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WOOD I BEAMS MANUFACTURED FROM SMALL DIAMETER LOGS

Thomas Gorman[1], Brad Miller[2], David Kretschman[3]

ABSTRACT: An innovative new concept for structural use of small diameter logs is a solid wood I-beam produced from a single log. We tested a set of 28 I-beams made from 15.25 cm diameter lodgepole pine (*inus contorta*) logs in bending to determine the MOE and MOR, to demonstrate the concepts and to determine if conventional stress design values for lodgepole pine logs could be applied. We also non-destructively assessed the MOE of individual logs prior to processing to determine if stress rating logs could predict final I-beam properties. I-beam stiffness was reasonably-well correlated with the stiffness of the log it was produced from; suggesting that non-destructive evaluation of raw logs offers a method for sorting to select high strength components.

KEYWORDS: I-beam, small log utilization, non-destructive evaluation, timber construction, beetle killed pine

INTRODUCTION

Harvests to control pine beetle infestations in the Intermountain Western United States should increase the availability of small diameter logs that could be used for manufacturing building products. An innovative new concept with potential for efficient use of this material is a solid wood I-beam produced from a single, small diameter log. This structural product could serve as a locally produced substitute for glued laminated beams, window and door headers, components for pedestrian and short span road bridges, or other beam applications.

OBJECTIVES

The main objective of this study was to demonstrate and test the concept of manufacturing structural I-beams from small diameter lodgepole pine (*inus contorta*) logs. We tested a set of I-beams in bending to determine the modulus of elasticity (MOE) and moduus of rupture (MOR), in order to determine if conventional stress design values for lodgepole pine logs could be applied. A second objective was to non-destructively assess the stiffness of individual logs prior to processing to determine if stress rating raw logs could be used to predict final I-beam properties and thus offer a procedure for selecting logs with the best potential for making I-beams.

BACKGROUND

By using small diameter logs as structural components themselves, rather than sawing into dimension lumber, more complete utilization of the log is achieved. This concept has been successfully demonstrated in several pavilions, kiosks, a library, and a pedestrian bridge [1].

A major European study has been completed on the utilization of round timbers for construction [2]. As part of that study, mechanical properties were obtained on several species tested in bending and in compression parallel to grain (Table 1). Overall, the logs averaged a little less than 127 mm (in diameter and were tested at a moisture content (MC) of about 16 percent. Bending tests were conducted with the logs simply supported and loaded symmetrically at the 1/3-point of the span. As is specified for lumber in Europe, the logs were tested at a span-to-depth ratio of 18:1. The MOE values were calculated using the average diameter of the log and the MOR values calculated using the diameter nearest failure. Short column compression tests were conducted using an unsupported free span of six times the log diameter, with compression MOE (*comp*) calculated using deformation measured over a span of four times the diameter. Tests in other test modes were also conducted but are not fully reported in the final report. Information on log characteristics, property relationships, and nondestructive testing options were also evaluated as part of the study. Initial emphasis in the material property phase of the study was on the development of visual grades geared to the European stress class system used for lumber [3], which are not directly applicable in the United States. However, the information on factors affecting log properties and relationships between properties is applicable.

Informaton on the correlation coefficient (r) between selected log characteristics and both bending and

[1] Thomas Gorman, Univ. of Idaho, USA, tgorman@uidaho.edu
[2] Bradley Miller, retired, USA, bradmillermt@gmail.com
[3] David Kretschmann, USDA FPL, dkretschmann@fs.fed.us

Country	Species	Bending				Compression			
		n	Age (yr.)	Diameter (mm)	MC (%)	n	Age (yr.)	Diameter (mm)	MC (%)
Austria	Norway spruce	85	--	135	--	--	--	--	--
Finland	Scots pine	175	20	124	15.9	175	19	117	15.3
	Norway spruce	200	28	112	15.6	200	24	107	15.7
Holland	Japanese larch	185	41	122	14.8	61	43	117	14.5
United Kingdom	Scots pine	100	33	130	18.9	100	33	127	17.3
	Sitka spruce	100	19	127	18.	100	19	124	17.3

a

Table 2 *Correlation coe icients o log characteristics ith mechanicalproperties or uropean small- iameter roun*

Characteristic	MOR	ucs	MOE	E_{comp}
Log diameter	-0.16	0.02	-0.02	-0.08
Knots				
Knot sum	-0.59	-0.56	-0.28	-0.46
Knot sum diameter	-0.56	-0.56	-0.27	-0.45
Maximum knot	-0.39	-0.43	-0.22	-0.45
Specific gravity				
Age	0.64	0.70	0.28	0.52
Density	-0.4I	0.61	0.40	0.59
Ring width	-0.55	-0.54	-0.25	-0.50
MC	-0.28	-0.59	0.06	-0.07
MOE	0.57	0.67	1.00	--

Table 3 *ultiple regression mo els or relating log characteristics o larch to R or potential mechanical gra ing applications*[a]

Model	MOE	Knots	Density	Ring width	r
5	X	--	--	--	0.76
7	X	X	--	--	0.80
6	X	--	X	--	0.79
8	X	--	--	X	0.79
12	X	X	X	--	0.82
11	X	X	X	X	0.82

[a] Ranta-Maunus [2].

compression strength values and MOE values [2] is presented in Table 2. For the species listed in Table 1, log diameter was less important than the relationship between MOE and strength. Except for ultimate compressive strength (UCS), MC was less important than other log characteristics.

Several measures of knot properties were obtained. The largest knot in the log (max knot) had some influence on both strength and stiffness prediction, but it was less correlated with these properties than was the sum of the knots in a given cross section (knot sum). The correlation of the sum of the knots divided by the diameter of the cross section was similar to the

correlation of the knot sum alone. Several different ways of looking at the overall specific gravity (SG) of the logs were evaluated, including the age of the tree, density at 12 percent MC, and ring width. One form or another of these indications of SG would appear important in a visual grading model, except, perhaps, for flexural MOE.

As noted earlier, visual methods were the primary grading focus in the study by Ranta-Maunus [2]. However, it was recognized that in the future there might be some interest in mechanical grading of logs. A number of multiple regression models were evaluated for larch for potential development of a mechanical grading system [2]. As can be seen from Table 3, adding some measure of knot size to MOE would appear to slightly improve the prediction of MOR (model 7 versus model 5), as does adding either density or ring width (model 6 or 8 versus model 5). The best model was that containing MOE, some measure of knots, and density (model 12). However, only slight improvement wasgained by using this model than just MOE and knots (model 7). Other measures of MOE, including dynamic measures, give correlations similar to those shown in Table 3 for static flexural MOE.

Barnard and Griffiths [4] presented information on the relationship between bending strength and compression strength for Sitka spruce (*icea sitchensis*) and Scots pine (*inus syl estris*) from the United Kingdom (see data summary for United Kingdom in Table 1). The relationship obtained for small-diameter logs is given in regressions (1) and (2) of Figure 1. Also shown is the relationship assumed for lumber in Eurocode, regression 1 [3, 5]. The European data on small-diameter round logs apparently show that the compression-bending relationship for logs is different from that for dimension lumber.

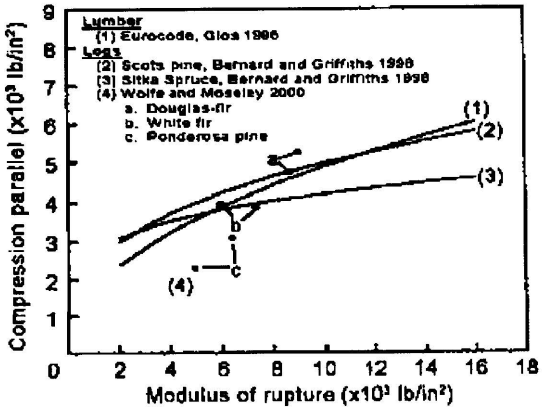

Figure 1: *Compression- en ing relationship or small-iameter logs , , l in k a*

Non-destructive grading methods for determining allowable design stresses for small diameter roundwood in the United States have been developed [6, 7, 8]. These methods are based on the machine stress grading evaluation procedure, for which the stiffness of components is evaluated as a mechanically measurable predictor of suitability for end use. Mechanical grading systems also employ some form of visual "override," a visual appraisal of specified characteristics that affect piece strength and stiffness, as well as limitations to end use performance such as warp and wane. Because machine stress grading sorts lumber into grades using a mechanically measurable predictor, such as MOE, grades are less variable in the predictor compared to similar visual grades [9]. When deflection criteria is the controlling limit to long span beams, preselecting logs with high stiffness characteristics to make structural components should be useful.

Green *et a1* [7] established the technical basis for mechanical grading 228 mm diameter logs. The material for that study was 236 logs of the Englemann spruce *icea engelmannii* -alpine fir *ies lasiocarpa* - lodgepole pine *inus contorta* species grouping (ES-AF-LP). The logs were cut from fire-killed trees and were at a moisture content of about 15 to 17 percent at time of test. Bending tests were conducted on 169 logs and short column compression tests on 67 logs. The relationships between properties are the basis for the mechanical grading of structural lumber. For machine stress rated lumber bending strength is estimated from modulus of elasticity. The coefficient of determination (r^2) between MOE determined by transverse vibration (E_{tv}) and determined by static test in third-point bending (MOE) was 0.83 for these 923 cm diameter logs. The r^2 value for the correlation between MOR and E_v, was 0.53, and that between MOR and MOE was 0.68. These correlations are similar to the results expected for softwood dimension lumber [10] and thus confirmed the potential for mechanical grading these logs for structural applications. The 90 percent lower confidence limit on the MOE-MOR relationship excludes 5 percent of the data on the lower side of the regression, and provides the regression equivalent to the 5th percentile traditionally used to assign properties to visually graded lumber.

Stepwise regression indicated that if MOE is measured, then addition of characteristics such as knot size and slope of grain provide only a marginal increase in the ability to predict MOR. In the initial phase of the study [11] the value between MOR and MOE increased from 0.61 to 0.67 with the addition of knot size (root mean square error increased from 4.46 MPa to 4.80 MPa). These results agree with results reported by Ranta-Maunus [2] for small-diameter logs from European species. It was recommended that MOE be the primary sorting criteria for the proposed grading system but that the maximum allowable knot size and slope of grain be limited to those allowed in No. 3 visual grade; knot size $\leq$ 3/4 of the diameter and slopes $\leq$ 1 in 6. Factors that might affect serviceability such as degree of roundness and warp were also set at the limits given for the No. 3 visual grade.

Green *et al* [7] concluded the following from their research on mechanical grading of structural roundwood:

- Property assignment procedures for visually graded logs using [12] produce slightly conservative assignment of MOE values and quite conservative assignment of allowable bending and compression strengths parallel to grain.
- A good correlation exists between static MOE in third-point bending and MOE determined by transverse vibration and between static bending strength, static MOE, and MOE by transverse vibration.
- Procedures traditionally used to assign allowable compressive strength parallel to grain to mechanically graded lumber also appear applicable to round timbers.
- There are apparently no technical barriers to developing a mechanical grading system for 228 mm diameter round timber beams.
- Additional research is needed to clarify anticipated grade yields at higher mechanical grades and the applicability of the proposed methods to logs of other sizes and species. Some of this research is in progress.
- Mechanical grading offers an opportunity to improve the precision of the property assignment for round timber beams and significantly increase grade yield for a given property specification.

In addition, earlier work demonstrated that mid-span, single point loading used to non-destructively determine the MOE of doweled logs gave good correlation (r^2 = 0.94) to the static MOE determined by ASTM D-198 third-point bending tests procedures [12]. The advantage of using single-point loading as a non-destructive method to determine MOE is the simplicity with which a measurement can be obtained, as well as the possibility for future implementation in an industrial setting.

In general, machining small-diameter logs to a constant diameter removes much of the mature wood on the outside of the beam, thus exposing more of the juvenile wood core. It also tends to expose more knots, especially in species that readily self-prune limbs on the lower part of the stem as the tree grows. The net effect of the machining is to lower both MOR and MOE. In a study on the effect of machining on small-diameter Douglas-fir (*seu otsuga men iesii*) and ponderosa pine (*inus pon erosa*) logs [1], suppressed-growth Douglas-fir logs, the MOR of 76- to 152-mm logs machined to a uniform diameter was reduced by about 8%, whereas the MOE was reduced about 15%. For 76- to 152-mm ponderosa pine logs, the MOR was reduced about 12% and the MOE about 33%. The greater effect of processing on the properties of ponderosa pine compared with those of Douglas-fir was probably a result of the respective ages of the trees, coupled with the relatively larger juvenile wood core of the shade-intolerant ponderosa pine. The suppressed-growth Douglas-fir trees had an average age of 67 years, whereas the average age of the ponderosa pine was only 42 years.

The concept of using small diameter logs to manufacture I-beams was developed to produce structural components that exceed the carrying capacity of individual structural logs (Figure 2). The conversion from roundwood to wood I-beams can potentially utilize over 80 percent of the material from a doweled log. For a tapered log, the conversion ratio would be reduced. The cross sectional moment of inertia increases nearly five times when converting roundwood to wood I-beams, effectively doubling the allowable span length. Table 4 provides examples of the estimated weights and cross sectional properties for six different small diameter timber sizes when converted to wood I-beams. If small diameter wood-I beams can perform at anticipated structural capacities, there is an opportunity to encourage beam production facilities in rural areas where pine beetle infestations have created the need for harvesting trees that are not large enough to be suitable for use as dimension lumber but adequate for production into I-beams.

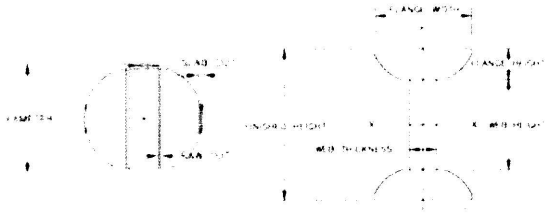

***Figure* 2:** *Cutting pattern le t or con erting a small iameter log into components to pro uce an - eam right*

METHODS

Logs used in the study were purchased from a cooperating post and pole manufacturer and preselected by measuring the stress wave velocity of logs using Fiber-gen Director HM200 acoustic log stress wave equipment [13]. The intent was to select logs that represented a range of stiffness values and to establish the correlation between stress wave velocities of logs and the MOE of I-beams produced from them. A total of 40, 15.25 cm diameter logs, measuring 4.9 m in length, were selected and brought to the laboratory. The logs were then non-destructively evaluated using a single-point, mid-span bending test to predict MOE, and from those results, we selected 28 logs that represented the 10 most stiff and 10 least stiff, plus 8 logs from the mid-range stiffness. The Equation (1) used to determine MOE from a single-point, mid-span load/deflection relationship is:

$$MOE = ({}^{3}/48)(/DI) \qquad (1)$$

where:
P / D = slope of load-deformation relationship
L = span
I = moment of inertia

Table 4: *amples o the eights an cross sectional properties o si i erent iameter roun oo - eams Roun oo alues are sho n a o e oo - eam alues*

Initial Roundwood Diameter & Finished Height (cm)	Area (cm^2)	Weight (kg/m)	Web Thick. (cm)	Web Height (cm)	Flange Width (cm)	Flange Thick. (cm)	Axis X-X I (cm^4)	Axis X-X S (cm^3)	C.G. (cm)	Axis Y-Y I (cm^4)	Axis Y-Y S (cm^3)
10.2	81.1	6.5					523	103		523	106
15.2	69.7	5.6	2.5	9.2	9.2	3.0	2,013	263	4.9	261	91
14.6	167.5	13.4					2,233	305		2,233	219
22.9	148.9	11.9	3.2	13.3	13.3	4.8	10,003	873	7.6	1,254	195
19.1	285.0	22.8					6,465	677		6,465	373
30.5	257.7	20.6	3.8	17.5	17.5	6.5	31,300	2,048	10.3	3,855	337
21.3	355.4	28.5					10,052	942		10,052	465
33.8	325.7	26.1	4.4	19.7	19.7	7.3	49,715	2,891	11.5	6,004	426
23.5	433.6	34.7					14,959	1,270		14,958	567
38.1	401.6	32.2	5.1	21.9	21.9	8.1	75,209	3,936	12.7	8,933	525
26.0	532.4	42.6					22,551	1,727		22,553	697
41.9	492.0	39.4	5.7	24.1	24.1	8.9	111,054	5,284	13.9	13,390	644

In addition, the stress wave velocity, as well as the volume and mass, of each log was measured in the laboratory to calculate the dynamic MOE (MOE_{dyn}), using the Equation (2) provided by Carter *et al* [13]:

$$MOE_{dyn} = pV^2 \qquad (2)$$

where:
p = nominal density
V = acoustic velocity

A portable bandsaw mill was used to cut each of the logs into three sections as shown in Figure 2, marked to identify the specific log that each component was made from, stacked, and air dried to approximately 12% moisture content. The components were then machined to create smooth surfaces for gluing, and a groove was machined into each of the flanges to assist with later assembly (Figure 3). I-beams were assembled by brushing a room temperature Curing phenol-resorcinol adhesive into each groove, stacking four I-beam assemblies at a time, and clamping overnight (Figure 4). Final dimensions of the I-beams were 21 cm high, 12.75 cm wide, and 3.66 m long.

After curing, the I-beams were kept in a conditioning room to maintain a 12% moisture content. Bending tests (Figure 5) were then carried out using ASTM D 198 third-point loading procedures [12] to determine MOE and ultimate bending stress for each I-beam.

Figure 3 *achine components prior to gluing he groo e cut in the langes as ma e to assist ith positioning the e s uring assem ly*

Figure 4 *Curing the glue an clampe sets o - eams*

Figure 5 *hir -point en ing test apparatus use to etermine an ultimate en ingstress*

RESULTS

The average cross sectional area for the 28 I-beams was 131.7 cm^2 (COV = 2.0). This area represents a utilization of 72% of the available wood fiber present in the raw logs obtained for the study. The bandsaw mill sawing and subsequent profile machining procedures used to prepare the components likely impacted the ratio of fiber utilization, such that a more precise sawing and machining procedure could improve the yield.

The average moment of inertia for the 28 I-beams was 7582.4 cm^4 (COV = 2.2). A higher moment of inertia could have been be achieved by reducing the depth of the groove used to position the web members (seen in Figure 2: This reduction would have improved the fiber yield and increased the carrying capacity of the I-beams.

Moisture content of the I-beams at the time of the bending tests averaged 12.7%. The mean static MOE for the 28 I-beams was 8.87 GPa (COV = 10.6).

The stress wave velocities measured in the field with the Director HM200 did not correlate well (r^2 = 0.3477) with the static MOE of the I-beams produced from them (Figure 6). However, when log density measurements were combined with stress wave velocity to predict MOE_{dyn} using Equation (2), the correlation was significantly improved (R^2 = 0.840) (Figure 7).

The static MOE of raw logs, determined by imposing a single-point, mid-span load on each log and measuring deflection, also correlated well (r^2 = 0.839) with the static MOE of the manufactured I-beams (Figure 8).

Seven of the 28 I-beams tested in bending failed due to shear in the web members (Figure 9). The ultimate bending loads on 5 of these samples were the highest recorded for all I-beams; the ultimate loads for the remaining 2 samples that failed in shear were the 10th and 11th highest recorded. The association of the shear failures with some of the highest levels of bending stresses suggest that the ultimate shear resistance of the wood I beams was well balanced with the ultimate bending stress resistance. Average shear stress at failure for the 7 specimens that failed in shear was 5,492 kPa (COV = 9.3), which is slightly higher than the value of 4,200 kPa reported for shear parallel to grain reported in the Wood Handbook [14] for lodgepole pine. No glueline failures were observed in any of the specimens.

The mean Modulus of Rupture (MOR) value for all of the I-beams was 59,623 kPa (COV = 22.4), which is somewhat lower than that reported in the Wood Handbook [14] for clear, straight-grained lodgepole pine bending samples (65,000 kPa), but consistent with the values found for No. 1 and Select Structural visually graded lodgepole pine dimension lumber in a previous study [15]. The correlation between static MOE and the 21 beams that failed in bending was poor (r^2 = 0.227) (Figure 10).

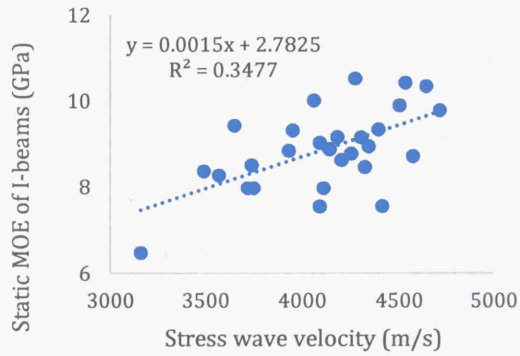

Figure 6: *Relationship et een iel measurements o the stress a e elocities o logs an the static o - eam pro uce rom the logs*

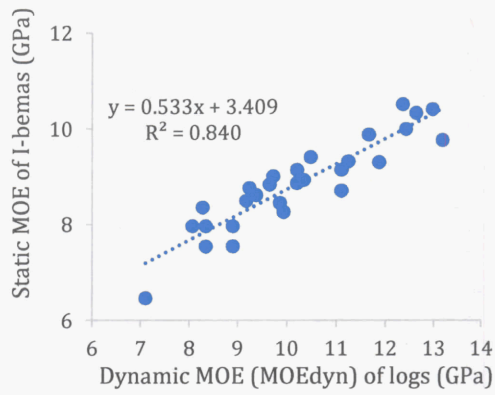

Figure 7: *Relationship et een ynamic o logs, as etermine y stress a e elocity an ensity measurements, an the static o - eams pro uce rom the logs*

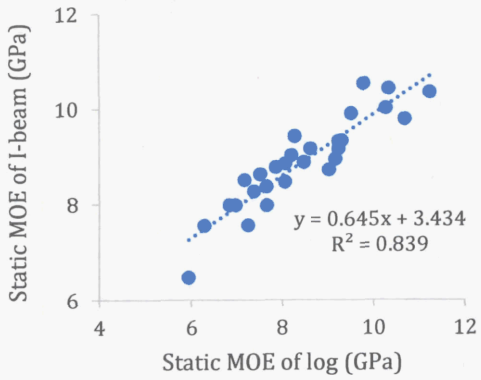

Figure 8: *Relationship et een static o logs, as etemine y single-point, mi -span loa ing, an the static o - eams pro uce rom the logs*

Figure 9: *e eno the - eams teste to ailure in en ing e hi ite shear ailure in the e s*

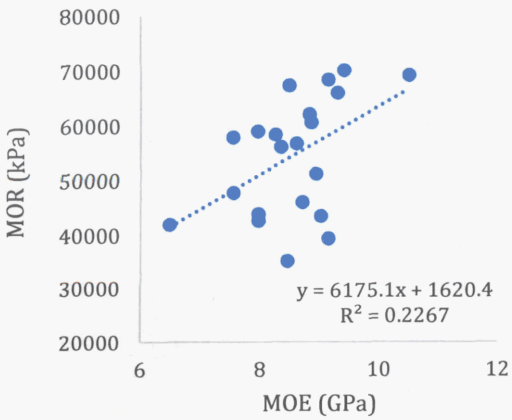

Figure 10: *Relationship et een the static an the R o the - eams that aile in en ing*

CONCLUSIONS

I-beams were succesfully made from doweled roundwood by sawing each log into 3 pieces and assembling the components into I-beams using structural glues. Since an I-beam made from a small diameter log has a significantly larger moment of inertia than the log it was produced from, this concept has the potential to significantly increase the structural use of small diameter roundwood. It is suggested that an improvement in the shear resistance of these I-beams can be made if the thickness of the web is increased slightly.

I-beam stiffness was reasonably-well correlated with the stiffness of the log it was produced from, suggesting that non-destructive evaluation of raw logs offers a method for sorting to select high strength components. There appears to be potential to predict, and therefore, assign, stiffness and strength values for I-beams made from beetle killed small diameter logs.

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