Effect of PVAc Bonding on Finger-Joint Strength of Steamed and Unsteamed Beech Wood (*Fagus sylvatica*)

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ABSTRACT: Beech wood is one of the most important species used in furniture production in Europe. In this work, the effects of poly(vinyl acetate) (PVAc) bonding [durability classes D1, D2, and D3 according to EN 204 : 2001), finger length (4 and 10 mm), and finger orientation on the bending strength of finger-jointed steamed and unsteamed beech wood (*Fagus sylvatica*) were studied. Specimens were prepared according to EN 385 (2001) and modulus of rupture (MOR) and modulus of elasticity (MOE) tests were performed according to the procedures detailed in the ISO 10983 (1999) and DIN 52186 (1978) standards. The MOR of unsteamed wood joints ranged from 33.51 to 82.24 N/mm^2, whereas the MOR of the steamed wood joints fluctuated from 34.9 to 80.27 N/mm^2. In both steamed and unsteamed wood the specimens with a finger length of 10 mm showed higher MOR than the specimens with a finger length of 4 mm. The MOE of the unsteamed specimens was not affected by finger jointing, whereas, the MOE of the steamed specimens increased slightly (by 5.4%) compared to the control solid wood. It was concluded that it was better to use a 10-mm finger length and the D3 durability class of PVAc adhesives when finger-jointed furniture lumber is produced. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 103: 1664–1669, 2007

Key words: adhesives; strength; thermoplastics; finger joint; beech wood

INTRODUCTION

Finger jointing has been in use in the wood industry for many years, yet it is only with the decline in the quality of resources that interest in its use for furniture has increased. Nonstructural finger joints are used if strength is not a primary concern. The benefits of finger joints in furniture and cabinet manufacturing are: (1) clear lumber from low-grade stock, (2) shorter length of waste material, and (3) increased yield of usable long parts.[1,2]

Poly(vinyl acetate) (PVAc) is one of the most common adhesives used in nonstructural applications. Poly(vinyl resin) emulsions are thermoplastic, softening if the temperature is raised and hardening again when cooled. They are prepared by emulsion polymerization of vinyl acetate and other monomers in water under controlled conditions. In emulsified form, PVAc is dispersed in water and has a consistency and nonvolatile content generally comparable to thermosetting resin adhesives. PVAc is capable of producing strong and durable bonds on hardwood and hardwood-derived products. Although PVAc adhesives are not generally recommended for joints under continuous load or subjected to high temperature and/or high humidity, these adhesives can be formulated for improved performance under such conditions. Thermosetting polyvinyl emulsions are modified PVAc emulsions and are more resistant to heat and moisture than are ordinary PVAc adhesives and perform well in most nonstructural interior and protected exterior uses.[1,3] Ordinary PVAc adhesives are marketed as milky white fluids for use at room temperature classified by durability class (D1, D2, D3, and D4) according to the EN-204 standard.[4]

Limited information is available on end-gluing hardwoods, in contrast to softwoods, which have been extensively investigated and industrially utilized.[5] Pena[5] studied the suitability of producing nonstructural finger joints made from beech wood (*Fagus sylvatica*) and European oak (*Quercus petraea*). He examined the effect of the geometry of finger joints in bending strength, using 9- and 12-mm finger lengths bonded with melamine-urea-formaldehyle (MUF) and epoxy resin adhesives and concluded that the modulus of elasticity (MOE) of jointed specimens did not differ significantly from unjointed ones. On the contrary, jointed specimens showed lower modulus of rupture (MOR) values than did unjointed ones (43%). Aicher et al.[6] studied the tension strength of finger joints in beech wood with a 20-mm finger

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length and bonded with melamine adhesive. They found that the mean tension strength of the finger-jointed specimens was 70 ± 11 N/mm^2. Örs et al.[7] studied the bonding strength of Oriental beech, Scotch pine, and Uludağ fir (*Abies bormülleriana* Mattf.) that had been impregnated and bonded with PVAc and PVAc-based adhesives (K_{303}, $K_{305.0}$, and SL_{308}). They found that the highest shear strength (11.839 N/mm^2) was obtained with beech wood impregnated with T-CBC according to the dipping method and K_{303} adhesives, whereas the lowest (3.1 N/mm^2) was obtained with Scotch pine impregnated with T-CBC by the vacuum method and $K_{305.0}$ adhesives.

Steam treatment is often applied to beech to improve the stability and permeability of the wood in order to obtain a desirable color and to soften the wood. The effect of steaming on the physical, mechanical, and chemical properties of wood has been studied extensively. Generally, the process of steaming beech wood is accompanied by decreased strength (compression strength and MOE) and physical properties (density).[8]

The objective of the present study was to examine the effects of PVAc bonding (durability classes D1, D2, and D3), finger length, and finger orientation on the bending strength of finger-jointed steamed and unsteamed beech wood (*Fagus sylvatica*).

EXPERIMENTAL

Experiments were carried out with steamed and unsteamed beech wood with dimensions of 50 × 30 × 400 mm. The steaming of the test material was carried out under atmospheric pressure from about 60°C to 90°C for 48 h. Natural defects were removed by trimming according to EN 385.[9] The material was placed in a conditioning room at 20°C and 65% relative humidity and allowed to reach a nominal equilibrium moisture content (EMC) of 12%. Two finger joints were performed by profiling cutterheads with the following characteristics: (1) 4 mm length with 0.4 mm tip, 1.6 mm pitch, and 12.0° angle and (2) 10 mm length with 0.16 mm tip, 3.8 mm pitch, and 11.0° angle.

Following finger jointing, the blocks were bonded in keeping with the technical recommendations provided by the adhesive manufacturers. Three classes of PVAc-based one-component adhesives (D1, D2, and D3) for interior use were studied. The technological properties of the PVAc adhesives used were: D1, density 1.013 g/cm^3, pH 4.41, solid content after drying 41.7%; D2, density 1.038 g/cm^3, pH 2.83, solid content after drying, 41.8%; and D3, density 1.045 g/cm^3, pH 2.81, solid content after drying, 46.8%. The viscosity of the three adhesives was about 13.000 mPa s at 20°C and 65% relative humidity. The adhesives, D1 (Durostick 35, D1T), D2 (Durostick D-100, D2T), were supplied from Durostick, a producer firm in Athens, Greece, and D3 (RACOLL, a German product introduced in Greek market), was supplied from RACOLL dealer in Greece.

A one-face adhesive application by brush was used. The assembled joints were pressed manually with a constant end pressure for 60 s. The jointed pieces were then cut to final dimensions of 20 × 20 × 360 mm in order to produce bending-strength samples. Modulus of rupture (MOR) and modulus of elasticity (MOE) tests were performed in accordance with ISO 10983[10] and DIN 52186[11] standards with a Shimatzu machine. The rate of crosshead movement was adjusted at 5 mm/min so that the maximum load was reached within 1.5 ± 0.5 min throughout the test. The loading was continued until a break or separation occurred on the surface of the test samples, and the modulus of rupture (σ_B) and modulus of elasticity (E_B) were calculated as follows:

$$\sigma_B = \frac{1.5 \cdot P \cdot S}{h \cdot b^2}\ \text{N/mm}^2 \quad (1)$$

$$E_B = \frac{S^3 \cdot \Delta F}{4 \cdot b \cdot h^3 \cdot \Delta f}\ \text{N/mm}^2 \quad (2)$$

where P is the maximum load at failure (N); ΔF is the increase in load on the straight line portion of the load-deflection curve (N); S is the span distance (mm); h is the height of the specimen (mm); b is the width of the specimen (mm); and Δf is the change in deflection at midlength of the specimen (mm; corresponding to ΔF).

For each finger length the influence of the finger orientation (horizontal and vertical) with regard to the direction of the load was also examined (Fig. 1). For every parameter 15 specimens were tested according to EN 385.[9] By using two test methods, three types of adhesive, two directions, two lengths of finger joints, and two types of wood as parameters, a total of 720 test samples (2 × 3 × 2 × 2 × 2 × 15) were prepared. After each bending test two samples were cut from each side of the failed joint, and moisture content (MC) and density were determined.

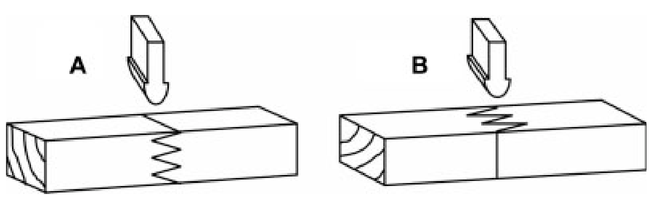

Figure 1 Orientation of finger joints and loading direction in samples (A, horizontal fingers; B, vertical fingers).

TABLE I
Bending Strength Properties of Finger-Jointed Unsteamed Beech Wood

		Finger length (mm)					
		PVAc category					
		4			10		
Bending strength (N/mm^2)	Solid wood	D1	D2	D3	D1	D2	D3
Horizontal fingers							
MOR	108.71 (5.77)[a]	33.51 (3.20)	56.02 (6.27)	61.49 (6.53)	52.51 (6.00)	65.20 (5.48)	82.24 (9.48)
MOE	11,643.0 (1130)	11,169.0 (1892.6)	11,054.0 (2268.1)	11,692.0 (1201.7)	10,839.0 (1334.7)	10,408.0 (1200.7)	11,828.0 (1064.0)
Vertical fingers							
MOR		34.36 (4.31)	53.12 (5.11)	59.99 (5.16)	46.20 (6.61)	64.45 (3.80)	78.65 (6.08)
MOE		11,782.0 (1768.1)	11,401.0 (1816.0)	11,692.0 (1263.8)	11,411.0 (1556.3)	10,715.0 (1091.1)	12,310.0 (986.2)

[a] Mean values of 15 samples with standard deviations in parentheses.

One-way ANOVA analysis was performed to determine the differences between the bonding strengths of the finger-jointed samples. The SPSS 12.0 program was used to investigate the effects of PVAc adhesive class, finger length, and orientation of finger joint on the bonding strength of the finger-jointed samples.

RESULTS AND DISCUSSION

Unsteamed Beech wood

Mean values of the bending strength properties measured on the unsteamed beech wood are given in Table I. The average density of the specimens was 0.605 g/cm^3 (SD 0.052), and the average moisture content was 10.1% (SD 0.171%).

The bending strength (MOR) of the tested specimens fluctuated from 33.51 to 82.24 N/mm^2 and was affected by the type of adhesive (D1, D2, D3), the finger length (4 and 10 mm), and the orientation of the finger joints (horizontal and vertical). Higher percentages compared to those for solid wood appeared in specimens with a 10-mm length with D3 adhesive class (75.7% in horizontal and 72.3% in vertical fingers).

Table I and Figure 2 show that MOR was affected by the PVAc adhesive class. Specimens bonded with D3 adhesive class showed a higher MOR values (from 59.9 to 82.24 N/mm^2), and specimens bonded with D1 adhesive class showed the lowest values (from 33.51 to 52.51 N/mm^2), and specimens bonded with D2 adhesive class showed intermediate values (from 53.12 to 65.2 N/mm^2).

For specimens with a 10-mm finger length, the increase in MOR from changing the adhesive class from D1 to D2 ranged from 19.5% to 42.7%. Correspondingly, the increase in MOR by changing the class of adhesive from D2 to D3 ranged from 7.6% to 18.6%. For specimens with a 4-mm finger length the increase in MOR by changing the class of adhesive from D1 to D2 ranged from 35.3% to 45.4%. Corre-

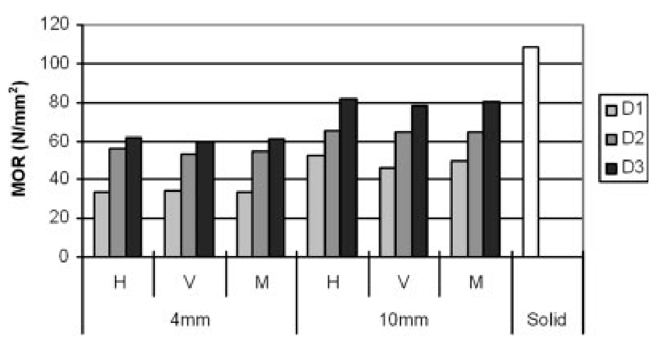

Figure 2 Effect of PVAc adhesive class on MOR of unsteamed beech wood (H, horizontal; V, vertical; M, without orientation of fingers).

TABLE II
Bending Strength Properties of Finger-Jointed Steamed Beech Wood

Bending strength (N/mm^2)	Solid wood	Finger length (mm) 4, PVAc category D1	4, D2	4, D3	10, D1	10, D2	10, D3
Horizontal fingers							
MOR	106.81 (7.38)[a]	36.53 (3.86)	66.89 (6.39)	71.52 (5.08)	46.11 (3.38)	73.96 (5.66)	80.27 (5.92)
MOE	11163.8 (1246.6)	11,734.0 (848.3)	11,855.0 (994.3)	11,468.0 (714.7)	12,864.0 (1392.6)	12,306.0 (1369.2)	11,382.0 (1063.7)
Vertical fingers							
MOR		34.90 (4.44)	60.49 (4.58)	68.98 (5.00)	41.78 (4.20)	72.89 (6.37)	78.65 (5.38)
MOE		10,963.0 (1161.9)	12,197.0 (1085.8)	11,140.0 (1085.0)	11,872.0 (1127.1)	11,978.0 (1189.8)	11,517.0 (966.4)

[a] Mean values of 15 samples with standard deviations in parentheses.

spondingly, the increase in MOR by changing the class of adhesive from D2 to D3 ranged from 6.5% to 12.3%.

From these results we concluded that the D1 class of PVAc adhesives was not very effective in the adhesion of unsteamed beech wood specimens relative to the D2 and D3 adhesives. Although the bonding mechanisms of PVAc adhesives are still not fully understood, this may be attributed to the different active or functional groups of the PVAc adhesive durability classes.

In all cases, specimens with a 10-mm finger length showed MOR values than did specimens with a 4-mm finger length. The increase ranged from 16.4% in specimens bonded with D2 adhesive to 56.7% in specimens bonded with D1 adhesive.

Also, it was found that in most cases the horizontal fingers had about 5% higher MOR values than the vertical fingers except for specimens with a 4-mm finger length bonded with a D1 class adhesive.

As Table I shows, the modulus of elasticity (MOE) of the tested specimens ranged from 10,400.0 to 12,310.0 N/mm^2 in specimens with a 10-mm finger length bonded with D2 and D3 class adhesives, respectively. From these results it was concluded that finger jointing of the unsteamed beech wood did not affect the MOE of the tested specimens in a distinct manner, which was in the same range as that of the control solid wood (11,643.0 N/mm^2). This conclusion was confirmed by the results of Pena for unsteamed finger-jointed beech wood.[5]

Steamed beech wood

The corresponding mean values of the bending strength properties measured on the steamed beech wood are given in Table II. The average density of the specimens was 0.595 g/cm^3 (SD 0.022), and the average moisture content was 10.4% (SD 0.235%).

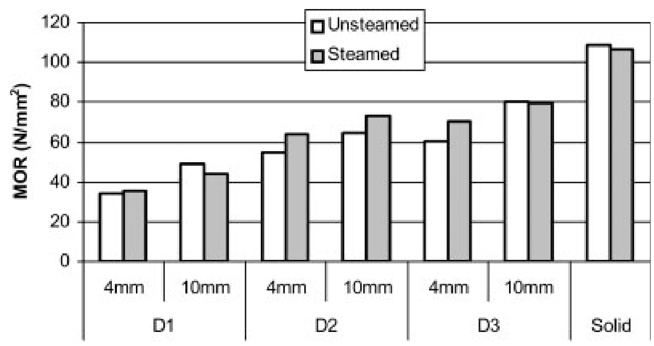

Figure 3 Effect of handling of material (steamed–unsteamed) on MOR of finger-jointed beech wood (D1, D2, and D3 are durability classes of PVAc adhesive).

The bending strength (MOR) of the steamed tested specimens fluctuated from 34.9 to 80.27 N/mm^2 and was affected by the same factors as the unsteamed specimens (PVAc adhesive class, finger length, finger joint orientation). Specimens 10 mm in length with D3 adhesive had higher values (75.1% in horizontal fingers and 73.6% in vertical fingers) compared to the solid wood.

Tables I and II show that in most cases the steamed-wood specimens had higher mean MOR values than the unsteamed wood specimens (Fig. 3). This was attributed to the better bonding performance of the steamed beech wood because of its lower extractive content in comparison to the unsteamed beech wood.

For specimens with a 10-mm finger length, the increase in MOR from chaning the adhesive class from D1 to D2 ranged from 60.4% to 74.5%. Correspondingly, the increase in MOR from changing the adhesive class from D2 to D3 ranged from 7.9% to 8.5%. For specimens with a 4-mm finger length, the increase in MOR from changing the class of adhesive from D1 to D2 ranged from 73.3% to 83.1%. Correspondingly, the increase in MOR from changing the class of adhesive from D2 to D3 ranged from 6.9% to 14.0% (Fig. 4).

From these results we also concluded that the D1 class of PVAc adhesive had very low effectiveness in the adhesion of steamed beech wood specimens relative to the D2 and D3 adhesive classes.

In all cases, specimens with a 10-mm finger length had higher MOR values than specimens with a 4-mm finger length (Fig. 4). The increase ranged from 10.6% in specimens bonded with D2 adhesive class to 26.2% in specimens bonded with D1 adhesive class. Also, it was found that, in all cases the horizontal fingers had higher MOR values (an average of about 5.5%) than the vertical fingers.

As can be seen in Table II, the modulus of elasticity (MOE) of the tested steamed specimens in most cases appeared to be slightly higher (mean of about 5.4%) than the corresponding MOE of the control solid wood (11,163.3 N/mm^2) and ranged from 10,963.0 to 12,864.0 N/mm^2 in specimens with 4- and 10-mm finger length bonded with D1 adhesive class, respectively. From these results it was concluded that finger jointing of the steamed beech wood resulted in the tested specimens having a slightly higher MOE.

Analysis of variance of the mean bonding strength with the Tamhane test showed significant differences in bonding strength in most cases. PVAc adhesive class and finger length had a statistically significant effect on the MOR of the finger-jointed steamed and unsteamed samples at the 0.05 significance level, whereas the MOE of the finger-jointed samples was not affected significantly by PVAc adhesive class and finger length.

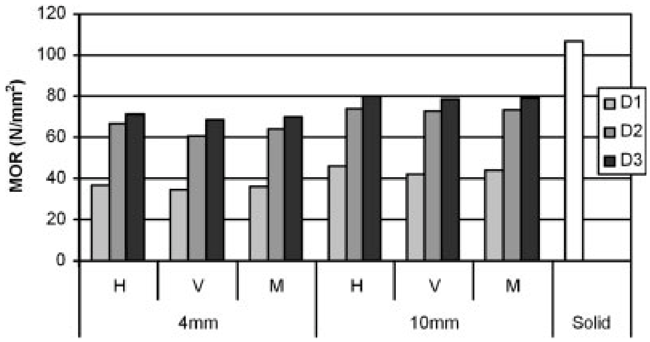

Figure 4 Effect of PVAc adhesive class on MOR of steamed beech wood (H, horizontal; V, vertical; M, without orientation of fingers).

CONCLUSIONS

Beech wood has very good potential in finger-jointed nonstructural uses. It is used mainly steamed but also unsteamed wood in many furniture applications. Within the range of parameters studied, the bending strength (MOR) of the finger-jointed beech wood was affected by the type of PVAc adhesive (durability classes D1, D2, and D3), finger length (4 and 10 mm), orientation of the finger joints (horizontal, vertical), and handling of the beech wood (steamed, unsteamed).

Specimens bonded with a D3 class adhesive showed the highest MOR values, specimens bonded with D1 class adhesive showed the lowest MOR values, and specimens bonded with D2 class adhesive showed intermediate MOR values. Specimens with a 10-mm finger length showed higher MOR values than specimens with a 4-mm finger length. The MOR was affected by the orientation of the fingers. Specimens with horizontal fingers appeared to have higher MOR values than specimens with vertical fingers. In most cases, the steamed wood specimens had higher MOR values than the unsteamed specimens. The MOE was affected by the handling (steamed, unsteamed) of the wood. The MOE of the steamed specimens increased slightly (by 5.4%) compared to the control solid wood. The MOE values of the unsteamed specimens were approximately the same as those of the control solid wood.

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