J Wood Sci (2010) 56:15–18
DOI 10.1007/s10086-009-1065-x

ORIGINAL ARTICLE

Jinghui Jiang · Jianxiong Lu · Haiqing Ren · Chao Long

Predicting the flexural properties of Chinese fir (*Cunninghamia lanceolata*) plantation dimension lumber from growth ring width

Received: December 17, 2008 / Accepted: July 10, 2009 / Published online: November 18, 2009

Abstract In this report, the 575 specimens were divided into ten groups based on range of growth ring width. The modulus of elasticity (MOE) and modulus of rupture (MOR) of 45 × 90 mm specimens of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) plantation dimension lumber were analyzed by average growth ring width and average density of each group. The results showed that the average growth ring width was in inverse proportion to density, MOE, and MOR of the dimension lumber. Furthermore, average density was in direct proportion to MOE and MOR of the dimension lumber. The coefficient of determination (R^2) for all the regression equations ranged from 0.7340 to 0.9207 at a significance level of 0.001. However, without such group classification, there was poor relationship between growth ring width, density, MOE, and MOR with a determination coefficient of 0.0901–0.1855. This finding suggested that it was feasible to predict the flexural properties of Chinese fir plantation dimension lumber by average growth ring width after specimen group classification.

Key words Chinese fir plantation · Dimension lumber · Average growth ring width · Density · Flexural properties

Introduction

The flexural properties [modulus of elasticity (MOE) and modulus of rupture (MOR)] of dimension lumber are used to determine the flexural design values of allowable bending strength and stiffness for each piece of lumber or group of lumber of a specific width.[1] Thus, predicting the flexural properties of dimension lumber has important practical significance. There is no doubt that MOE and MOR are affected by many factors including specific gravity (SG), growth ring width, defects (knots, slope of grain), moisture content (MC), and percentage of latewood.

Doyle and Marwardt established the following relationship between MOR and SG: $\mathrm{MOR}_{\mathrm{psi}} = 21\,481(\mathrm{SG}) - 4\,701$, with a very low coefficient of determination ($R^2 = 0.24$), for southern yellow pine (*Pinus ponderosa*) dimension lumber of three different cross sections (2 by 4 in., 2 by 6 in., and 2 by 8 in.).[2] Dunham et al. studied the relationship of knot area ratio (KAR) and MOR of birch (*Betula pendula*) dimension lumber, and they reported MOR = 67.8 − 0.62 KAR, with $R^2 = 0.18$.[3] Biblis et al. established the regression relationship of MOE to growth rings per inch and SG: MOE = 322 683 + 74 996 (rings/in.) + 1 238 971 (SG), with $R^2 = 0.21$, and the relationship of MOR to growth rings per inch, SG, and latewood percentage: $\sqrt{MOR}_{\mathrm{psi}} = 9.9848 + 1.5972$ (rings/in.) + 0.8795 (%latewood) − 0.0129 $(\%\mathrm{latewood})^2$ + 84.8307 (SG), with $R^2 = 0.25$, for 2 by 4 in., 40-year-old loblolly pine (*Pinus taeda* L.) dimension lumber.[4] However, Dai et al. studied the relationship among MOE, density, growth ring width, and latewood percentage for small clear specimens and found that they were correlated with a coefficient of determination of 0.76.[5] Zhang established the linear equation of MOR to SG: MOR = −1.2 + 149 (SG), with $R^2 = 0.93$; and the linear equation of MOE to SG: MOE = 0.167 + 1.54 (SG), with $R^2 = 0.87$, for a small clear specimen of Chinese semi-ring-porous wood category.[6,7]

As already mentioned, compared with the small clear specimen, a lower relationship between MOE or MOR and SG, KAR, growth rate, and latewood percentage could be obtained for the dimension lumber. This observation may result from the existence of other factors such as knots, slope of grain, and shake affecting the strength of dimension lumber. Therefore, it is possible to decrease the influence of these factors by specimen group classification so that the relationship between strength and density, growth ring width, etc. of the dimension lumber increases.

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is one of the most widely planted trees in China; it grows very fast, vertical, with straight and uniform grain. Traditionally, it was used as a construction material.[8] With the publication

J. Jiang · J. Lu (✉) · H. Ren · C. Long
Research Institute of Wood Industry, Chinese Academy of Forestry, Wan Shou Shan, Haidian, Beijing 100091, China
Tel. +86-10-6288-9482; Fax +86-10-6288-1937
e-mail: jianxiong@caf.ac.cn

of a code for design of timber structures in China,[9] Chinese fir plantation wood has great potential to be used in structural applications as a dimension lumber. Therefore, the strength properties of Chinese fir plantation dimensional lumber have been extensively studied in recent years.[10,11] In this study, the flexural properties of Chinese fir plantation dimension lumber predicted from the width of growth rings were determined. To improve the effectiveness of the prediction, the specimens were divided into ten groups based on growth ring width, which ranged from <3 mm, to 4–5 mm, to 5–6 mm, and to >11 mm, respectively. The relationship among the average growth ring width of group and corresponding values of MOE, MOR, and density was investigated.

Materials

A Chinese fir tree, 34 years old, with a breast diameter of 25–35 cm, was felled from Jiangle Country of Fujian Province. The logs were sawn to the dimensions of 50 mm × 100 mm, and the lumber was kiln-dried to approximately 15% MC, planed into dimension lumber 45 × 90 × 3700 mm,[9] and graded by a qualified lumber grader to four grades: Select Structural (SS), No. 1, No. 2, and No. 3, according to the visual grading technical manual of the national lumber grades authority (NLGA) of Canada.[12] The total number of specimens was 575 pieces.

Methods

All specimens were destructively tested along their edges under third-point loading at a span-to-depth ratio of 18:1 according to ASTM D4761.[13] Load and corresponding deflection-to-failure data were obtained with a data acquisition system connected to a computer for processing. MOE, MOR, MC, and density for each tested piece of lumber were subsequently calculated. In addition, a slice of wood with a depth of 1 cm was taken from the broken area to calculate the growth ring width. Finally, all the density, MOE, and MOR values were adjusted to a standard MC of 15% according to ASTM D1990.[14]

In NLGA, measuring the average rate of growth was determined by counting the number of rings in a 3-in. line that was perpendicular to the growth rings (also called a radial line) and dividing by 3 in., with a unit of rings/inch. Then the average growth ring width equals to 25.4 mm (1 in.) divided by the average rate of growth, with a unit of mm/ring. It should be noted that this kind of calculation is suitable for species with evenly distributed growth ring width.[12] However, for Chinese fir plantation wood, as shown in Fig. 1, there was a great difference of growth rings between wide and narrow. In this case, if the method described above was applied to determine the average growth ring width, it may cause inaccurate results. Therefore, the cross section of each specimen in this study was divided into two parts, i.e., first, to wide and narrow growth rings areas, and then the average growth ring width and the area ratio of the cross section for each part were measured, respectively. Finally, the average growth ring width for the specimen was calculated by the sum of the growth ring width multiplied by the area ratio of the two parts. In this study, the growth ring width of 4 mm chosen as the demarcation of the two parts was mainly based on the following considerations. For Chinese fir plantation trees with mature wood at age of 16 years, Bao et al. compared the properties of juvenile wood and mature wood and reported that the average growth ring width was 7.08 mm for juvenile wood, with a standard deviation of 0.64 mm, and 3.58 mm for mature wood with a standard deviation of 1.03 mm.[15] Considering the effect of growth ring on the variations of properties, the cross section of the tested specimen was also different in Chinese national standard GB1933-91. For the small clear specimen with a growth ring width of no more than 4 mm, the cross section of the test specimen is 20 × 20 mm; for those with growth ring width greater than 4 mm, the cross section of the test specimen is 50 × 50 mm.[16] Finally, the distribution of the growth ring width in each specimen was investigated, and it was found that 4 mm was suitable for the demarcation of wide and narrow growth rings. In this study, the area ratio of growth ring width that is greater than 4 mm was recorded as X% and that no more than 4 mm was (100 – X)%; the growth ring width of the two parts was measured as A or B, respectively, according to NLGA. Therefore, growth ring width (GRW) of each specimen was obtained as follows: GRW = $X\% \times A + (100–X)\% \times B$.

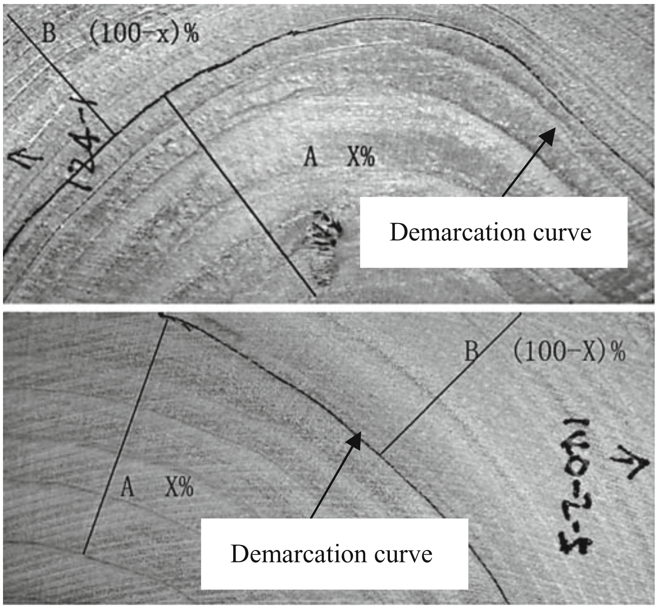

Fig. 1. Cross section of Chinese fir plantation dimension lumber. *A*, Growth ring width of the wide growth rings part; *B*, Growth ring width of the narrow growth rings part; *X*%, area ratio of the wide growth rings part; *(100–X)*%, area ratio of the narrow growth rings part

Results and analysis

Table 1 shows the relationships based on the data from all specimens. Poor relationships were seen between growth ring width, density, MOE, and MOR with a determination coefficient of 0.0901–0.1855, and between MOE and MOR with a determination coefficient of 0.365. This result was quite similar to the preceding results with a lower coefficient of determination.[2–4] Two reasons could be suggested. On one hand, it appeared that the effectiveness of the prediction became poorer as the number of samples increased. On the other hand, such relationships were very complex because they were influenced by other defects such as knots, slope of grain, and shake. Therefore, the specimen group classification was further carried out. All specimens were divided into ten groups based on the range of the growth ring width. The number of samples, average growth ring width, average density, average MOE, and average MOR, etc., for each group are shown in Table 2. The coefficient of variation of density in each group was less than 11%, and the coefficient of variation of MOE and MOR was in the range of 11.37% to 27.30% for each group.

Table 1. Results of regression analyses of MOE, MOR, density, and growth ring width: the linear equation is $Y = A\ X + B$

Y	X	A	B	R^2
Density	Growth ring width	–0.0057	0.4084	0.0901
MOE	Growth ring width	–0.3912	11.784	0.1855
MOR	Growth ring width	–2.4431	55.986	0.1777
MOR	MOE	3.854	5.5664	0.3649

MOE, modulus of elasticity; MOR, modulus of rupture

Density versus average growth ring width

Table 3 shows the relationships based on the data after the specimen group classification. The linear relationship of average density and average growth ring width was established: density = –0.0047 × (average growth ring width) + 0.404, where coefficient of determination (R^2) was 0.8031 at a significant level of 0.001 (Table 3). It was concluded that the density was in inverse proportion to growth ring width; this was in agreement with the previous results. Bao et al. also found that the wider growth rings near the pith had lower density.[15] Li et al. reported a linear relationship between air-dried density and growth ring width for small clear Chinese fir plantation specimens.[17]

MOE and MOR versus average growth ring width and density

It is clear from Table 3 that MOE and MOR were in inverse proportion to average growth ring width: their linear equations were MOE = –0.2928 × (average growth ring width) + 11.23 and MOR = –1.7312 × (average growth ring width) + 52.55, with a coefficient of determination (R^2) of 0.8285 and 0.734 at a significance level of 0.001, respectively. Then, MOE and MOR were in direct proportion to density: their linear equations were MOE = 56.334 × (average density) – 11.72 and MOR = 361.38 × (average density) – 93.614, with a coefficient of determination (R^2) 0.8510 and 0.8876 at a significance level of 0.001, respectively.

Compared to previous studies, this study showed that the coefficient of determination (R^2) was obviously higher than that in the previous studies, which may be related to the

Table 2. Results of average growth ring width, average density, MOE, MOR, and moisture content (MC)

Growth ring width (mm)	Number of samples	Average growth ring width (mm)	Average density (g/cm^3)	CV of density (%)	Average MOE (GPa)	CV of MOE (%)	Average MOR (MPa)	CV of MOR (%)	MC (%)
<3	42	2.7	0.400	9.55	10.75	19.62	52.29	25.99	11.56
3–4	112	3.5	0.388	10.97	10.33	14.27	48.41	23.12	11.39
4–5	129	4.5	0.378	8.60	10.21	13.56	44.29	21.64	10.25
5–6	122	5.5	0.379	8.49	9.67	17.27	41.49	25.19	11.91
6–7	68	6.4	0.369	8.65	8.92	18.13	39.17	24.12	12.02
7–8	40	7.4	0.371	10.70	8.66	14.99	35.93	20.04	11.74
8–9	27	8.4	0.348	7.73	8.35	24.97	33.77	21.03	10.79
9–10	14	9.3	0.360	8.98	8.06	15.52	35.30	19.23	11.52
10–11	16	10.3	0.359	10.40	8.33	20.64	37.26	27.30	11.61
>11	5	12.1	0.354	2.35	8.43	23.20	36.05	11.37	10.85

CV, coefficient of variation

Table 3. Results of regression analyses of MOE, MOR, density, and average growth ring: the linear equation is $Y = A\ X + B$

Y	X	A	B	R^2	Significance level
Average density	Average growth ring width	–0.0047	0.404	0.8031	***
MOE	Average growth ring width	–0.2928	11.23	0.8285	***
MOE	Average density	56.334	–11.72	0.8510	***
MOR	Average growth ring width	–1.7312	52.55	0.7340	***
MOR	Average density	361.38	–93.614	0.8876	***
MOR	MOE	6.0269	–14.875	0.9207	***

*** Significant at 0.001 level

specimen group classification. After all specimens were divided into ten groups, the variation of 575 specimens was transformed into the differences among the ten groups. The influence of other defects on the flexural properties of dimension lumber was decreased by this specimen group classification. Therefore, the advantage of this kind of statistical method was to reduce specimen variation to clarify the relationship between MOE, MOR, and average growth ring width.

MOR versus MOE

From Table 3, the linear relationship of MOR and MOE was obtained as follows: $\mathrm{MOR} = 6.0269 \times \mathrm{MOE} - 14.875$, where coefficient of determination was 0.9207 at a significance level of 0.001. The regressions of MOR and MOE for each dimension lumber have important practical significance because the MOE value of each lumber piece can be determined nondestructively, easily, and quickly. Using the regressions for each lumber piece, the corresponding MOR value can be predicted from the MOE value.

Conclusions

In this study, to improve the prediction method of flexural properties using growth ring width of Chinese fir plantation dimension lumber, the growth ring width of each specimen was divided into wide and narrow parts to get the average growth ring of the specimen, and then specimen group classification was carried out based on the average growth ring of the individual specimen. The results could be summarized as the following:

1. With specimen group classification, the average growth ring width was in inverse proportion to density, MOE, and MOR of the dimension lumber. The average density was in direct proportion to MOE and MOR of the dimension lumber. The coefficient of determination (R^2) for all the regression equations ranged from 0.7340 to 0.9207 at a significance level of 0.001.
2. Without specimen group classification, there was a poor relationship between growth ring width, density, MOE, and MOR with a determination coefficient of 0.0901–0.1855.
3. The results suggested that it was feasible to predict the flexural properties of Chinese fir plantation dimension lumber by the average growth ring width after specimen group classification. Further investigations about the influence of knots, knot sizes, knot location, and slope of grain on MOR and MOE are needed.

Acknowledgments The author extends gratitude to Prof. Xiuqin Luo, Dr. Yafang Yin, and Assistant Prof. Zhaohui Luo for their support for this study. Parts of this work were financially supported by the standard system on forestry engineering supported by Ministry of Science and Technology (2004DEA7090-1) and machining and processing technology of constructional lumber supported by key project of Ministry of Science and Technology (2006BAD18B07).

References

1. American Society for Testing and Materials (2002) Annual Book of ASTM standards. Vol. 04.10 Wood. American Society for Testing and Materials, West Conshohocken, PA, pp 79–94
2. Doyle DV, Marwardt LJ (1996) Properties of southern pine in relation to strength grading of dimension lumber. Research Paper FPL-64. USDA Forest Service, Forest Products Laboratory, Madison, WI
3. Dunham R, Cameron A, Petty J (1994) The effect of growth rate on the strength properties of sawn beams of silver birch. Scand J For Res 14:18–26
4. Biblis E, Meldahl R, Pitt D (2004) Predicting flexural properties of dimension lumber from 40-year-old loblolly pine plantation stands. For Prod J 54:109–113
5. Dai D, Qiao Y, Wang S, Luan S (1988) Predicting strength properties of wood by width of growth ring. J Shenyang Agric Univ 19:55–60
6. Zhang S (1994) Mechanical properties in relation to specific gravity in 342 Chinese woods. Wood Fiber Sci 26:512–526
7. Zhang S (1997) Wood specific gravity-mechanical property relationship at species level. Wood Sci Technol 31:181–191
8. Ren H, Nakai T (2006) Intratree variability of wood density and main wood mechanical properties in Chinese fir and poplar plantation. Sci Silvae Sin 42:13–20
9. The National Standards of the People's Republic of China (2005) GB50005-2003. Code for design of timber structures. China Building Industry Press, Beijing, pp 74–78, 121
10. Jiang J, Lu J, Ren H, Luo X, Chao L, Guo W (2008) Evaluation of modulus of elasticity for dimension lumber by three nondestructive techniques. J Zhejiang For Coll 25:277–281
11. Chao L (2007) Comparative study on the influence of various testing methods on mechanical properties of Chinese fir plantation dimension lumber. Doctoral dissertation, Chinese Academy of Forestry, Beijing
12. National Lumber Grades Authority (2003) Standard grading rules for Canadian lumber. NLGA, British Columbia, Canada, pp 70–75, 182–183
13. American Society for Testing and Materials (2002) Annual Book of ASTM standards. Vol. 04.10 Wood. American Society for Testing and Materials, West Conshohocken, PA, pp 524–533
14. American Society for Testing and Materials (2002) Annual Book of ASTM standards. Vol. 04.10 Wood. American Society for Testing and Materials, West Conshohocken, PA, pp 300–325
15. Bao F, Jiang Z (1998) Wood properties of main tree species from plantation China. China Forestry Publishing House, Beijing, p 5
16. China State Bureau of Technical Supervision (1991) GB1933-91. Method for determination of the density of wood. Standards Press of China, Beijing
17. Li J, Liu Y, Cui Y, Xu Z (1999) Demarcation of juvenile and mature wood of planted Chinese fir and its wood quality prediction. J Northeast For Univ 27:24–28