WOOD RESEARCH
64 (3): 2019
471-482

RELIABILITY ANALYSIS ON COMPRESSION STRENGTH PROPERTY OF CHINESE LARCH VISUALLY-GRADED DIMENSION LUMBER

Liuyang Han
Chinese Academy of Forestry, Research Institute of Wood Industry
Beijing, China

Xiu Zhao
Heilongjiang Institute of Wood Science
Harbin, China

Haibin Zhou
Chinese Academy of Forestry, Research Institute of Wood Industry
Beijing, China

Xiuqin Luo
Chinese Academy of Forestry, Research Institute of Wood Industry
Beijing, China

(Received January 2018)

ABSTRACT

The reliability analysis method was investigated in this study to obtain design values of ultimate compression strength parallel to grain (UCS) of Chinese larch visually-graded dimension lumber of common size. A total of 748 lumber samples of 40 by 90 mm were tested for static full-size compression strength according to Chinese National Standards' requirements of the reliability index. The goodness of fit for the UCS distribution of four visual grades was analyzed and the first-order second-moment reliability analysis under different load cases was performed based on all the test data. The log-normal distribution was the optimizing fitted distribution of the compression strength of Chinese larch dimension lumber. Design values of the compression strength for grades I_c, II_c, III_c and IV_c were suggested for the minimum reliability index. These design values will be recommended to the standard committee of Chinese National Standards.

KEYWORDS: Reliability analysis, compression strength, Chinese larch, dimension lumber, design value.

INTRODUCTION

Dimension lumber is a building material of standardized sizes designed for a variety of applications (Gong et al. 2017). In China, this lumber has been imported from many countries including the United States, Canada, and Russia (Yuan et al. 2011, Zhou 2012) to meet increasing market demands. Chinese larch (*Larix gmelinii*) has been developed as a kind of dimension lumber that is strong and also has a large plantation area so that the study of properties of Chinese larch becomes urgent (He et al. 2016, Song et al.2017, Xie et al. 2016, Yin et al. 2016). In the field of structural application, the design value of a material property is quite important. Two methods have been used to determine the design value of the mechanical properties of structural wood (Zhong and Ren 2014). One is the analysis method of allowable properties, which is used widely in North America (ASTM 2007). The second is the reliability analysis method, as specified in China Standards (MOHURD 2001, 2008).

All design values of strength properties of Chinese larch were determined through the reliability analysis method and small clear specimen test data based on the national standards. However, one species was designated for only one grade and as a result, its design value was lowered. The assignment of a range of grades for the solid wood from each species improves the utilization of the wood as well as the safety of the structural utility.

Since 2002, Chinese research institutes have been dedicated to building the grade system for prospective species under the guidance of Forintek Canada. The grading rules were derived from the National Lumber Grades Authority (NLGA) standard of Canadian-based grading rules (NLGA 2005). In GB50005-03 (MOHURD 2005), the visual grade I_c is equivalent to NLGA SS, the visual grade II_c NLGA No. 1, the visual grade III_c NLGA No. 2, and the visual grade IV_c NLGA No. 3. Each visual grade denotes a different degree of strength-reducing characteristics in the lumber. These four visual grading rules were included in the Chinese design code of timber construction. However, the design values were not given for each visual grade. Although the design values for the visual grades of Chinese larch dimension lumber could be determined according to ASTM D1990 (ASTM 2007) in North America, the design values from the allowable stress method aren't suitable to Chinese structure design system originated from the reliability analysis method (Zhu and Pan 2011). Reliability analysis using first-order second-moment (FOSM) is a probabilistic method to determine the stochastic moments of a function with random input variables. FOSM analysis is based on the derivation, which uses a first-order Taylor series and the first and second moments of the input variables (Haldar and Mahadevan 2000). FOSM was recommended in national code GB 50068-2001 to determine the design value of a material property, so it was also used to develop the design values for visual grades of Chinese larch dimension lumber.

As the example of the compression strength of 40 by 90 mm Chinese larch dimension lumber, the objective of this study was to obtain the design value of compression strength of each visual grade based on full-size in-grade test in accordance with the target reliability level of the national standards of China (MOHURD 2001).

MATERIALS AND METHODS

Sampling

There is currently no commercial production of Chinese larch dimension lumber, so 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, both in the Daxing'anling region in Northeast China. In these forestry centres, Chinese 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 was focused on collecting representative logs of small-end diameters ranging from 160 to 340 mm. The number of selected logs was roughly proportional to the annual cut of each forestry centre resulting in a sample group that was representative of the entire 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 planned to standard sizes of dimension lumber.

Grading

Visual grading is a stress grading method based on the premise that the mechanical properties of lumber differ from the mechanical properties of clear wood given that the growth characteristics can affect wood properties and these characteristics can be observed and judged by visual inspection. Lumber was visually graded according to the grading rules provided in the Chinese timber design code GB50005 (MOHURD 2005). Each visual grade denotes a different degree of strength reducing characteristics in the lumber. Grade Ic is the highest grade and grade IV_c the lowest. The grading process included the identification and the record of these grade controlling defects and maximum strength reducing defect (MSRD) for each specimen.

Grouping

To build the relationship among the bending strength, tension strength and compression strength,the same lumber group should be theoretically used. Each strength test is destructive test, therefore the process needs three test groups. To ensure the same strength distribution among these three groups, test groups were matched by nondestructive test of the dynamic Young's modulus (E_f). The paper is only based on the compression test group and it is one of the studies series for the whole research project. For 40 by 90 mm specimens, E_f of the lumber was measured by 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 an 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 selectedand assigned similarly. This process was repeated until all lumber for each grade was assigned to the bending, tension, or compression groups. Similar processes were used for the other three grades.

All samples were stored in a conditioning chamber maintained at 20°C and 65% relative moisture content before testing, to arrive at the equilibrium moisture content.

Testing

Compression tests were conducted according to GB/T28993 (SAC 2012) for the compression group 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 mm specimens, 350 mm test spans for 40 by 90 mm specimens, 450 mm test spans for 40 by 140 mm 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 were needed to be cut from the full-length lumber. One of the samples was selected as 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 assigned as 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 as the lowest strength value of the three samples.

Tab. 1: The basic physical properties and the statistics for the compression strength of the samples.

			Basic information	UCS(MPa)	
	Number	Density ($g \cdot cm^{-3}$)	ARW(mm)	Mean value	Median
I_c	230	0.647(10.95)	1.46(48.98)	49.61(17.70)	48.81
II_c	173	0.643(10.36)	1.58(48.44)	38.54(38.54)	38.34
III_c	220	0.644(11.98)	1.54(51.38)	42.83(23.78)	41.63
IV_c	125	0.650(11.21)	1.60(53.53)	40.58(26.86)	39.02

Note: Values in parentheses are coefficients of variation (%). The density and ARW values are mean values. The values in parentheses of "Mean value" column are the δf for Eq.2-3.

ARW (the annual ring width) 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). The numbers and basic physical properties of the samples are shown in Tab. 1.

Statistical analysis

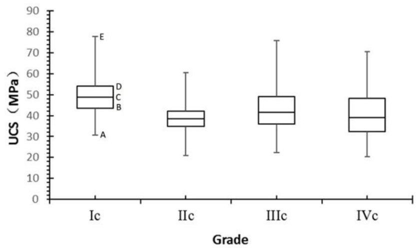
The statistical analysis and the associated graphics were performed using Matlab 7.0, Origin 9.0, SPSS 17.0 software. Analysis of variance (ANOVA) was also used for the test of the significance on the group difference between different grades. The UCS distribution of each grade was fitted to normal, log-normal, and 2P-Weibull distributions, respectively. The mean value, the standard deviation (SD), and the coefficient of variation (COV) were determined for the UCS. The design value of the UCS strength was calculated using the estimated optimizing fitted distribution based on first-order second-moment reliability analysis.

RESULTS AND DISCUSSION

UCS distribution

Results for the mean value, the median value, and COV of the compression strength of the lumber samples are shown in Tab. 2 and the boxplot of UCS for each grade is shown in Fig. 1.

The means were compared with 'One-way ANOVA' and the 'Equal variances assumed' was 'Least-Significant Difference'. The significance level in our test was set to 0.05. Highly significant differences ($p<0.05$) was shown between different grades, consistent with the findings of Jiang et al. (2012). Notably, Guo et al. (2011) reported that the bending strength, ultimate tension strength, and compression strength of Chinese fir lumber also showed statistically significant differences between three different grades at the 0.01 significance level.



Note. A: Minimum Value; B: 25th Percentile; C: Median; D: 75th Percentile; E: Maximum Value.

Fig. 1: The box plot of UCS for each grade.

Ic lumber had higher mechanical properties than IIc, IIIc, and IVc lumber. In some cases, IIIc and IVc lumber was stronger than IIc lumber, even though the latter should have smaller knot sizes. In the whole in-grade test project, the MSRD about each visual grade was statistically counted and listed in Tab. 2. It can be found that, the biggest ratio for the MSRD of grade II_c was the knot while that for III_c and IVc grades was the check or wane. That is to say, II_c grade is mainly determined from knots, while III_c and IV_c grade is more caused by checks and wanes. The wane or check defect has a less effect on tested compression strength parallel to grain compared with the knot. Therefore, the USC of II_c lumber was a little lower than that of III_c and IV_c lumber. The case that strength of III_c lumber was stronger than IIc lumber was also seen in analysis of the mechanical properties of Canadian coastal Douglas-fir, Hem-fir and Chinese larch (Chen et al. 2009, Han et al. 2016, Zhou et al. 2015). It can be concluded that the grading rules for visual grades should cause this case.

Tab. 2: Summary of MSRD (maximum strength reducing defect) ratio.

Dimension	Visual	Knot		Wane		Check/split		Decay		Skip		Others	
(mm×mm)	grades	N	R(%)	N	R(%)	N	R(%)	N	R(%)	N	R(%)	N	R(%)
40×65	II_c	320	96.4	2	0.6	1	0.3	-	-	3	0.9	6	1.8
	III_c	233	28.9	86	10.7	328	40.8	50	6.2	62	7.7	44	5.5
	IV_c	435	51.2	80	9.4	177	20.9	74	8.7	19	2.2	64	7.5
40×90	II_c	604	95.3	10	1.6	3	0.5	-	-	4	0.6	11	1.7
	III_c	236	16.7	77	8.7	307	34.7	101	11.4	109	12.3	55	6.2
	IV_c	167	33.0	71	14.0	98	19.4	95	18.8	15	3.0	60	11.9
40×140	II_c	68	76.4	2	2.3	1	1.1	1	1.1	6	6.7	11	12.4
	III_c	33	8.4	24	6.1	123	31.2	56	14.2	124	31.5	34	8.6
	IV_c	9	4.8	33	17.7	61	32.6	48	25.7	19	10.2	17	9.1

Note: N: number of pieces, R: ratio of MSRD pieces to total pieces.

The normal, log-normal, and 2P-Weibull distributions are often used to fit mechanical properties of wood. These basic parameters for each distribution are shown in Tab. 3. Based on basic parameters in Tab. 3, these CDFs of UCS were shown in Fig. 2.

Tab. 3: The basic parameters for each distribution.

Distribution type		Basic fitted parameters			
		I_c	II_c	III_c	IV_c
Log-normal	σ	0.1756	0.1678	0.2374	0.2657
	μ	3.8888	3.6378	3.7294	3.6682
Normal	σ	8.78	6.45	10.19	10.90
	μ	49.61	38.54	42.83	40.58
2P-Weibull	k	6.982	7.356	5.188	4.540
	l	52.889	40.937	46.344	44.138

Note: μ is the location parameter and σ is the scale parameter for the log-normal distribution; μ is the mean or expectation and σ is its SD in normal distribution; k is the shape parameter and l is the scale parameter for 2-P Weibull distribution.

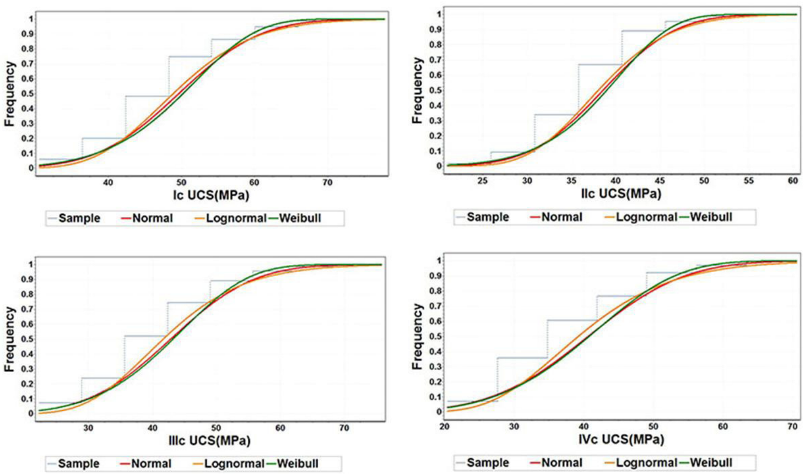


Fig. 2: CDFs of normal, log-normal and 2P-Weibull best-fits of UCS.

The Anderson-Darling (A-D) test method, in which the significance level was set to 0.05, was used for evaluating the difference of CDFs between tested and fitted data, as shown in Tab. 4.

Tab. 4: The comparison about goodness of fit among three distributions.

Grade	Goodness of fit		
	Log-normal	Normal	2P-Weibull
I_c	0.3465	1.2320	4.1784
II_c	0.6898	1.0875	2.7818
III_c	0.2413	1.2288	2.8919
IV_c	0.2832	1.2398	2.1464

Note: For the same grade, the better distribution has smaller value in AD test.

For the same grade, the better distribution has lower value in AD test. The distribution, which is the lowest value of goodness of fit for A-D test, should be the optimizing fitted distribution in this study. The result of A-D test indicated that the log-normal distribution was the optimizing fitted distribution among three fitting distribution models, which is consistent with several reports (Dahlen et al. 2012, Han et al. 2016, Zhong and Ren 2014). Therefore, the log-normal distribution for UCS was selected for the final reliability analysis.

Reliability analysis

According to Chinese national code of Timber structure, the resistance (R) of 40 by 90 mm Chinese larch lumber based on full-size test results was calculated by the Eq. 1, which will be used to determine the UCS design value (MOHURD 2005):

$$R = K_1 K_2 K_3 f_0 \tag{1}$$

where: K_1, K_2, K_3, f_0 are mutually independent random variables, K_1, K_2, and K_3 are adjusting factors for the equation precision, geometric character, and effect of long-term load respectively (Tab. 5); f_0 is compression strength of 40 by 90 mm Chinese larch visually-graded dimension lumber.

Tab. 5: Statistical parameters of adjusting factors (MOHURD 2005).

Parameters	K_1	K_2	K_3
Mean value	1.00	0.96	0.72
COV (%)	5	6	12

Note: The values of row in "COV" are the δ_{K1}, δ_{K2}, δ_{K3} for R.

According to the above strength distribution analysis, the random variable of f_0 obeyed the log-normal distribution. Its mean value and COV were approximately equal to the experimental values of the UCS.

Because these random variables are mutually independent, the mean value and COV of the R can be determined by Eq. 2-3 (MOHURD 2005, Wang 2002). Where δ_{K1}, δ_{K2}, δ_{K3} are shown in Tab. 6 and δf are shown in Tab. 1. According to the central limit theorem of probability theory, the R also obeyed the log-normal distribution approximately.

$$\mu_R = \mu_{K_1}\mu_{K_2}\mu_{K_3}\mu_f \tag{2}$$

$$\delta_R = \sqrt{\delta_{K_1}^2 + \delta_{K_2}^2 + \delta_{K_3}^2 + \delta_f^2} \tag{3}$$

Thus the R value can be analyzed in the limit state function (MOHURD 2005). The calculated mean value and COV of R for all grades are presented in Tab. 6.

Tab. 6: Summary of statistics for R of 40 by 90 mm Chinese larch lumber.

Statistical parameters	R(MPa)			
	$\mathrm{I_c}$	$\mathrm{II_c}$	$\mathrm{III_c}$	$\mathrm{IV_c}$
Mean value	34.29	26.64	29.61	28.05
COV (%)	22.77	22.04	27.76	30.44
Distribution types	Log-normal	Log-normal	Log-normal	Log-normal

The loads applied to the timber structure were divided into two groups: dead load (G), and live load (L). The former includes the self-weight of structural members and other materials, while the latter includes the office occupancy load (L_O), residential occupancy load (L_R), wind load (L_W), and snow load (L_S). According to Chinese National Standard GB50009 (MOHURD

2012), a normal distribution was used to express the randomness of G, and extreme type-I distribution, commonly used to represent the distribution of different live loads, expressed the randomness of L_O, L_R, L_W, and L_S. Statistical parameters of the loads are shown in Tab. 7.

Tab. 7: Statistical parameters of load types.

Statistical parameters	Load type				
	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-1	Extreme-1	Extreme-1	Extreme-1

Two-load combinations G+L_O, G+L_R, G+L_W, and G+L_S were subject to reliability analysis (MOHURD 2005). The limit state design equation for the compressive resistance can be expressed as:

$$a_D D_K + a_L L_K = fK_S \tag{4}$$

where: f - the design value,
a_D and a_L - the dead load factor (1.2) and live load factor (1.4), respectively,
D_K and L_K - the nominal dead loads and nominal live loads respectively,
K_S - an adjusting factor for the service life, defined as 1.0 for 50 years (MOHURD 2012).

The performance function, developed for relative compressive resistance and the effect of loads under first-order second-moment reliability analysis, is as follows (Li 2011, Zhuang 2004):

$$Z = R - (D+L) \tag{5}$$

where R, D, and L are random variables representing the compressive resistance, dead load, and live load respectively. The random variable R was assumed as log-normally distributed according to the above analysis.

Assuming Eq. (4) is satisfied, it is possible to rewrite the performance function Z of Eq. 5 as:

$$Z = R - \frac{fK_S}{a_D + \rho a_L}(g + \rho l) \tag{6}$$

where: ρ i- load-equivalent to L_K/D_K, D/D_K,) L/L_K respectively.

Reliability level, which must meet the target level (β_0 = 3.2) to meet the UCS design value (MOHURD 2001) effectively, was determined by taking an average of the reliability index under the combinations of two loads. ρ = 0.25, 0.5, 1.0 and 2.0 (Fig. 3) according to the survey of the timber structure in China (MOHURD 2005, 2012).

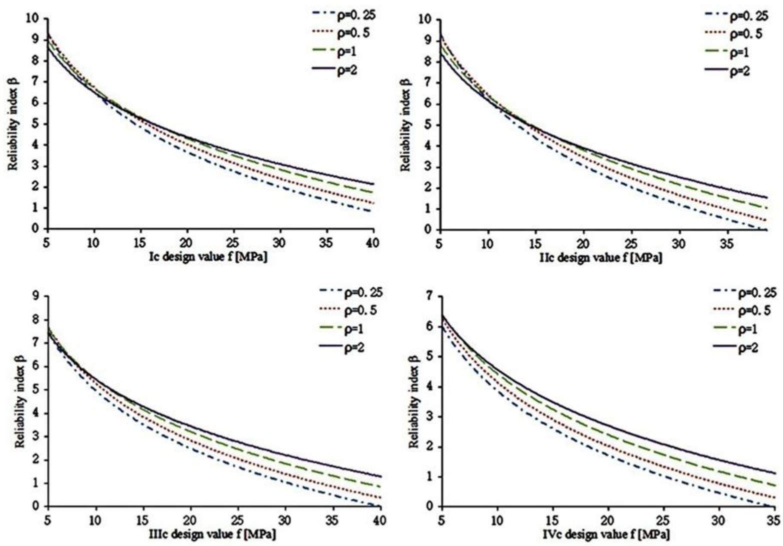


Fig. 3: Relationship between reliability index (β) and design value (f) for G+Lo.

To determine the UCS design value of 40 by 90 mm Chinese larch dimension lumber, first-order second-moment reliability analysis was performed for all data cells and simulation load cases, *G+LO, G+LR, G+LW*, and *G+LS*. A calculation program for *β* was developed by Matlab 7 software. Reliability results of 40 by 90 mm Chinese larch lumber for different load combinations are shown in Tab. 8 For instance, the relationship between the reliability index (*β*) and the design value of UCS (*f*) of 40 by 90 mm Chinese larch lumber, for both *Lo* and *G*, is shown in Fig. 3. Reliability analysis results indicated that the *β* value decreased non-linearly with the increase of the design value in all simulation load cases, as seen previously (Folz and Foschi 1989, Li 2011, Zhong and Ren 2014, Zhuang 2004).

Tab. 8: Reliability index β and design values of 40 by 90 mm Chinese larch lumber for different load combinations.

Load combinations	ρ	β			
		I_c (20.6 MPa)	II_c (16.4MPa)	III_c (15.3MPa)	IV_c (13.4MPa)
$G+L_O$	0.25	3.207	3.201	3.176	3.154
	0.5	3.590	3.593	3.509	3.464
	1.0	3.913	3.913	3.839	3.790
	2.0	4.026	4.018	4.007	3.977
$G+L_R$	0.25	3.107	3.098	3.091	3.076
	0.5	3.421	3.420	3.363	3.329
	1.0	3.695	3.693	3.636	3.595
	2.0	3.800	3.790	3.785	3.759
$G+L_S$	0.25	2.772	2.754	2.814	2.822
	0.5	2.822	2.802	2.868	2.876

	1.0	2.792	2.767	2.869	2.888
	2.0	2.707	2.677	2.817	2.850
$G+L_W$	0.25	2.812	2.795	2.846	2.850
	0.5	2.909	2.894	2.935	2.935
	1.0	2.949	2.930	2.991	2.996
	2.0	2.915	2.891	2.989	3.006
Average		3.215	3.202	3.221	3.210

Note: Values in parentheses are design values.

The limit state function of Chinese larch lumber, g (R, g, l), was described by Eq. 7. R and l were equivalently normalized; thus, FOSM can be used to calculate the reliability index. The reliability index was obtained through several iterative calculations of Eq. 8, 9 and 10. The initial values of R^*, $g^*$and l^* were mean values of R, g and l, and the iterative calculation was continued until g (R, g, l) = 0.

$$Z = g(X) = g(R, g, l) = R - \frac{fKs}{a_D + \rho a_L}\left(g + \rho l\right) = 0 \tag{7}$$

$$\beta = \frac{-\sum_{i=1}^{3} \frac{\partial g}{\partial X_i} X_i^*}{\sqrt{\left(\sum_{i=1}^{3} \frac{\partial g}{\partial X_i}\right)^2}}, i = 1,2,3 \tag{8}$$

$$\alpha_i = \frac{\sigma_{X_i}\left(\frac{\partial g}{\partial X_i}\right)_{X^*}}{\sqrt{\sum_{i=1}^{3}\left(\sigma_{X_i}\frac{\partial g}{\partial X_i}\right)_{X^*}}}, i = 1,2,3 \tag{9}$$

$$X_i^* = m_{X_i} + \alpha_i \beta m \sigma_{X_i}, i = 1, 2, 3 \tag{10}$$

In the above equations, α_{Xi} is the sensitivity factor of random variable; β is reliability index; Xi is random variable, when i is 1, 2, 3, X_i stand for R, g and l, respectively; m_{Xi} is the mean value of random variable; σ_{Xi} is the standard deviation of random variable; and X^* is figure point. Iterative method was used to solve the value of X^*, α_i and β.

According to the reliability analysis and the requirements for the minimum reliability index ($\beta \geqq \beta_0$) (MOHURD 2001), the average of β for all load combinations was 3.215 for grade I_c, 3.202 for grade II_c, 3.221 for grade III_c, and 3.210 for grade IV_c. Additionally, the simulation load case of the maximum and minimum β were reported to be the load combination $G+L_O$ and $G+L_S$, for the same ρ value respectively (Li 2011, Zhuang 2004). For example, the value of β for grade Ic lumber was 3.150 under $G+L_O$, and 2.855 under $G+L_S$, when ρ was 0.25.

After calculated, the design value for UCS was 20.6 MPa for grade I_c, 16.4 MPa for grade II_c, 15.3 MPa for grade III_c, and 13.4 MPa for grade IV_c (Tab. 9). The results will be submitted to the standard committee of GB 50005 (MOHURD 2005) for discussion about design value of Chinese larch dimension lumber so that the structural use of Chinese larch will be further promoted.

CONCLUSIONS

In this work, the static compressive test and the reliability analysis were performed to determine the design values of the compression strength of Chinese larch 40 by 90 mm visually-graded dimension lumber. Based on the analysis of the test data, the following conclusions were drawn as follows. Log-normal distribution was the optimizing fitted distribution of UCS for 40 by 90 mm Chinese larch visually-graded dimension lumber. The design values of UCS for 40 by 90 mm Chinese larch visually-graded dimension lumber for the specified reliability level (β_0=3.2) should be 20.6 MPa for grade I_c, 16.4 MPa for grade II_c, 15.3 MPa for grade III_c and 13.4 MPa for grade IV_c.

ACKNOWLEDGMENTS

This project was supported by the National Key Research and Development Project (2018YFD0600303) and National Natural Science Foundation of China (31770603). This technical guide was provided by FPInnovations in Canada and Great appreciation was given to Professors Conroy Lum and Chun Ni in FPI innovations.

REFERENCES

1. ASTM D1990-07, 2007: Standard practice for establishing allowable properties for visually-graded dimension lumber from in-grade tests of full-size specimens.
2. Chen, Y., Barrett, D., Lam, F., 2009: Mechanical properties of Canadian coastal Douglas-fir and hem-fir. Forest Products Journal 59(6): 44-54.
3. Dahlen, J., Jones, P.D., Seale, R.D., Shmulsky, R., 2012: Bending strength and stiffness of in-grade Douglas-fir and Southern pine No.2 2x4 lumber. Canadian Journal of Forest Research 42(5): 858-867.
4. Folz, B., Foschi, R.O., 1989: Reliability-based design of wood structural systems. Journal of Structural Engineering 115(7): 1666-1680.
5. MOHURD, GB50005-03, 2005: Code for design of timber structures.
6. MOHURD, GB50009, 2012: Load code for the design of building structures.
7. MOHURD, GB50068, 2001: Unified standard for reliability design of building structures.
8. SAC, GB/T1930-2009, 2009a: Test method for ring width of small clear wood.
9. SAC, GB/T1933-2009, 2009b: Test method for density of small clear wood.
10. SAC, GB/T28993-2012, 2012: Standard test method for mechanical properties of structural lumber.
11. Gong, Y.C., Wang, Z.H., Jiang, J.H., Luo, X.Q., Ren, H.Q., 2017: Design values of compressive and tensile strength for visually graded Chinese fir dimension lumber. Journal of Forestry Engineering 2(2): 22-27.
12. Guo, W., Ren, H.Q., Fei, B., Lyu, J.X., 2011: Mechanical properties of three grades of Chinese fir dimension lumber. Scientia Silvae Sinicae 47(11): 139-143.
13. Haldar, A., Mahadevan, S., 2000: Probability, reliability, and statistical methods in engineering design. John Wiley & Sons. New York.
14. Han, L., Zhao, X., Zhou, H., Luo, X., 2016: Comparison between allowable properties method and reliability analysis method to determine design values of visually graded Chinese larch 40 x 65 mm lumber. BioResouces 11(1): 651-662.
15. He, Y.C., Li, G.Y., Xiang, Q., Lao, W.L., 2016: Fast extraction and spectroscopy analysis of Proanthocyanidins from bark of two larch species. Journal of Forestry Engineering 1(6): 70-74.
16. Jiang, J., Lu, J., Ren, H., Long, C., 2012: Effect of growth ring width, pith and visual grade on bending properties of Chinese fir plantation dimension lumber. European Journal of Wood and Wood Products 70(1-3): 119-123.

17. Li, T.E., 2011: Determining the strength design values of wood based on the reliability requirements. Dissertation, Harbin Institute of Technology. China.
18. NLGA standard, 2005: Grading rules for Canadian lumber.
19. Song, Y.P., Guo, M.H., Gong, X.C., 2017: Effect of ASD flame retardant on fire-retardant efficiency of larch wood. Journal of Forestry Engineering 2(4): 51-56.
20. Wang, Y.W., 2002: Reliability analysis on timber structure. Building Science Research of Sichuan 28(2): 1-9.
21. Xie, L.S., Liu, J.Q., Qiao, L.T., 2016: Influence of knot on the agglutination properties of Chinese larch glulam. Journal of Forestry Engineering 1(1): 21-24.
22. Yin, T.T., Lu, X.N., Han, Z.H., 2016: Characterization of bonding interface of modified glass-fiber/larch composites. Journal of Forestry Engineering 1(4): 45-50.
23. Yuan, D., Wang, X.H., Fei, B.H., Du, M., 2011: Status and advantage analysis of developing modern wood construction in China. Forestry Economics 10: 61-64.
24. Zhong, Y., Ren, H., 2014: Reliability analysis for the bending strength of larch 2×4 lumber. Bio Resouces 9(4): 6914-6923.
25. Zhou, H.B., 2012: Current and future status of wood structure in China: Part I. China Wood Industry 26(1): 7-10.
26. Zhou, H.B., Han, L.Y., Ren, H.Q., Lyu, J.X., 2015: Size effect on strength properties of Chinese larch dimension lumber. Bio Resouces 10(2): 3790-3797.
27. Zhu, E.C., Pan, J.L., 2011: Improving technical standards for wood structures with reference to international experience. China Wood Industry 25(3): 26-29.
28. Zhuang, X.J., 2004: Reliability study of North American dimension lumber in the Chinese timber structures design code. Dissertation, University of British Columbia. Canada.

Liuyang Han
Chinese Academy of Forestry
Research Institute of Wood Industry
Haidian District, Beijing
China

Xiu Zhao
Heilongjiang Institute of Wood Science
Harbin
China

*Haibin Zhou
Chinese Academy of Forestry
Research Institute of Wood Industry
Haidian District, Beijing
China
*Corresponding author: zhouhb@caf.ac.cn

Xiuqin Luo
Chinese Academy of Forestry
Research Institute of Wood Industry
Haidian District, Beijing
China