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Variation of tensile strength with annual rings for lumber from the Japanese larch

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Abstract To examine the effectiveness of long rotation forestry and the potential of complete utilization of Japanese larch (*Larix kaempferi* Carriere), we designed a tensile test using the lumber from six 87-year-old sample trees. Results showed that strength properties of lumber varied greatly in the radial direction within trees, but all sample trees showed a similar trend. There was little difference in dynamic Young's modulus but a large difference in tensile strength (TS) between the lumber and small clear specimens from undestroyed parts of the lumber. These differences decreased with an increase in ring number and became constant after 30 years. The presence and distribution of knots markedly affected the TS; and among the knot indices, the knot number (Kn) and knot area ratio of a maximum single knot (Km) proved to be effective for explaining the effect of knots. The distribution of Kn and Km in the radial direction agreed with the variation of TS in the radial direction. By investigating the variation patterns of lumber and small clear specimens in the radial direction, it was found that the strength properties of both required a long time, about 30 years, to reach a relatively constant state.

Key words Tensile test · Small clear specimens · Knot · Long rotation · Japanese larch

Introduction

Japanese larch (*Larix kaempferi* Carriere), a tree species native to Japan, is mainly distributed in the mountain areas of central Japan.[1] It is suited to cold climates and characterized by fast growing and good adaptation to site. After World War II, as the main species subjected to short rotation and widespread afforestation, it was planted in the central region, the northeast, Hokkaido, and even in Kyushu.[2,3] More than 50 years have now passed, and the wood from these trees has begun to be used. Today utilization of Japanese larch is mainly recommended for use in structural glued laminated timber. During manufacture, however, due to the effects of juvenile wood and other factors, the timber often presents warp, check, cracks, and other defects, resulting in low quality products.[4]

Numerous studies on the wood properties of Japanese larch have been reported. Shiokura and Watanabe[5] reported that Japanese larch is a tree species with an apparent occurrence of juvenile wood that ranged from pith to 14–15 annual rings within a distance about 5–8 cm. Zhu et al.[6] studied the differences of the annual ring structure between corewood and outerwood. By studying the thinning wood of Japanese larch from Hokkaido, Koizumi et al.[7] concluded that the juvenile zone ran from the pith to the 15th annual ring, and the width of the zone was about 8 cm. Shigematsu[4] studied wood properties of Japanese larch produced in Nagano and pointed out that the growth of trees after a mature age not only cause the increase of diameter but also produce quality wood.

Many researchers have focused on evaluating the classification and the grading method of the laminae of Japanese larch lumber used for glued laminated timber by measuring strength properties.[8,9] The variation of localized Young's modulus within lumber has also been reported.[10] Takeda and Hashizume[11,12] investigated the size effect and the effect of knots on tensile strength distribution.

Little has been reported on the variation or distribution of lumber strength properties within the tree bole. Although we can simply deduce its general trend from the research results about juvenile and mature wood, we do not think the variation of lumber strength properties completely agreed with this observation, as it was done on the micro level. For lumber the situation is more complicated, as lumbers usually vary by the proportion of juvenile and

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mature wood contained in the same board, and they are affected by such factors as knots and the slope of the grain. Hence we think it is necessary to know the variation of strength properties depending on the sawing positions when lumber is cut continuously from a log.

Based on the above considerations, we designed this experiment to investigate the variation of strength properties in the radial direction using the lumber of Japanese larch. The final objectives were to examine the effectiveness of long-rotation forestry and the potential of complete utilization of Japanese larch wood.

Materials and methods

Materials

Six 87-year-old trees of Japanese larch were harvested from Togakusi, Nagano, Japan, with a diameter at breast height of 32 cm for sample tree no. 1, 43 cm for no. 2, 36 cm for no. 3, 32 cm for no. 4, 41 cm for no. 5, and 34 cm for no. 6.

For each sample tree, a 2-m long log was cut from a height of 2.2 m above the ground. The lumber was then continuously sawn from one side through the pith to the other side. The size of the cut lumber was about 2.5 cm thick, 15 cm wide, and 200 cm long.

Measurement

First, the ring number and distance from the pith to the center of each piece of lumber were measured at the end section of the log by restoring the lumber to its original shape. Here it should be noted that although the tree ages were 87 years, the actual ring numbers counted indicated an age of less than 60 years, for the end section of sampled logs located about 4.2 m above the ground. The mean annual ring width (ARW) and specific gravity (SG) were then determined. The number, position, and size of knots within a span with a diameter of >5 mm on each face of the lumber were measured; and the knot area ratios[13] of the maximum grouped knots, the maximum single knot, and the maximum edge knot were calculated.

The dynamic Young's modulus (Ef) of lumber was measured by the longitudinal vibration method.[14,15] The tensile test was conducted with the tensile test machine (NET-501E) manufactured in Japan in accordance with JAS.[16] The test span was 100 cm, and the time to failure was about 3–5 min. All of the lumber was tested in the same air-dried conditions, with 13.8% mean moisture content, which was measured near the rupture position by the oven-dried method.

After the tensile test, an average of three pieces of small, clear specimens were cut randomly from the nondestroyed part of each tested lumber. A mean of three pieces of small, clear specimens was used to represent the clear timber value of the lumber, so it was thought that the ring number from pith of small, clear specimens agreed with the lumber from which it came. The Ef of each small, clear specimen was measured using the same method with lumber. The specimens were then processed to use them for the tensile strength (TS) test parallel-to-grain in accordance with Japanese Industrial Standard.[17] Each specimen was 390 mm long, 23 mm wide, and 15 mm thick in both grip ends and 5 mm in the middle. The tensile test was conducted using the universal testing machine.

Results and discussion

Tensile strength of lumber

Table 1 shows the mean values for the physical and mechanical properties of the lumber for each sample tree. It can be seen that the mean values for Ef and TS were higher than the results reported by Kadowaki et al.[18] The reason may be the effect of the environmental and genetic differences between plantations sampled. Figure 1 shows the variations of ARW, SG, Ef, and TS in the radial direction for six sample trees. As expected, the SG, Ef, and TS presented an increasing trend and ARW showed a decreasing trend from center to outside for all sample trees, although there were irregular deviations within the trees during the increasing or decreasing processes for all wood property indices. It was thought that these variations were caused by both systematic factors (e.g., the characteristics of juvenile and mature wood) and random ones (e.g., knots).

Tensile strength of small clear specimens

Small, clear specimens from the nondestroyed part of the tested lumber were examined, and the basic information is presented in Table 2. Among the sample trees, there were no significant differences for ARW, SG, Ef, or TS. The

Table 1. Mean values for physical and mechanical properties of lumber for each sample tree

Variable	Sample trees					
	1	2	3	4	5	6
ARW (mm)	2.34	2.98	2.20	2.03	2.83	3.28
SG	0.51	0.51	0.60	0.58	0.50	0.50
Ef (GPa)	12.9	11.7	15.6	13.7	10.9	10.7
TS (MPa)	56.1	52.9	58.3	60.8	37.7	34.7

ARW, annual ring width; SG, specifity gravity; Ef, dynamic Young's modulus; TS, tensile strength

Table 2. Mean values for physical and mechanical properties of small clear specimens for each sample tree

Variable	Sample trees					
	1	2	3	4	5	6
ARW (mm)	2.47	2.7	2.16	1.68	2.93	3.08
SG	0.51	0.52	0.59	0.59	0.48	0.50
Ef (GPa)	13.5	12.7	16.4	15.5	10.8	12.1
TS (MPa)	114.9	93.5	122.9	137.4	99.2	88.0

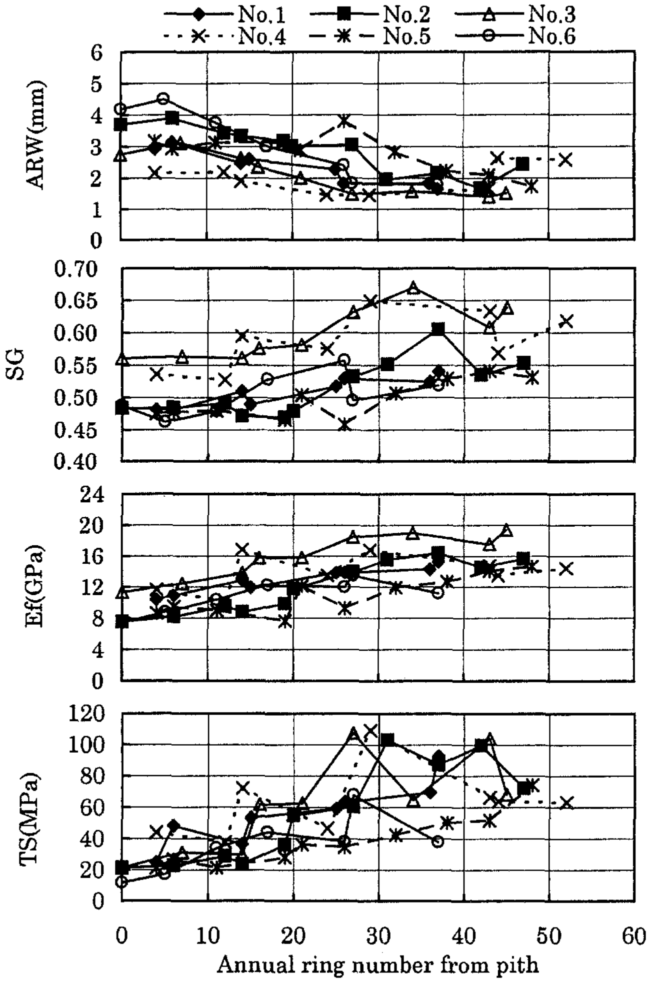

Fig. 1. Variation of annual ring width (*ARW*), specific gravity (*SG*), dynamic Young's modulus (*Ef*), and tensile strength (*TS*) of lumber with annual ring number from pith to bark for six sample trees

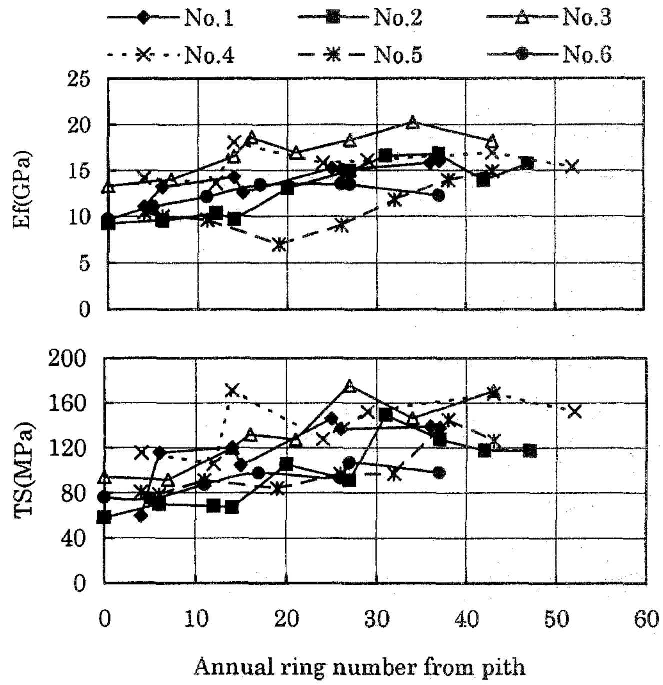

Fig. 2. Variation of Ef and TS of small clear specimens with annual ring number from pith to bark for six sample trees

values of TS were high compared with 83.3 MPa, the mean value of TS for Japanese larch.[19]

The Ef and TS of each sample tree are plotted against annual ring number in Fig. 2. Despite the considerable fluctuation within trees and diversification among trees, the data showed the expected trend of increasing Ef and TS with aging.

Relation of strength properties of lumber and small clear specimens

We found that all sample trees showed the same variation trend in the radial direction (Figs. 1, 2), so we compared the variations of the lumber and small clear specimens using the mean value of six sample trees. Figure 3 illustrates the variations of Ef and TS and their standard deviations for the small clear specimens and the sawn lumber in the radial direction. Although the small clear specimens had a somewhat higher Ef than sawn lumber, there were no obvious differences between them. The mean values were 13.4 GPa for small specimens and 12.5 GPa for lumber, with a rate of decrease of 7%. On the other hand, the TS of small clear specimens was much higher than that of sawn lumber. The mean values were 108.9 MPa for small specimens and 47.7 MPa for lumber, with a rate of decrease of 56%. However, similar radial patterns were seen for small clear specimens and sawn lumber for both Ef and TS; that is, they increased abruptly from pith outward, and following this rapid change they displayed a trend of slight increase from about the 30th annual ring.

We then examined the variation of ratios for lumber and small clear specimens in regard to ring numbers (Fig. 4). For Ef, the ratio had little variation in the radial direction, but the ratio for TS demonstrated an increasing trend before about 30 years and remained constant after that. This meant that the decrease rates from small clear specimens to lumber decreased, and the difference between them became less with an increase of tree age, then remained constant after 30 years.

From Figs. 3 and 4, it seems that the trend of variations in lumber strength properties in the radial direction was different from that observed in juvenile and mature wood, which emphasizes the 15th annual ring as the demarcation of juvenile and mature wood. The reasons for this difference may be the occurrence of knots, the varied proportion of juvenile and mature wood contained in the lumber, or the slope of grain, among others. Therefore, it seems reasonable to conclude that for lumber the strength properties of wood need a longer time than was thought to reach a constant state. This fact supports the statement that long rotation is necessary for Japanese larch to acquire quality trees.

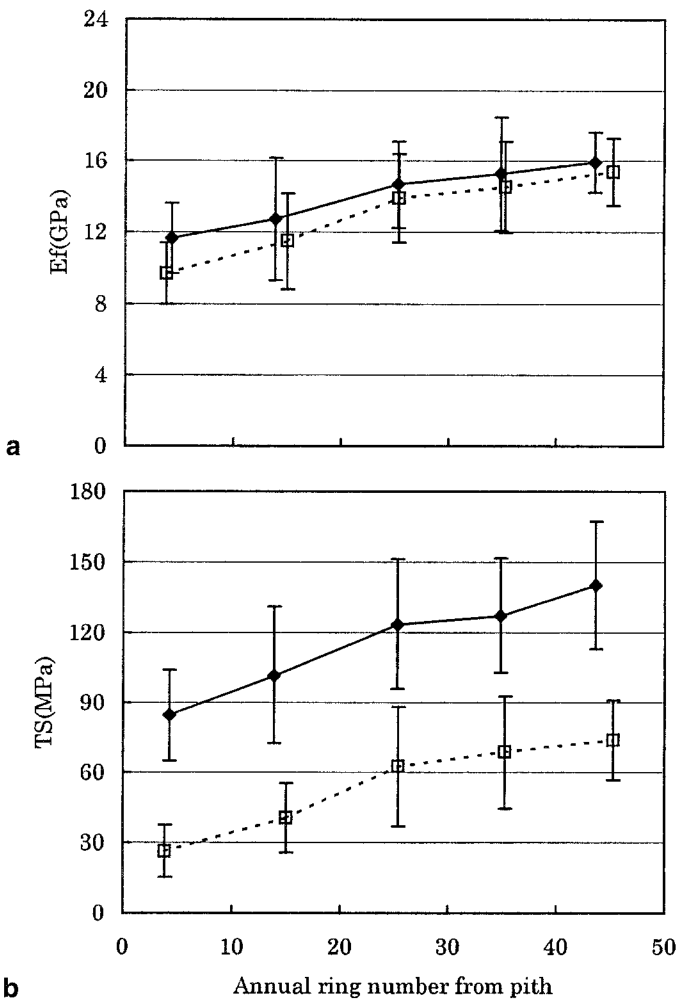

Fig. 3. Variation of Ef (**a**) and TS (**b**) for small clear specimens and lumber in the radial direction. *Filled diamonds*, small clear specimens; *open squares*, lumber; *error bars*, standard deviation

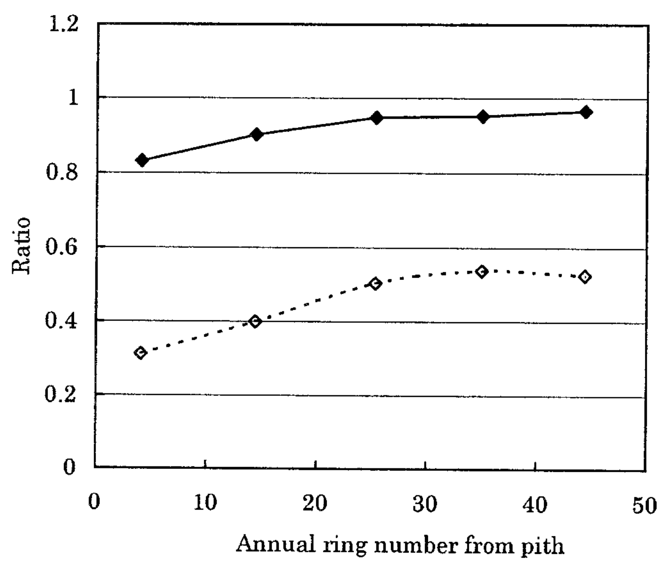

Fig. 4. Variation of Ef and TS described by the ratio of lumber and small clear specimens. *Filled diamonds*, Ef; *open diamonds*, TS; Ratio, lumber/small specimen

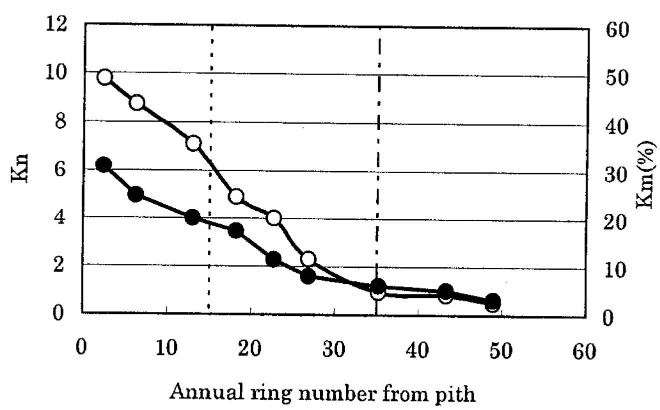

Fig. 5. Distribution of knot numbers (*Kn*) and knot area ratio of the single maximum knot (*Km*) in the radial direction. *Open circles*, Kn; *filled circles*, Km; *broken line*, 15th annual ring; *dash line*, 35th annual ring

Effect of knots on tensile strength of lumber

To understand better the variable trend of TS for lumber, we investigated the relation between strength properties and knots and their distribution in the radial direction. It was found that 61% of lumber in this tensile test failed in the presence of knots. This finding is consistent with the result reported by Takeda and Hashizume[12] that knots were the most influential factor for TS. Furthermore, we found that among knot indices the most prominent ones for TS were the number of knots (Kn) and knot area ratio of the maximum single knot (Km) testified, not only by their correlation coefficient but also by their rupture location. Hence we investigated the distribution of Kn and Km in the radial direction, as shown in Fig. 5. It was found that from pith to bark, both Kn and Km decreased abruptly and became constant at about the 30th annual ring, which agreed with the variation of TS in the radial direction. We think this curve can well explain the distribution of the ratios between lumber and small clear specimens.

Conclusions

To examine the effectiveness of long-rotation forestry and the potential for utilization of Japanese larch wood, we conducted tensile strength tests of lumber from Japanese larch and investigated the variation in the trend of tensile strength properties in the radial direction within trees. The following results were obtained.

1. Strength properties of lumber varied greatly in the radial direction within trees, but all sample trees showed a similar trend.

2. Small clear specimens from nondestroyed parts of the lumber showed little difference from lumber in dynamic Young's modulus (Ef) but a large difference in tensile strength (TS).

3. It was verified that the presence and distribution of knots greatly affected the TS. Among the knot indices, the

knot number (Kn) and knot area ratio of the maximum single knot (Km) proved to be effective for explaining the effect of knots. The distribution of Kn and Km in the radial direction agreed with the TS variation in the radial direction.

4. By investigating the variation patterns of lumber and small clear specimens in the radial direction, it was found that the strength properties of both need a longer time, about 30 years, to reach a relatively constant state. This finding supported the fact that for Japanese larch the forestry goal should be based on long-rotation management to acquire quality wood.

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