile reinforced wood," in: *Fracture of Nano and Engineering Materials and Structures: Proc. of the 16th Eur. Conf. of Fracture*, E. E. Gdoutos (ed.), Springer Netherlands, Alexandroupolis, Greece, pp. 453-454. DOI: 10.1007/1-4020-4972-2_224
Raftery, G. M., Harte, A. M., and Rodd, P. D. (2009). "Bond quality at the FRP-wood interface using wood-laminating adhesives," *International Journal of Adhesion and Adhesives* 29(2), 101-110. DOI: 10.1016/j.ijadhadh.2008.01.006
SGT (2016). "Urunler," Fiber Sinek Teli, (http://www.sgt.website/kategoriler/teller/20), Accessed 20.10.2016.
Söğütlü, C., and Döngel, N. (2007). "Tensile shear strengths of some local woods bonded with polyvinyl acetate and polyurethane," *Gazi University Journal of Polytechnic* 10(3), 287-293.
Stoeckel, F., Konnerth, J., and Gindl-Altmutter, W. (2013). "Mechanical properties of adhesives for bonding wood – A review," *International Journal of Adhesion and Adhesives* 45, 32-41.
Taheri, F., Nagaraj, M., and Khosravi, P. (2009). "Buckling response of glue-laminated columns reinforced with fiber-reinforced plastic sheets," *Composite Structures* 88(3), 481-490. DOI: 10.1016/j.compstruct.2008.05.013
TS 2470 (1976). "Wood-sampling methods and general requirements for physical and mechanical tests," Turkish Standard Institute, Ankara, Turkey.
TS EN 408+A1 (2015). "Timber structures – Structural timber and glued laminated timber- Determination of some physical and mechanical properties," Turkish Standard Institute, Ankara, Turkey.
Togay, A., and Ergin, E. (2014). "Determination of some physical attributes for wooden construction elements strengthened with woven wire fiberglass," *BioResources* 9(3), 3883-3900. DOI: 10.15376/biores.9.3.3883-3900
Triantafillou, T. C., and Deskovic, N. (1992). "Prestressed FRP sheets as external reinforcement of wood members," *Journal of Structural Engineering* 118(5), 1270-1284. DOI: 10.1061/(ASCE)0733-9445(1992)118:5(1270)
Widmann, R., Steiger, R., and Gehri, E. (2007). "Pull-out strength of axially loaded steel rods bonded in glulam perpendicular to the grain," *Materials and Structures* 40(8), 827-838. DOI: 10.1617/s11527-006-9214-9
Xu, H., Nakao, T., Tanaka, C., Yoshinobu, M., and Katayama, H. (1998). "Effects of fiber length and orientation on elasticity of fiber-reinforced plywood," *Journal of Wood Science* 44(5), 343-347. DOI: 10.1007/BF01130445

Article submitted: October 22, 2016; Peer review completed: November 28, 2016; Revised version received: January 12, 2017; Accepted: January 22, 2017; Published: February 13, 2017.
DOI: 10.15376/biores.12.2.2466-2478