Size Effect on Strength Properties of Chinese Larch Dimension Lumber

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An experimental study was conducted to investigate the effect of size on the strength properties of Chinese larch (*Larix gmelinii*) dimension lumber. 7546 pieces of dimension lumber were sampled in three sizes, 40 by 65 mm, 40 by 90 mm, and 40 by 140 mm. After visually-grading and grouping, mechanical properties of bending strength, tensile strength, and compression strength parallel to grain were measured in a full-size test. Using nonparametric estimates, the combined length and width size effect parameters of H and L were 0.21 and 0.23 for the bending strength. The width effect parameters were 0.29 in H and 0.33 in L for the ultimate tensile strength parallel to grain. The width effect parameters of H and L were 0.12 and 0.20 for the ultimate compression strength parallel to grain. These size effect factors between H and L could be used when using the lumber for practical purposes.

Keywords: Bending strength; Chinese larch; Compression strength; Size effect; Tensile strength; Visual grading

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INTRODUCTION

The use of timber in structures requires that the mechanical properties of dimension lumber be properly estimated, so that design values can be developed in design codes. In the past, the design properties of Chinese timber in the Chinese timber design code GB50005-2003 (MOHURD 2005) were derived from test data of small, clear specimens, with adjustments for defects such as knots and the slope of the grain (The Editorial Committee 2005). A more recent approach to the development of strength properties involves testing full-size lumber. Since the 1970s, full-size in-grade tests have been used in North America, and other countries, to determine the mechanical properties of dimension lumber (Bodig 1977). As the full-size, in-grade test can accurately estimate the mechanical properties of dimension lumber, optimal design values can be developed based on the reliability approach in limit state (Madsen 1992). In China, the full-size test method of mechanical properties and the developing method of characteristic mechanical properties for structural lumber have officially issued (SAC 2012a, SAC 2012b). ASTM D1990 (American Society for Testing and Materials 2007) indicates that the property values of test data should be adjusted to the characteristic size. Because no existing strength data are available for Chinese species, the size adjustment on strength properties hasn’t been specified in the Chinese standards.

The model to quantify the effect of size was based on the weakest link theory. Bohannan (1966) reported the first study in which the Weibull brittle fracture theory was applied to wood. Madsen and Buchanan (1986) showed species dependence of the size effect. It was thought that Chinese fir dimension lumber has a clear difference in the size effect of strength properties, compared with SPF in North America (Zhou *et al*. 2010). Therefore, the size factor in ASTM D1990 standard, which was derived from North American grown species of Douglas fir, Hem-Fir, Southern Pine, and Spruce-Pine-Fir, may not be appropriate for adjusting strength properties of Chinese larch lumber. The size effect is also dependent on the strength grade of the lumber, because characteristics such as numbers and sizes of knots likely are different for each grade. The conclusion was validated by some researcher (Lam and Varoglu 1990; Takashi Takeda and Takeo Hashizume 1999; Zhou *et al*. 2010).

Evidence supports the need to study size effects in visually graded Chinese larch (*Larix gmelinii*). In this study the differences in the size effect between visually graded high-grade and low-grade Chinese larch lumber were studied and compared based on test results and appropriate data analyses.

EXPERIMENTAL

Sampling

Because there is currently no commercial production of Chinese larch dimension lumber, the sampling of dimension lumber cannot be conducted in sawmills. The material used in this study was collected from two regional forestry centres, Cuigang and Pangu, in the Daxing'anling region in Northeast China. In these forestry centres, the larch logs with diameters at breast heights (DBH) above 240 mm were sawn from secondary forests and cut into logs 4000 mm in length. The sampling plan focused on collecting representative logs with small-end diameters ranging from 160 to 340 mm. The number of selected logs was roughly in proportion with the annual cut of each forestry centre, in order to provide a sample group that was representative of the whole growing location. A total of 454 m^3 Chinese larch logs were sampled; 286 m^3 from Cuigang, and 168 m^3 from Pangu.

Lumber was sawn from the logs following a cant sawing pattern typically used in China, and then kiln-dried to a target moisture content (MC) of approximately 12%. After being kiln-dried, all sawn lumbers were planed to standard sizes of dimension lumber. The dimensions and numbers of the target sample sizes are shown in Table 1.

Table 1. Sampling Plan

Dimension thickness (mm) by width (mm) by length (mm)	Number of Specimens
40 by 65 by 4000	2705
40 by 90 by 4000	3357
40 by 140 by 4000	1484

Grading

Visual grading is a stress grading method, which is based on the premise that mechanical properties of lumber differ from mechanical properties of clear wood because many growth characteristics affect properties and these characteristics can be seen and judged by eye. Lumber was visually graded according to the grading rules provided in the Chinese timber design code GB50005-2005 (MOHURD 2005). The grading rules were derived from the NLGA Standard Grading Rules (NLGA 2005). In GB50005, the visual grade I_c is equivalent to NLGA SS; the visual grade II_c is equivalent to NLGA No.1, the visual grade III_c is equivalent to NLGA No.2, and visual grade IV_c is equivalent to NLGA No.3. Each visual grade denotes different degree of strength reducing characteristics existing in lumber. I_c is the highest grade and IV_c is the lowest grade.

During grading, the grade controlling defect, and maximum strength reducing defect (MSRD) were identified and recorded for each specimen.

Grouping

For 40 by 65 mm specimens, the dynamic Young's modulus (E_f) of the lumber was measured using the longitudinal vibration method (FAKOPP). The values were calculated from the resonance frequency determined by a fast Fourier transform spectrum analysis of the tap tone. Specimens were ranked according to their E_f values, in ascending order for each grade. Three groups of matched specimens were obtained by assigning the lumber with the lowest E_f value to the bending group, lumber with the next lowest E_f value to the compression group, and lumber with the third lowest E_f value to the tension group. The specimens with the next three lowest E_f values were then selected, and assigned similarly. This process was repeated until all lumber for each grade, and size was assigned to the three groups. Similar processes were used for the other three grades, and the 40 by 90 mm, and 40 by 140 mm specimens.

All samples were stored in a conditioning chamber maintained at 20℃, and 65 percent relative humidity before test.

Testing

The edge-wise bending test was conducted in accordance with ASTM Standard GB/T28993-12 (SAC 2012a) to evaluate the MOE, and bending strength (Fig. 1). For each specimen, MOE was first measured using the Yoke deflectometer; this was then followed by determination of the maximum load leading to failure. Test procedures are summarized as: one-third point loading conditions, an 18:1 span to depth (width) ratio, tension edges of bending specimens randomly selected, MSRD located randomly within the total test span, a loading rate to cause failure of about 10 minutes, and the total deflection of neutral axis at midspan was measured at both sides using a full-span yoke.

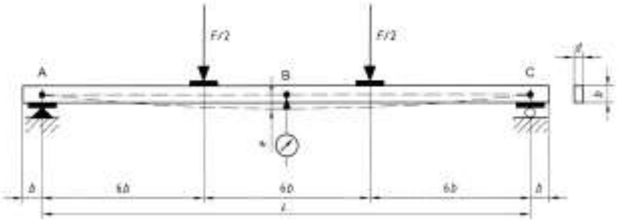

Fig. 1. Experimental setup of a third-point bending test based on ASTM D198; F:load; e: deflection; d: thickness; b: width

Tensile tests were conducted according to GB/T28993-12 to evaluate the tensile strength of each specimen. The tensile test machine (Metriguard Model 401) was used for the tension test. The tension machine was equipped with serrated plates to grip the specimens. Test procedures are summarized as: 2500 mm test spans for three sizes, MSRD randomly located within total test spans, and tests conducted at a loading rate to cause failure of 1 to 5 minutes.

Compression tests were conducted according to GB/T28993-12 using the compression test machine (WE-1000B) to evaluate the compression strength parallel to grain of each specimen. The test procedures can be summarized as: short column methods (without lateral support), 250 mm test spans for 40 by 65 specimens, 350 mm test spans for 40 by 90 specimens, 450 mm test spans for 40 by 140 specimens, and tests conducted at a loading rate to cause failure within 10 minutes. Because of the use of the short column method, several samples may need to be cut from the lumber in the whole length. One of the samples should be selected as the representative of the lumber according to their strength properties. Two samples were sawn from each I_c grade specimen, one containing MSRD, and the other with no defects. The compression strength value of each I_c grade specimen was derived from the lower strength value of the two samples. For II_c, III_c, and IV_c, three samples were taken for each specimen; one containing MSRD, the second one with minor defects, and the third one without defects. The compression strength value was determined from the lowest strength value of the three samples.

The annual ring width (ARW) and density for each specimen was measured near the rupture location according to the national standards GB/T1930-2009 (SAC 2009a) and GB/T1933-2009 (SAC 2009b).

Data Processing

The size effect on the strength of lumber is based on the weakest link theory (Madsen 1992). The size effect on strength using the brittle fracture theory is described as a relation between the volume, and strength of two members. The relation is given by

$$\frac{x_1}{x_2} = \left(\frac{V_2}{V_1}\right)^{s} = \left(\frac{V_1}{V_2}\right)^{-s} \tag{1}$$

where x_1 and x_2 are the strengths of members of volumes V_1 and V_2, respectively, and s is the size effect parameter. The change in strength for doubling the volume can be obtained by setting $V_2/V_1 = 0.5$. If s becomes greater, then the effect of doubling the volume becomes severe, and for $s = 0.3$ only 81% of the strength remains.

In general, there are three methods to obtain estimates of the size effects from experiments: the slope method, the shape parameters, and the fracture position (Madsen 1992). The slope method was the only one used in this paper. Using the slope method, Eq. (1) can be rearranged to give a linear relation between the logarithm of strength and the logarithm of volume,

$$\frac{\ln x_2 - \ln x_1}{\ln V_2 - \ln V_1} = -s \tag{2}$$

where s is the size effect parameter, which is the slope of the regression line of x on V (disregarding the negative sign).

The ASTM 1990 standard indicates that the length effect parameter is 0 for compression strength parallel to the grain, and the thickness effect parameter is 0 for bending strength. Tension strength and compression strength tests were both carried out parallel to the grain.

RESULTS AND DISCUSSION

Mechanical Properties of Chinese Larch Dimension Lumber

The ARW and the density at 12% moisture content were 1.47 mm and 0.64 g/cm^3, respectively. The 5th percentile of strength distributions was obtained by the nonparametric method according to GB/T28987-12 and ASTM Standard D2915-10 (ASTM International 2010) and shown in Tables 2.It can be noted that I$_c$ lumber had higher mechanical properties than II$_c$, III$_c$, and IV$_c$ lumber. In some cases, III$_c$ lumber was stronger than II$_c$ lumber, even though the latter should have smaller knot sizes according to grading rules in national standard GB50005-2003. This is also found in test data of mechanical properties of Canadian coastal Douglas-fir and Hem-fir (Chen *et al*. 2009).

Table 2. Characteristic Mechanical Properties of Chinese Larch

Size	Visual grade	MOE(GPa)	Bending strength (MPa)	Tensile strength parallel to the grain (MPa)	Compression strength parallel to the grain (MPa)
40 by 65 by 4000	I$_c$	11.65(17.60)	39.55(34.33)	20.85(37.76)	37.01(18.82)
	II$_c$	10.28(17.81)	29.51(38.67)	12.49(39.90)	33.18(15.60)
	III$_c$	9.69(20.06)	29.44(39.41)	13.91(48.78)	30.89(23.02)
	IV$_c$	8.38(23.31)	22.38(44.16)	11.39(49.46)	23.78(29.94)
40 by 90 by 4000	I$_c$	10.16(19.05)	38.38(32.59)	20.76(37.53)	37.40(21.13)
	II$_c$	9.09(18.58)	25.85(39.19)	14.35(32.48)	28.95(27.90)
	III$_c$	8.78(21.94)	26.57(37.79)	13.88(39.15)	25.89(29.59)
	IV$_c$	8.45(23.62)	19.57(44.49)	9.07(58.15)	24.53(31.39)
40 by 140 by 4000	I$_c$	10.77(17.80)	28.93(36.01)	16.80(37.95)	31.73(19.67)
	II$_c$	10.03(17.28)	14.22(45.72)	14.11(29.95)	24.19(17.03)
	III$_c$	10.67(20.21)	24.17(42.75)	12.64(46.67)	24.77(25.08)
	IV$_c$	10.56(19.31)	22.62(38.56)	13.01(42.23)	22.17(27.14)

Note: Values in parentheses are coefficients of variation (%).

Size Effect on Strength Properties of Chinese Larch Dimension Lumber

Based on all test data, the size effects on the bending strength, tensile strength, and compression strength of Chinese larch visually-graded lumber were analyzed. For each lumber size, the test data of I$_c$ grade lumber was integrated as the high-grade group, and test data of II$_c$ and III$_c$ lumber as the low-grade group. In the following section, the high-grade group is called the H group, and the low-grade group is called the L group. The size effects of 5th percentile of strength properties for each sample group were estimated using the slope method (HB Zhou *et al*. 2010). The effect parameters were calculated by the least squares method as shown in Figs. 2 through 4. The summary and comparison of size parameters are listed in Table 3. The combined length and width size effect parameters of H and L were 0.21 and 0.23 for the bending strength. The estimated width effect parameters were 0.29 in H and 0.33 in L for the ultimate tensile strength parallel to grain. The estimated width effect parameters of H and L were 0.12 and 0.20 for the ultimate compression strength. The size effect parameters for H were close to the recommended size effects in ASTM D1990, while all those for L were constantly bigger. The result also validated the difference of lumber characteristics between Chinese grown species and North American grown species. The parameters of L were always larger than those for H. It was thought that different size effects are observed in different grades, because characters such as frequency and size of defects, likely differ for each grade. H has fewer strength-reducing defects, such as knots and other growth defects, than L.

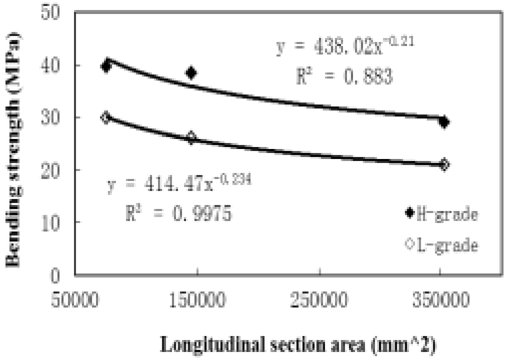

Fig. 2. Effect of longitudinal section area on bending strength of Chinese larch lumber

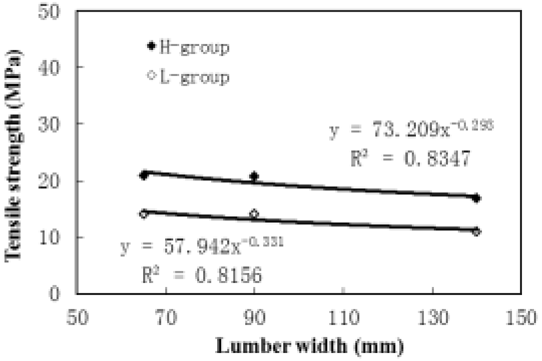

Fig. 3. Effect of width on tensile strength parallel to the grain of Chinese larch lumber

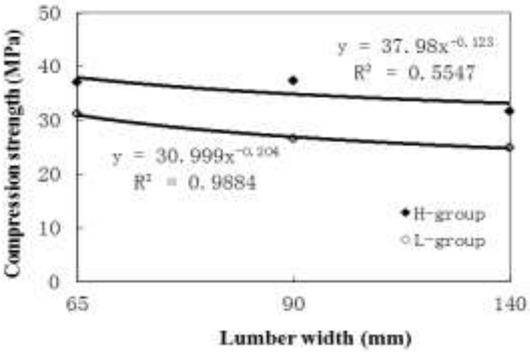

Fig. 4. Effect of width on the compression strength parallel to the grain of Chinese larch lumber

Table 3. Summary and Comparison of Size Parameters

Strength properties	Chinese larch			ASTM D1990	
	Visual grade	Longitudinal section area	Width	Length	Width
Bending	H	0.21	——	0.14	0.29
	L	0.23	——		
Tension parallel to the grain	H	——	0.29	0.14	0.29
	L	——	0.33		
Compression parallel to the grain	H	——	0.12	0	0.13
	L	——	0.20		

CONCLUSIONS

The characteristic values of mechanical properties of 40 mm thick Chinese larch dimension lumber with four visual grades were presented. The Ic grade lumber always showed higher mechanical properties than IIc, IIIc, or IVc grade lumber. Some strength properties of IIc grade lumber were not consistently higher than that of IIIc or IVc lumber.

These characteristic values may be further modified for a standard size to be converted to the allowable stress for normal loading conditions. The test value further validates that both different visual grades and species have different size effects. The size effect factors, as defined as the ratio of the strengths when the width has been doubled and the length has been constant, were 0.86 in H and 0.85 in L for bending strength, 0.82 in H and 0.80 in L for tensile strength, and 0.92 in H and 0.87 in L for compression strength.

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