MECHANICAL PROPERTIES OF SMALL-SCALE LAMINATED WOOD COMPOSITE POLES: EFFECTS OF TAPER AND WEBS[1]

Cheng Piao

Postdoctoral Research Associate

Todd F. Shupe†

Professor
Louisiana Forest Products Development Center
School of Renewable Natural Resources
Louisiana State University AgCenter
Baton Rouge, LA 70803

R. C. Tang†

Professor
School of Forestry & Wildlife Sciences
Auburn University
Auburn, AL 36849

and

Chung Y. Hse†

Principal Wood Scientist
USDA Forest Service
Southern Research Station
2500 Shreveport
Pineville, LA 71360

(Received February 2006)

ABSTRACT

Laminated hollow wood composite poles represent an efficient utilization of the timber resource and a promising alternative for solid wood poles that are commonly used in the power transmission and telecommunication lines. The objective of this study was to improve the performance of composite poles by introducing the bio-mimicry concept into the design of hollow wood composite poles. Five laminated hollow wood composite poles with taper and plywood-made webs, acting like the nodes in the bamboo, were made and tested in cantilevered static bending. Results indicated that node-like webs had a positive effect on the integrity, static bending properties, and shear resistance of the members tested, and their strength performance is comparable to that of the solid wood composite poles. However, the laminated hollow wood composite poles with taper showed slightly lower resistance to horizontal shear as compared to the members without taper.

Keywords: Cantilevered static bending, mechanical properties, taper, wood poles.

INTRODUCTION

The growth of electric power and telecommunications industries in North America during the later part of the 19[th] century and in the 20[th] century has been phenomenal. Approximately 160 to 170 million preservative-treated solid wood poles are currently in service in the United States (Bratkovich 2002), and both power and telecommunication companies consume about 2 million preservative-treated poles in construction of new lines annually. Furthermore, approximately two million poles in the US are required annually for use in replacing the poles

† Member of SWST.

[1] This paper (940-40-0678) is published with the approval of the Director of the Louisiana Agricultural Experiment Station.

that failed in service due to decay, termite attack, and hurricane/storm, and/or mechanical damage (Cooper 1996). Because of the ever-increasing population and demand for wood and lumber/timbers, high quality tree-length logs suitable for transmission and distribution poles are becoming scarce and more costly.

According to American National Standards Institute (ANSI), wooden utility poles are grouped into nine classes (Class 1–10 excluding Class 8) based on the wood species, dimensions [i.e., length of pole (ft), minimum circumference (in.) at 6 ft from the butt and top], breaking load under cantilevered bending, and their fiber stress level (ANSI 2002). For example, in the southern pine poles group, a 20-ft [6.1-m]-long Class 1 pole must have at least 31 in. and 27 in. [78.74 cm and 68.58 cm], respectively, in circumference at 6 ft from the butt and at the top (i.e., 9.87-in. and 8.59-in. [25.07-cm and 21.82-cm] diameter) while the requirements for an identical length Class 10 pole are only 14 in. and 12 in. in circumference at 6 ft from the butt and at the top (i.e., 4.46-in. and 3.82-in. [11.33-cm and 9.70-cm] diameter), respectively. Large-size wood poles (e.g., 50 ft [15.24 m] or longer Class 1–3) are commonly used in the high voltage transmission lines with heavy and large diameter conductors. For example, the minimum diameter requirements for a 70-ft [21.34-m] Class 1 southern pine pole are 16.23 in. (41.22 cm) at the position 6 ft to the butt and 8.59 in. (21.82 cm) at the top. However, for the power distribution and telecommunication lines, 50-ft [15.24-m] or less Class 4/5 poles and 35-ft [10.67-m] or less Class 6/7 poles, respectively, are commonly used and their dimensions are much smaller than that of Class 1–3. For example, the minimum diameter requirements for a 40-ft [12.19-m] Class 5 southern pine pole are 10.66 in. and 6.68 in. [27.08 cm and 16.97 cm], at the position 6 ft to the butt and at the top, respectively, while the corresponding values for a 30-ft [9.14-m] Class 6 pole would be 7.96 in. and 5.41 in. [20.22 cm and 13.74 cm], respectively. Due to an emphasis of short-rotation plantation forests in the last few decades, the availability of these long and large diameter tree-length southern pine logs has severely diminished. Thus, in recent years, the wood pole industry has been faced with the challenges of losing its share of the utility pole markets, and concurrently the power and telecommunication industries have tried to find satisfactory substitutes for preservative-treated solid wood poles.

During the last four decades, many approaches have been investigated for an alternative to solid wood poles and various composite poles have been developed for this purpose (e.g., glulam poles (Hockaday 1975; McKain 1975); mechanical-fastened wood composite poles (Marzouk et al. 1978); pressed wood flake poles (Adams et al. 1981); reinforced plastics jacketed (RPJ) composite poles (Tang and Adams 1973); hollow veneered poles (HVP) (Erickson 1994, 1995); and thin-wall LVL cylinder (Sasaki et al. 1996). More recently, the Louisiana Forest Products Development Center at the Louisiana State University Agricultural Center, the School of Forestry and Wildlife Sciences at Auburn University, and the USDA Forest Service, Southern Research Station have jointly conducted research on the design and development of laminated hollow wood composite poles with a uniform diameter, as another potential alternative for solid wood poles currently used in power distribution and telecommunication lines (Piao et al. 2004, 2005). Results from the tests of small-scale hollow members (i.e., a tube-type design) subjected to a cantilevered bending showed that shear failure was the main failure mode (Piao et al. 2004). This is due to the fact that the removal of material from the center will reduce the shear capacity of the composite poles. In order to minimize the shear failure, concepts for increasing the shear resistance of wood composite poles while still retaining the tube-type design for lightweight and structural performance, taper and node-like plywood webs for reinforcement were considered for the new design of laminated hollow wood composite poles. In this regard, the concept of the biomimicry of the bamboo nodal structure was incorporated within the design for the next generation of laminated hollow wood composite poles under consideration for this study.

It is well known worldwide that bamboo is a superior naturally occurring engineered material. Bamboo culms are lighter in weight than most building materials including solid wood. The structural characteristics of bamboo (i.e., high density, thin wall, nodal and hollow segments) provide it with superior mechanical properties for use as poles and beams as compared with structural-use wood. For example, results from a study of Moso bamboo by Zeng et al. (1992) revealed that its mechanical properties, including modulus of rupture in static bending, compression strength parallel-to-grain, and shear strength, are much higher than that of the longleaf pine (*Pinus palustris* Mill.) wood as reported in the USDA Wood Handbook (1999). Longleaf pine is recognized as the primary softwood species for manufacturing utility poles among the four major southern pine species (i.e. loblolly, longleaf, shortleaf, and slash) in the southern US (Koch 1972), and about 80% of wood poles used in USA are southern pine species (USDA FPL 1999).

The mechanical properties of various bamboo species have been extensively studied and reported (Janssen 1991); however, information regarding the effects of nodes on the mechanical properties of bamboo was very limited. In a study of the strength of six bamboo species, Tang (1989) reported that the strength properties of bamboo material vary with the age of bamboo, the longitudinal position of bamboo culms, and its strength, which reaches its maximum at the age of 3–5 years depending upon the species. When the specific gravity level is the same, bamboo material shows a higher bending strength than that of wood. The nodal portion of bamboo weakens the strength of bamboo materials except that of shear strength, which shows a higher value than that of the clear section of bamboo culms. Also, in a study on the effect of node on mechanical properties of bamboo materials (*Phyllostachys pubescens* and *Phyllostachys bambusoides*), Zeng et al. (1992) indicated that the static bending strength, compression strength parallel-to-grain, shear strength parallel-to-grain, tensile strength parallel-to-grain, and toughness in impact bending of the strip-type bamboo specimens (bamboo strips cut from bamboo culms) with a node tend to be less than that of those without a node. However, the cleavage strength and tensile strength perpendicular-to-grain markedly increased in the tube-type specimens (bamboo culm sections) with a node at the center, but significant effect of nodes on the compressive strength parallel-to-grain was not observed. Lee et al. (1994) studied some selected mechanical properties of South Carolina grown giant timber bamboo (*Phyllostachys bambusoides*), and testing results of strip-type specimens indicated that the presence of a node greatly reduced the compressive strength parallel-to-grain, tensile strength parallel-to-grain, and the static bending strength (MOR), but only slightly affected static bending stiffness (MOE).

Since nodes increase the moment of inertia in the cross-section, they have the function of increasing bamboo's load capacity, providing resistance to shear, and reducing the lateral buckling in bending and the torsion buckling, and also improving bamboo's structural integrity. Thus, the characteristics of nodal structure in bamboo were bio-mimicked in the design of laminated tapered and hollow wood composite poles for increasing their shear resistance, lateral stability in bending, and torsional stability. The objective of this preliminary study was to assess the effects of the taper and node-like webs on the mechanical properties of laminated hollow wood composite poles subjected to a cantilevered static bending.

MATERIALS AND METHODS

Southern yellow pine (SYP: *Pinus* sp.) No. 1 dimension lumber, 3.81 cm × 13.97 cm × 2.44 m (1.5 in. × 5.5 in. × 8 ft) was obtained locally and used as the raw material for this study. The process for fabricating the engineered hollow composite poles includes ripping the lumber into trapezoid wood strips (thickness: 3 cm (1.18 in.)), applying a synthetic resin to the strips, and consolidating a number of carefully selected defect-free strips into a pole in a steel mold. The detailed procedures can be found in our previous study on the mechanical properties of small-scale wood laminated composite poles without taper (Piao et al. 2004).

Five taper and hollow composite poles were made for this study. Four of these composite poles, designated as Pole-A, -B, -D, and -E, had a hollow structure and were fabricated with 9 equal-dimension trapezoid SYP strips. Pole-A and Pole-B had a round cross-section and they were lathed to a taper of 0.3°. Pole-D and Pole-E had a 9-side polygonal cross-section with a uniform diameter (i.e., without taper) through the entire length. The 5th member was a solid pole with a taper of 0.3°, and it was made by first face-to-face gluing four pieces of 3.81-cm by 10.2-cm (1.5 in. × 4 in.) SYP No. 1 dimension lumber and then circularly shaving into a round and tapered pole by using a lathe. The node-like plywood-webs were placed only in Pole-A and -D at intervals of 61 cm (2 ft). Detailed descriptions on the parameters on the tested members are given in Table 1. Note that the 0.3° taper is slightly larger than the value specified by ANSI 05.1–2002 (ANSI 2002) to maximize the taper effect.

All fabricated poles were 2.44 m (8 ft) in length and 10.2 cm (4 in.) in circumscribed diameter, which is slightly larger than those tested in our previous study (i.e., 1.22 m (4 ft) in length and 7.6 cm (3 in.) in diameter) (Piao et al. 2004). The node-like webs designed in this study were made from a 5.72-cm (2.25-in.)-thick composite board which was fabricated with two sheets of 2.86-cm (1.126-in.)-thick, 30-cm (11.8-in.)-square 7-ply southern pine plywood by applying resorcinol phenol-formaldehyde (RPF) resin. The outside diameter as well as the shape of these 5.72-cm (2.25-in.)-thick node-like plywood-webs was carefully monitored to ensure that a tight adhesive-bond between them and the inner wall of the hollow members can be produced. Figure 1 shows a node-like web and a section of the laminated hollow wood composite pole. Plywood was used as the web material because it has more uniform and less in-plane swelling than solid SYP wood. Before the pole fabrication, all edges of the plywood-webs were wrapped with four layers of Kraft paper that was impregnated with RPF resin. These RPF resin-impregnated paper layers may work as fasteners for the plywood-webs and the pole shell so that a strong bond can be achieved. It may also seal the air chamber between any two webs to slow down the upward moisture movement in the hollow poles. This was done as a simulation of bamboo diaphragms, which completely seal the chamber of a bamboo culm. Very high moisture content [i.e., 65–75%] was observed at the butt section below the groundline of long-term field-tested full-size transmission poles laminated with reinforced plastics, but the moisture content decreased rapidly to about 20% at the groundline and further decreased to about 8–10% above the groundline (Tang 1977). Thus, it is expected that the insertion of node-like plywood-webs inside the hollow composite poles may substantially reduce the upward movement of moisture vapor inside the butt section, which is embedded in the ground for field-installation, especially when the air temperature surrounding the poles is rising.

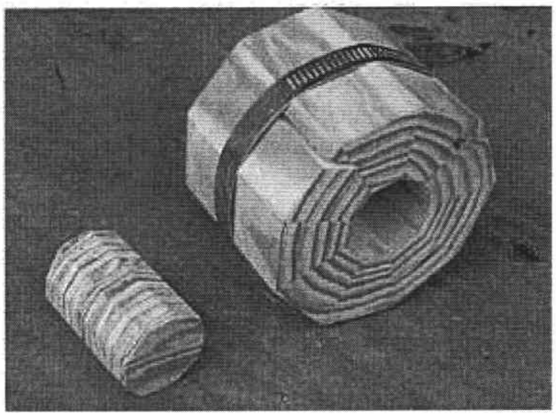

FIG. 1. A plywood-web (5.72 cm [2.25 in.] thick) and a section of the wood-laminated composite pole (diameter: 10.2 cm [4 in.]).

TABLE *Specifications of the tested wood composite poles.*

Pole #	Cross-section	Taper (°)	Plywood-webs
			Yes
			No

This hygro-thermodynamic hypothesis will be verified in our future test by using a specially designed moisture and temperature measuring device installed inside the hollow members with inserted plywood-webs.

The paper wrapped plywood-webs were placed inside the pole at intervals of 61 cm (2 ft) along its length axis and in both ends of each member. Due to the fact that the maximum stress was found to be located near the clamped line (i.e., the section below this line was clamped in the mold) in hollow composite poles when they were subjected to a cantilevered bending (Piao et al. 2005), then a thicker element bonded with three 5.72-cm (2.25-in.)-thick plywood-webs [total thickness: 17.16 cm (6.75 in.)] was placed in the clamped section of the tested poles with a hollow cross-section for reinforcing that section.

All the pole specimens were stored in an air-conditioned laboratory for two months and then tested in a cantilevered bending using a RIEHLE testing machine and a method similar to our previous study on the small-scale laminated composite poles was used (Piao et al. 2004). The butt end of each pole specimen was clamped 61 cm (2 ft) in a built steel frame. In the clamped section, the segment was tightly fastened in a cradle as specified by the ASTM standard (ASTM D1036-99) (2004). The loading cross arm of the RIEHLE applied loads to the free end of each tested pole through a steel cable and a pulley. Before testing, thin steel pins (0.2 mm in diameter) were nailed every 5.1 cm (2 in.) along the length of the pole in its neutral plane. A thin nylon line was aligned with the clamped section to a fixed steel post in front of the pole's free end such that the nylon line ran just above each of the steel pins. A digital caliper was used to measure the vertical distance, or displacement, between the nylon line and the pins after each loading of the poles.

The tests were conducted in two phases, I and II. In phase I, poles were tested in their elastic range. Each pole was loaded consecutively from 45 N (10 lbs) to 667 N (150 lbs). Displacement along the pole was recorded for each increment of 45 N loading. These data were used to calculate the stiffness (modulus of elasticity or MOE) of the poles. In phase II, all members were loaded to failure according to ASTM D 1036 (ASTM 2004) for obtaining the maximum load. After failure, the failed section in each pole tested was inspected, and failure modes and positions as well as the length of the failed section were recorded. The bending strength (modulus of rupture or MOR) and MOE of the poles tested were then calculated based on the formulas given in ASTM D1036-99 (ASTM 2004). In the calculation of MOE, the effect of shear was neglected. Shear stress was evaluated for both tapered and non-tapered poles and its value along the neutral plane at the free end of each member at failure was calculated by using the following formula (Gere and Timoshenko 1990):

$$\tau = \frac{VQ}{It}$$

where V is the shear force, Q is the first moment of the cross-section, I is the moment of inertia of the cross section, and t is the pole shell thickness at the measured section.

RESULTS AND DISCUSSION

Failure modes

As expected, Pole-A, -B, -C, -D, and -E failed in different modes under cantilever static bending. Pole-A, -C, -D, and -E failed in a normal failure mode, which displays extreme fiber failure at or close to the clamped line. Pole-B, a tapered and hollow composite pole without plywood-webs, failed at its free end in shear. The failure started from a bonding defect in the gluelines close to the neutral plane and developed into wider and deeper wood breakage toward the clamped end. The failure surfaces of the wood breakage mostly occurred in the springwood and were parallel to the wood grain of the failed strips. This failure mode was also observed in the failure of the other experimental poles. For example, extreme fiber failure was observed near the clamped line in the top 3 strips located at the tension side of Pole-A (tapered with plywood-webs). The failure surface then developed

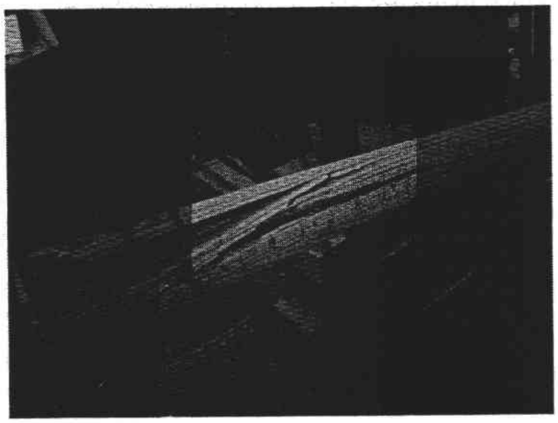

FIG. 2. The failure of a round and tapered hollow laminated composite pole with inserted node-like plywood webs when subjected to a cantilevered bending.

along the wood grain toward the free end and the bottom of the pole (Fig. 2). Table 2 shows the characteristics of failure of the five poles tested in this study. It was found that taper and/or hollow members had a longer failure zone (FZ).

Since extreme fiber failure occurred in a small section along the pole, a large portion of the FZ in each pole was observed in the springwood in the failed strips. For the tapered solid pole, which was lathed from the stock laminated with four pieces of 5-cm × 10-cm (nominal 2- by 4-in.) SYP No. 1 dimension lumber (1.5 in. × 3.5 in. × 8 ft), the failure occurred mostly in the springwood of the failed strips. As shown in Fig. 3, the failure started from a small portion of extreme fiber failure on the top surface 8.13 cm (3.2 in.) away from the clamped end. The failure cracks became wider and deeper as they developed toward the free end. There was more extreme fiber failure during the crack development, but the breakage parallel to wood surfaces dominated the FZ. The diving grains [slope of grains] and exposed juvenile may have played an important role in the failure of the poles (Wolfe and Murphy 2005). Furthermore, the depth of failure at the end of the FZ was about a quarter of the pole diameter from its top surface. The composition of the laminated solid and hollow wood composite poles may have advantages for confining the failure development and compensate for the adverse effects of juvenile wood.

As indicated in Table 2, the node-like plywood-webs prevented the propagation of wood failure because the hollow poles with webs had a shorter FZ length. Therefore, the node-like webs increased the integrity of the poles and improved the static bending performance. Certainly, these node-like plywood-webs are important for the improvement of structural performance of full-size laminated hollow wood composite poles when they are subjected to static/dynamic bending and torsion under adverse environments such as a wind-storm. Theoretically, these plywood-webs increased the section modulus of the section in which they were installed and also increased the shear capacity of those webbed sections. Therefore, the laminated hollow wood composite poles were reinforced periodically along their length by these plywood-webs, which essentially performed the same mechanical function as the nodes in the bamboo. The effects of node-like plywood-webs on the mechanical properties of laminated hollow members will be discussed in the following sections. The sizes of the node-like webs and their distributions in the laminated large-scale hollow composite poles subjected to a static/

TABLE 2. *Failure positions of laminated wood composite poles subjected to a cantilevered static bending at the free end. (Values were measured from the clamped line.)*

Pole	Composition	*Extreme fiber failure (cm)	Failure start (cm)	Failure end (cm)	Failure zone (cm)
	Round, tapered, hollow w/webs	0.0	−1.9	85.7	87.6
	Round, tapered, hollow w/o webs	—	62.2	182.9	120.7
	Round, tapered, solid	8.2	8.2	85.7	77.5
	9-side, no taper, hollow w/webs	15.2	0.0	44.5	44.5
	9-side, no taper, hollow w/o webs	7.6	−7.0	55.9	62.9

Display a large scale of fiber breakage in the cross-fiber-length direction.

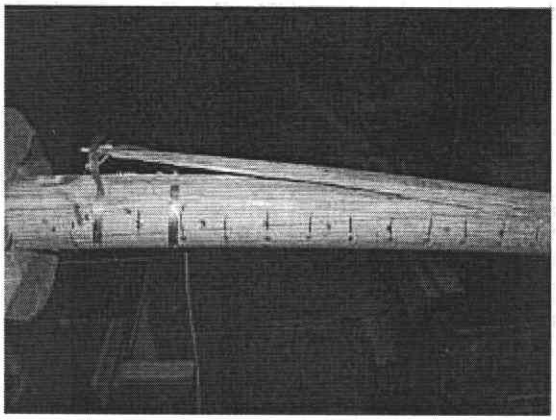

FIG. 3. The failure of a round and tapered solid wood composite pole when subjected to a cantilevered bending.

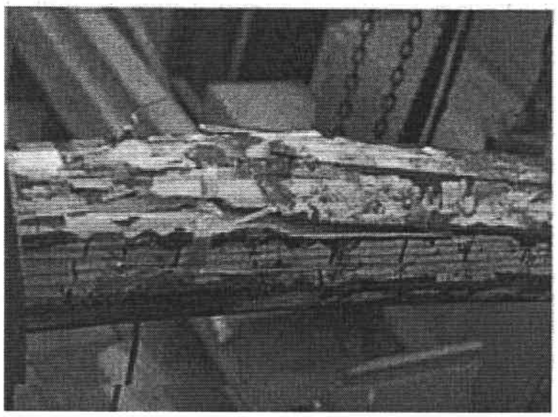

FIG. 4. The failure of a uniform diameter hollow wood laminated composite pole with inserted node-like plywood webs when subjected to a cantilevered bending.

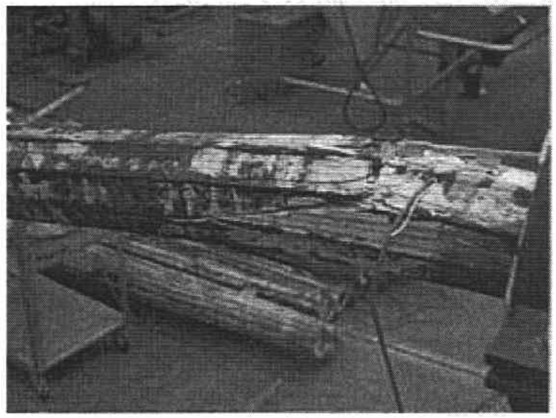

FIG. 5. The failure of a uniform diameter hollow wood laminated composite pole without inserted node-like plywood webs when subjected to a cantilevered bending.

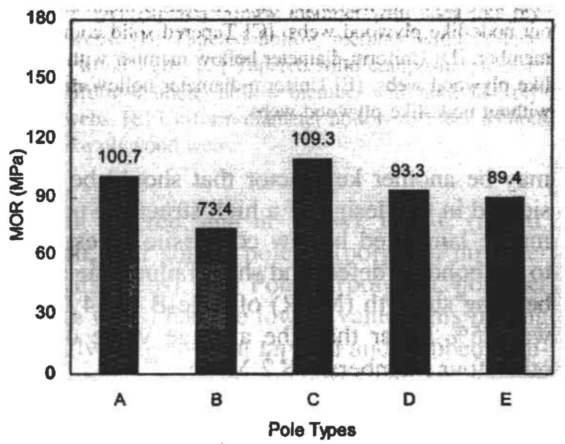

FIG. 6. Modulus of rupture of five laminated wood composite poles subjected to a cantilevered static bending. (1 MPa = 145 psi) [A] Tapered hollow member with node-like plywood webs. [B] Tapered hollow member without node-like plywood webs. [C] Tapered solid composite member. [D] Uniform-diameter hollow member with node-like plywood webs. [E] Uniform-diameter hollow member without node-like plywood webs.

dynamic bending will be the major topics of our future composite pole research.

As compared to the tapered composite poles, the two non-tapered members showed a shorter FZ length and had much more extreme fiber failure. Large-scale fiber failures occurred in the top four strips near the clamped end for webbed (Pole-D) and unwebbed (Pole-E) as shown in Figs. 4 and 5, respectively.

Modulus of elasticity (MOE) and modulus of rupture (MOR)

The MOR and MOE of each laminated composite pole were calculated based on the data recorded from the cantilever static bending test and the results are shown in Figs. 6 and 7, respectively. Since Pole-B failed in shear, which started at the free end, its MOR value shown in Fig. 6 was not its maximum bending stress. A bonding defect near the tip region of the pole triggered the shear failure during the test and initiated a long horizontal shear failure surface. The bonding quality between the wood strips

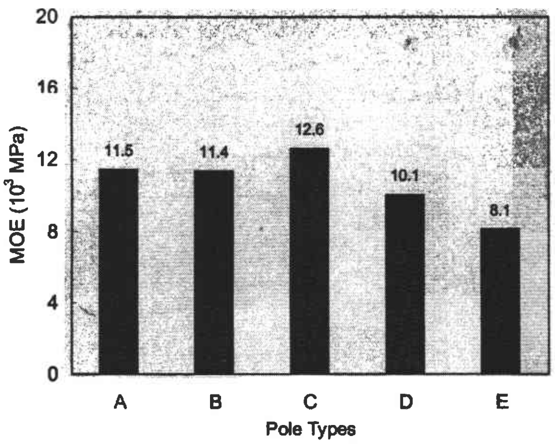

FIG. 7. Modulus of elasticity of five laminated wood composite poles subjected to a cantilevered static bending. (1 GPa = 145 × 10^3 psi) [A] Tapered hollow member with node-like plywood webs. [B] Tapered hollow member without node-like plywood webs. [C] Tapered solid composite member. [D] Uniform-diameter hollow member with node-like plywood webs. [E] Uniform-diameter hollow member without node-like plywood webs.

may be another key factor that should be considered in the design of a high structural performance laminated hollow composite poles. Due to the bonding defect and shear failure, the static bending strength (MOR) of Pole-B (73.4 MPa) was 25% lower than the average value of the other four members (98.2 MPa).

As shown in Figs. 6 and 7, the tapered composite poles had a better cantilevered bending performance than the non-tapered members. The average MOR values of Pole-A (100.7 MPa) and -C (109.3 MPa) were about 13% higher than that of Pole-D (93.3 MPa) and Pole-E (89.4 MPa). For the MOE, the average values of Pole-A (11.5 GPa), Pole-B (11.4 GPa), and Pole-C (12.0 GPa) were about 23% higher than those of Pole-D (10.1 GPa) and Pole-E (8.1 GPa). Thus, when comparison was made between the tapered and non-tapered members, the cross-section properties must be taken into account. All tapered members had a round cross-section and had a smooth stress distribution on their surfaces, compared to polygonal members. However, stress concentration may be developed on the vertexes in the cross-section of polygonal composite poles during the cantilevered static bending test. As compared to the solid and laminated composite poles (1.22 m long, 7.6 cm in diameter and without taper) tested in our previous study (Piao et al. 2004), the tapered solid pole (Pole-C) tested in this study had a slightly higher MOR (109.3 MPa vs. 99.1 MPa) but Pole-E (hollow with a 9-side polygonal cross-section and no taper) showed a lower value than that of the 9-strip non-taper members tested in our last study (89.4 MPa vs. 108.9 MPa) (Piao et al. 2004). However, for MOE, both Pole-C and Pole-E tested in this study showed a higher value than those tested in the previous study (12.0 GPa vs. 8.0 GPa and 8.1 GPa vs. 6.1 GPa, respectively).

The product of MOE and moment of inertia (EI) is generally considered as a measure of stiffness or resistance to deflection in a beam subjected to bending. The tapered laminated solid pole (Pole-C) had the highest stiffness value, and the non-taper hollow member (Pole-E) had the lowest. This indicated that the laminated solid pole had the highest resistance to bending as compared to other members tested. It is well known that in structural engineering, the effectiveness and efficiency of a material/member for using in structural applications are generally measured by the specific mechanical properties [i.e., the ratio of the mechanical property to the density or mass (Tang and Pu 1997)]. In this study, these specific mechanical properties (i.e., specific MOR and specific MOE) of the tested composite poles were examined and the results are presented in Figs. 8 and 9. In the groups with a round-shape cross-section, the specific MOR (MPa/Kg mass) of Pole-A (tapered, hollow, and with webs) was higher than that of Pole-B (tapered, hollow, and without webs) and Pole-C (tapered and solid) as shown in Fig. 8, which indicates that hollow poles will be more effective and efficient on a per weight basis in structural performance than those of solid composite poles when reinforced webs are inserted along its length axis. However, the effect of webs on the specific MOR was not observed in the 9-side polygon-design and non-taper groups (i.e., Pole-D: with webs and Pole-E: without webs).

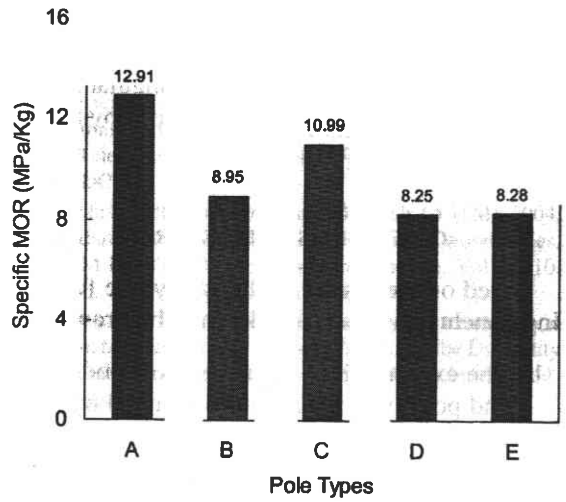

FIG. 8. Specific MOR (MPa/Kg mass) of five laminated wood composite poles subjected to a cantilevered static bending. [A] Tapered hollow member with node-like plywood webs. [B] Tapered hollow member without node-like plywood webs. [C] Tapered solid composite member. [D] Uniform-diameter hollow member with node-like plywood webs. [E] Uniform-diameter hollow member without node-like plywood webs.

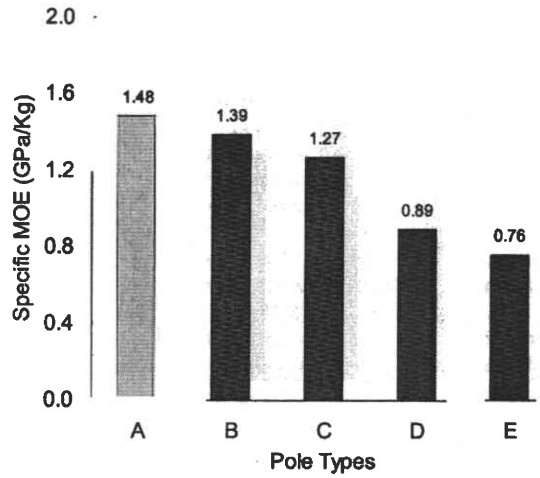

FIG. 9. Specific MOE (GPa/Kg mass) of five laminated wood composite poles subjected to a cantilevered static bending. [A] Tapered hollow member with node-like plywood webs. [B] Tapered hollow member without node-like plywood webs. [C] Tapered solid composite member. [D] Uniform-diameter hollow member with node-like plywood webs. [E] Uniform-diameter hollow member without node-like plywood webs.

The effect of node-like plywood-webs on the static bending MOE of the laminated wood composite poles tested was uncertain. As shown in Fig. 7, among the round and tapered members, the MOE of Pole-A (with plywood-webs) (11.5 GPa) was very close to that of Pole-B (without plywood-webs) (11.4 GPa). However, among the polygonal and non-tapered poles, the member with plywood-webs (Pole-D) showed higher MOE (10.1 GPa) than that of the one without plywood-webs (Pole-E, 8.1 GPa). Obviously, placement of the plywood-webs in the clamped lines may increase the moment of inertia and decreased the bending stress at that section. Furthermore, webs increased the area of the neutral plane where the shear stress reaches the maximum and increased the resistance of the laminated hollow composite poles to shear (elementary mechanics). The effect of taper and webs on the specific MOE (GPa/Kg mass) of the pole members tested was observed as illustrated in Fig. 9. The highest value of specific MOE was observed in the round and tapered member with plywood-webs (Pole-A) and followed by Pole-B (round, tapered, and no webs), Pole-C (round, tapered, and solid), pole-D (polygon, no taper but with webs), and Pole-E (polygon, no taper and no webs) had the lowest value. This finding strongly suggests that tapered and webbed composite poles are more effective and efficient in structural performance than those of non-tapered and non-webbed composite poles. Further improvement of the structural performance of these laminated hollow and taper composite poles may be achieved if wood strips with high strength and stiffness are used in the pole fabrications.

Shear stress when pole failed in bending

Figure 10 shows the calculated shear stress at the neutral plane of the very tip sections where shear stress reached its maximum for the tapered composite poles. Since the shear capacities of the poles are a function of material strength and cross-sectional properties, the tapered hollow poles had the least section modulus at the tip, and hence they exhibited the lowest shear capacity. The non-taper (i.e., uniform diameter) poles

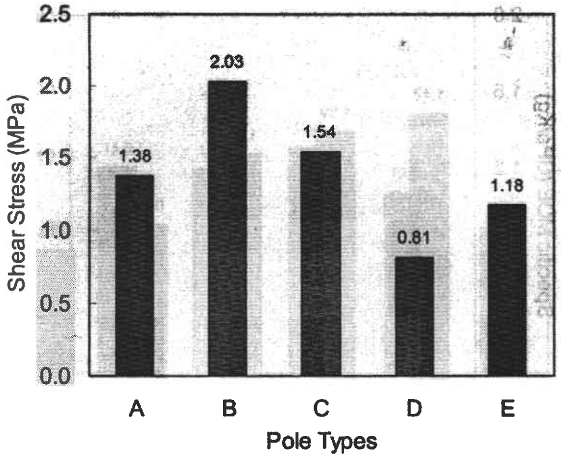

FIG. 10. Shear stress in the neutral plane at the free ends of five laminated wood composite poles when the poles failed in bending. (1 MPa = 145 psi) [A] Tapered hollow member with node-like plywood webs. [B] Tapered hollow member without node-like plywood webs. [C] Tapered solid composite member. [D] Uniform-diameter hollow member with node-like plywood webs. [E] Uniform-diameter hollow member without node-like plywood webs.

with webs had the highest section modulus and showed the highest shear capacity. These findings suggest that the node-like plywood-webs should be considered in the design of composite poles to withstand the shear stress, which would be the main cause of failure, especially for tapered and/or thin shell composite poles

The bonding defects between the wood strips would result in a reduction in shear resistance. These defects are usually caused by insufficient pressure in the consolidation of the strips during the fabrication of the poles, machining errors in the dimension of wood strips, or lack of resin in the gluelines. Any one of these errors would have a significant effect on the load capacity of the laminated composite poles and they should be minimized as much as possible. However, these material parameters [e.g., accurate shape and dimension of trapezoid wood strips and finger-joints in the long strips] and the optimal fabricating techniques [e.g., adequate pressure for better bonding of the wood strips] can be easily managed and digital-controlled in the industrial manufacturing processing of hollow wood composite poles. For example, long members of trapezoid wood strips with accurate shape and cross-section dimension can be easily produced from finger-jointed rectangular wood stock by using a specially designed moving jig in an industrial-type table router.

CONCLUSIONS AND REMARKS

Based on the results of this study, the following conclusions and remarks may be drawn.

1. The extreme fiber failure in the wood strips and poles was always accompanied by long and deep springwood failure along the wood grain of the failed strips. The tapered hollow poles showed longer failure zone than the non-tapered members.
2. Plywood-webs reduced the propagation of wood failure along the pole length axis.
3. Plywood-webs had a positive effect on the static bending properties per weight of the laminated hollow composite poles due to the increase of their shear capacity.
4. The tapered solid composite pole had higher static bending MOR and MOE values than the other members tested in this study. However, as expected, the specific MOR and MOE values were lower than those of tapered hollow composite poles.
5. The specific MOR and MOE of tapered poles were greater than those of uniform-diameter poles.
6. As expected, the maximum shear stress at failure in tapered poles was greater than that of uniform-diameter poles.
7. For practical industrial applications, static and dynamic tests of full-sized laminated hollow and tapered wood composite poles (e.g., 30 ft [9.14 m] or longer Class 4 or 5 members) fabricated with high strength/stiffness and dimensional stable wood strips and webs by applying the newly developed nano-technogy are highly recommended.

REFERENCES

ADAMS, R. D., G. P. KRUEGER, S. LONG, A. E. LUND, AND D. D. NICHOLAS. 1981. Compole™—the composite wood material utility pole. American Wood-Preservers' Association, April 27–29, 1981. Birmingham, AL.

American National Standards Institute (ANSI). 2002. American national standard for wood poles–specifications and dimensions: ANSI 05.1–2002. Alliance for Telecommunications Industry Solutions, Washington, DC.

American Society for Testing and Materials (ASTM). 2004. Standard test methods of static tests of wood poles. ASTM D 1036-99. Section 4: Construction, Vol. 04-10, Wood. ASTM. West Conshohocken, PA.

Bratkovich, S. M. 2002. Markets for recycled treated wood products. Pages 37–40 *in* Proc. Enhancing the Durability of Lumber and Engineered Wood Products. Forest Products Society, Madison, WI.

Cooper, P. A. 1996. Management of used poles removed from service. Pages 102–112 *in* Proc. 2nd Southern Pole Conference. Forest Products Society, Madison, WI.

Erickson, R. W. 1994. The hollowed veneered pole. Pages 465–468 *in* J. Wells, ed. Proc. Pacific Timber Engineering Conference. July 11–15, 1994, Gold Coast, Australia. Queensland University of Technology, Brisbane, Australia.

———. 1995. Hollow veneered pole. United States Patent: Number 5,438,812.

Gere, J. M., and S. P. Timoshenko. 1990. Mechanics of materials. 3rd ed. PWS-KENT Publishing Company, Boston, MA. 807 pp.

Hockaday, E. 1975. What does structural glue laminated wood have to offer the electrical utility industry. *In* Proc. 6th Wood Pole Institute, Colorado State University. Fort Collins, CO.

Janssen, J. J. A. 1991. Mechanical properties of bamboo. Kluwer Academic Publishers, Dordrecht, The Netherlands. 1344 pp.

Koch, P. 1972. Utilization of the southern pines. Parts I & II. Agriculture Handbook No. 420. U.S. Department of Agriculture Forest Service, Southern Research Station. 1618 pp.

Lee, A. W. C., X. S. Bai, and P. N. Peralta. 1994. Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. Forest Prod. J. 44(9):40–46.

Marzouk, H. M., M. U. Hosain, and V. V. Neis. 1978. Built-up utility poles using prairie timber. Forest Prod. J. 28(11):49–54.

McKain, B. 1975. Laminated wood for utilities—a combination of versatility, economics and beauty. *In* Proc. 6th Wood Pole Institute, Colorado State University. Fort Collins, CO.

Piao, C., T. F. Shupe, and C. Y. Hse. 2004. Mechanical properties of small-scale wood-laminated composite poles. Wood Fiber Sci. 36(4):536–546.

———, ———, R. C. Tang, and C. Y. Hse. 2005. Finite element analyses of wood-laminated composite poles. Wood Fiber Sci. 37(3):535–541.

Sasaki, H., H. Yamauchi, A. Koizumi, Y. Lijima, Y. Tamura, T. Sasaki, and S. Kawai. 1996. Cylindrical LVL for structural use made by spiral-winding method. Pages 3.538–3.540 *in* Proc. International Wood Engineering Conference, October 28–31, 1996. New Orleans, LA.

Tang, J. L. 1989. Strength properties on bamboo materials. Forest Prod. Ind. 8(3):65–78.

Tang, R. C. 1977. Environmental effects on transmission poles laminated with reinforced plastics. Pages 403–424 *in* Proc. Conference on Environmental Degradation of Engineering Materials. Virginia Tech Univ., October 10–12, 1977, Blacksburg, VA.

———, and S. F. Adams. 1973. Application of reinforced plastics for laminated transmission poles. Forest Prod. J. 23(10):42–46.

———, and J. H. Pu. 1997. Edgewise bending properties of laminated veneer lumber: Effect of veneer grade and relative humidity. Forest Prod. J., 47(5):64–70.

USDA Forest Products Laboratory (FPL). 1999. Wood Handbook: Wood as an engineering material. Forest Prod. Soc., Madison, WI.

Wolfe, R., and J. Murphy. 2005. Strength of small-diameter round and tapered bending members. Forest Prod. J., 55(3):50–55.

Zeng, Q., S. Li, and X. Bao. 1992. Effect of bamboo nodes on mechanical properties of bamboo. Scienta Silvae Sinicae. 28(3):247–252.