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ORIGINAL ARTICLE

Takashi Takeda · Takeo Hashizume

Differences of tensile strength distributions between mechanically high-grade and low-grade Japanese larch lumber III: effect of knot restriction on the strength of lumber

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Abstract It is well known that the presence of knots in structural lumber is one of the most important strength-reducing factors. For practical purposes, visual grading including knot restriction is an effective method for nondestructive evaluation of strength. Edge knot restriction for not only visually graded lumbers but also mechanically graded lumbers is specified in the Japanese agricultural standards for glued laminated lumber. We conducted experimental studies on differences of tensile strength distributions between mechanically high-grade and low-grade Japanese larch (*Larix kaempferi*, carriere) lumbers daily used for manufacturing glued laminated timbers in Nagano, Japan. We then examined the additional visual grading of mechanically graded lumbers for nondestructive evaluation. We visually graded the prepared mechanically graded lumber by focusing on the knots' area ratio of grouped knots. We confirmed that the higher visual grade related to the stronger tensile strength, similar to our present knowledge; but the effects of knot restriction were reduced when the length of the lumber increased in view of nonparametric 5th percentiles of tensile strength. The differences in the strength/elasticity ratio between mechanically high-grade and low-grade lumber were negligible. It was clear that the length effect on the ratio in visually graded high-grade lumber was smaller than that of visually graded low-grade lumber. It was thus concluded that knot restriction should have little effect on the tensile strength of mechanically graded lumber.

Key words Mechanical grading · Visual grading · Tension parallel to grain · Young's modulus

T. Takeda (✉)
Faculty of Agriculture, Shinshu University, 8304 Minamiminowa-mura, Nagano 399-4598, Japan
Tel. +81-265-77-1508; Fax +81-265-72-5259

T. Hashizume
Nagano Prefectural General Forestry Research Center, Kataoka, Shiojiri, Nagano 399–0711, Japan

Introduction

It has become clear that all users select engineered wood products for structural uses in Japan, as noted by Hayashi[1] regarding the concept and recent stage of the engineered wood products. The intention to guarantee timber strength for columns and beams used for modern Japanese-style houses seemingly reflects the Japanese agricultural standard for structural softwood timber[2] established in 1991. Yet it is also true that many users judge the quality of timbers with defects such as knots, checks, and so on by their own criteria of appearance. The development of a mechanical method for grading structural lumber should be promoted, however, which includes the effect of knots on the strength of such materials, rather than using appearance alone.

Knowledge obtained from various investigations concerning the effect of knots on the strength of lumber can be found in the literatures.[3] We could introduce many studies by Japanese researchers here, but only a few are included owing to space limitation. Hatayama[4] investigated the relation between knot diameter and tensile/compressive strength derived from the distribution of the sloping grain around a single knot. Nakai et al. investigated the relation between the knot diameter ratio and bending strength for Douglas fir timber[5] and the relation between the knot diameter ratio and tensile strength for Japanese cedar square sawn timber.[6] Iijima and Nakai[7] investigated the Young's modulus/bending strength relation and the effect of knots on bending strength to establish practical mechanical grading rule for structural timber in Japan. Masuda et al.[8] detected the location of the heat-generating portion by using thermal image equipment and noted that the stress concentration around knots can be caused by a crack at or around the knot. Japanese larch lumber, used daily for structural glued laminated timber, was studied by Hashizume et al. for the differences in mechanical properties between visually and mechanically graded lumber.[9]

These reports make it clear that the presence of knots is one of the most important strength-diminishing factors. The restriction of the knot diameter ratio of edge knots is specified for the mechanically grading method in the Japanese Agricultural Standard (JAS) for structural glued laminated timber.[10] This method should be acceptable, as lumber may be assigned various visual grades but only one mechanical grade. We believe that more precise research about knots in each mechanically graded type of lumber should relate to a more accurate evaluation of strength. We focused on the differences of tensile strength distribution between mechanically graded high-grade and low-grade Japanese larch lumber and reported on the effect of length[11] and knots[12] on strength. We investigated the effect of knot restriction on strength by referring to the JAS specification.[10]

Experiment

Specimens for the tensile strength test were obtained from mechanically graded Japanese larch lumber used for manufacturing glued laminated timber in Nagano, Japan. The specimens were high-grade (H) and low-grade (L) lumber. The dynamic Young's modulus (E_f) of each specimen was measured by the longitudinal vibration method before the tensile tests. The tensile test spans were 60, 100, and 180cm; and tensile strength (TS) values were adopted in case failure occurred within the span. We designated specimens with combinations of a mechanical grade and test span; for example, "H060" denotes mechanically graded high grade and 60cm of test span. We measured the knot area ratio of grouped knots for each specimen instead of the knot diameter ratio, as specified in JAS,[10] as the knot's area ratio should be a stronger estimate for predicting tensile strength than the knot's diameter ratio. We also measured the knot's area ratio of an edge knot, which is defined by the specification for manufacturing structural glued laminated timber.[13] The knot area ratio was used when lumber failed within the span in the tensile tests. In the following sections, GK and EK denote the knot's area ratio of grouped knots and edge knots, respectively. Further information may be found in the previous papers[11,12] in this series.

Results

Distributions of GK

Distributions of GK are shown in Fig. 1a for mechanically graded high-grade lumber (H) and in Fig. 1b for low-grade lumber (L). The spindle in the figures expressed cumulative probability [= $i/(n+1)$] the same as that set forth by the American Society for Testing and Materials (ASTM).[14] The transversal axis expressed 100 − GK instead of GK to imitate the usually found figures for strength distributions. The curves were obtained by data fitting to two-parameter Weibull distribution function. It is shown that the shift of curves in L are larger than in H; and the shift of the lower tails are larger than that of the upper heads when the span is increasing. This result was expected based on the trends that length effect on tensile strength in L would be strong compared to that in H.

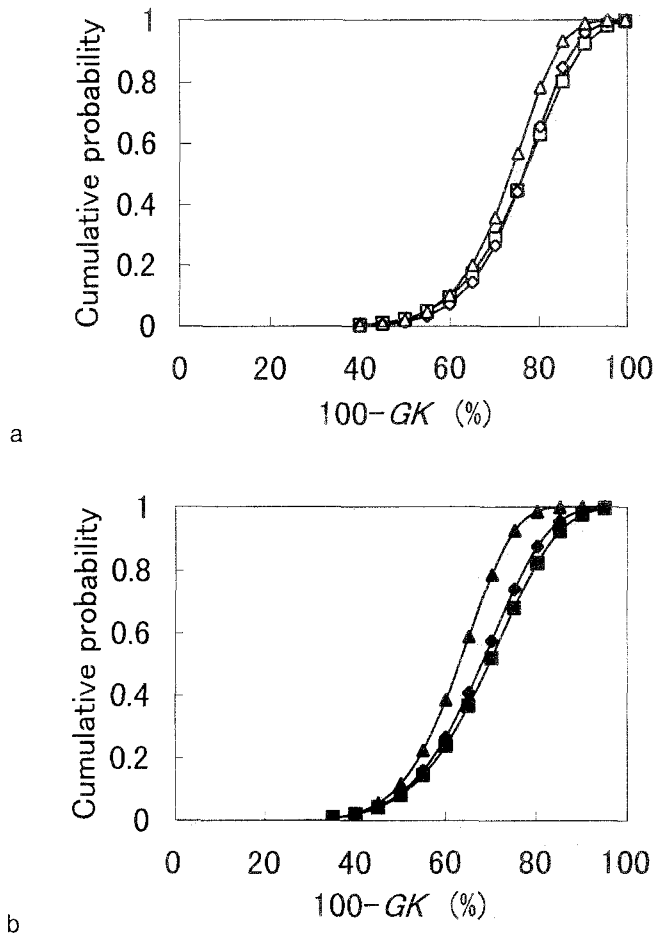
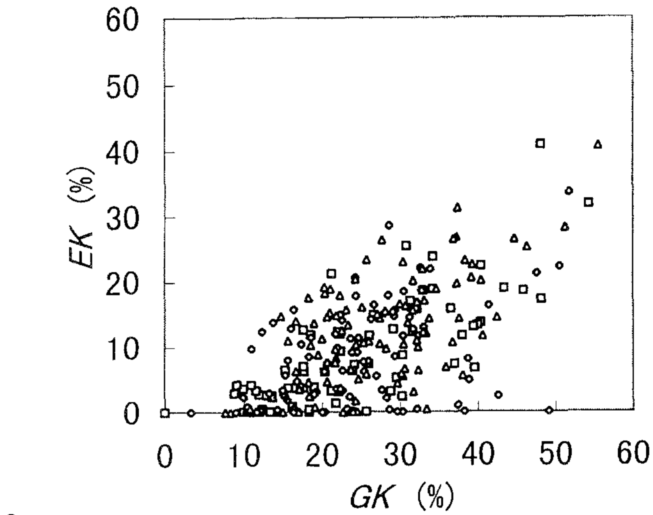


Fig. 1. Distributions of knot area ratio of grouped knots (*GK*). **a** H: mechanically graded high-grade lumber (H060, *squares*; H100, *diamonds*; H180, *triangles*). **b** L: mechanically graded low-grade lumber (L060, *squares*; L100, *diamonds*; L180, *triangles*)

Relation between GK and EK

Though grouped knots and edge knots are specified separately in JAS, knotty lumbers have many knots regardless of whether they are grouped knots or edge knots. GK and EK were plotted for each specimen (Fig. 2). The large variations of EK, even when their GK values are almost equal, are surprising; but correlation coefficients are relatively high: H060 (0.750), H100 (0.440), H180 (0.608), L060 (0.599), L100 (0.635), L180 (0.542). Many specimens had no edge knots, with the percentage of EK specimens (EK = 0) among all specimens 8.5%. We analyzed the effect of knot restriction on tensile strength (TS) using GK data, as the amount of useful data for analysis would be small if we used EK = 0 specimens.



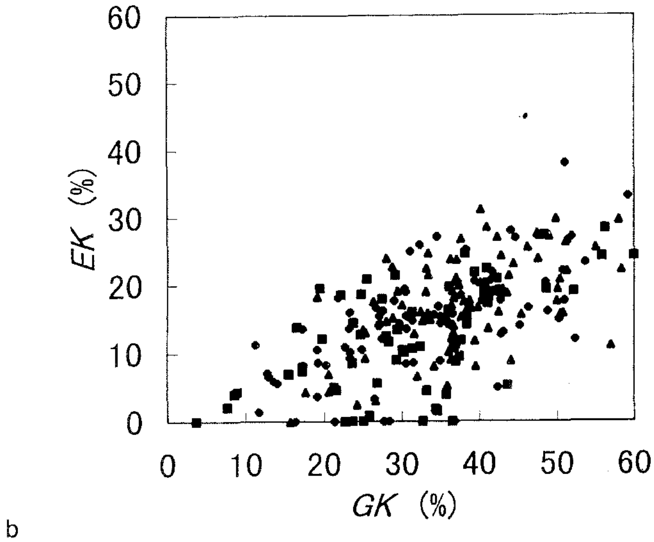


Fig 2. Relation between knots' area ratios of grouped knots (*GK*) and edged knots (*EK*). **a** High-grade lumber. **b** low-grade lumber. See Fig. 1 for explanation of symbols

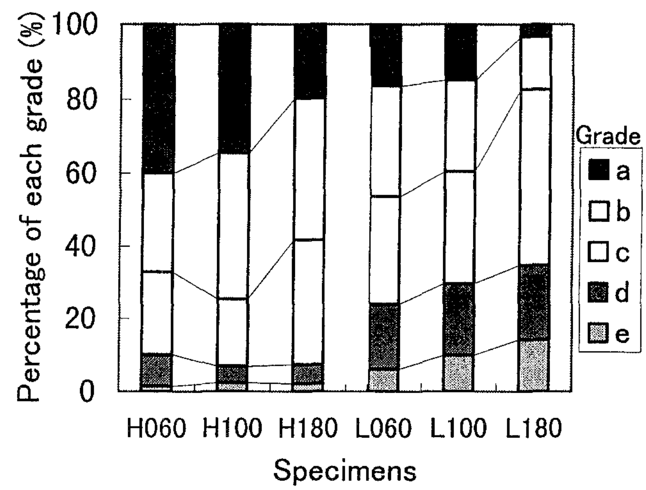


Fig. 3. Percentage of each visual grade. For explanation of grades a–d, see Table 1. Grade e, downgrade of grade d

Table 1. Knot specification of visual grading rule in JAS[10]

Item	Grade a	Grade b	Grade c	Grade d
Grouped knots diameter ratio	Not more than 20%	Not more than 30%	Not more than 40%	Not more than 50%
Diameter ratio in width	Not more than 17%	Not more than 25%	Not more than 33%	Not more than 50%

Table 2. Young's modulus for each visual grade

Specimen	E_f (GPa)			
	a	b	c	d
Grade H				
H060	12.36 (9.4)	12.75 (12.4)	12.96 (7.2)	12.53 (10.9)
H100	13.06 (7.9)	13.10 (8.7)	12.44 (12.4)	12.14 (11.0)
H180	13.04 (5.7)	12.72 (6.8)	12.80 (6.7)	12.48 (11.8)
Grade L				
L060	7.93 (12.6)	7.67 (13.3)	7.47 (13.9)	7.24 (13.5)
L100	7.49 (14.6)	7.66 (10.6)	7.43 (13.7)	7.50 (10.3)
L180	6.98 (2.7)	7.62 (10.7)	7.57 (14.1)	7.49 (10.4)

E_f, dynamic Young's modulus measured by the longitudinal vibration method; a–d, visual grade (see Table 1); Grade H, L, mechanically high grade and low grade, respectively
Values in parentheses are coefficients of variation (%)

Combination of visual and mechanical grading

Knot specification of the visual grading rule in JAS[10] is shown in Table 1. Though there are other specifications in JAS[10] (e.g., grain inclination, width of annual ring), we focused on GK data, which should be an effective index for estimating TS. We then classified specimens according to each visual grade (Table 1). Figure 3 shows the percentages for each visually graded lumber. Grade e in Fig. 3 denotes downgraded grade d. It was shown that visual grades of H were higher than those of L, and the length effect on the percentages of grade e lumber in L was stronger than that for H. This result is related to differences between H and L in terms of the length effect on TS presented in a previous paper.[11] In contrast, the differences of E_f among visual grades were small, and there was no tendency for coefficients of variation, as shown in Table 2. Only three figures were responsible for the small coefficient of variation for grade a in L180. The mechanical grading method seems to work somewhat as the visual grading method also.

Figure 4 shows the TS for each visual grade. The variations of TS were large, whereas differences of TS among the visual grades were small. We presumed that the efficiency of visual grading after mechanical grading would be low in view of nondestructive evaluating strength. This phenomenon is more apparent in L.

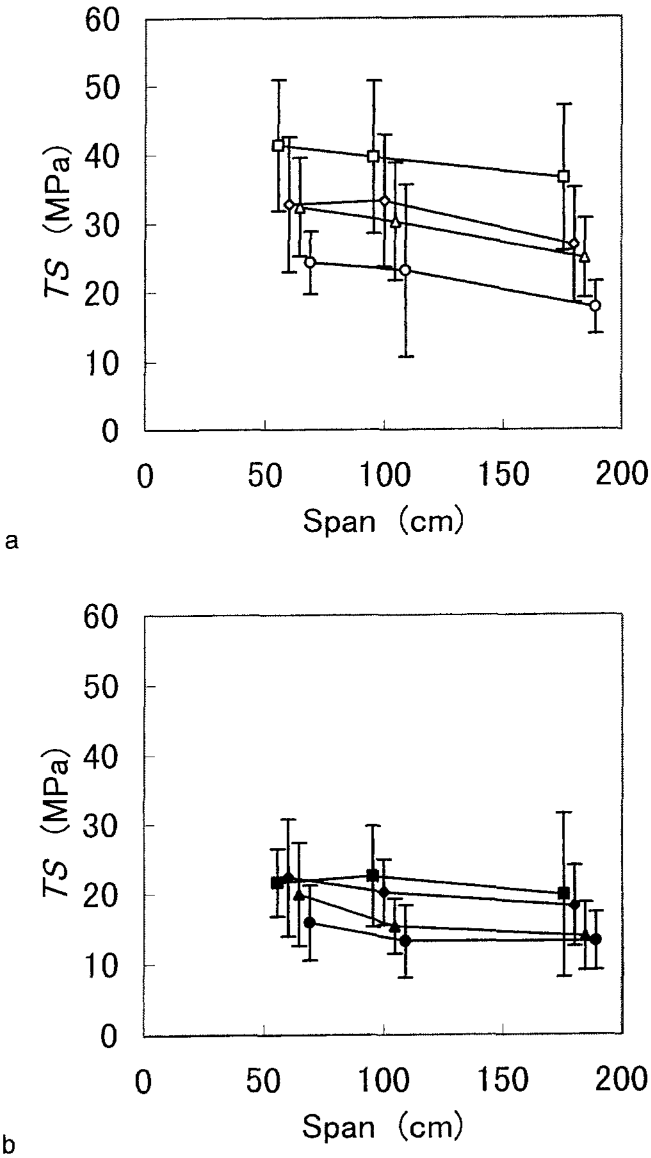


Fig. 4. Tensile strength (*TS*) for each visual grade. **a** High-grade lumber. **b** Low-grade lumber. Squares, diamonds, triangles, circles represent visual grades a, b, c, d, respectively; error bars are standard deviations

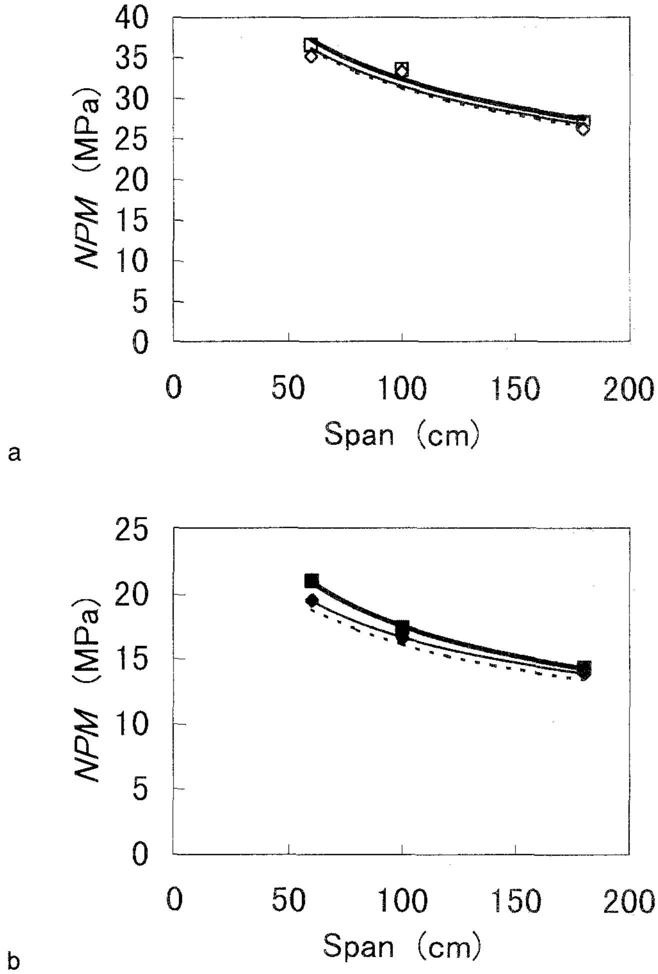


Fig. 5. Effect of knot restriction on the 50th percentile of tensile strength (*NPM*). **a** High-grade lumber. **b** Low-grade lumber. Squares and diamonds represent visual grades a–c (C) and a–d (D), respectively. Thick lines, thin lines, broken lines represent regression curves of C, D, all visual grades, respectively

Discussion

Effect of knot restriction on TS

The JAS[10] involves requirements for grade composition of laminae of glued laminated timber (glulam). For example, a mixed-grade glulam of symmetrical composition, with the outermost layer class 1, should be composed with the outermost layer having a knot diameter ratio at the edge of the width surface of not more than 17%. Also required is that the grade of the outermost layer correspond to the strength grade. In short, the edge knot restriction is provided for mechanically graded lumber for glulam.

We obtained the 50th percentile (NPM) and 5th percentile (NPL) of TS by the nonparametric method according to ASTM standard D2915-94[14] under the restriction of GK instead of edge knots. The relation between span and NPM is shown in Fig. 5 with regression curves. In Figs. 5 and 6, "C" and "D" denote grades a–c and grades a–d, respectively. It is clear that the effect of the restriction on TS was small in both H and L. In the case of NPL, shown in Fig. 6, the difference of TS between C and all grates was slightly larger than the differences for NPM. In all cases when the span length was 180 cm, it seems that there is no need to distinguish differences of TS; hence we judged that the effect of the restriction is negligible.

Differences in strength/elasticity ratio

The ratio of strength to elasticity has often been used to analyze the mechanical properties of structural lumber, as noted in the early literature.[15] Tsujii and Sugiyama[16] wrote: "It seems that approximate equation of bending elasticity = 220 × bending strength may be consistent regardless of species in clear small wood" and "The value of 2/3 may be

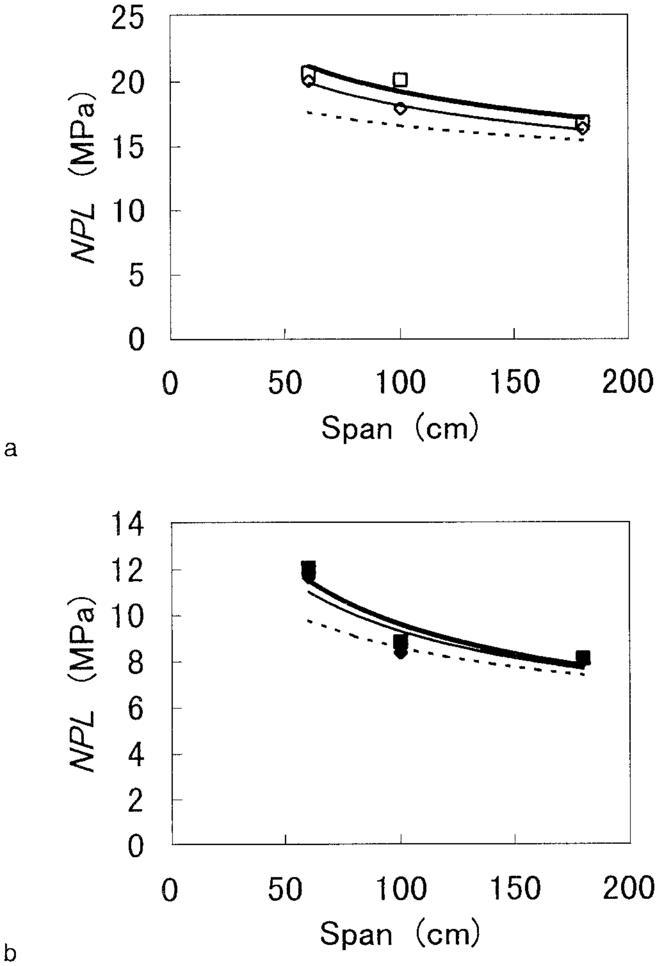


Fig. 6. Effect of knot restriction on 5th percentiles of tensile strength (*NPL*). **a** High-grade lumber. **b** Low-grade lumber. Squares, diamonds, broken lines represent a–c, a–d, all visual grades, respectively. See Fig. 5 for other explanations

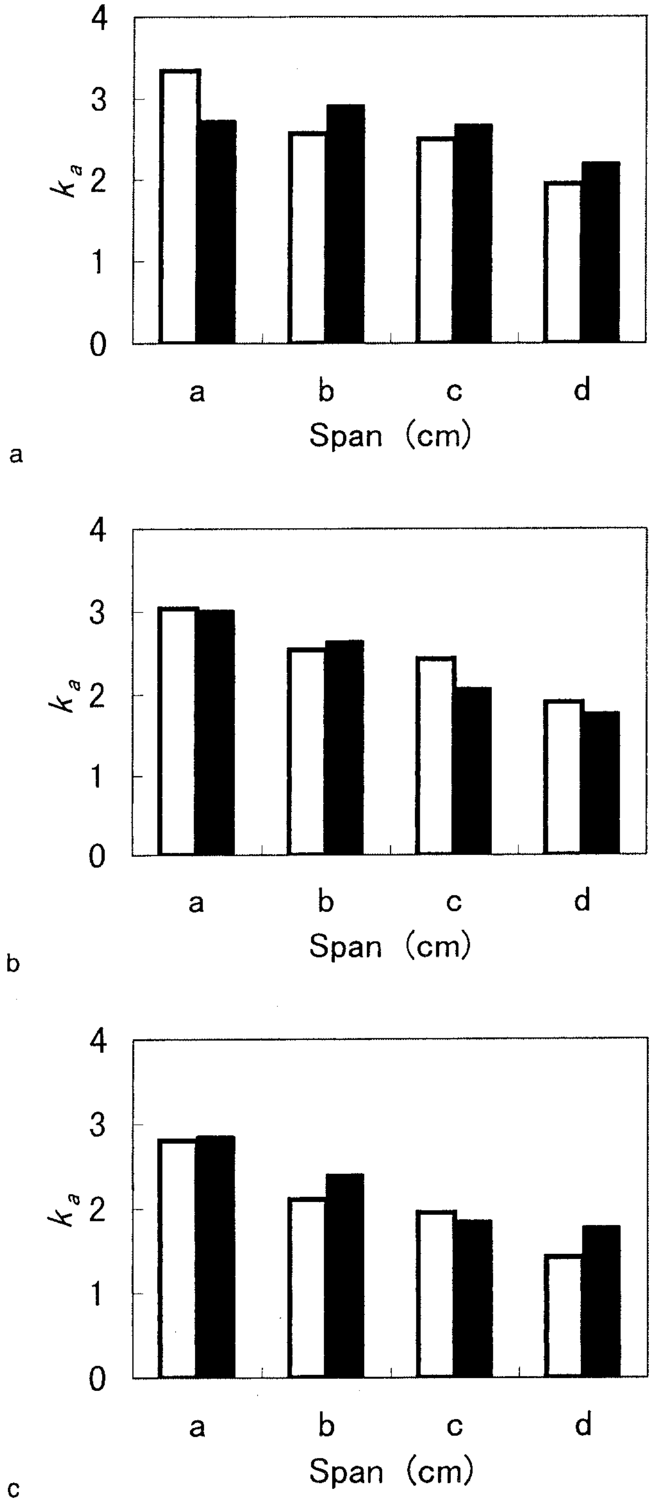
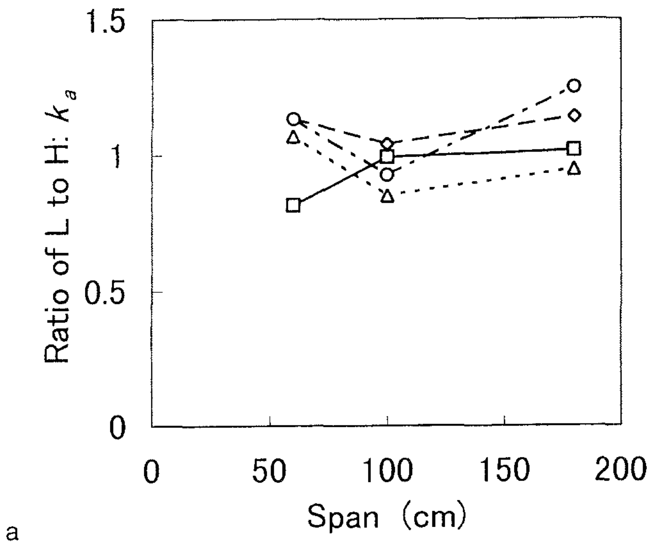


Fig. 7. Strength/elasticity ratio (k_a) for each grade. Specific ratio is defined as k_a = TS/E_f × 1000, when TS is the tensile strength and E_f is the dynamic young's modulus. Test span is 60cm (**a**), 100cm (**b**), and 180cm (**c**). *Open bars*, H average; *filled bars*, L average

acceptable as the ratio obtained from dividing strength of commercial timber by strength of small clear wood." These opinions lead us to believe that the ratio of bending strength to bending elasticity is 3.03 × 1000 in structural timber. Although this ratio is seldom found in recent reports, many researchers express the relation by using linear regression lines, which have a positive intercept of the objective variance. Suppose that elasticity is 0; if it never occurs on earth, these lines suggest that strength should not be zero. In this sense, it might be necessary to revive the ratio expressed as $k_a = \sigma_a/E_a$ for evaluating mechanical properties of structural timber. The subscript a in the equation denotes average; σ and E denote strength and elasticity, respectively.

Then we calculated k_a by multiplying by 1000 the values obtained from substituting the average TS for σ_a and E_f for E_a into the above equation for each specimen. Figure 7 shows the k_a for each specimen. The values of k_a decreased as the grade decreased and as the span length increased. The differences of k_a in H and L were small and not consistent.

To clarify the length effect on k_a, the L/H ratio was obtained for each visual grade. Figure 8a shows the relation between span and L/H in terms of k_a. All values were near 1.0, and there was no consistent tendency regarding length. Because we judged that there was no need to distinguish H and L, we calculated averages of H and L. The relation between span and the averages of H and L in k_a is



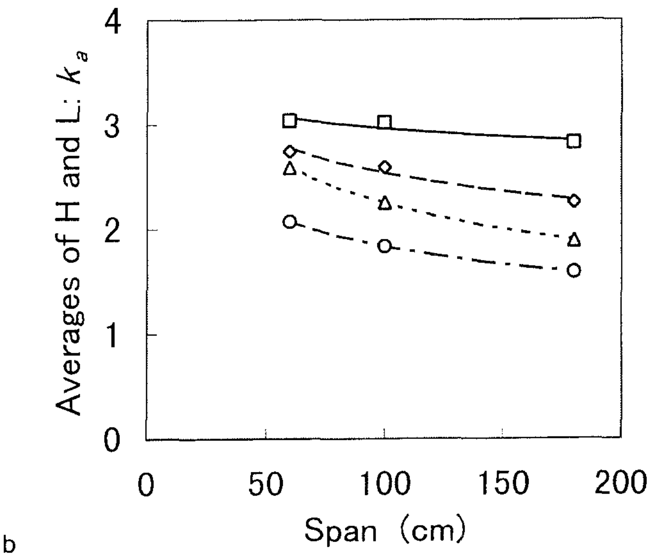


Fig. 8. Comparison of mechanically graded high-grade (H) and low-grade (L) lumber in terms of k_a (see Fig. 7). We calculated L/H (**a**) and averages of H and L (**b**) using k_a values. Squares, diamonds, triangles, circles represent visual grades a, b, c, d, respectively

shown in Fig. 8b. The length effects on the averages in visually graded low-grade lumber were stronger than in the high-grade lumber. The H and L averages fit the $k_a = p\ X^q$ by the least-squares method; X denotes span (centimeters) in the equation. The obtained q values of visual grades a, b, c, and d were 0.066, 0.180, 0.283, and 0.236, respectively. For each visual grade, the relation between the mean k_a at the three spans tested and q can be expressed with the linear regression line: $q = -0.164\ k_a + 0.583$; the coefficient correlation was 0.835. The lower k_a means larger length effects, and the length effects is weaker in the visually graded high-grade lumber than in the low-grade lumber.

These results suggest that the length effects on TS should vary in the visually graded lumber, but the knot restriction has little effect on TS distribution in each mechanically graded lumber with sufficient length. It may be that measurements of Young's modulus should be added to the visual grading method owing to the dependence of the TS distribution on Young's modulus.

Conclusions

We conducted tensile tests on mechanically graded high-grade and low-grade Japanese larch lumber and evaluated the results using the visual grading rule for focusing on grouped knots. Based on the test results, we investigated the effect of knot restriction on tensile strength and obtained the following results.

1. Tensile strength of visually graded high-grade lumber was stronger than visually graded low-grade lumber for both mechanically graded high- and low-grade lumber.
2. The effects of knot restriction diminished when the length of the lumber increased in terms of nonparametric 5th percentiles of tensile strength.
3. The differences in the strength/elasticity ratio between mechanically graded high-grade and low-grade lumber were negligible. It was clear that the effect of length on the ratio in visually graded high-grade lumber was smaller than that of low-grade lumber. In practical use, knot restriction should have little effect on the tensile strength of mechanically graded lumber.

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