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Mechanical Properties of Finger-Jointed Wood from Composite Utility Poles Made of Small Diameter Timber

Mehanička svojstva zupčasto spojenog drva od kompozitnih stupova proizvedenih od tanke oblovine

Preliminary paper – Prethodno priopćenje
Received – prispjelo: 21. 10. 2014.
Accepted – prihvaćeno: 29. 1. 2016.
*UDK: 630*812.7; 630*824.113*
doi:10.5552/drind.2016.1436

ABSTRACT • *Engineering small diameter timber into structural members may provide an efficient way to utilize low-value material obtained after forest thinning operations. This study evaluates the strength and stiffness properties of finger-jointed and solid wood small clear samples cut from composite poles made of small diameter timber. The strength and stiffness of finger-jointed small clear samples were compared with the strength and stiffness of solid wood small clear samples and the strength and stiffness of composite poles. Finger-jointed samples tested in a perpendicular orientation, yielded the lowest bending strength but were not significantly lower than samples tested in a parallel orientation. Therefore, finger joint orientation was not a significant factor regarding the strength of the poles. The bending strength of composite poles was usually lower than the strength of the solid wood samples but higher than the strength of finger-jointed samples cut from the poles. However, the bending stiffness of the composite poles was substantially higher than the bending stiffness of both solid wood and finger-jointed samples cut from the poles.*

Key words: *bamboo, finger-joints, poles, small diameter timber*

SAŽETAK • *Prerada tanke oblovine u konstrukcijske elemente može biti učinkovit način iskorištavanja oblovine niske vrijednosti dobivene nakon operacije prorjeđivanja šuma. U ovoj studiji procjenjuju se čvrstoća i krutost uzoraka drva sa zupčastim spojem i uzoraka cjelovitog drva od kompozitnih stupova proizvedenih od tanke oblovine. Čvrstoća i krutost malih uzoraka drva sa zupčastim spojem uspoređena je s čvrstoćom i krutošću malih uzoraka od cjelovitog drva te s čvrstoćom i krutošću kompozitnih stupova. Uzorci sa zupčastim spojem opterećeni okomito na spoj imali su najmanju čvrstoću na savijanje, no čvrstoća im nije bila znatno manja od čvrstoće uzoraka sa zupčastim spojem opterećenih paralelno sa spojem. Dakle, orijentacija zupčastog spoja nije bio važan činitelj čvrstoće stupova. Čvrstoća savijanja kompozitnih stupova uglavnom je bila manja od čvrstoće uzoraka od cjelovitog drva ali je bila veća od čvrstoće uzoraka drva sa zupčastim spojem izrađenih od kompozitnih stupova. Međutim, krutost kompozitnih stupova bila je znatno veća od krutosti uzoraka od cjelovitog drva, kao i uzoraka sa zupčastim spojem izrađenih od kompozitnih stupova.*

Ključne riječi: *drvo bambusa, zupčasti spoj, stupovi, tanka oblovina*

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1 INTRODUCTION
1. UVOD

Wildfires and forest diseases and insects are major threats to a forest. Studies have shown that silvicultural techniques such as thinning offer the most promising and long-lasting means of preventing insect attacks (Nebeker *et al*., 1985). Catastrophic wildfires have also created an incentive to manage forest fuel loading and restore healthy forests via the removal of bio-fuels by thinning operations. The restoration to a healthy forest and the minimization of forest wildfires both require thinning of overstocked forests. As a result, an ample supply of small-diameter timber (SDT) will continue for the foreseeable future.

The current processing options for using SDT for value-added products, however, are limited. Most SDT produced in the southeastern U.S. is used as feedstock for the production of oriented strand board or pulp and paper (Hodges *et al*., 2005). According to Wolfe (2000), the value of roundwood from SDT can be twice that in the square form, and nine times that of wood chips. Round timber has less strength variability and more mature wood in the surface rings. Therefore, engineering SDT into structural members may greatly improve the value of SDT and its utilization efficiency.

In a previous report, we have evaluated a novel technique for making laminated utility poles using SDT (Piao *et al*., 2015). Eight laminated utility poles, each consisting of four tapered round logs, were fabricated. Each round log was finger-jointed together by round segments made from southern pine (*Pinus* spp.) SDT. The eight laminated utility poles along with three commercial solid wood poles were mechanically tested in a cantilever mode. In this report, finger joint samples and solid wood samples were cut from seven of the eight laminated utility poles. The mechanical properties of roundwood finger joints were not found in the literature. The objective of this study was to determine the strength and stiffness of finger joints along each pole and compare these values with the strength and stiffness of solid wood next to the finger joints in the poles.

2 MATERIALS AND METHODS
2. MATERIJAL I METODE

The fabrication details of laminated utility poles is described in Piao *et al*., (2014) and is briefly described below. A total of three hundred and fifty-six small-diameter, southern pine (*Pinus* spp.) logs were collected for an on-going series of studies. Logs were collected during thinning operations conducted in typical southern pine plantation forests. The butt diameters of the logs ranged from 3.6 to 12.8 cm. All logs were approximately 12.2 m in length. After harvest, the logs were air dried in sheds for six months to an approximate equilibrium moisture content of 19 %. After air drying, each log was manually debarked. Each debarked log was visually marked off and cut into several (straight) segments. Each log segment was shaved into a tapered, round segment using a 2.4-m, heavy-duty wood lathe.

A heavy-duty, finger-joint shaper was used to cut finger joints into the shaved log segments at one or both ends of each segment. The cutter of the shaper contained 15, two-wing, cutter blades. Each cutter blade had a tip angle of 10.7 degrees. The length, tip thickness, and pitch length of the blades measured 28, 1.588, and 7.938 mm, respectively. All finger joints at one end of each log segment were cut in one pass through the cutter.

Tapered, finger-jointed logs were fabricated using shaved segments of decreasing circumferences (from bottom to top). Segments were consolidated into a tapered, finger-jointed log in a 12.2-m long finger-joint press using a resorcinol phenol formaldehyde resin at 506 g/m^2. Each finger-jointed, tapered, roundwood log had a butt-end diameter of 15.5 cm and a length of either 9.1 or 9.6 m at test. The taper of all finger-jointed logs was 2.3 degrees, which equals the standard pole log taper required by the American National Standard Institute (ANSI) (ANSI, 2008).

Thirty six tapered, finger-jointed segmented logs were made. Nine laminated utility poles, each consisting of four of the finger-jointed logs, were fabricated and tested. Six of the nine were reinforced with bamboo strips, while three were not. Locations of the finger joints in the segmented logs were different for the four logs comprising a laminated utility pole, so that at most one finger joint would appear in any cross section of a laminated utility pole (Figure 1). Data categorized by finger joint location is not presented in this paper because an insufficient number of test samples could be obtained from upper locations in the pole due to taper.

Of the four finger-jointed logs comprising a laminated utility pole, three of the logs consisted of five finger-jointed segments, while one log consisted of four finger-jointed segments. The minimum distance between finger joints on two logs comprising a side surface of a laminated utility pole was 0.6 m.

To construct all laminated utility poles, two adjacent flat surfaces were cut into each finger-jointed, tapered log using a portable bandmill. After the first flat

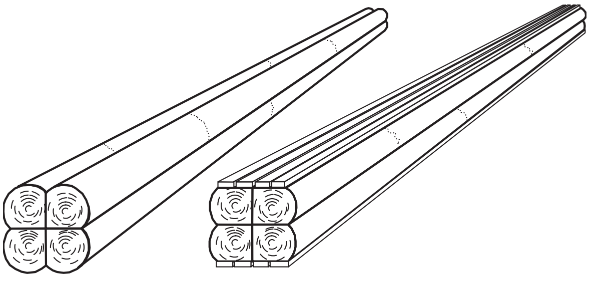

Figure 1 Schematic diagrams of laminated utility poles made from small-diameter timber: (a) depicts an unreinforced utility pole and (b) portrays a pole reinforced by bamboo strips on the top and bottom surfaces

Slika 1. Shematski prikaz lameliranih stupova proizvedenih od tanke oblovine: (a) nacrtan je nearmirani kompozitni stup i (b) prikazan je stup ojačan bambusovim trakama na gornjoj i donjoj površini

Table 1 Number of solid wood (A and C) and finger joint (B) bending samples obtained from laminated composite poles made of small diameter timber
Table 1. Broj uzoraka cjelovitog drva (A i C) i uzoraka sa zupčastim spojem (B) izrađenih od lameliranih kompozitnih stupova proizvedenih od tanke oblovine

Pole# / *Stup*	A and/or C	B
1	62	57
2	67	66
3	62	58
4	14	15
5	26	23
6	49	31
7	17	15

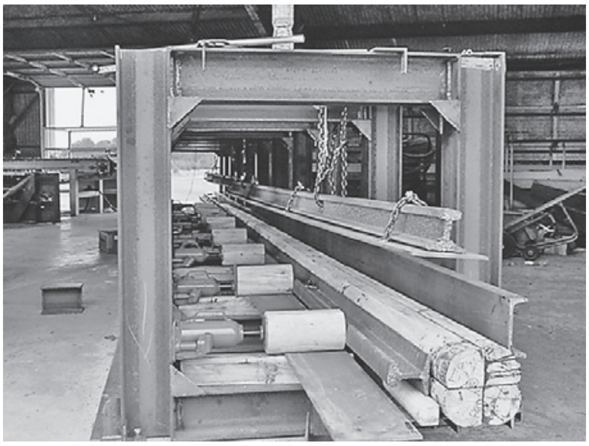

Figure 2 Cold press used to assemble laminated poles
Slika 2. Hladna preša za sastavljanje lameliranih stupova

surface was cut, each log was turned 90 degrees, and the second flat surface was cut. One additional flat surface was cut into each of the four finger-jointed logs that were to form a bamboo reinforced laminated utility pole. Before gluing, the flat surfaces of each log were sanded using a hand-held sander equipped with 100-grit sandpaper. This removed the saw-blade marks and smoothed the surfaces.

Using a roller spreader, the same type resorcinol formaldehyde resin that was used to glue the finger joints together was applied evenly to the two flat surfaces of each of the four logs that were to be pressed into an unreinforced laminated utility pole. These four glued pole logs were assembled and consolidated into a single unreinforced pole in a cold press (Figure 2).

Of the seven composite poles elected for finger joint test in this study, Poles 1 to 3 were made of wood only (without bamboo strip reinforcement), while Poles 4 to 7 were reinforced with bamboo strips. As shown in Table 1, Poles 1 to 3 produced more bending samples (finger-jointed and solid wood) than Poles 4 to 7. Since some materials were removed from the logs cut from bamboo strip-reinforced Poles 4 to 7, they usually produced less finger joint and solid wood samples than the composite poles without bamboo strip reinforcement. In addition to bamboo reinforcement, the number of bending samples obtained from each pole is also dependent on the diameter of the finger joint logs in the poles, and the failure locations and taper of the poles in the bending tests. Therefore, there is substantial variation in the number of bending samples obtained from the seven composite poles.

A finger joint in a log usually consisted of two log sections obtained from different trees. As a result, the strengths of the two pieces of wood consisting of a finger joint sample are usually different. To correct for the difference, solid wood samples were removed from the segments on both sides of a finger-jointed segment and were used as a control in the strength analysis of the finger joint.

After testing the poles in a cantilever fashion in accordance with ASTM D 1036-1999 (ASTM, 1999), Poles 1 to 7 were used to measure the finger joint strength of the poles. Each selected laminated pole was split along the glue lines of the pole into four finger-jointed pieces (Figure 3). Solid wood and finger joint bending samples from these logs were obtained as follows. A 1.3m segment was marked off at each finger-joint location along the entire length of each finger-jointed log with the finger joint being located at the midpoint of the segment. The segment location in a finger-jointed log (1 to 5 from the bottom to the top) was labeled. After removal, each 1.3m segment was cut into three 42 cm sections, which were labeled as Segments A, B, and C, respectively, in Figure 4. Segment B, which contained a finger joint in the middle, was used to measure the strength and stiffness of the finger joint, while Segments A and C were used to measure the strength and stiffness of solid wood (without joints). The failure modes of all samples were recorded and will be reported in a separate manuscript.

Bending samples 46 cm long by 2.5 cm wide by 2.5 cm thick were then cut from Segments A, B, and C. Each segment was first cut into 2.5 cm thick boards. Each board was trimmed to remove any curved surfaces (obtain true shaped boards for the bending samples). Two to five contiguous bending samples were removed from the board, depending on the width of the board. Samples having defects in the wood, such as splits and knots in the middle of the samples, were discarded. The total number of usable bending samples obtained from each composite pole is summarized in Table 1. All test variables and their levels are shown in Table 2.

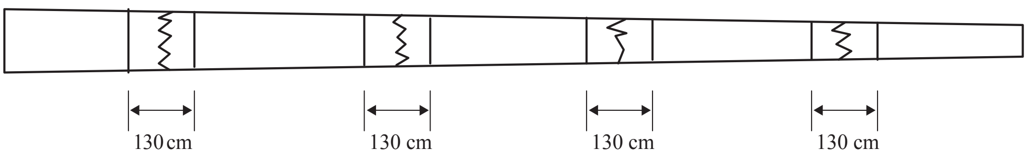

Figure 3 Diagram of an individual finger-jointed log (one of four) removed from the pole
Slika 3. Skica zupčasto spojene drvene grede (jedne od četiri) izdvojene iz stupa

Table 2 Test variables and their levels
Tablica 2. Varijable testa i njihove razine

Variables *Varijable*	**Number of laminated poles fabricated**[1] *Broj proizvedenih lameliranih stupova*	**Sample sections in each pole**[1] *Sekcije uzoraka u svakom stupu*	**Loading directions**[2] *Smjer opterećenja*
Levels / *Razine*	7	4	2

[1] Sections from 1 (bottom section) to 4 (top section) / *Sekcije od 1. (donja sekcija) do 4. (gornja sekcija)*. [2] Perpendicular and parallel / *Okomito i paralelno*.

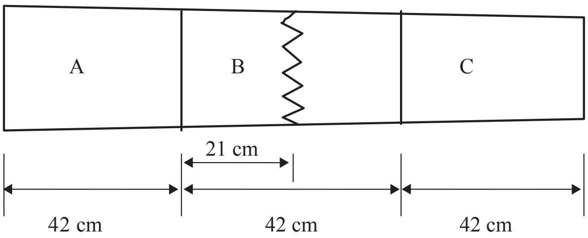

Figure 4 Cutting plan for samples A and C (solid wood) and B (with finger joint)
Slika 4. Plan izrade uzoraka A i C (cjelovito drvo) te uzorka B (sa zupčastim spojem)

Prior to bending testing, samples were conditioned in an air-conditioned room maintained at 21 °C for 5 weeks. The annual growth rings were counted on both ends of each finger joint sample. Of the two ring counts obtained from both ends of a finger joint or a solid wood sample, the mean value was used as the number of annual growth rings of the sample. Of all the finger joint samples obtained in a pole, half of the samples were loaded with the cross head parallel to the joint fingers (hereafter referred to as parallel orientation) and the other half were loaded with the cross head perpendicular to the joint fingers (hereafter referred to as perpendicular orientation). All samples were tested in static bending and loaded to failure on an Instron testing machine according to ASTM D143-94 (ASTM, 1994). All samples were loaded continuously throughout the test at a movable crosshead rate of 1.3 mm/min on a 360 mm loading span.

After testing, a 2.5 cm section was immediately cut from each sample near the point of failure and was used for moisture content (MC) measurement. The section was weighed and then put in an oven at 103±2 °C for 24 h. Each section was weighed again after drying, and the MC of each sample tested was calculated. The density at the time of testing was determined.

In the data analysis, the strength and stiffness of the small clear samples cut from segments A and C (Figure 4) were pooled and their strength average was used as the solid wood control to the strength of finger joint samples obtained from Segment B. Analysis of variance (ANOVA) was adopted to analyze the bending strength and stiffness data using Model 1 given below,

$$\text{Model 1: } y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ijk} + \varepsilon \qquad (1)$$

where y_{ijk} denotes MOR/MOE, μ is the overall mean, α_i is an effect due to poles, β_j is an effect due to sections where the samples were cut, γ_k is an effect due to loading directions, $\alpha\beta\gamma_{ijk}$ is an effect due to the interaction between blade profile and joint orientation, and ε_{ijk} is the random residual error. Analyses were carried out using the GLM procedure of the SAS software computing system (SAS 2010). A significance level of 0.05 was used for each statistical analysis.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Numeric values for density, growth ring counts, MC at test, and moduli of rupture (MOR) of the finger joint and solid wood samples tested in this study are given in Table 3, while the moduli of elasticity (MOE) of the samples are given in Table 4. Also enclosed in Tables 3 and 4 are the MOR and MOE averages, respectively, for the composite poles from which the finger joint and solid wood samples were cut. The MOR and MOE values of laminated composites poles in Tables 3 and 4 were obtained from a previous study (Piao *et al*., 2013). Except for Composite Poles 2 and 5, the

Table 3 Physical properties and bending strength (MOR) of finger joints and solid wood cut from small-diameter timber laminated utility poles
Tablica 3. Fizikalna svojstva i čvrstoća savijanja (MOR) uzoraka sa zupčastim spojem i uzoraka cjelovitog drva izrađenih od lameliranih stupova od tanke oblovine

Pole# *Stup*	**Density** *Gustoća*	**Ring count average** *Prosječan broj godova*	**MC** *Sadržaj vode*	**MOR of small clear samples** *MOR malih uzoraka*			**MOR of composite poles** *MOR kompozitnih stupova*
				Test direction / *Smjer opterećenja*		Solid wood *Cjelovito drvo*	
				Parallel *Paralelno*	Perpen-dicular *Okomito*		
	g/cm^3	rings/cm	%	MPa	MPa	MPa	MPa
1	0.40	2.57	9.6	32.7	31.9	40.9	31.8
2	0.48	3.00	10.3	42.7	40.0	51.1	53.1
3	0.45	2.45	10.2	39.0	38.2	50.9	45.9
4	0.45	3.83	10.1	30.5	30.9	39.1	38.0
5	0.46	3.63	10.4	26.9	30.3	31.7	39.3
6	0.48	3.18	11.3	39.3	30.7	40.0	38.7
7	0.46	3.66	11.1	38.7	26.1	39.5	38.6

Table 4 Physical properties and bending stiffness (MOE) of finger joints and solid wood cut from small-diameter timber laminated utility poles
Tablica 4. Fizikalna svojstva i modul elastičnosti (MOE) uzoraka sa zupčastim spojem i uzoraka cjelovitog drva izrađenih od lameliranih stupova od tanke oblovine

Pole# *Stup*	**MOE of small clear samples** / *MOE malih uzoraka*			**MOE of composite poles** *MOE kompozitnih stupova*
	Test direction / *Smjer opterećenja*		Solid wood *Cjelovito drvo*	
	Parallel / *Paralelno*	Perpendicular / *Okomito*		
	GPa	GPa	GPa	GPa
1	5.76	5.93	4.88	8.87
2	6.94	6.50	5.61	17.27
3	6.86	6.95	5.67	11.96
4	7.49	6.12	6.15	9.32
5	6.38	5.68	6.14	12.01
6	7.38	6.74	6.29	11.17
7	7.11	6.20	6.58	11.11

bending strength averages of composite poles were lower than the bending strength averages of small clear solid wood samples cut from these poles. However, except for Composite Pole 1, the bending strength averages of composite poles were higher than the bending strength averages of finger joints in the poles, regardless of finger joint orientations (parallel or perpendicular) in the test. These results indicate favorable strength of a composite pole that is made of finger-jointed small diameter timber.

As expected, of all the seven composite poles tested in this study, the solid wood samples gave significantly higher ($p =< 0.0001$) bending strength than finger-jointed samples, regardless of finger joint orientations in the test (Table 3). The bending strength averages of finger joints tested in the parallel orientation, finger joints tested in the perpendicular orientation, and solid wood samples were 36.1, 32.8, and 42.3 MPa, respectively. Finger-jointed samples tested in the perpendicular orientation (32.6 MPa) yielded the lowest bending strength but were not significantly lower ($p = 0.0939$) than samples tested in the parallel orientation (36.1 MPa). The strength of the finger joints ranged from 26.9 MPa to 42.7 MPa when tested in the parallel orientation and 26.1 MPa to 40.0 MPa when tested in the perpendicular orientation (Table 3). Standard deviations were used instead of range of values. The ANOVA showed that both the pole effect and test orientation significantly affected ($p =< 0.0001$) MOR. The effect of section locations of finger joints along the poles was not significant ($p = 0.1726$). There was no significant difference for MOR among the finger joint locations.

It is important to know the strength of finger joints as compared to the strength of solid wood. Table 5 shows the strength percentages of finger joints to solid wood in both orientations. Of the seven poles tested in this study, the strength of finger joints in the parallel orientation was 76.6 to 97.8 percent of the strength of solid wood, while the percentages were 66.1 to 95.5 for finger joints in the perpendicular orientation. The strength averages for parallel and perpendicular orientations were 85.6 and 78.4 percent of the strength of solid wood samples, respectively. The overall strength percentage of finger joints (both orientations) to solid wood was 82.0.

The MOE results of the poles are presented in Table 4. The ANOVA found that pole and test direction main effects were marginally significant ($p = 0.0390$ and 0.0206, respectively). The MOE for solid wood was lower than parallel jointed MOE ($p = 0.0057$). Table 4 also shows that the MOE of composite poles was substantially higher than the MOE of small clear samples, regardless of finger jointing or not. This is partly attributable to the resorcinol phenol formaldehyde (RPF) resin used in this study. In the jointing of both composite poles and finger joints, RPF was used as resin to bond wood members together. The cured RPF resin usually has a higher stiffness that the wood used in the study (Piao *et al*., 2005). The MOE did not significantly vary based on pole locations in the finger-

Table 5 Percentages of finger joint MOR as compared to the MOR of solid wood. Both finger joint and solid wood samples were cut from small-diameter timber laminated utility poles
Tablica 5. Postotak vrijednosti čvrstoće savijanja (MOR) uzoraka drva sa zupčastim spojem u odnosu prema čvrstoći savijanja uzoraka od cjelovitog drva; obje vrste uzoraka izrezane su od lameliranih stupova izrađenih od tanke oblovine

Pole# *Stup*	**Parallel** / *Paralelno* %	**Perpendicular** / *Okomito* %	**Pole main effects** / *Utjecaj na čvrstoću stupa* %
1	79.9	77.9	78.9
2	83.5	78.2	80.9
3	76.6	75.1	75.8
4	78.1	79.1	78.6
5	84.7	95.5	90.1
6	98.4	76.7	87.6
7	97.8	66.1	82.0
Joint main effects *Zajednički učinak*	85.6	78.4	82.0

jointed logs ($p = 0.2054$). In addition, these differences can be partly attributable to the addition of the bamboo strips on the composite poles, which enhanced strength properties over poles without bamboo strips. Finally, due to the well known pattern of increased density from pith to bark in southern pine trees, the poles contained the highest density on the surface, which is critical because the surface properties are essential for determining the overall strength and stiffness of any member under static loading.

4 CONCLUSION
4. ZAKLJUČAK

Finger-jointed and solid wood small clear samples cut from seven composite utility poles were evaluated for their strength and stiffness properties. The strength and stiffness of the finger-jointed small clear samples were compared with those of small clear solid wood samples and those of composite poles made of small diameter timber. The bending strength of composite poles was less than the strength of the solid wood samples but greater than the strength of finger-jointed samples cut from the poles. However, the bending stiffness of the composite poles was substantially higher than the bending stiffness of both solid wood and finger-jointed samples cut from the poles primarily due to a number of factors including the RPF resin that was used to bond finger joints and finger-jointed logs in the poles, inclusion of bamboo strip reinforcement of the poles, and a likely higher percentage of mature wood in the poles as in the small test samples. Finger-jointed samples tested in a perpendicular orientation yielded the lowest bending strength but were not significantly lower than samples tested in a parallel orientation, indicating that joint orientation was not an important issue regarding the strength of the poles. The strength averages for parallel and perpendicular orientations were 85.6 and 78.4 percent of the strength of solid wood samples, respectively. The overall strength percentage of finger joints (both orientations) to solid wood was 82.0. This study has demonstrated that small diameter timber can potentially be used to make finger-joint logs for the production of laminated utility poles.

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