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ORIGINAL ARTICLE

Research on design value of compressive strength for Chinese fir dimension lumber based on full-size testing

Yingchun Gong[1] · Guofang Wu[1] · Xiuqin Luo[1] · Zhaohui Wang[1] · Jinghui Jiang[1] · Haiqing Ren[2]

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Abstract The objective of this study was to obtain design value, which was calculated according to the limit states design method, for the utilization of Chinese fir in the building structure field as a green building material. A total of 342 specimens were tested by static compression method. The normal and lognormal distributions were selected to fit the experimental data. The results indicated that reliability index increased nonlinearly with the live-to-dead ratio and resistance partial coefficient increased. To meet the target index ($\beta_0 = 3.2$), it was suggested that design values of compressive strength of Chinese fir were set to 13.751, 13.186, and 13.123 MPa for SS, No. 1, and No. 2 grade, respectively.

Keywords Design value · Chinese fir · Compressive strength · Limit states design method

Introduction

With the rapid development of the wooden structure in China, the demand for wood resources has been increasing in recent years. However, due to enforcing logging-ban at the natural forest effective in 2015 in China, wood nature resources is in serious shortage. Therefore, plantation resources need to be developed and utilized in China. Chinese fir (*Cunninghamia lanceolata*) is one of the three main plantation tree species in China. It distributes from latitude 22–34°N and longitude 100–122°E. Chinese eighth national forest resources survey shows that the area of plantation of Chinese fir is 9.21 million ha [1, 2]. In the meantime, Chinese fir has many advantages, such as fast-growing, good mechanical performance, and decay resistance. It has been widely used to fabricate dimension lumber, glued lumber, and wood-based composites [3, 4]. However, due to the lack of design values of mechanical properties for engineered wood products, thus it is unsafe to use these in the building structure filed.

Dimension lumber has standardized design dimensions. It has been used in a variety of applications including in building frame, floor, and wall components [5, 6]. The visual grading and machine stress rated methods were applied to evaluate the strength grading of dimension lumber. According to National Lumber Grades Authority (NLGA)–Standard Grading Rules for Canadian Lumber [7], the visual grading divided lumber into four grade including SS, No. 1, No. 2, and No. 3, based on wood growth characteristics. It lines up with the classification in Chinese National Code [8] including Ic, IIc, IIIc, and IVc grade.

There are significant differences on the design value of mechanical properties for the same grade dimension lumber, because different countries have different evaluation methods, load statistics, and load combinations. For example, the statistics of snow load (q), which equals the ratio average value and standard value, is 1.04 in China, but q value ranges from 0.61 to 0.82 in the United States [9]. Furthermore,design value of wood strength is generally determined by full-size testing and small clear specimens testing [10]. Comparing these two methods, the full-size

✉ Haiqing Ren
renhq@caf.ac.cn

[1] Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing 100091, People's Republic of China

[2] Research Institute of Forestry New Technology, Chinese Academy of Forestry, Beijing 100091, People's Republic of China

testing takes natural defect, size effect, and other factors into consideration. Therefore, the test results are much closer to the actual situation. The previous research [11] reported that the length had significant effect on tensile strength of visually graded Chinese fir dimension lumber. Currently,the full-size testing method has been applied in the United States, Canada, and Japan to determine the flexural, compressive, and tensile strength of dimension lumber [12, 13]. However, according to Code for design of timber structures [8], the design value is still based on small clear specimens testing for dimension lumber fabricated with native tree species.

In this study, a total of 342 specimens were tested by static compressive method. The object was to determine design values of full-size compression strength parallel to grain (UCS) for Chinese fir dimension lumber based on the first-order second-moment reliability analysis. The research on design value will provide basic data for the application of Chinese fir in the building structures filed.

Materials and methods

Materials

To ensure random and representative of samples, Chinese fir (*Cunninghamia lanceolata*) was harvested from Huangshan mountain forest farm of Anhui Province, Xuefeng mountain forest farm of Hunan Province, and Helong forest farm of Sichuan Province, China. In total, 80 logs with 3 m long and the diameter at breast heights ranged from 250 to 320 mm were selected. The logs were cut into dimension lumber using four sawing method. Due to measure in millimeters (mm) using in Chinese Code, sizes of the 40 mm × 90 mm were deemed identical to 2 × 4 of North American commercial lumber sizes. The length of dimension lumber was 2550 mm. The samples were graded by visual grading according to NLGA. The samples were divided into SS, No. 1, and No. 2 grade. Two compression samples with dimensions 40 × 90 × 350 mm for UCS testing were cut from the normal dimension lumbers of Chinese Fir, and one of them contained the maximum strength-reduced defect. Sample size for each grade is shown in Table 1.

Table 1 Sample size of each grade

Grade	Sample size
SS	136
No. 1	98
No. 2	108

Static test methods

The compressive tests were performed in accordance with ASTM D4761-2009 [14]. The required failure time was between 3 and 10 min. To accommodate the time to failure requirement, loading speed was adjusted to 2 mm/min. The specimens were tested using a universal machine (INSTRON 5582) and the maximum load was recorded as the failure load. All specimens were conditioned at 20 °C and at 65% relative humidity (RH). Weight, dimensions, and moisture content of each specimen were measured after the equilibrium moisture content reached. The compressive strength of Chinese Fir dimension lumber was calculated using Eq. 1.

$$\sigma = \frac{F_{\max}}{bt}, \tag{1}$$

where σ is the compressive strength, $F_{\max}$ is the maximum compressive strength applied to the specimens during the test (N), b is the width of the specimens (mm), and t is the thickness of the specimens (mm).

The UCS for each specimen, adjusted to 15% moisture content (UCS_{15}) in accordance with ASTM D1990-2007 [13], can be calculated by the following equation:

$$UCS_{15} = \begin{cases} UCS & UCS \le 9.66\ \text{MPa} \\ UCS + (M_1 - 15) \times (UCS - 9.66)/(34 - M_1) & UCS > 9.66\ \text{MPa} \end{cases}, \tag{2}$$

where M_1 is the moisture content of the specimen (%).

Probability distribution

The normal and lognormal distributions are generally adopted as parametric statistical model in the analysis of mechanical properties. The probability density function

$f(x)$ and cumulative distribution function of standard normal distribution $\phi(x)$ can be expressed as follows:

1. Normal distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left\{ -\frac{(x-\mu)^2}{2\sigma^2} \right\}, \tag{3}$$

$$\phi\left(\frac{x-\mu}{\sigma}\right) = p, \quad (4)$$

where x is the random variable, μ and σ are mean and standard deviation, respectively. p is percentile value of cumulative distribution function.

2. Lognormal distribution

$$f(x) = \frac{1}{xs\sqrt{2\pi}}\exp\left\{-\frac{(\ln x - M)^2}{2S^2}\right\}, \quad (5)$$

$$\phi\left(\frac{x-M}{S}\right) = p, \quad (6)$$

where M is the mean value of logarithm of x, and S is the standard deviation of In x.

Kolmogorov–Smirnov test

The *Kolmogorov–Smirnov test* (K–S test) can be used to verify fitting optimization of distribution curve [15]. The formula can be expressed as follows:

$$D = \max(|\phi(x) - s(x)|), \quad (7)$$

where $\phi(x)$ and $s(x)$ represent the cumulative probability value and theoretical distribution value, respectively. D is the maximum absolute difference between $\phi(x)$ and $s(x)$.

At the 0.05 level of significance,the $D_{0.05}$ is equal to $1.36/\sqrt{n}$ and n is the number of samples. If D is smaller than $D_{0.05}$, the theoretical distribution $s(x)$ can provide a good fit to the cumulative probability value $\phi(x)$ obtained by the static testing. If D is larger than $D_{0.05}$, the theoretical fitting distribution $s(x)$ failed.

Results and discussion

Results of compressive test

The mean value, standard deviation, and coefficient of variance of compressive strength adjusted to 15% moisture content for Chinese Fir dimension lumber were shown in Table 2. The mean values of UCS_{15} for SS, No. 1, and No. 2 grade were 30.71, 28.38, and 29.37 MPa, respectively. And the mean value of UCS_{15} for No. 1 grade was lower than the SS and No. 2 grade. It is due to the great influence of knots on wood strength. Besides, No. 1 grade lumber contained more knots [16]. In addition, the wane and skips in No. 2 grade had no significant effect on the wood strength [17]. The coefficient of variance (COV) of UCS_{15} for SS, No. 1, and No. 2 grade were 15.90, 13.55, and 15.70%, respectively. The COV for strength was mainly affected by size, defect, and species. Previous research reported that the COV of dimension lumber ranged from 10.70 to 36.70% [18]. Thus, comparison of COV obtained in this study to those publications shows that the characteristic of large variability for wood could be reflected by the test data.

Difference between measurement data of each grade was conducted through analysis of variance (ANOVA). The results showed that the UCS_{15} values showed the highly significant differences between each grade of dimension lumber ($P < 0.05$, at the significance level of 0.05). Therefore, the NLGA visual grading method is an adequate method to divide the UCS_{15} for Chinese fir dimension lumber.

Probability distribution

It is important to determine the probability distribution of mechanical strength of dimension lumber for its utilization in building structures filed. Histogram, the normal and lognormal distributions curves of UCS_{15} for each grade were shown in Fig. 1. The basic fitted parameters were important to determine the characteristic values, and the values of fitted parameters for two models were shown in Table 2.

K–S test was performed using SPSS Statistics software and the results are listed in Table 3. Different sample size had different critical D values. Table 3 indicated that all D values of UCS_{15} for each grade were less than the critical D values. It proved that the normal and lognormal distributions were judged to be good fit for the actual distribution of UCS_{15} for Chinese Fir dimension lumber. Smaller D value indicates better fitting, the D value of lognormal distribution for SS grade is less than that of normal distribution. Therefore, the lognormal distribution fitted the UCS_{15} data for SS grade seems to be better than normal distribution. In contrast, normal distribution fitted No. 1 and No. 2 grade better than lognormal distribution. To

Table 2 The compression strength adjusted to 15% moisture content for Chinese Fir dimension lumber

Statistical parameters	UCS_{15}			In(UCS_{15})		
	SS	No. 1	No. 2	SS	No. 1	No. 2
Mean value (MPa)	30.71	28.38	29.37	3.41	3.28	3.30
Standard deviation (MPa)	4.88	3.84	4.61	0.16	0.11	0.14
COV (%)	15.90	13.55	15.70	4.70	3.35	4.24

UCS_{15} compressive strength adjusted to 15% moisture content, *In(UCS_{15})* logarithm of compressive strength adjusted to 15% moisture content, *COV* coefficient of variance

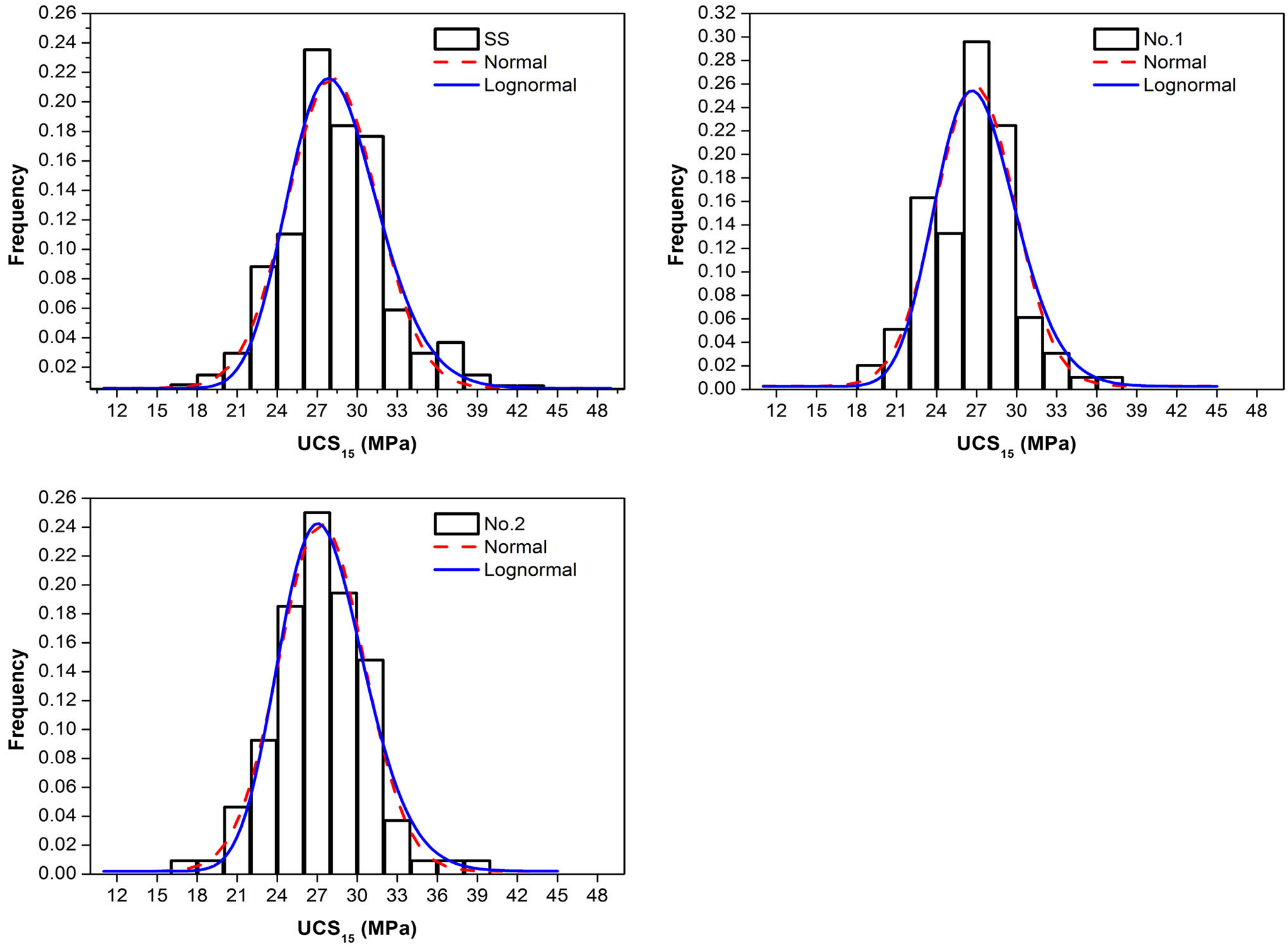

Fig. 1 Lognormal and normal fit of UCS_{15} for Chinese Fir dimension lumber

Table 3 Results of compressive strength using K–S method

Distribution	K–S test (*D* value)		
	SS	No. 1	No. 2
Normal	0.081	0.070	0.063
Lognormal	0.052	0.086	0.071
Critical value	0.117	0.137	0.131

K–-S is the Kolmogorov–Smirnov test. *D* value is the maximum absolute difference between the cumulative probability value and theoretical distribution value

assess the strength index more safely, both the normal and lognormal distribution of UCS_{15} for Chinese fir dimension lumber were selected to calculate the characteristic values in this study.

Characteristic values

According to the Chinese national standards GB 50068-2001 [19] and ASTM D 2915-2010 [20], the characteristic values of UCS_{15} for Chinese Fir dimension lumber could be estimated at 5% percentile with 75% confidence. As a lognormal distribution, the calculated characteristic values can be calculated by the following equation:

$$f = e^{\mu_f(1-k\delta_f)}, \quad (8)$$

where μ_f is the mean value of logarithmic UCS_{15} for SS, No. 1, and No. 2 grade, δ_f is the COV of logarithmic UCS_{15} (Table 2). k is a confidence level factor. Different standards and samples have different k values ($k = 1.645$ in Chinese national standards GB 50068-2001 [19] for all grades and $k = 1.739$ for SS grade; $k = 1.758$ for No. 1 and No. 2 grade in ASTM D 2915-2010 [20] at 5% percentile with 75% confidence).

As a normal distribution, the calculated characteristic values can be expressed as follows:

$$f = \mu_f - ks, \quad (9)$$

where μ_f is the mean value of UCS_{15} for SS, No. 1, and No. 2 grade; s is the standard deviation of UCS_{15} for each grade (Table 2). The characteristic values of UCS_{15} for SS, No. 1, and No. 2 grade were shown in Table 4.

Table 4 The characteristic values of UCS_{15} according to different standards and distributions

Distribution	Characteristic values	UCS_{15} (MPa)		
		SS	No. 1	No. 2
Lognormal	f_1	23.25	22.18	21.54
	f_2	22.90	21.90	21.20
Normal	f_3	22.67	22.05	21.78
	f_4	22.12	21.62	21.26

f_1 and f_2 represent the calculated characteristic values using the Chinese national standards GB50068-2001 [19] and ASTM D2915-2010 [20], respectively, corresponding with lognormal distributions. f_3 and f_4 represent the calculated characteristic values using the Chinese national standards GB50068-2001 [19] and ASTM D2915-2010 [20], respectively, corresponding with normal distributions

Table 4 indicated that the calculated characteristic value for SS grade was the highest. There were no significant differences for the characteristic values of UCS_{15} calculated according to the GB 50068-2001 [19] and ASTM D2915-2010 [20]. It is because confidence level factor k value is not significantly different between GB 50068-2001 [19] and ASTM D2915-2010 [20]. Meanwhile, according to the Chinese National Standards, the calculated characteristic values of UCS_{15} (f_3) were 22.67, 22.05, and 21.78 MPa for SS, No. 1, and No. 2 grade, respectively, corresponding with the normal distribution, which were less than those of lognormal distribution (f_1). From the structure security concerns, the calculated characteristic values of UCS_{15} using Chinese National Code (f_3) were selected to calculate the design values.

Design values

The design value (f_d) of UCS_{15} for Chinese fir dimension lumber based on the full-size testing and the reliability analysis is calculated using Eq. 10. The mean value (μ_R) and coefficient of variance (δ_R) of the resistance stress (R) can be calculated using Eqs. 11 and 12.

$$f_d = \frac{\mu_{k3} f_3}{\gamma_R}, \tag{10}$$

$$\mu_R = \mu_{k1} \times \mu_{k2} \times \mu_{k3} \times \mu_f, \tag{11}$$

$$\delta_R = \sqrt{\delta_{k1}^2 + \delta_{k2}^2 + \delta_{k3}^2 + \delta_f^2}, \tag{12}$$

where f_3 is the characteristic values (Table 4). μ_f is the mean value of UCS_{15} and δ_f is the coefficient of variance of UCS_{15} (Table 2). γ_R is the resistance partial coefficient. k_1, k_2, and k_3 are adjusting factors for the equation precision, geometric character, and the effect of duration of load, respectively. The statistical parameters of the adjusting factors according to literature [8] are shown in Table 5. According to statistical theory, the R value of dimension lumber with different grades is also in line with the normal distribution. The mean value and COV of R are shown in Table 6.

Table 5 Statistical parameters of the adjusting factors (GB 50005-2003 [8])

Parameters	k_1	k_2	k_3
Mean value	1.00	0.96	0.72
COV (%)	5.00	6.00	12.00

k_1, k_2, and k_3 are adjusting factors for the equation precision, geometric character, and the effect of duration of load, respectively

COV coefficient of variance

Table 6 Statistical parameters of resistance stress (R) for each grade dimension lumber

Statistical parameters	Resistance stress (R)		
	SS	No. 1	No. 2
Mean value (MPa)	21.23	19.62	20.30
Standard deviation (MPa)	4.54	3.87	4.40
COV (%)	21.40	19.71	21.25

COV coefficient of variance

To obtain the resistance partial coefficient, the limit state design equation and performance function are established based on first-order second-moment reliability analysis [19]. The limit states design method can aim to satisfy the criteria of a target safety level. The reliability evaluation of the design values can provide the reference for the future strength values updating of the dimension lumber in the Chinese standard [9]. The limit state design equation is expressed as follows:

$$\gamma_0 \left[\gamma_D E(D)_n + \psi_C \gamma_L E(L)_n \right] \le f_d, \tag{13}$$

where γ_0 is the structure importance coefficients and equals to 1.0 for design life of 50 years. γ_D is the dead load effect factor and equals to 1.2. γ_L is the live loads effect factor and equals to 1.4. ψ_c is the combination factor for the live load and equals to 1.0. $E(D)_n$ is the nominal dead load effects. $E(L)_n$ is the nominal live load effects. Therefore, the Eq. 13 can be written $1.2E(D)_n + 1.4E(L)_n \le f_d$.

The performance function (G) is expressed as follows:

$$G = g(R, S) = R - S = R - [E(D) + E(L)], \tag{14}$$

where $E(D)$ is the dead loads effects (random variable), which includes the self-weight of structural members and other materials. $E(L)$ is the live loads effects (random variable), which includes the office occupancy load (L_O), residential occupancy load (L_R), wind load (L_W), and snow

Table 7 Statistical parameters of the loads (GB 50009-2012 [21])

Statistical parameters	Load types				
	G	L_O	L_R	L_W	L_S
Mean/nominal	1.060	0.524	0.644	1.000	1.040
COV (%)	7.0	28.8	23.3	19.0	22.0
Distribution types	Normal	Extreme-I	Extreme-I	Extreme-I	Extreme-I

G dead load, which includes the self-weight of structural members and other materials, L_O office occupancy load, L_R residential occupancy load, L_W wind load, L_S snow load, *COV* coefficient of variance

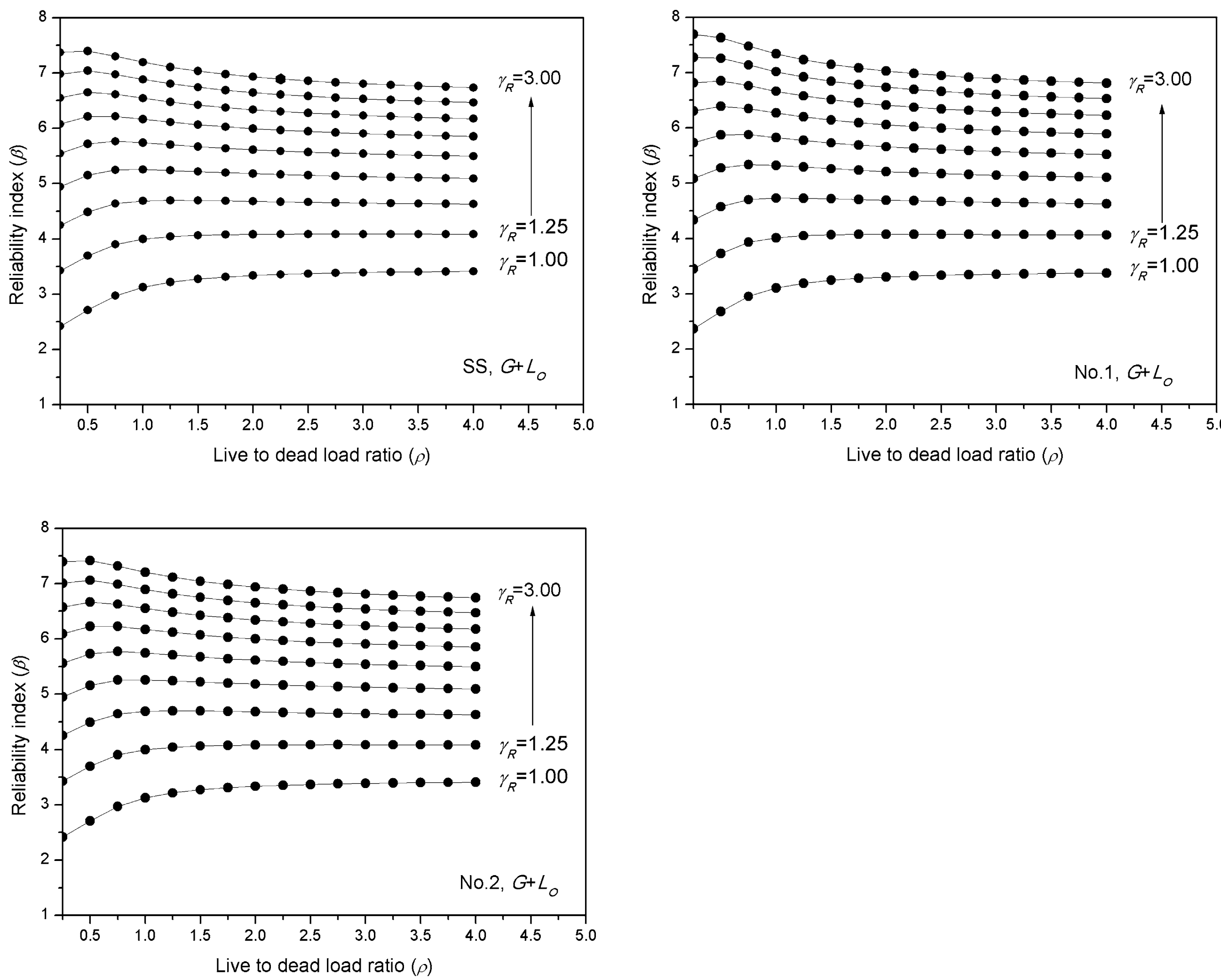

Fig. 2 Relationship between reliability index and live-to-dead ratio

load (L_S). According to Chinese National Standard GB50009-2012 [21], the data of dead loads are in line with the normal distribution, and the data of different live loads are fitted to the extreme type-I distribution. The statistical parameters of the dead and live loads are shown in Table 7.

Combined with Eqs. 11, 13, and 14, the performance function can be expressed as follows:

$$G = R - \frac{\mu_{k3} f_3 [E(D) + E(L)]}{\gamma_R \gamma_0 [\gamma_D E(D)_n + \psi_C \gamma_L E(L)_n]} = R - \frac{f_d (g + q\rho)}{(1.2 - 1.4\rho)}, \quad (15)$$

where g is the ratio of live load to nominal live load ($E(L)/E(L)_n$). q is the ratio of dead load to nominal dead load($E(D)/E(D)_n$). ρ is the load ratio $E(D)_n/E(L)_n$.

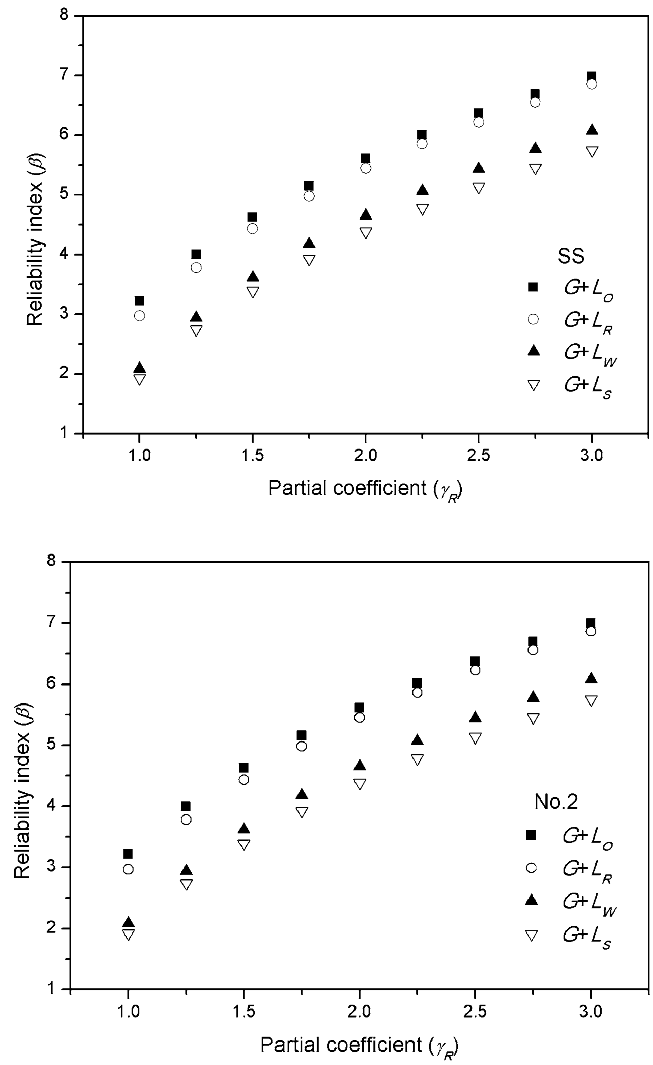

Fig. 3 Relationship between reliability index and partial coefficient

In addition, live-to-dead load ration is an important factor to determine the target reliability assessment. The reliability index (β), which needs to meet the target index ($\beta_0 = 3.2$), is used to determine the design value of UCS_{15}. This is acquired by taking an average of the reliability index under the live-to-dead load ratio (ρ), which is specified as 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0. Four load combinations, including $G + L_O$, $G + L_R$, $G + L_W$, and $G + L_S$, were used in the target reliability assessment.

Figure 2 showed that the relationship between reliability index (β) and live-to-dead load ratio (ρ) of each grade, under dead load (G) plus live office load (L_O). With the increase of ρ, the β increased nonlinearly, but the increasing trend was gradually slowed down.

Meanwhile, the relationship between reliability index (β) and resistance partial coefficient (γ_R) for each grade, taking the average of all simulation load cases including

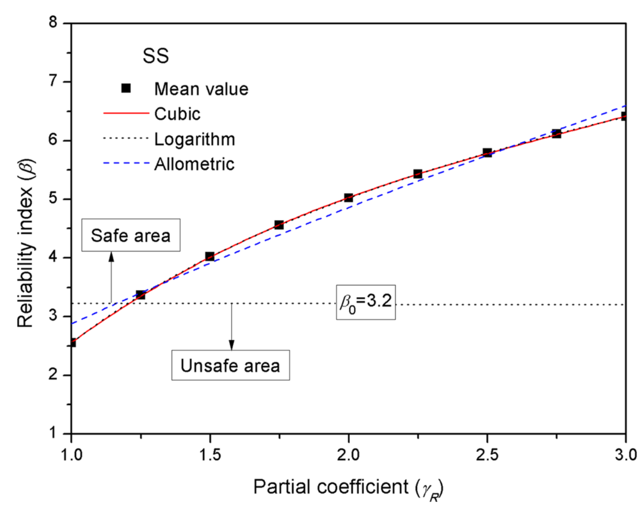

Fig. 4 Prediction of reliability index by partial coefficient for SS grade

Table 8 Fitting results by various model

Grade	Model	Calculation formula	r^2	Std. error
SS	Cubic	$y = 0.215x^3 - 1.828x^2 + 6.450x - 2.275$	0.999	0.150
	Logarithm	$y = 2.957 + 3.261\ln(x - 0.116)$	1000	0.015
	Allometric	$y = 2.881x^{0.754}$	0.981	0.101
No. 1	Cubic	$y = 0.228x^3 - 1.933x^2 + 6.779x - 2.572$	0.999	0.163
	Logarithm	$y = 2.937 + 3.383\ln(x - 0.123)$	1.000	0.021
	Allometric	$y = 2.848x^{0.781}$	0.979	0.108
No. 2	Cubic	$y = 0.216x^3 - 1.837x^2 + 6.479x - 2.301$	0.999	0.151
	Logarithm	$y = 2.955 + 3.271\ln(x - 0.117)$	1.000	0.016
	Allometric	$y = 2.878x^{0.757}$	0.981	0.101

Std. error standard error

$G + L_O$, $G + L_R$, $G + L_W$, and $G + L_S$, is shown in Fig. 3. The reliability index increased with the resistance partial coefficient ranged from 1.0 to 3.0. Different load combinations have different reliability index. The maximum β value was corresponding to dead load (G) plus live office load (L_O). The results obtained in this study are similar to those of previous researchers [22, 23].

To determine the resistance partial coefficient (γ_R), the correlation between reliability index (β) and resistance partial coefficient (γ_R) fitted by cubic, logarithm, and allometric models for SS grade Chinese fir was shown in Fig. 4.

Table 8 indicated that the logarithm model could better fit the data than other models. The value of adjusted r-square is equal to 1.000 for each grade, respectively. Moreover,the stander error of logarithm model for each grade was the smallest. Therefore, logarithm model was selected to calculate the resistance partial coefficient (γ_R).

To meet the reliability index (β) of 3.2, the resistance partial coefficients (γ_R) were 1.187, 1.204, and 1.195 for SS, No. 1, and No. 2 grade, respectively. And the design values of compressive strength calculated by Eq. 10 were set to 13.751, 13.186, and 13.123 MPa for SS, No. 1, and No. 2 grade, respectively.

Conclusions

The objective of this study was to determine the design value of compression strength parallel to grain for Chinese fir dimension lumber based on full-size testing. The results will provide fundamental parameters for the application of Chinese fir in the building structure field as a green building material. The conclusions are as follows:

1. The mean values of UCS_{15} for SS, No. 1, and No. 2 grade were 30.71, 28.38, and 29.37 MPa, respectively.
2. The results of reliability analysis indicated that reliability index increased nonlinearly with the live-to-dead ratio and resistance partial coefficient increased. The logarithm model fitted the data better than other models.
3. To meet the reliability index ($\beta = 3.2$), it was suggested that the design values of compressive strength were set to 13.751, 13.18, and 13.123 MPa for SS, No. 1, and No. 2 grade, respectively.

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