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Study of the Distribution Properties and LRFD Code Conversion in Japanese Larch[*1]

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ABSTRACT

This study was performed to develop an LRFD (Load Resistance Factored Design) Code for Domestic Larch. To accomplish this, we evaluated bending, compression, tension and shear strength. The results of the strength evaluation were utilized to verify the distribution and code conversion. For bending, tension and compressive strength, the Weibull distribution was well-fitted, but for shear strength we observed a normal distribution. For evaluating the bending and compressive strength, a full-sized specimen was used. A small clear specimen was used to test tension and shear strength. Compressive strength in particular was found to be affected by tight knots, although there was little difference between grades. In the code conversion, the design value of the LRFD was larger than the existing allowable stress value in the Korean Building Code. However, the allowable stress in this study was about two times higher than the value listed in the Korean Building Code. This result induced the difference between the soft and hard conversions. For greater reliability, the accumulation of additional data is necessary and further studies should be performed.

1. INTRODUCTION

The market for domestic wooden structures has been growing continuously since the introduction of light-framed structures from North America in the late 1980s. Recently, interest in and demand for traditional Korean post-beam buildings have been increasing, with much of the interest focused on structural features, such as exposed wooden frames and diversity in the organization of space. Moreover, there is an emotional appeal of nostalgia. With increasing attention paid to wooden-framed buildings, designing criteria to guarantee structural stability has become a priority. The ASD (allowable stress design), based on determinism, has been the most common framework used in Korea. However, this method offers no scientific proof of structural stability and therefore cannot objectively reflect material displacement. Accordingly, research on codes based on theories that can be reliably proven is now in process, and the findings are used as actual design codes in North America and Europe. In Korea,

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such a code was adopted for steel concrete structures in the civil engineering and construction fields.

Probabilistic design in wooden construction began with the assumption of normal distributions for load and resistance with the development of a reliability analysis model by Cornell in 1967. Since then, the concept of algebraic normal distribution has been introduced. There have been various attempts at using a linear approximation with a Taylor series in the boundary of limit state function (Hasofer *et al.*, 1974): the reliability analysis of glulam (Ellingwood *et al.*, 1982), and the reliability analysis of a engineering wood (Murphy *et al.*, 1988). Since the 1990s, additional research (Foschi *et al.*, 1982～1996) based on those studies has been conducted, reflecting on the actual design code and results have been adapted into code in America, Canada, Australia and Europe. Since the adaptation, running parallel with the existing ASD, a conversion to an LRFD is now in progress. The 1990s was a time of economic evaluations (Ratrick *et al.*, 2000) of ASD and LRFD. As a result, it has been shown that LRFD is superior to ASD. Various computerized methods were developed to research and develop a more exact theory. Basic systems for code conversion were proposed (Park *et al.*, 2004), and continuing attempts are now underway in Korea. To convert code into a probability method, distribution characteristics of structural performance should be closely examined and numerous experiments should be conducted.

The purpose of this research is to examine the distribution properties and characteristics of probabilistic design in domestic Larch, which is abundant and superior in structural performance, and also to convert the design code based on existing standards.

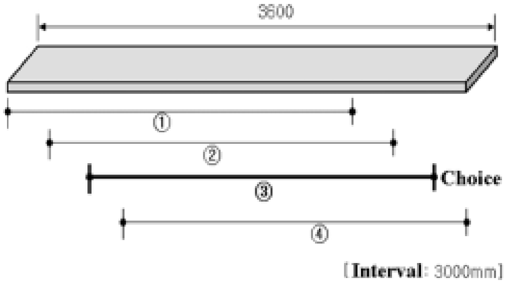

Fig. 1. Method for grading and locating the target cut on bent specimens.

2. MATERIALS and METHODS

2.1. Materials

Japanese Larch (*Larix leptolepis*) which is prepared from the commercial mill was used in this study. The moisture contents of specimens were controlled such that moisture remained below 18%. The specimens' dimensions were 38 × 140 × 3600 (mm). Nine hundred and forty-five pieces, excluding those that had severe cracks and curves, were used in this study.

2.2. Methods

2.2.1. Visual Grading

Specimens were visually graded following the Korean Standard and the KFRI (Korea Forestry Research Institute) notice. The locations and sizes of each knot, curve, and crack were investigated with the naked eye. The resultswere input into a database after having been graded in the range of 3,000 mm. The position for each cut was determined to ensure uniformity in the grade numbers.

2.2.2. Measurement of Strength

Full-sized specimens were used for the measurements of bending and compressive strengths.

Table 1. Sizes, numbers, loading speeds, apparatus and standards for strength test

Strength	Size (mm)	Numbers	Loading speed (mm/min)	Apparatus (Manufacturer, Capacity)	Standard
Bending	38 × 140 × 3000	No.1 275 No.2 298 No.3 213	10	UTM (Zwick, 10 t)	KS F 2208
Compression	38 × 140 × 200	No. 1 182	2	UTM (Samhan, 30 t)	KS F 2206
Tensile	200 × 25 × 10 Tensile block : 50 × 5 × 10	132	2	UTM (Instron, 20 t)	KS F 2207
Shear	50 × 50 × 50 Shear surface : 40 × 50	113	2	UTM (Zwick, 10 t)	KS F 2209

Fig. 2. Images of the strength tests (from left to right, bending, compressive, tensile and shear strengths).

For tensile and shear strengths, small clear specimens were used. The modulus of elasticity (MOE) was not investigated in this study because the same MOE value was used in both the LRFD (Load-Resistance Factored Design) and the ASD (Allowable Stress Design). Table 1 describes the specifications of the tests, such as the number of specimens, dimensions, load speed, apparatus and testing standards. All tests were carried out with the load acting parallel to the grain, except for the bending test, in which a four-point test was carried out.

2.2.3. Verification of Best-fit Distribution of Each Type of Strength

To find the best-fit distribution for each type of strength, the parameters for normal, log-normal and Weibull distributions were determined, and the root mean square error (RMSE) of each distribution type was compared with those of the others. The distribution type showing the lowest RMSE was determined to be the best-fit distribution. The probability density functions of each distribution are as follows.

Weibull distribution :

$$f_T(t) =- \overline{F}'_T(t) = \lambda(t)\exp\left[-\int_t^0 \lambda(s)ds\right]$$

$$=(\frac{\alpha}{\beta})t^{\alpha-1}\exp(\frac{-t^{\alpha}}{\beta})I_{(0,\infty)}(t)$$

Normal distribution :

$$f_x(x) = f_x(x;\mu\sigma^2) = \frac{1}{\sqrt{2\pi}\,\sigma}exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

$$(-\infty < x < \infty, -\infty < \mu < \infty, \sigma > 0)$$

Lognormal distribution :

$$f_x(x) = f_x(x;\mu,\sigma^2) = \frac{1}{x\sqrt{2\pi}\,\sigma}exp\left[-\frac{1}{2\sigma^2}(\ln x - \mu)^2\right]$$

$$(0 < x < \infty, -\infty < \mu < \infty, \sigma > 0)$$

Table 2. Results of Visual Grading in each interval (3000 mm)

Interval (mm)	No. 1	No. 2	No. 3	out of grade	Total
0～3600	235	388	232	90	945
210～3210	279	390	203	73	945
410～3410	278	383	212	72	945
110～3110	274	394	202	75	945
600～3600 **(%)**	**277** **(29)**	**377** **(40)**	**214** **(23)**	**77** **(8)**	**945** **(100)**
0～3000	274	394	202	75	945

2.2.4. Code Conversion into LRFD

Design values were converted to a reference resistance of LRFD using ASTM D 5457 and the procedure of Park *et al.* (2004). The hard conversion values were obtained by the requested factors calculated from the best-fit distribution and the number of specimens. The soft conversion values were also determined from the design value of the existing ASD code. These two design values were compared and analyzed.

3. RESULTS and DISCUSSIONS

3.1. Visual Grading of Japanese Larch

To prepare the bending test specimens for those tests that require the longest pieces, several ranges were re-investigated, and the proper position for the cut was determined for each specimen. The results of visual grading for bending specimens are shown in Table 2. The pieces remaining after cutting were used for the compression test, as compressive specimens that were prepared preferentially were not sufficient in number (No. 2 (20), No. 3 (26)). Only No. 1 (182) specimens were used to verify the distributions.

Fig. 3. Failure modes of the compressive specimens (No.1).

3.2. Evaluation of Each of the Properties of Strength

The results of the strength evaluations are shown in Table 3. No difference was found between the two grades with respect to compressive strength, possibly due to the small samples sizes. Visual grading only reflects the ratio of area to size, but there is also a difference between encased and tight knots. In the compressive test, encased knots had a more significant effect on failure than did tight knots. Fig. 3 shows the failure mode of No. 1 compressive specimens. Although the sizes of the knots were the same (10 mm), failures occurred on the encased knots. According to this, a low strength value was observed when there was an encased knot, even when it was small. However, a high degree of strength was observed with tight knots of the largest sizes. Additional studies must be conducted on the standards and evaluation of visual grading on full-sized specimens.

3.3. Verification of Best-fit Distribution

In our analysis of the final distribution, we considered the bending strength distribution of each grade, compressive, tensile and shear strength on No. 1 grade samples, and the number of

Table 3. Strength performances of the mechanical properties for each grade

	Bending			Compression			Tensile	Shear
Number of specimen	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3	132	113
	275	298	213	182	20	26		
Mean (N/mm^2)	63.11	47.70	43.98	42.69	44.96	41.85	9.38	10.94
Standard Deviation (N/mm^2)	27.32	15.30	15.69	6.85	5.90	4.48	3.45	1.89

Table 4. Root mean square for verification of best-fit distribution

		Normal	Weibull	Lognormal
Bending	No. 1	3.700	**3.358**	9.356
	No. 2	2.101	**1.736**	5.871
	No. 3	2.716	**2.504**	4.262
Compression (NO. 1)		1.114	**0.881**	1.879
Tensile		0.512	**0.478**	0.511
Shear		**0.279**	0.323	0.301

specimens used. Table 4 shows the comparison and our analysis of root mean square. Every structural performance was suited to the Weibull distribution except for that of shear strength. These results were also confirmed through graphs of the probability density functions (Figs. 4～6).

As in earlier studies, full-size bending strength fit the Weibull distribution (Lee *et al.*, 2003). However, it was found that the Weibull distribution was appropriate for tensile strength of small clear specimens, although it is well-known that a normal distribution is suitable. For that reason, further studies are required.

Based on the best-fit distribution shown above, Table 5 shows the distribution parameters for each structural distribution.

3.4. LRFD Code Conversion

Based on the results of our best-fit distribution, each code conversion factor was calculated. On the basis of those factors, KBC soft conversions and hard conversions were calculated (Table 6).

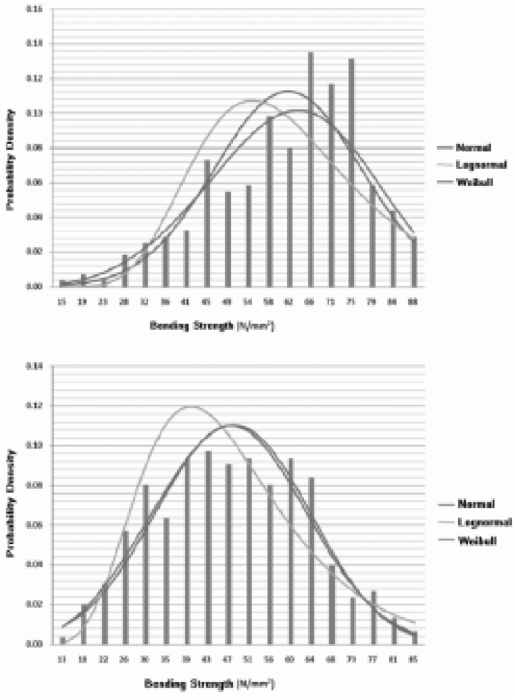

Fig. 4. Probability density function graph [bending No. 1(L), No. 2 (R)].

As shown in Table 6, the allowable stress calculated from this study was twice as large as that of the KBC. An earlier study (Park *et al.*, 2004) had shown the same result, but additional study is required. Moreover, there a large difference was seen when comparing soft conversions and hard conversions, which we attribute to the

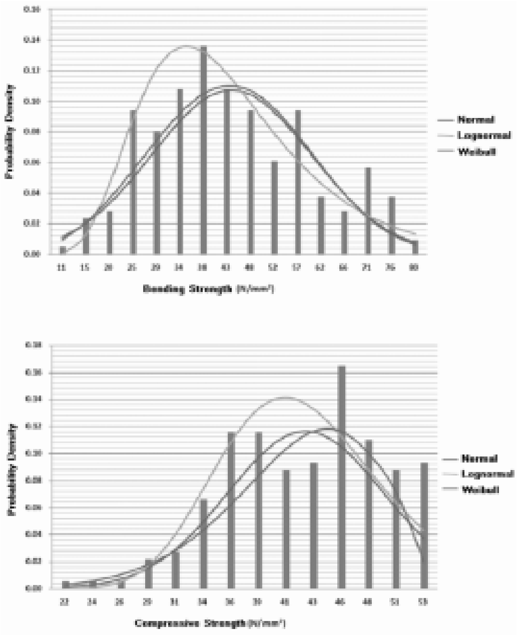

Fig. 5. Probability density function graph [bending No. 3 (L), compressive (R)].

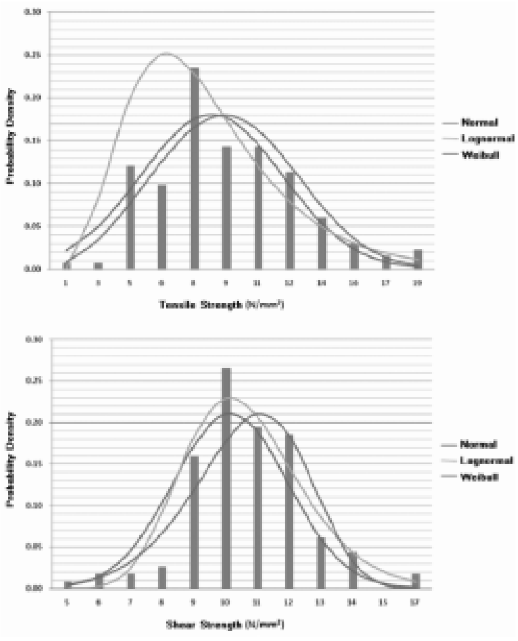

Fig. 6. Probability density function graph [tensile No. 1 (L), shear (R)].

Table 5. Distribution property parameters of each mechanical property

		Shape parameter (m)	Scale parameter (c)
Bending	No. 1	4.234	68.025
	No. 2	3.532	52.942
	No. 3	3.228	48.979
Compression	No. 1	7.256	45.521
Tension		3.085	10.478
Shear		Mean : 10.94 Standard Deviation : 1.89	

aforementioned cause. Hard conversions and KBC soft conversions must progress simultaneously. Also, continuous collection of data will be required.

4. SUMMARY

This study was performed to complete the LRFD code for Japanese Larch. For this purpose, an evaluation of strength and a verification of the distribution of each structural performance parameter was carried out. We conclude that the Weibull distribution is suitable for bending, compressive and tensile strengths, but that the normal distribution is best for shear strength. In particular, our results show that the Weibull distribution is appropriate for tensile strength even when small clear specimens are used. More study is required to replicate these results. We attempted further analysis through a test on soft conversions, and the corresponding result was obtained. Still, we call for further studies. It is clear that additional collection of data and further study will be needed. Inparticular, we suggest that future studies incorporate more test specimens, and that more reliable design codes be developed. The results of this study will be of increasing practical value for LRFD conversions in Korea as a basic source.

Table 6. Code conversion values and test values in Japanese Larch

	Bending			Compression	Shear	Tensile
	No. 1	No. 2	No. 3	No. 1		
Allow stress	16	10	9	15	1.9	1.9
KBC (Allow stress)	8	6	3.5	9	0.65	2.5
KBC code conversion (Soft conversion)	18	14	8	26	2	6
Calculated value from test (Hard conversion)	34	21	18	37	5	4
Best-fit distribution	Weibull	Weibull	Weibull	Weibull	Normal	Weibull

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