Compression, Cleavage, and Shear Resistance of Composite Construction Materials Produced from Softwoods and Hardwoods

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ABSTRACT: The process of manufacturing laminated wood board is an effective technique for reducing or eliminating the negative properties of solid wood materials and for obtaining high-performance materials. More economical composite laminated materials, which use different types of wood together and have the strength suitable for the purpose, can be produced with this technique. In the present study, composite laminated specimens containing beech (*Fagus orientalis Lipsky*), a type of hardwood, and poplar (*Populus nigra*), a softwood, were produced with layers of two thicknesses: 4 and 5 mm. Poly(vinyl acetate) (PVAc) and polyurethane (PU) glues were used in gluing. The results of the tests were compared with those for the solid wood specimens, and it was found that new composite building materials with high mechanical strength and lower cost could be produced for the construction materials sector in Turkey instead of solid wood. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 3673–3678, 2006

Key words: composite laminated wood; compression resistance; cleavage resistance; shear resistance; adhesives

INTRODUCTION

By eliminating the negative properties stemming from both the external influences on and the anatomical structure of wood materials, new high-performance products that can be used as construction materials can be produced. One technique for making such products is lamination. The material produced with this technique is called laminated wood (glulam) in TS EN 386, which defines it as ''the construction element obtained with the gluing under pressure in a manner where the grain of the layers are parallel to each other and also parallel to the longitudinal axis of the element obtained.''[1] In general, laminated elements are named according to the thickness of the layers used: glulam (glued laminated timber), LVL (laminated veneer lumber), and microlam.[2] In addition to these materials, it is possible to produce new materials that perform suitably by applying the lamination technique to different wood types, number of layers, dimensions, shapes, and layer thicknesses. In the present study, composite laminated materials composed of layers with a thickness of either 4 or 5 mm were produced using poplar, a type of wood that grows quickly and is abundant, and beech, which grows over a long period and has high resistance.

The properties of laminated wood materials change according to such factors as type of wood and the faults it contains, thickness of layers, number of layers, whether number of layers is single or double, type of glue used, and compression force used during pressing.[3] In general, it is known that the resistance of hardwoods (hornbeam, beech, oak, etc.) is higher than that of softwoods (poplar, willow, linden, etc.).[3,4] Consequently, the strength of a material produced as a laminate from hardwoods is higher than that from material produced using softwoods. The resistance properties of a laminated material with a composite character are variable. For this reason, it is necessary to conduct tests to determine the properties of the composition of the layers of the composite material.

Within this context, the purpose of this study was to determine the properties of the compression parallel to the grain, the cleavage perpendicular to the grain, and the shear resistance parallel to the grain of this newly produced material and compare them with those of solid wood specimens in order to determine the limits of usability in construction.[5]

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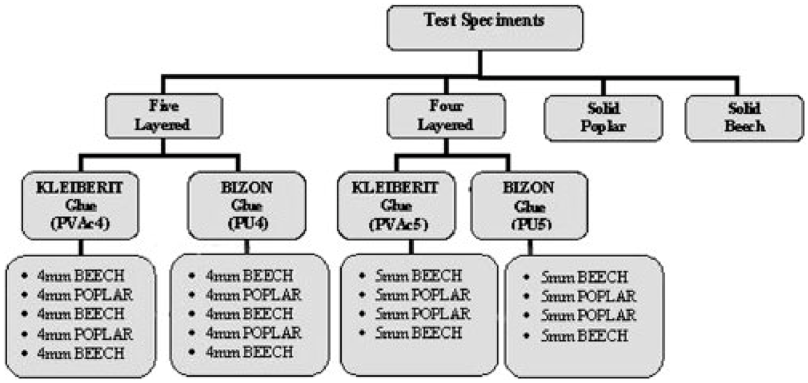


Figure 1 Preparation plan for the test specimens: PVAc4, specimens in which five layers with a thickness of 4 mm were glued with PVAc; PU4, specimens in which five layers with a thickness of 4 mm were glued with PU; PVAc5, specimens in which four layers with a thickness of 5 mm were glued with PVAc; PU5, specimens in which four layers with a thickness of 5 mm were glued with PU.

EXPERIMENTAL

Materials

As mentioned above, beech and poplar were the woods used as test specimens. Beech was obtained from the Mengen, Bolu, Yaylacık Research Forest, where it grows naturally, and poplar was obtained from Beytepe, Ankara. They were cut into specimens 70 × 600 mm in size in accordance with the ISO 4471 (TS 4176) standard.[7] The cut lumber was dried in a drying oven until it reached an air dry humidity level of 12%. Subsequently, a circular ripsaw was used to cut the specimens in the form of panels with a thickness of 6 mm. The cut layers were sanded down to thicknesses of 4 and 5 mm. Then the test specimens were obtained gluing the layers with different glues and in two combinations (Fig. 1).

Types of glue

Poly(vinyl acetate) (PVAc; Kleiberit 303) glue suitable for use in gluing processes in closed and dry environments and polyurethane (PU; Bizon Timber PU-Max Express) glue suitable for use in open places and humid environments were used in the preparation of the specimens. The PVAc glue was of D3 adhesion quality according to the BS EN 204 standard,[7,8] and the PU glue was of D4 adhesion quality according to the BS EN 204.[9]

Preparation of the test specimens

Layers obtained by the slicing (cutting) method from beech (*Fagus orientalis Lipsky*) and poplar (*Populus nigra*) wood were glued with the PVAc (Kleiberit 303) and PU (Bizon Timber PU-Max Express) glues in two different compositions, and the test specimens were prepared according to the plan shown in Figure 1. In addition to these test specimens, solid beech and poplar specimens of the same dimensions were also prepared as controls.

During the preparation of the test specimens, care was taken that the layers had thicknesses of 4 or 5 mm without fault. The PVAc glue was spread on a single surface of the layers with a calculation of 160 g/m^2 and was pressed with a pressure of 0.7 N/mm^2 at 20°C for 15 min. The PU glue was spread on a single surface of the layers with a calculation of 200 g/m^2 and was pressed with a pressure of 0.7 N/mm^2 at 20°C for 2 h. A nail gun was used to hammer 18-mm-long nails without heads into the ends of the laminated materials so that the glued layers would not slip during pressing. A total of 25 specimens were prepared from four groups and from the solid specimens according to layer thickness and type of glue, and 20 of these were used in the tests. The specimens were prepared according to the rules in TS 2595,[10] ASTM D 143,[11] and BS EN-373[12] and with the dimensions shown in Figures 2–4.

The specimens were placed in a climatization room for 1 month at a temperature of 20°C ± 2°C and a rela-

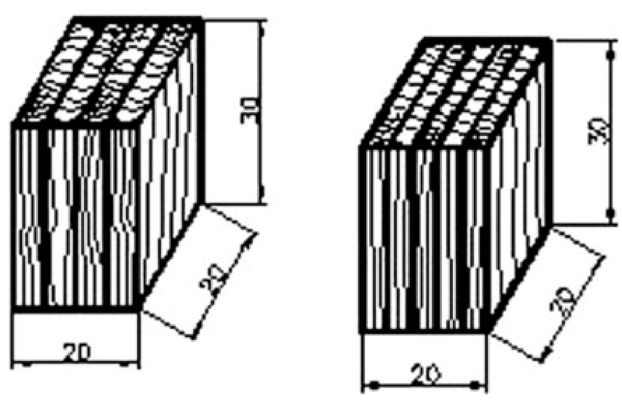


Figure 2 Four- and five-layer test specimens prepared for measuring compression resistance (in mm) in a direction parallel to the grain.

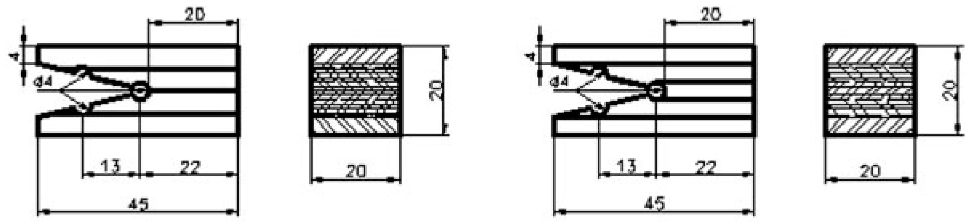


Figure 3 Four- and five-layer test specimens prepared for measuring cleavage resistance in a direction perpendicular to the grain.

tive humidity of 65% ± 5%, which allowed them to reach an air dry humidity level.

Test method

The dimensions of the specimens removed from the climatization room were measured with a digital compass that could measure to 1/100 mm. The specimens were placed in the test equipment [Fig. 5(a–c)] for measuring compression resistance (TS 2595), cleavage resistance (ASTM D 143 and BS EN-373), and shear resistance (ASTM D 3110).

To determine compression resistance, specimens whose dimensions are given in Figure 2 were placed in the calibrated test equipment as shown in Figure 5(a), and the tests were conducted according to TS 2595.[10] During the compression test a fixed loading was applied to the cross sections of the specimens in order to crush them for 1.5–2 min. Application of the load was continued until the specimens broke, and maximum load (P_{max}) at the moment of breaking was read from the dial of the machine. Compression resistance was calculated by the following equation:

$$\sigma_B = \frac{P_{max}}{A} \tag{1}$$

where σ_B is the compression resistance (N/mm^2), P_{max} is the maximum load (N), and A is the surface area subjected to pressure (mm^2).

To determine cleavage resistance, specimens whose dimensions are given in Figure 3 were placed in the test equipment as shown in Figure 5(b) and were tested according to the ASTM D 143[11] and BS EN-373[12] standards. Two separate forces were applied to the specimens placed in the pulling apparatus at a speed of 2.5 mm/min in the opposite direction, and it was attempted to break it from the glueline, and the maximum load (P_{max}) at the moment of breaking was read from the dial of the test equipment and recorded. Cleavage resistance was calculated by the following equation:

$$\sigma_{Ç} = \frac{P_{max}}{A} \tag{2}$$

where $\sigma_{Ç}$ is the cleavage resistance perpendicular to the grain (N/mm^2), P_{max} is the maximum force measured at the moment of breaking (N), and A is the surface area glued (mm^2).

To determine shear resistance, specimens whose dimensions are given in Figure 4 were placed in the test equipment as shown in Figure 5(c) and were tested according to the rules specified in ASTM D 905-98.[13] During the test, the machine loading speed was adjusted to 12.7 mm/min, and it was operated in a manner to break the glue layer within 1.5–2 min. The maximum load (P_{max}) at the moment of breaking was measured. Shear resistance was calculated by the following equation:

$$\sigma_M = \frac{P_{max}}{A} \tag{3}$$

where σ_M is the compression resistance (N/mm^2), P_{max} is the maximum load at the moment of breaking (N), and A is the surface area glued (mm^2).

RESULTS

The F test was used to determine the effects of the two glues (PVAc and PU) and the two layer thicknesses (4 and 5 mm) on compression, cleavage, and shear resistance. If significant difference among groups were found, then the Duncan test was used to compare them at a confidence level of $\alpha = 0.05$. SPPS version 11.5 was

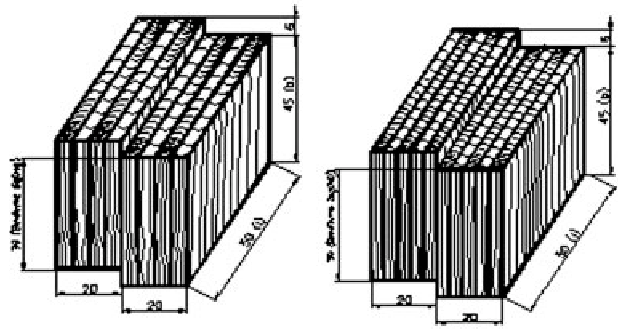
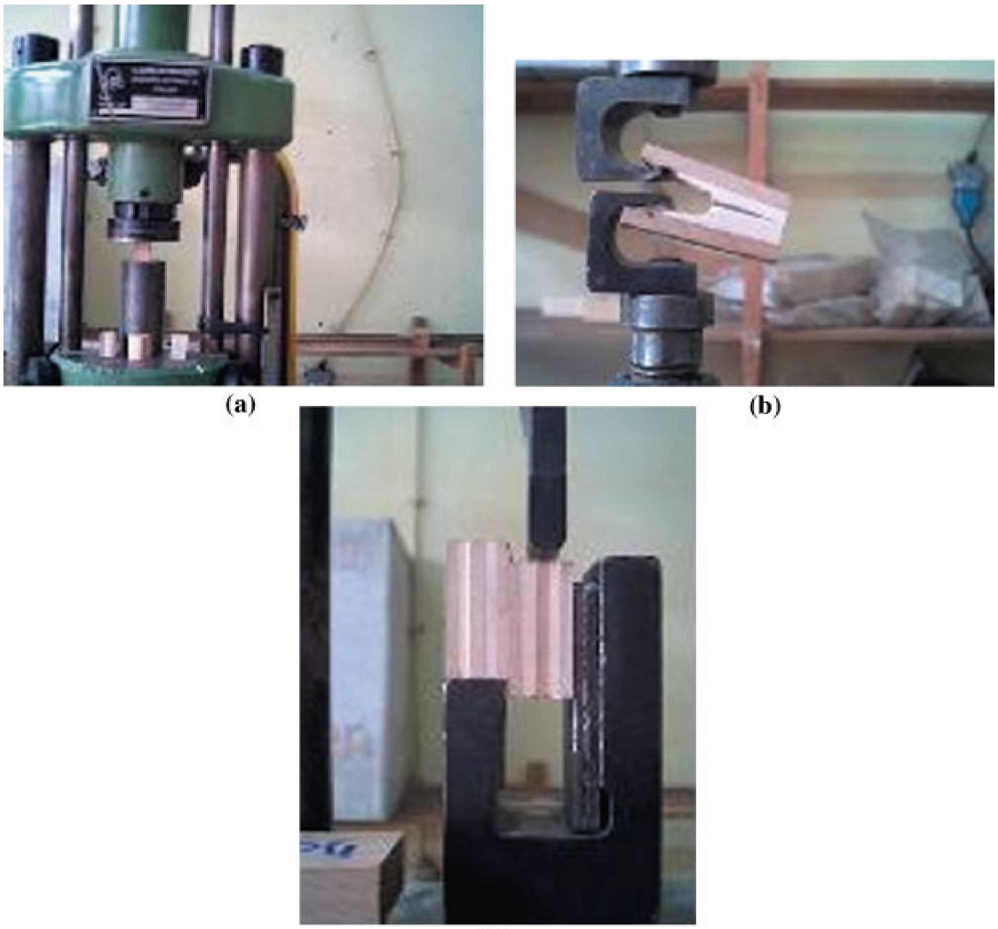


Figure 4 Four- and five-layer test specimens prepared for measuring shear resistance in a direction parallel to the grain.



(c)

Figure 5 Test arrangements for measuring (a) compression resistance, (b) cleavage resistance, and (c) shear resistance of four- and five-layer specimens. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

used to calculate analysis of variance (ANOVA), arithmetical averages, and standard deviations.[14]

Descriptive statistics for the compression, cleavage, and shear resistance of the composite laminated wood and solid wood specimens are given in Table I.

The F test was applied with the objective of determining whether there were differences between the compression, cleavage, and shear resistance values obtained at the end of the tests. If a significant difference was found, then the Duncan test was performed in order to determine among which groups there was a difference. From this, it was determined that the difference in the compression, cleavage and shear resistance values according to the material combinations was

TABLE I
Descriptive Statistics of Compression, Cleavage, and Shear Resistance

Material type	Number of specimens	Compression resistance (N/mm^3) $F = 140.20$, $P = 0.000$		Cleavage resistance (N/mm^2) $F = 102.77$, $P = 0.000$		Shear resistance (N/mm^2) $F = 53.38$, $P = 0.000$	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Solid beech	20	71.59	5.23	0.73	0.09	—	—
Solid poplar	20	46.13	3.42	0.40	0.03	—	—
Beech PU	20	—	—	—	—	13.77	0.96
Beech PVAc	20	—	—	—	—	14.38	1.46
Poplar PU	20	—	—	—	—	9.82	1.35
Poplar PVAc	20	—	—	—	—	10.02	0.46
PU5	20	52.91	2.23	0.57	0.04	11.93	1.07
PVAc5	20	51.02	2.22	0.54	0.02	12.38	0.62
PU4	20	57.85	1.99	0.63	0.02	10.66	0.92
PVAc4	20	56.78	3.45	0.61	0.04	11.05	1.00

TABLE II
Homogeneous Groups according to Compression, Cleavage, and Shear Resistance (Duncan Test Results)

Material	N	$\alpha = 0.05$			
		1	2	3	4
Groups homogenous for compression resistance					
POPLAR	20	46.13			
PVAc5	20		51.02		
PU5	20		52.91		
PVAc4	20			56.78	
PU4	20			57.85	
BEECH	20				71.56
Groups homogenous for cleavage resistance					
POPLAR	20	0.40			
PVAc5	20		0.54		
PU5	20		0.57		
PVAc4	20			0.61	
PU4	20			0.63	
BEECH	20				0.73
Groups homogenous for shear resistance					
POPLAR PU	20	9.82			
POPLAR PVAc	20	10.02			
PU4	20		10.66		
PVAc4	20		11.05		
PU5	20			11.93	
PVAc5	20			12.38	
BEECH PU	20				13.77
BEECH PVAc	20				14.38

significant at a 95% confidence interval and an $\alpha = 0.05$ significance level ($p < 0.05$; Table I). According to the results of the Duncan test (Table II), the highest compression, cleavage and shear resistance values were obtained in solid beech, followed in order by PU4, PVAc4, PU5, PVAc5, and solid poplar materials. In addition, the Duncan test showed a statistically significant difference between PU4 and PVAc4 and between PU5 and PVAc5.

At the end of the experiments, the highest compression resistance and cleavage resistance values were obtained in solid beach, followed in order by PU4, PVAc4, PU5, PVAc5, and poplar.

It was believed that a comparison of the compression and cleavage resistance values of the laminated and solid materials would show that the PU4 and PVAc4 materials, both made up of five layers, had the properties of beech at a ratio of 3 : 5 and of poplar at a ratio of 2 : 5 and that the PU5 and PVAc5 materials, both made up of four layers, had the properties of beech at a ratio of 2 : 4 and of poplar at a ratio of 2 : 4. It was assumed that better results could be obtained relative to the total of the ratios because of the influence of the glues used in the materials. According to this, for compression resistance the sum of the ratios (61.39 N/mm^2) of the solid values for the five-layer specimens was greater than the PU4 and PVAc4 averages. For the four-layer laminations as well, the sum of the ratios (58.84 N/mm^2) of the solid values was greater than that of PU5 and PVAc5. As for cleavage resistance, the sum of the ratios (0.6022 N/mm^2) of the solid values for the five-layer specimens was smaller than the PU4 and PVAc4 averages. As for the four-layer laminations, the sum of the ratios (0.569 N/mm^2) for the solid values was close to PU5 and smaller than PVAc5. In the cleavage resistance test, the specimens with PU glue produced higher results than the specimens with PVAc glue.

Among the wood materials, the highest shear resistance was obtained in oriental beech with the PVAc glue. This was followed by beech with PU, PVAc5, PU5, PVAc4, and PU4 and by poplar with PVAc and PU, respectively. In the shear resistance tests, specimens with PVAc glue produced higher values than those of the specimens with PU glue. The greater penetration of the PVAc glue into the wood than the PU glue and the greater elasticity of the PVAc glue both played a role in these results.

DISCUSSION

It was observed that durable new materials could be obtained with the use of wood types that have low resistance in the interior layers of composite materials. Although the specimens of both combinations had the same dimensions, it was observed that with an increase in the number of layers of the wood with higher resistance, the compression, cleavage, and shear resistance values of the composite material also increased.

In the specimens made up of four layers each with a thickness of 5 mm glued with PVAc5 and PU5 glues, the poplar–beech content of the composite material was in a 50%–50% ratio. It was found that the compression, cleavage, and shear resistance values of these specimens were higher than those of solid poplar. The specimens made up of five layers each 4 mm thick glued with PVAc4 and PU4 were 60% beech and 40% poplar. The compression resistance of these specimens was higher than that of solid poplar.

Compression resistance is a reaction against forces aimed at squeezing and crushing the wood material. Among the structural system elements of construction, such as upright wooden beams, props, the perpendicular components of wooden window joinings, furniture feet, and perpendicular space-dividing panels, are the elements subjected to compression load. Among the composite materials the highest compression resistance was obtained in materials with a layer thickness of 5 mm that had been glued with PU4, followed in decreasing order by PVAc4, PU5, and PVAc5. From these results, it was determined that it would be more suitable to use PU4 instead of composite laminated materials, which are subjected to compression forces.

Wood construction materials remain under the influence of tensile forces in the places where they are used. As a result, these materials could split and partially or completely lose their resistance. For this reason, it is necessary to select materials suitable for use in those places where the tensile forces would be effective. It is especially important to know the cleavage resistance in advance when wood will be used together with fastenings such as metal, nails, and screws. In the present study, the highest cleavage resistance among the composite laminated materials was obtained with PU4, followed in decreasing order by PVAc4, PU5, and PVAc5. Therefore, PU4 should be the preferred material in situations where composite laminated materials are used together with fastenings.

In practice, shear resistance is a property that helps to determine the resistance of the construction materials in joining places. In this study, the highest shear resistance was obtained in beech glued with the PVAc glue, followed in decreasing order by beech glued with PU, PVAc5, PU5, PVAc4, and PU4 and by poplar glued with PVAc and PU, respectively. The results showed that the type of glue did not influence shear resistance, but the thickness of the layers did.

CONCLUSIONS

The results of the present study showed that the composite materials that used poplar, a more easily grown type of wood that is less expensive and has relatively low resistance, and beech, a type of wood grown over a long time that is expensive and has higher resistance, could be used as an alternative in place of solid materials. The composites produced for the tests showed that wood materials, a scarce resource, can be utilized in a rationalized manner, that the production model in the study would make a considerable contribution to the economy of the country, and that the composites could be used as construction materials.

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