TECHNICAL NOTE: USING NONDESTRUCTIVE TESTING TO IDENTIFY PREMIUM GRADES IN SOUTHERN PINE AND DOUGLAS-FIR UTILITY CROSSARMS

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Abstract. Unlike lumber, wood utility crossarms are not currently available in premium grades that indicate a higher level of performance in service. Previous research has shown that nondestructive testing (NDT) techniques are able to predict performance properties of solid wood products with considerable accuracy. The aim of this study was to determine the suitability of NDT methods for predicting the stiffness and strength properties of wood utility crossarms and possibly aiding in the identification of a premium grade that exhibits higher average performance values. Samples of Douglas-fir and southern pine were subjected to multiple NDT technologies to estimate MOE. Each specimen was also measured for MOE and MOR with a static bending test. Bivariate correlations and corresponding R^2 values showed that Fibre-gen's Director HM200 and Metriguard's E-computer were the most accurate NDT devices among those tested for predicting both MOR and MOE. Means tests also suggested that the devices could possibly be used to identify a premium grade that shows significantly higher average performance values.

Keywords: Crossarms, strength, bending, modulus of elasticity, modulus of rupture, southern pine, Douglas-fir, nondestructive, grading.

INTRODUCTION

Wood utility crossarms provide an efficient economical, structural, and sustainable solution to the distribution and transmission of electric utilities. The majority of these crossarms in the United States are made from two species: Douglas-fir (*Pseudotsuga menziesii*) and southern pine (*Pinus* spp.).

Crossarms are commonly graded per American National Standards Institute (ANSI) O5.3. Pieces meeting the minimum requirements of the standard are designated "on-grade." Those not meeting the minimum requirements are designated "off-grade." Unlike lumber, crossarms are not

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currently available in premium grades that indicate a higher level of performance in service.

Previous research has shown that nondestructive testing (NDT) techniques are able to predict performance properties of solid wood products with considerable accuracy (Shmulsky et al 2006; Hu 2008; Yang et al 2015). These NDT methods provide accurate and efficient information that could supplement visual grading techniques making it possible for manufacturers to assess the potential performance of crossarms with greater precision. Greater precision in grading could allow for the identification and marketing of premium crossarm grades.

The objective of this study was to determine the suitability of NDT techniques for predicting the stiffness and strength properties of wood utility crossarms and possibly aiding in the identification of a premium grade that exhibits higher average performance values.

MATERIALS AND METHODS

Materials and Sampling

Douglas-fir (*P. menziesii*) and southern pine (*Pinus* spp.) crossarms were selected from mill run candidate stock and graded at two different wholesale manufacturers: one in Louisiana and the other in South Carolina. The manufactures procured their materials from a variety of regional sources. In general, the Douglas-fir came from Oregon and Washington. The southern pine came from throughout the southern pine producing region (from the Gulf states to the Carolinas). This sampling scheme was intended to increase variability in the sampling. Each manufacturer selected 60 on-grade and 60 off-grade southern pine pieces along with 60 on-grade and 60 off-grade Douglas-fir pieces for a total of 120 southern pine and 120 Douglas-fir crossarms. All crossarms were untreated, not-yet-drilled and kiln dried. Most (209 pieces) measured approximately $8.9 \times 11.4 \times 244$ cm. The remaining 31 measured approximately $8.9 \times 11.4 \times 305$ cm. All were tested at their full length; none was crosscut. In this manner, any potential strength or stiffness reducing characteristics in the graded material were included in the evaluation. In all, 240 pieces were tested.

Specifications

The following standards and guidelines were followed. Material was graded, stored, and conditioned in accordance with ANSI O5.3-2015 (ANSI 2015). Specimen MC was measured with a handheld moisture meter per ASTM D7438-13 (ASTM 2013). Preliminary specimen measurements, load setups, destructive testing procedures, and data recordings were performed according to ASTM D198-14 (ASTM 2014).

Testing and Analysis

On receipt, the crossarms were stored for 2-4 wk in a climate controlled laboratory at approximately 21°C/65% RH to aid moisture conditioning. A preliminary evaluation was subsequently administered. This included labeling each specimen with a unique item code and measuring thickness, width, and length in accordance with ASTM D198-14 (ASTM 2014).

Final weight and MC measurements were performed on the day of testing. Moisture readings were taken with a Wagner L601-3 handheld meter[1] (Fig 1). The penetration depth was approximately 25.4 mm. The mean MC was 15.9% for southern pine and 15.2% for Douglas-fir. Shortly before destructive testing, weight was measured with a calibrated scale while MC was taken with a handheld moisture meter. Densities were also calculated. The average density for southern pine and Douglas-fir were 670 and 559 kg m^{-3}, respectively.

Nondestructive tests were conducted with three different devices: Metriguard's E-computer Model 340[2] (hereafter E-computer), Falcon

[1]Wagner Electronic Products Inc., Rogue River, Oregon, USA. www.wagnermeters.com
[2]Metriguard Inc., Pullman, Washington, USA. www.metriguard.com

Figure 1. Wagner L601-3 handheld moisture meter.

Engineering's A-grader[3] (hereafter A-grader), and Fibre-gen's Director HM200[4] (hereafter Director). The E-computer estimates MOE by measuring transverse vibration. Both the A-grader and the Director estimate MOE by measuring longitudinal stress waves.

The nondestructive tests were performed first with the E-computer. The setup involved two tripods (Fig 2), one of which was topped with a transducer (Fig 3) connected by cord to a laptop computer. After calibration, the specimen dimensions were entered. The ends of each specimen were aligned with the tops of each tripod allowing for a 2.5 cm overhang at each end. Each specimen was tapped lightly on the top center, and the transducer sensed the resulting vibration. Two tests were performed with this device per crossarm: one with the specimen lying on its face (flatwise) and one on its edge (edgewise). E-computer produced an "E-value" in million psi as the output, which is directly comparable to MOE_{stat} psi (later converted to GPa).

Next, the same specimens were subjected to the Director HM200. The same tripod setup from

Figure 2. Tripod setup for all nondestructive tests.

the E-computer test was used. The Director is a handheld device that measures the acoustic velocity of a stress wave traveling through a board in meters per second. The device is held against the end of the specimen, and a small tap is given with a hammer just above the device sending vibration through the specimen (Fig 4). In theory, denser pieces with straighter grain achieve higher acoustic velocities. Each output was recorded and an MOE estimate in GPa was derived from the acoustic velocity according to the following formula where E is elasticity, ρ is density, and V is acoustic velocity (Ross and Pellerin 1994).

$$E = \rho V^2 \tag{1}$$

The final nondestructive test was performed with the A-grader. The same tripod setup from the E-computer test was used. After the weight

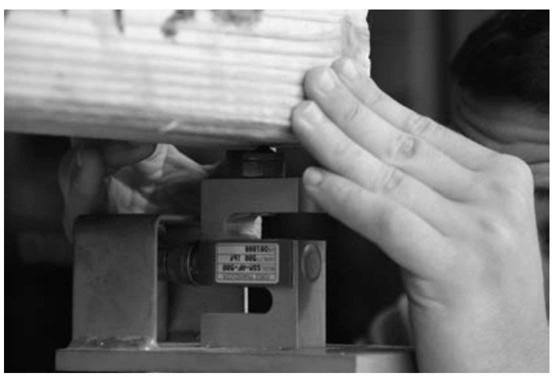

Figure 3. Transducer used for the E-computer test.

[3]Falcon Engineering Ltd., Inglewood, Taranaki, New Zealand. www.falconengineering.co.nz
[4]Fibre-gen Limited, Christchurch, New Zealand. www.fibre-gen.com

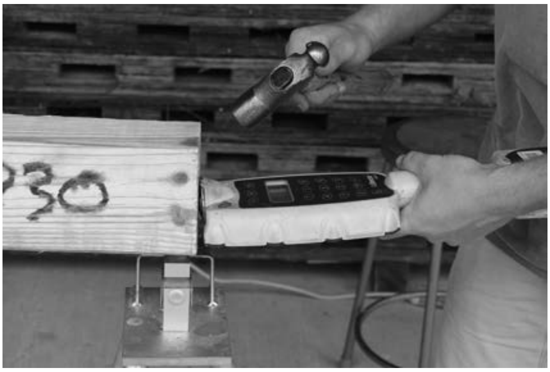

Figure 4. Measuring acoustic velocity with the Director HM200.

Figure 5. The microphone used in the Falcon A-grader test.

and dimensions of each crossarm were entered into the device, a microphone (Fig 5) was held approximately 2.5 cm from one end of the specimen while a small tap was made with a hammer at that end. Like the E-computer, the A-grader generated an E-value in million psi that is directly comparable to MOE_{stat} psi (later converted to GPa).

The destructive bending tests were performed on an Instron universal testing machine.[5] Fixture setup and third-point loading were executed per the Flexure Test Method procedure within ASTM D198-14. A span-to-depth ratio of 17 to 1 was chosen. Specimens were loaded in an edgewise orientation.

Each specimen was placed in the machine to simulate the orientation of how a crossarm would be positioned on a utility pole. Where applicable, the two chamfered corners were placed upward in the edgewise position (Fig 6). Before zeroing the deflectometer, each specimen was loaded with approximately 1030 N to ensure proper placement and seating of the load heads. The test was then applied until full rupture. The average length of time until rupture was kept to approximately 5 min.

In reviewing the raw data output, one specimen of southern pine was found to have an MOE value that was more than 7 standard deviations from the mean. This value appears to have occurred as the result of a data acquisition malfunction in the test machine's deflectometer. It was determined to be an extreme outlier. This MOE data point was removed from the dataset due to its disproportionate influence on the mean and standard deviation. The MOR value for that specimen was retained as MOR is not affected by the deflectometer.

Data from the destructive test and the three nondestructive tests were compiled together into one data file by item code. Due to data corruption in the output of the Instron machine, a consecutive batch of MOE and MOR values for cases 61-90 (off-grade pine) were lost. The remaining data for these 30 pieces were eliminated from the

Figure 6. Third-point loading setup. If the crossarm had chamfered edges, they were oriented upward.

[5]Instron (an ITW company), Norwood, Massachusetts, USA. www.instron.us

Table 1. Correlation coefficients and R^2 values for southern pine.

	MOR	MOE	E-computer (flat)	E-computer (edge)	Falcon A-grader	Director HM200
MOR *r*	—	0.663	0.623	0.679	0.475	0.623
R^2	—	0.440	0.388	0.461	0.226	0.388
MOE *r*	0.663	—	0.910	0.933	0.372	0.941
R^2	0.440	—	0.828	0.870	0.138	0.885

r, Pearson's correlation coefficient; R^2, coefficient of determination. All correlations are significant at $\alpha = 0.01$ (two tailed).

dataset listwise. This action reduced the sample size of southern pine from 120 to 90 (60 on-grade and 30 off-grade). The sample size of Douglas-fir remained unchanged at 120 (60 on-grade and 60 off-grade).

After testing, a bivariate correlation analysis was conducted between the outputs of each nondestructive test and the MOE/MOR values of the static bending test as well as between the static MOE and MOR values themselves. The two species were analyzed separately. For one of the Douglas-fir pieces (case 112), the E-value for the E-computer (edgewise) test was more than 5 standard deviations from the mean. It was determined to be an extreme outlier—most likely due to electronic equipment malfunction. That value was eliminated through pairwise deletion. The other values for that specimen were retained. R^2 values were also used to evaluate the effectiveness of the NDT devices in predicting the performance of the crossarms.

After the correlation analysis, the NDT devices with the highest R^2 values were identified. Per device, an E-value cutoff was applied only to the on-grade pieces in an attempt to separate high-performing pieces from the rest of the on-grade materials. The pieces that met or exceeded the cutoff were reclassified as premium grade. Means comparisons were administered by analysis of variance to determine whether the new grade was statistically different from the other grades.

RESULTS AND DISCUSSION

The results of the bivariate correlation analyses for southern pine and Douglas-fir are shown in Tables 1 and 2, respectively. Coefficients of determination (R^2 values) appear below each correlation coefficient.

In predicting the MOE of southern pine, the Director HM200 produced the highest R^2 values (0.885) followed by E-computer (edgewise 0.870 and flatwise 0.828) and then A-grader (0.138). In predicting MOR, E-computer was highest (edgewise 0.461 and flatwise 0.388) followed by Director (0.388) and then A-grader (0.226). In predicting the MOE of Douglas-fir, Director produced the highest R^2 values (0.834) followed by E-computer (edgewise 0.728 and flatwise 0.724) and then A-grader (0.601). In predicting MOR, E-computer was highest (edgewise 0.498 and flatwise 0.469) followed by Director (0.450) and then A-grader (0.398). In both species, the Director exhibited the best predictive accuracy for MOE and E-computer the best predictive accuracy for MOR.

The NDT devices used in this study were designed to estimate MOE values. As shown in

Table 2. Correlation coefficients and R^2 values for Douglas-fir.

	MOR	MOE	E-computer (flat)	E-computer (edge)	Falcon A-grader	Director HM200
MOR r	—	0.681	0.685	0.706	0.631	0.671
R^2	—	0.464	0.469	0.498	0.398	0.450
MOE r	0.681	—	0.851	0.853	0.775	0.913
R^2	0.464	—	0.724	0.728	0.601	0.834

r = Pearson's correlation coefficient; R^2 = coefficient of determination. All correlations are significant at $\alpha = 0.01$ (two tailed).

Table 3. Means comparisons of two grades separated by species.

Species	Grade	Mean MOE (GPa)		Mean MOR (MPa)		N
Southern pine	On-grade	13.4	A	70.0	A	60 (59)[a]
	Off-grade	11.6	B	55.7	B	30
Douglas-fir	On-grade	13.4	A	63.1	A	60
	Off-grade	11.9	B	49.7	B	60

Means followed by different letters are significantly different at $\alpha = 0.01$.
[a] N for MOE was reduced by 1 due to the removal of an extreme outlier.

Tables 1 and 2, MOE and MOR themselves are moderately correlated with each other (southern pine: $r = 0.663$; Douglas-fir: $r = 0.681$) so it appears reasonable that these NDT devices are better at directly predicting MOE than MOR.

There is an alternative to using NDT devices to directly predict pieces with high MOR. Because MOE and MOR are moderately correlated, it is reasonable to assume that pieces with the highest MOE values also exhibit high MOR values (Verrill et al 2014). Accordingly, it should be possible to isolate pieces with the highest MOE values and at the same time benefit from the higher MOR values that come along with them. In this manner, one might be able to identify premium grade pieces that exhibit both higher stiffness and higher strength properties.

Because Director and E-computer exhibited strong predictive accuracy for MOE in both species, both devices were used to identify the pieces with the highest MOE values. For the E-computer device, data from both the flatwise and edgewise orientations were analyzed.

As a baseline for comparison, the mean MOR and MOE values for on- and off-grade were tested for statistical differences in both species. The results appear in Table 3. The grouping letters in the table show that the mean values of both MOE and MOR differ significantly between on-grade and off-grade materials in both species (all p values ≤ 0.003).

Means were also compared when the species variable was ignored and the two species were considered together. The results appear in Table 4. The grouping letters in the table show that the mean values of both MOE and MOR differ significantly between on-grade and off-grade materials when the variable of species is ignored (all p values <0.001).

In an attempt to use the Director device to isolate the top 20% of on-grade pieces into a high-performing premium grade, an E-value reading of 2.45×10^6 psi (16.9 GPa) was designated as a cutoff/threshold. Cutoff values for the flatwise and edgewise orientations of the E-computer were accordingly approximated based on the ratio of their respective E-value means to that of the Director device. Those cutoff values were 2.20×10^6 psi (15.2 GPa) and 2.00×10^6 psi (13.8 GPa), respectively. On-grade pieces that met or exceed the cutoff/threshold values for each device were considered premium grade. On-grade pieces below the cutoff/threshold for each species were still called "on-grade."

When the species were analyzed separately across three grades, the means of two of those grades commonly showed no statistical difference in either MOR or MOE. In some cases, on-grade was statistically different from off-grade but not premium grade. In other cases, on-grade was statistically different from premium grade but not off-grade. This failure to find a consistent statistical difference among all three potential

Table 4. Means comparisons of two grades when species are considered together.

Species	Grade	Mean MOE (GPa)		Mean MOR (MPa)		N
Southern pine and Douglas-fir	On-grade	13.4	A	66.6	A	120 (119)[a]
	Off-grade	11.8	B	51.7	B	90

Means followed by different letters are significantly different at $\alpha = 0.01$.
[a] N for MOE was reduced by 1 due to the removal of an extreme outlier.

Table 5. Means comparisons of three grades when species are considered together. (Premium grade was determined by Director test.)

Species	Grade	Mean MOE (GPa)		Mean MOR (MPa)		N
Southern pine and Douglas-fir	Premium	16.1	A	76.0	A	24
	On-grade (w/out premium pcs.)	12.8	B	64.2	B	96 (95)[a]
	Off-grade	11.8	C	51.7	C	90

Means followed by different letters are significantly different at $\alpha = 0.01$, Tukey's honest significant difference multiple comparisons.
[a] N for MOE was reduced by 1 due to the removal of an extreme outlier.

grades could have been due to insufficient statistical power and, in part, to the low variability and high quality among on-grade crossarms. To increase the power, the variable of species was ignored and all specimens were considered together with a total N of 210.

Table 5 shows what happened when the Director was used to separate out a premium grade from the rest of the on-grade material. When the species are considered together, all three grades are statistically different from each other in both mean MOR and mean MOE. The mean grouping letters show that the mean values of both MOE and MOR differ significantly among on-grade, off-grade and premium grade crossarms when species is ignored (all p values for Tukey's honest significant difference (HSD) multiple comparisons ≤ 0.004).

Table 6 shows what happened when E-computer was used in a flatwise orientation to separate out a premium grade from the rest of the on-grade material. When the species are considered together, all three grades are statistically different from each other in both mean MOR and mean MOE. The mean grouping letters show that the mean values of both MOE and MOR differ significantly among on-grade, off-grade, and premium grade crossarms when species is ignored (all p values for Tukey's HSD multiple comparisons ≤ 0.011).

Table 7 shows what happened when E-computer was used in an edgewise orientation to separate out a premium grade from the rest of the on-grade material. When the species are considered together, all three grades are statistically different from each other in both mean MOR and mean MOE. The mean grouping letters show that the mean values of both MOE and MOR differ significantly among on-grade, off-grade, and premium grade crossarms when species is ignored (all p values for Tukey's HSD multiple comparisons <0.001).

Depending on which E-value from which device/orientation is used to identify the cutoff/threshold, the percentage of premium grade changes as do the mean values of MOE and MOR. Nonetheless, regardless which device is used, separating out the premium grade with the Director and E-computer devices creates three distinct grade categories that are significantly different in both mean MOR and MOE.

CONCLUSIONS

Based on this dataset, it appears possible to identify a premium grade of crossarms with the Director and E-computer devices that exhibits a significantly higher average MOE and MOR value than the rest of the on-grade material. These results have promising implications for

Table 6. Means comparisons of three grades when species are considered together. (Premium grade was determined by E-computer flatwise test.)

Species	Grade	Mean MOE (GPa)		Mean MOR (MPa)		N
Southern pine and Douglas-fir	Premium	15.2	A	73.4	A	35 (34)[a]
	On-grade (w/out premium pcs.)	12.7	B	63.7	B	85
	Off-grade	11.8	C	51.7	C	90

Means followed by different letters are significantly different at $\alpha = 0.05$, Tukey's honest significant difference multiple comparisons.
[a] N for MOE was reduced by 1 due to the removal of an extreme outlier.

Table 7. Means comparisons of three grades when species are considered together. (Premium grade was determined by E-computer edgewise test.)

Species	Grade	Mean MOE (GPa)		Mean MOR (MPa)		*N*
Southern pine and Douglas-fir	Premium	16.2	A	80.9	A	14 (13)[a]
	On-grade (w/out premium pcs.)	13.1	B	64.7	B	106
	Off-grade	11.8	C	51.7	C	90

Means followed by different letters are significantly different at $\alpha = 0.01$, Tukey's honest significant difference multiple comparisons.
[a] *N* for MOE was reduced by 1 due to the removal of an extreme outlier.

the possibility of increasing the value of the highest performing on-grade crossarms by marketing them as a premium grade.

Additional testing is recommended to determine the repeatability of the results. Larger sample sizes per species would increase the statistical power and aid in detecting significant differences among all three grades even when species are considered separately. This inherent, high quality of crossarms, however, makes this type of separation challenging.

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