Effect of PF Impregnation and Surface Densification on the Mechanical Properties of Small-Scale Wood Laminated Composite Poles

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Abstract

The wood poles in the United States are from high-valued trees that are becoming more expensive and less available. Wood laminated composite poles (LCP) are a kind of alternative to solid poles. Considerable interest has developed in last century in the resin impregnation and wood surface densification to improve its physical and mechanical properties. In this study, southern pine lumbers were impregnated with a low molecular weight, water-soluble PF (phenol formaldehyde) resin and compressed while heated to make the surface densified. Furthermore, small-scale LCP were fabricated with treated trapezoid southern pine strips cut from treated lumbers and untreated trapezoid southern pine strips cut from control lumbers respectively. In comparison with the control wood, bending MOE and MOR of treated wood were improved from 11.573 to 16.517 GPa and from 90.68 to 125.63 MPa respectively, and an analysis of variance indicated that both the MOE and MOR differences were significant at 5% probability level. While compared with the control poles bending MOE and MOR of LCP fabricated with treated strips were improved respectively from 9.077 GPa to 10.381 GPa, and 67.67 to 73.28 MPa, and an analysis of variance indicated that these differences were not significant at 5% probability level. Compared with the control poles, the glue line shear strength of LCP fabricated with treated strips decreased from 7.50 to 7.23 MPa for the air-dried samples, from 3.58 to 3.22 MPa for the two hour boiling treatment samples, and these differences were not significant at 5% probability level.

Introduction

Research on resin impregnation and compression of wood with the aim of improving certain properties has been explored in the past decades. Treated wood possessed increased dimensional stability, hardness, abrasion resistance compared to the untreated ones (Inoue, 1990; Ryu, 1991; Liu, 2002). Furthermore, biological resistance and mechanical properties including MOE and MOR are improved significantly (Inoue, 1990; Ryu, 1991; Liu, 2002).

In our previous work, we showed that the maximum bending stress of wood laminated composite poles was comparable to that of solid poles of the same size, and this kind of poles could be a possible substitute for solid poles (Piao, 2004). Wood laminated composite poles are continuously exposed to weather, fungi, termites, etc., which result in a very significant deterioration of their load bearing capacity with time. The service life of laminated composite poles may extend when using treated wood with resin impregnation and compression to produce poles.

To compare the properties of composite poles and to test the dynamic properties of solid wood poles, 6-, 9-, and 12-sided (polygonal) poles were made. Two materials were used. One was the same material as those of composite poles, i.e., the southern yellow pine; the other one was white spruce.

This research was performed to determine the improvements in bending capacity of wood through PF impregnation and compression, and to investigate the bending load carrying capacity of small-scale wood laminated composite poles manufactured using impregnated and compressed wood.

Experimental

Materials

Southern yellow pine (SYP) lumber with sizes 5.08 cm by 6.1 m was commercially obtained. Lumber selected had small (diameter <1 cm) knots. The lumbers were cut into small ones with the length of 152 cm (60 inches) and reduced to target thickness (3/4inch) with a planer. The average specific gravity of the wood was 0.57 g/cm^3. The lumbers were divided into 2 groups with the approximately identical MOE distribution by stress wave method. The lumbers from one group were sawn directly into wood strips with trapezoid section with which to make the control poles. The lumbers from the other group were impregnated for two hours in the aqueous solution of low molecular weight glue: phenol formaldehyde (average molecular weight: about 200, pH 8, concentration: 25%). After impregnation for 1.5 hours, the lumbers were air-dried for two days. The impregnated lumbers were compressed with a compression rate of 15% in the radial direction for 8 minutes and the heating temperature is 191°C. The percentage of size reduction from the original to the compressed state was calculated as:

$$\text{Compression Rate} = (T_0 - T_C)/T_0 \cdot 100(\%)$$

Where T_0 is original lumber thickness before compression and T_C is lumber thickness after compression.

Poles fabrication

In this study only wood composite poles with hexagonal cross section were fabricated and studied. The treated (impregnated and compressed) and untreated lumbers were sawn into strips with trapezoid section to fabricate the poles, and the parameters of the trapezoid section of the strips are listed in Table 1. The strip size determination, strip-cutting and fabrication procedure had been described in our previous paper (Piao, 2004), and Fig. 1 only illustrated strip-cutting and fabrication procedure.

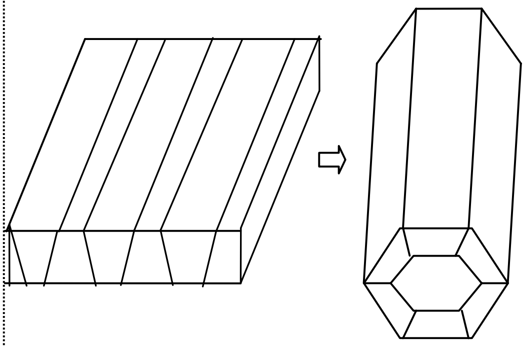

Fig. 1. Schematic diagram of a strip-cutting and fabrication plan for a six-strip composite pole

Table 1. Strip parameters of trapezoid section of wood composite poles

Treatment	Thickness (inch)	Angle of the trapezoid(°)	Width of larger side (inch)	Width of smaller side (inch)
No Treatment (control)	0.75	60	1	0.133
PF Impregnation and Hot Compression	0.6	60	1	0.306

Test methods

Flexural test of poles

Each kind of poles was divided into two groups randomly. The poles were tested in the air-dried condition following the cantilever bending test procedures described in the previous paper (Piao, 2004). A clamp with hard maple wood liner on a fixed supporting frame was used to confine the bottom portion of the pole, below the point identified as ground line, and 21 cm of the pole was embedded in the clamp. Loads were applied 2.5 cm from the pole tip. A steel cable was tied to the crosshead of the mechanical machine (Riehle) through a pulley, and the mechanical machine was used to control load. Loading speed was 51 mm per minute.

This paper intended to assess of bending modulus of elasticity (MOE) and the maximum fiber stress at the ground line of two kinds of wood laminated composite poles. The MOE and MOR values were derived assuming the pole's section is a homogeneous hexagon.

The equations used for MOE and MOR in this case are:

$$MOE=PL^3/(3\delta I); \qquad MORGL=PLh/(2I)$$

Where:

δ =tip deflection in the direction of the cantilever load. $\delta = 2L^3 \varepsilon c/(h(L-C))$

Where:

C =the distance between the midpoint of strain gauge and the ground line

ε c= the strain at x=C

P=applied load at tip end

L=length from ground line to tip support of wire

I=the effective moment of inertia for the hexagon section 0.5413R4. R=radius of the hexagon section.

h=the height of the hexagon section

Glue-line shear test of poles

After the bending test of each small-scale composite pole, the part measured 20 cm (8 in) from the clamped end of the pole was cut and kept for records. Four more samples measuring 5 cm (2 inch) each were cut from the same end and used for the glue-line shear test. Each sample was first cut into two halves. One glue line was randomly selected from each of the halves. The height of the glue line was reduced to 3.6 cm (1.4 in). Two of the samples were used to determine the glue-line shear in the dry condition. The samples were kept in an air-conditioned room for two weeks and tested to failure. The maximum load and wood failure of each sample were recorded.

The other two samples for each pole were used to test in wet conditions. The samples were put in a container measuring 36×72×23 cm (14×28×9 in). Water in the container was heated to 50°C and the samples were put 2.5 cm (1 in) below the water surface using a net. The water was heated to boiling point in two hours and samples were kept in the boiling water for another two hours. At the end of the boiling test, the samples were taken out and immediately put in plastic bags. After the samples cooled to the ambient temperature in the bags, they were shear-tested to failure. The load to failure and percentage of wood failure on the glue-line were recorded. The load values in the wet condition and glue-line dimensions in the dry condition were used to calculate the shear strength for each sample.

A standard apparatus was used to hold the samples and an Instron machine was used to add the load. Before the test, each glue line in each sample was labeled, and measured for length and width.

The testing procedure is similar to the standard ASTM D 1037 glue-line shear test procedure except that the width of the samples was narrower because of the limited shell thickness of the poles. The shear stress at failure was calculated based on the maximum load and the glue line area, and the percentage of wood failure for each specimen was recorded after the test.

Bonding properties of the treated and control lumbers

After the bending test of each small-scale composite pole, the part measured 40 cm (16 in) from the clamped end of the pole was cut and kept for records. Four more samples measuring 50.8 cm (20 inch) each were cut from the same end and used for the glue-line shear test.

Results and discussion

Bending properties of the PF treated and compressed lumbers

The MOR and MOE of the wood strips from the PF treated and control lumbers listed in Table 2. In comparison with the control wood, the mean bending MOE and MOR of PF treated and compressed wood were improved from 11.573 to 16.517 GPa and from 90.68 to 125.63 MPa respectively, and ANOVA results indicated that PF impregnation and compression had a significant effect (p = 0.01) on both the MOE and MOR.

Table 2. Bending properties of the wood strips from the PF treated and control lumbers (MOE: GPa; MOR: MPa).

property	Strip types	N	Mean	Std. Deviation	Minimum	Maximum
MOR	control	15	90.682	11.04348	72.184	117.581
	PF treated pole	15	125.627	18.49975	87.42	152.9
MOE	control	15	11.573	2.597556	5	15.566
	PF treated pole	15	16.517	3.967586	7.774	22.921

Table 3. ANOVA results of the bending properties of wood strips from the treated and untreated lumbers.

		Sum of Squares	df	Mean Square	F	Sig.
MOR	Between Groups	9158.787	1	9158.787	39.46061	8.6E-07
	Within Groups	6498.786	28	232.0995		
	Total	15657.57	29			
MOE	Between Groups	183.2988	1	183.2988	16.30117	0.00038
	Within Groups	314.8464	28	11.24451		
	Total	498.1452	29			

Maximum bending stress of small-scale composite poles

While compared with the control poles bending MOE and MOR of small-scale poles fabricated with PF treated and compressed strips were improved respectively from 9.077GPa to 10.381GPa, and 67.67 to 73.28 MPa, and ANOVA results indicated that these differences were not significant at 5% probability level.

Table 4. Maximum bending stress of two kinds of small-scale poles (MOE: GPa; MOR:MPa).

		N	Mean	Std. Deviation	Minimum	Maximum
MOR	control	6	67.67133	11.10414	54.179	80.252
	PF treated pole	6	73.28	19.48706	53.595	100.713
MOE	control	6	9.077333	1.810747	6.246	11.502
	PF treated pole	6	10.38133	0.559213	9.593	11.033

Table 5. ANOVA analysis results of maximum bending stress of two kinds of small-scale poles.

		Sum of Squares	df	Mean Square	F	Sig.
MOR	Between Groups	94.37143	1	94.37143	0.375199	0.553857
	Within Groups	2515.238	10	251.5238		
	Total	2609.61	11			
MOE	Between Groups	5.101248	1	5.101248	2.840714	0.122803
	Within Groups	17.95763	10	1.795763		
	Total	23.05888	11			

Glue-line shear strength of composite poles

Glue-line shear strength in both dry and wet conditions for two kinds of small-scale poles are listed in Table 6.

After two hours boiling test, glue-line shear strength of the PF treated pole and the control pole were all reduced much. Compared with the control poles, the glue line shear strength of small-scale poles fabricated with treated strips decreased from 7.50 to 7.23 MPa for the air-dried samples, from 3.58 to 3.22 MPa for the two hour boiling treatment samples, and these differences were not significant at 5% probability level.

Table 6. Glue-line shear strength values before and after water soaking of small-scale composite poles (MPa).

PF treatment	Water soaking treatment	N	Mean	Std. Deviation	Std. Deviation	Minimum	Maximum
control	Dry condition	24	7.502423	2.377031	2.377031	4.119960447	12.05515652
	Wet condition	24	3.58325	1.084825	1.084825	1.830911906	6.31468398
PF treated pole	Dry condition	23	7.226353	1.872359	1.872359	4.221228189	11.02771263
	Wet condition	24	3.215245	0.933881	0.933881	1.715786035	5.253217268

Table 7. ANOVA analysis results of glue-line shear strength values before and after water soaking of small-scale composite poles.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	390.527(a)	4	97.632	34.950	.000
Intercept	311.721	1	311.721	111.588	.000
Wet treatment	373.279	1	373.279	133.624	.000
PF treatment	5.672	2	2.836	1.015	.366
Wet * PF	.050	1	.050	.018	.894
Error	254.209	91	2.794		
Total	3364.930	96			
Corrected Total	644.736	95			

a R Squared = .606 (Adjusted R Squared = .588)

Conclusions

PF impregnation and compression improved lumber bending capacity significantly. However, no improvement in the bending load carrying capacity of small-scale wood laminated composite poles manufactured by using impregnated and compressed wood.

PF impregnation and compression had insignificant effect on the glue line shear strength of small-scale poles.

The two hour heating plus two-hour boiling treatments resulted in a reduction in shear strength.

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