Influence of Sawing Patterns on Lumber Quality and Yield in Large Sugi (*Cryptomeria japonica*) Logs

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Abstract

Appropriate log sorting and optimal sawing patterns are indispensable for efficient lumber production. It is also important to clarify the relationship between the quality of logs and that of sawn lumber to determine effective sorting and optimal sawing patterns. Although some information on lumber quality has been obtained for medium sugi (*Cryptomeria japonica* D. Don) logs, little is known about lumber quality in large logs, the supply of which is expected to increase imminently. We investigated the influence of the sawing patterns of large sugi logs on lumber quality. Large sugi logs (30 to 40 cm in diameter) were converted into sawn lumber using different sawing patterns. Sawing yields varied for each sawing pattern. Sorting logs by Young's modulus (E_{fr}) would be useful for the efficient production of reliable sawn lumber from large logs, especially when the dimensions of the main products are large. Conversely, it is important to note the variation of E_{fr} in logs when several main products were sawn. Lumber warp was affected by sawing pattern rather than the log sweep. There is potential to produce reliable lumber by considering sawing patterns based on the variation of E_{fr} within a log and the difference of lumber warp.

In 2007, Japan had 25 million hectares of forest, comprising about 67 percent of the country. The growth stock is 4.4 billion m^3, increasing by 80 million m^3 annually, while about 10 million hectares of the forest area is softwood planted forest. In 2006, about 35 percent of the forest in the planted area was older than 50 years old, which is expected to increase to about 60 percent in the coming decade (Ministry of Agriculture, Forestry and Fisheries, Japan 2009). The majority of both the planted area and forest stock in Japan are sugi (*Cryptomeria japonica* D. Don). As the ratio of the forest area of high age classes increases, the supply of large-diameter logs is also expected to expand, and it is important to ensure that such mature forest resources are used sustainably. Because the main application of domestic logs in Japan is as sawn lumber, efficient lumber production is needed.

Appropriate log sorting and optimal sawing patterns are indispensable for efficient lumber production. Modern large-scale sawmills incorporate scanning and optimization technologies to maximize lumber volume by measurement of the log shape. Log sorting and optimal sawing patterns are required to produce reliable lumber, according to the log and lumber qualities needed for end use. It is important to clarify the relationship between the quality of logs and that of sawn lumber to determine an effective sorting and optimal sawing pattern. For log sorting, certain parameters were investigated to predict the lumber quality of logs. Tsehaye et al. (2000) showed that the quality and grade recovery of structural timber would be increased by selecting trees on the basis of stiffness, while Ridoutt et al. (1999) compared Pilodyn penetration, branch size, and longitudinal stress-wave velocity as methods for log segregation. Petutschnigg and Katz (2004) elaborated a

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statistical model to predict the lumber quality depending on related characteristics, such as reaction wood, number and size of knots, discoloration, and curvature. Ross et al. (1997) showed that a strong relationship was observed between the modulus of elasticity (MOE) of the logs and the lumber produced from the same. Where lumber strength is required, Young's modulus of logs would be one of the useful factors for log sorting (Iijima et al. 1997; Koizumi et al. 1997a, 1997b; Ikeda et al. 1999; Matsumura et al. 2005, 2007).

To meet the demand for the end use of lumber, as well as log grade, sawn position within a log must be also considered (Iijima et al. 1997, Aratake and Morita 1999). Sawing patterns can influence both sawing yield and lumber quality. Previous studies showed the potential to produce lumber suitable for end use efficiently by sorting logs considering Young's modulus and moisture content and sawing them using optimal sawing patterns.

In the Japanese Agricultural Standards (JAS) for logs (Ministry of Agriculture, Forestry and Fisheries, Japan 2007a), logs with a top-end diameter less than 14 cm are defined as small logs, those with a top-end diameter of 14 to less than 30 cm are defined as medium logs, and those with a top-end diameter of 30 cm or more are defined as large logs. Although some information on lumber quality has been obtained in medium sugi logs (Matsumura et al. 2005, 2007), little is known about quality in large logs, the supply of which is expected to increase imminently. Variations in sawing patterns also rise with increasing log diameter. The relation between sawing patterns and the lumber quality or yield in large sugi logs must be investigated. However, there have been fewer studies on lumber quality and sawing yields based on data obtained by actual sawing for large sugi logs.

The purpose of this study was to examine the influence of log quality and sawing patterns on sawing yields and lumber quality in large sugi logs. In this study, we focused on the Young's modulus and warp of lumber as parameters of lumber quality. We also investigated the relationship between logs and lumber quality for several sawing patterns, while the volume and value yields for each were also calculated.

Materials and Methods

Materials

A total of 141 large sugi logs grown in Tochigi Prefecture were used in this study, ranging in diameter from 30 to 40 cm and 3.65 m long. After debarking, the lengths, top- and butt-end diameters, number of growth rings, and heartwood percentage were measured. Chord height was measured in units of 1 mm using a thread and ruler, and the log sweep was calculated using Equation 1.

$$S = \frac{H}{D} \times 100 \qquad (1)$$

where S (%) is the log sweep, H (cm) is the chord height of the log, and D (cm) is the top-end diameter. The logs were graded based on the JAS for logs (Ministry of Agriculture, Forestry and Fisheries, Japan 2007a). The natural frequency of the vibration of the log was measured by a longitudinal vibration method, and Young's modulus of the logs was calculated using Equation 2,

$$E_{\mathrm{fr}} = 4 \times L^2 \times \mathrm{fr}^2 \times \rho \times 10^{-9} \qquad (2)$$

where E_{fr} (GPa) is Young's modulus, L (m) is the length, fr (Hz) is the natural frequency of vibration, and ρ (kg/m^3) is the bulk density.

Sawing test

A 1,200-mm band mill with an auto-feed carriage and a 1,100-mm auto-roller table band resaw installed in the Forestry and Forest Products Research Institute, Japan, were used in this study. Only one sawyer operated these band saw machines throughout this study. Logs were sawn using the four sawing patterns shown in Figure 1. Sawing patterns were defined according to the kind of main products. The main products of the sawing patterns were as follows: Sawing Pattern 1 (SP1), flat square lumber, 25.0 cm wide

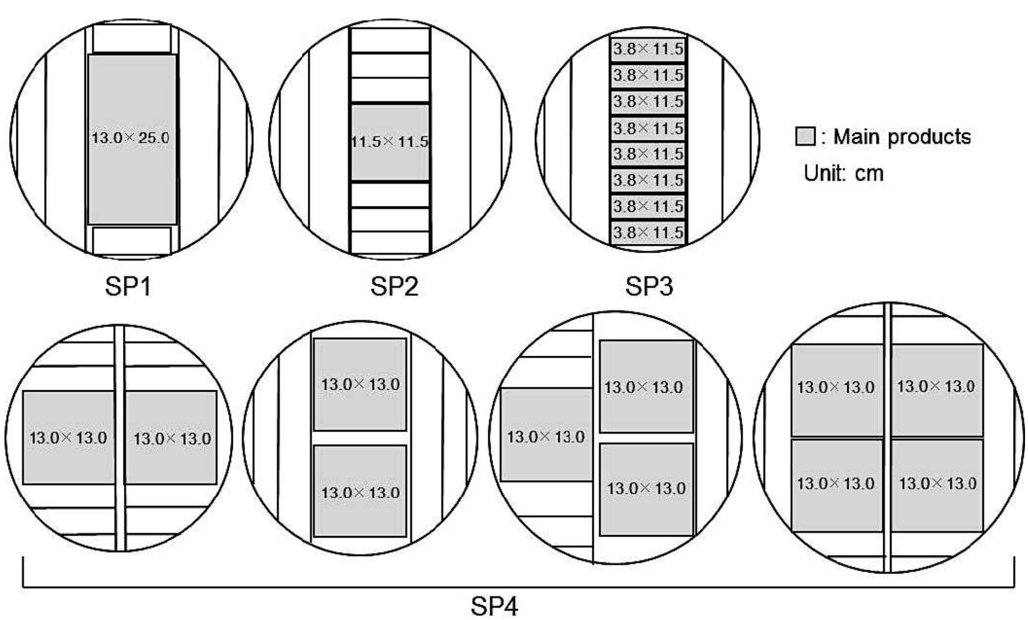

Figure 1.—Sawing patterns used. Shaded areas are the main products of each sawing pattern.

and 13.0 cm thick; Sawing Pattern 2 (SP2), squared lumber with pith, 11.5 cm wide and 11.5 cm thick; Sawing Pattern 3 (SP3), scantling, 11.5 cm wide and 3.8 cm thick; and Sawing Pattern 4 (SP4), squared lumber without pith, 13.0 cm wide and 13.0 cm thick. In SP4, several pieces of squared lumber may have been sawn depending on the diameter of the logs.

Lumber quality and sawing yields

Immediately after sawing, lumber was graded based on the JAS for sawn lumber (Ministry of Agriculture, Forestry and Fisheries, Japan 2007b). The main products of each sawing pattern were weighed, and their width, thickness, and length were measured. Chord height of the lumber was measured in units of 1 mm using a thread and ruler, and lumber warp was calculated using Equation 3.

$$W_1 = \frac{H_1}{L_1} \times 100 \tag{3}$$

where W_1 (%) is the lumber warp, H_1 (mm) is its chord height, and L_1 (mm) is the length.

The natural frequency of the lumber vibration was measured by a longitudinal vibration method, and Young's modulus of the lumber was calculated using Equation 2. The volume and value yields in each sawing pattern were calculated using Equations 4 and 5.

$$Y_{\mathrm{vol}} = \frac{\left(\sum V_i\right)}{V_0} \times 100 \tag{4}$$

$$Y_{\mathrm{val}} = \sum \left(\frac{V_i}{V_0} \times \frac{P_i}{P_0}\right) \times 100 \tag{5}$$

where Y_{vol} (%) is the volume yield, Y_{val} (%) is the value yield, V_i (m^3) is the volume of each sawn lumber, V_0 (m^3) is the volume of the log calculated by the squared diameter method, P_i (Japanese yen [JPY]/m^3) is the price of each sawn lumber, and P_0 (JPY/m^3) is the price of a standard lumber. Squared lumber of sugi that made up the majority of the domestic lumber market was used as standard lumber in this study, and the price of each sawn lumber was the Japanese average price. In Japan, the value yield is often expressed as the value of lumber per unit log volume (Edamatsu and Mori 1963). Although simple lumber was used to compute the value solution, chips, sawdust, and bark were not included in the value. This value yield could evaluate the value of lumber regardless of log price fluctuations.

Results and Discussion

Specification of the logs used

In all logs sawn, the average diameter of the top end was 33.0 cm, that of the butt end was 38.5 cm, the volume was 0.414 m^3, the number of growth rings was 52, and the percentage of heartwood was 47.7 percent (Table 1).

Sawing yields

The volume and value yields for each sawing pattern are shown in Table 2. One log for SP1 was excluded from the samples for sawing yields because it could not be graded correctly owing to a serious defect of the main product. The average volume and value yields varied among the sawing patterns from 55.6 to 59.2 percent, and from 56.9 to 65.5 percent, respectively. Multiple comparisons among four sawing patterns were made by the Tukey-Kramer test, with the level of statistical significance taken as $P < 0.05$. The P values are shown in Table 3. The volume yield of SP1 significantly exceeded SP2 and SP3. In general, the volume yield tends to be high in sawing patterns producing large dimension lumber, because the decrease caused by kerf is small. The peak value yield was that of SP1, while that of SP4 significantly exceeded SP3. The value yield for logs with a high volume yield also tends to be high when the log grade is at the same level (Murata et al. 1991). We confirmed the prevalence of this tendency for large-diameter logs because of the high value yields of SP1 and SP4.

Young's modulus of log and lumber

The relationship between Young's modulus (E_{fr}) of the logs and the mean E_{fr} of lumber within each log are shown in Figure 2. A significant correlation was observed between the E_{fr} of the logs and the main products ($P < 0.05$), which indicates the potential to estimate the E_{fr} of sawn lumber from the E_{fr} of large sugi logs as well as the case of medium sugi logs (Aratake and Morita 1999, Matsumura et al. 2007). To consider the influence of the sawing pattern on the estimation of E_{fr} of lumber from that of logs, the relationships in each sawing pattern were examined. The relationship between E_{fr} of the logs and the individual E_{fr} of lumber for each sawing pattern are shown in Figure 3. Simple regression analysis revealed a significant correlation between the E_{fr} of logs and the E_{fr} of lumber for all sawing

Table 1.—Specifications of the logs used.

Sawing pattern[a]	No. of logs		Diameter (cm)		Length (cm)	Volume (m^3)	Weight (kg)	No. of growth rings	Heartwood (%)[b]	E_{fr} (GPa)[c]
			Top end	Butt end						
SP1	53	Mean	32.5	37.4	376.3	0.400	265.6	58	48.0	8.16
		SD	2.4	3.6	4.0	0.063	53.4	17	8.4	0.81
SP2	26	Mean	33.8	40.6	374.1	0.429	283.2	54	51.9	6.14
		SD	2.3	3.9	2.2	0.058	56.0	13	8.9	0.63
SP3	37	Mean	33.0	39.1	381.3	0.416	256.5	42	44.9	6.07
		SD	2.0	2.8	3.5	0.053	42.6	3	7.7	0.51
SP4	25	Mean	34.1	38.4	374.2	0.422	264.7	50	46.9	7.28
		SD	2.4	3.2	1.4	0.066	47.0	5	6.0	1.01

[a] Sawing patterns are shown in Figure 1.
[b] Heartwood = percentage of heartwood area on top end.
[c] E_{fr} = Young's modulus measured by longitudinal vibration method.

Table 2.—The volume and value yields for each sawing pattern.

Sawing pattern[a]	n	Volume yield, mean (SD) (%)	Value yield, mean (SD) (%)
SP1	52	59.2 (0.41)	65.5 (0.57)
SP2	26	56.9 (0.58)	58.5 (0.80)
SP3	37	55.6 (0.48)	56.9 (0.67)
SP4	25	57.5 (0.59)	60.9 (0.82)

[a] Sawing patterns are shown in Figure 1.

Table 3.—The P values by Tukey-Kramer test ($P < 0.05$) for sawing yields of each sawing pattern.[a]

	SP1	SP2	SP3	SP4
Volume yield				
SP1	—	0.007	<0.0001	0.076
SP2	—	—	0.321	0.896
SP3	—	—	—	0.072
SP4	—	—	—	—
Value yield				
SP1	—	0	0	<0.0001
SP2	—	—	0.386	0.165
SP3	—	—	—	0.001
SP4	—	—	—	—

[a] Sawing patterns are shown in Figure 1.

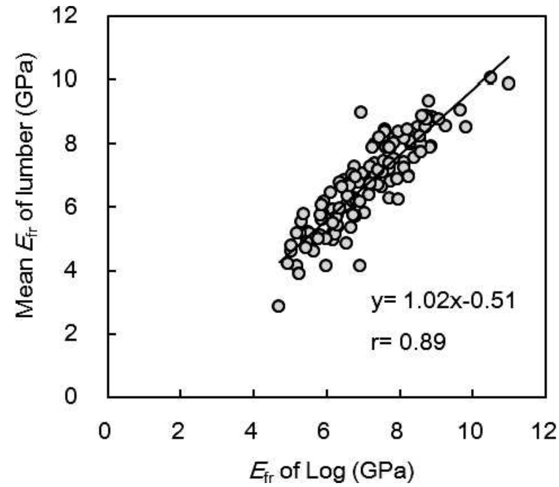

Figure 2.—Relationship between Young's modulus (E_{fr}) of logs and mean E_{fr} of lumber.

patterns ($P < 0.05$). If the dimensions of the main products were relatively large, as in SP1 and SP4, the E_{fr} of lumber would indicate a similar E_{fr} of original logs, which suggests that sorting logs by E_{fr} would be useful especially for the efficient production of reliable sawn lumber from large logs.

The E_{fr} of the flat square of SP1 and squared lumber without pith of SP4 would show the average Young's modulus of the whole log because they included both juvenile and mature wood at a similar ratio to the whole log. Conversely, the squared lumber with pith of SP2 had more

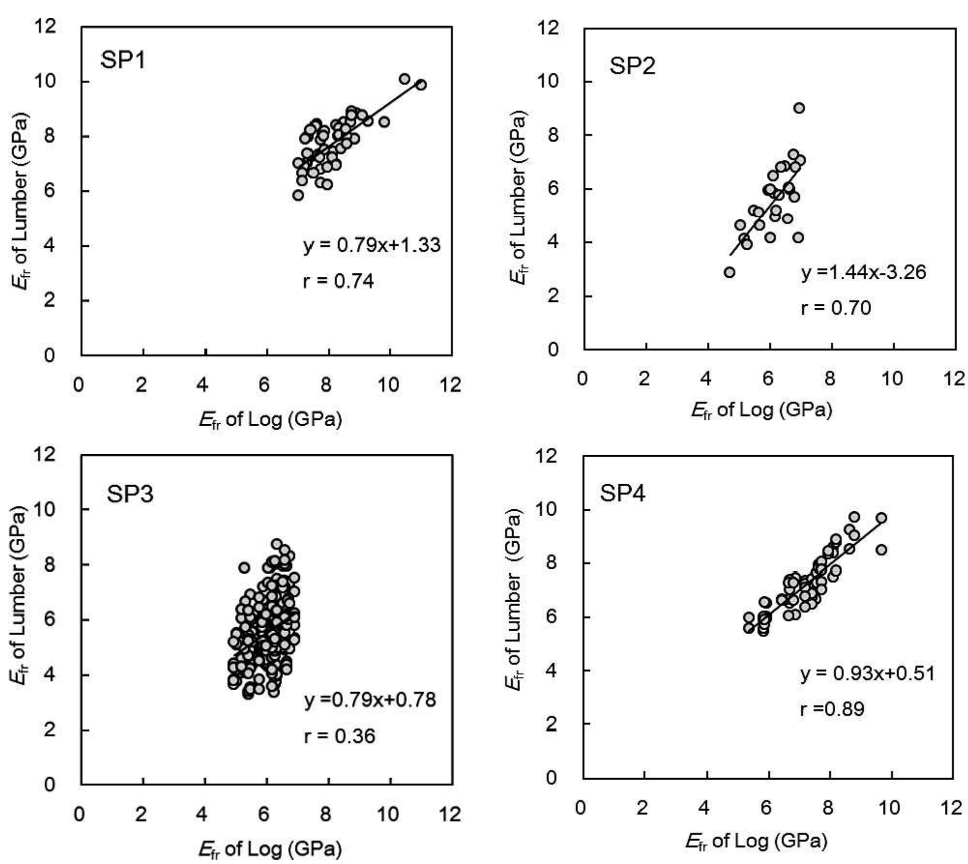

Figure 3.—The relationship between Young's modulus (E_{fr}) of the logs and the individual E_{fr} of lumber for each sawing pattern.

juvenile wood and probably more exposed defects, so E_{fr} will differ from original logs. SP3 must be considered separately from other sawing patterns. In general, E_{fr} varies within the log according to its position (Iijima et al. 1997, Nagao et al. 2003, Matsumura et al. 2005). The E_{fr} of the log shows the average E_{fr} for the whole log, and E_{fr} varies within a log according to its position. Therefore, this variation is reflected in the difference of each E_{fr} of lumber, because of the small dimensions of the lumber in SP3.

We examined the influence of the lumber position on the log on the variation of E_{fr} of the lumber. The lumber positions on the log in SP3 are illustrated in Figure 4. Here, ‘‘center’’ is the position including the pith or part thereof, ‘‘outer’’ is the outermost position of the log, and ‘‘inner’’ is a position between the two. The respective totals for lumber pieces corresponding to center, inner, and outer were 47, 148, and 70. The frequency distributions of E_{fr} of logs for SP3 and the lumber E_{fr} for each position are represented in Figure 4. The mean lumber E_{fr} corresponding to center, inner, and outer were 4.64, 5.44, and 6.48 GPa, respectively. One-way repeated measures of analysis of variance were used to compare means among positions, with the level of statistical significance taken as $P < 0.05$. There was a significant difference in mean lumber E_{fr} among positions. This tendency resembles the result of other studies, whereby specific MOE increased significantly from pith to bark in sugi (Iijima et al. 1997, Zhu et al. 2003). The variation factor of the E_{fr} within the sugi log was explained by microfibril angles and density as well as variables (Hirakawa et al. 1997, Yamashita et al. 2000). This suggests that it is important to note the variation of E_{fr} in logs when several main products were sawn from large sugi logs as in SP3, especially when lumber strength is required.

Lumber warp

The average log sweep was 5.5 percent in all logs used. The relationships between log sweep and lumber warp in SP1, SP2, and SP4 are shown in Figure 5. There were no significant correlations between the log sweep and lumber warp by simple regression analysis ($P < 0.05$). When the log diameter is sufficient, the influence of the log sweep might be small. It is reasonable to consider the influence of log sweep as minor because of the large diameter and comparatively small sweep of the logs.

The lumber warp for flat square, squared lumber with pith, and squared lumber without pith are shown in Figure 6. In Figure 6, W_a is parallel warp with log sweep and W_b is vertical warp with log sweep. Multiple comparisons among means W_a and W_b for SP1, SP2, and SP4 were made by the Tukey-Kramer test, with the level of statistical significance taken as $P < 0.05$. There were significant differences between W_a of the flat square and squared lumber with pith, and between the flat square and squared lumber without pith. There were also significant differences among W_b of flat square, squared lumber with pith, and squared lumber without pith. Of the three products, the squared lumber without pith had the largest W_b. Moreover, a significant difference between W_a and W_b of squared lumber without pith was observed by analysis of variance ($P < 0.05$). Though both flat square and squared lumber with pith included pith, the fact that the warp of flat square is smaller than that of squared lumber with pith is considered attributable to the fact that the dimension of the flat square exceeded that of the squared lumber with pith. The crooking

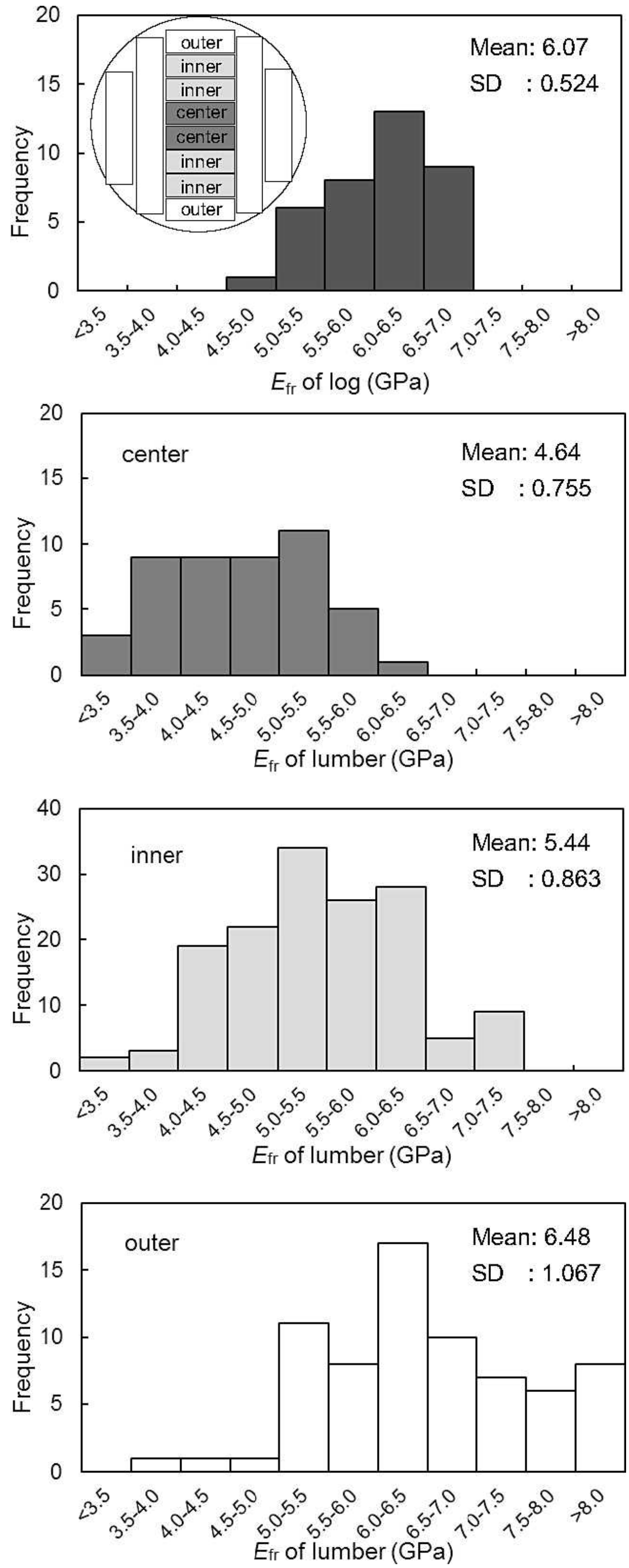

Figure 4.—Comparison of the frequency distribution of Young's modulus (E_{fr}) of lumber in Sawing Pattern 3 for each position on the log.

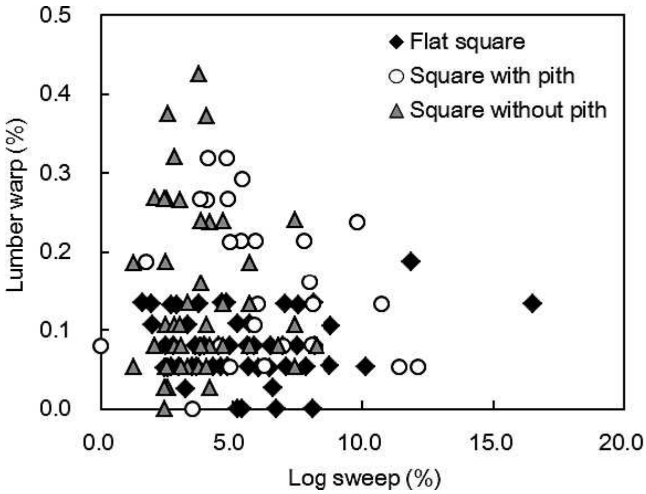

Figure 5.—Relationship between the log sweep and lumber warp in Sawing Patterns 1, 2, and 4. Plots indicate parallel lumber warp with log sweep.

of lumber would be influenced by growth stress (Okuyama and Sasaki 1979, Ormarsson et al. 2009) and pith location (Ikami et al. 2009). Because the dimension of the flat square exceeded that of squared lumber with pith, the warp of the flat square might be subject to comparatively little influence by both gradient growth stress and pith location. Conversely, the warps of squared lumber with and without piths, respectively, differed because of their grain. The warp of squared lumber without pith would be larger because the longitudinal sections could not be accurate flat sawn or quarter sawn grains. Particularly in the case of production of three or four squared lumber without pith, the influence of the grain could be larger.

These facts suggest that the lumber warp was affected by the sawing pattern. There is potential to produce reliable lumber by using a sawing pattern taking the variation of lumber warp into consideration. The processing accuracy of finishing would improve by enlarging the rough sawn size for the sawing pattern that causes large lumber warp. Consequently, upgrading the lumber might lead to improvement in the value yield.

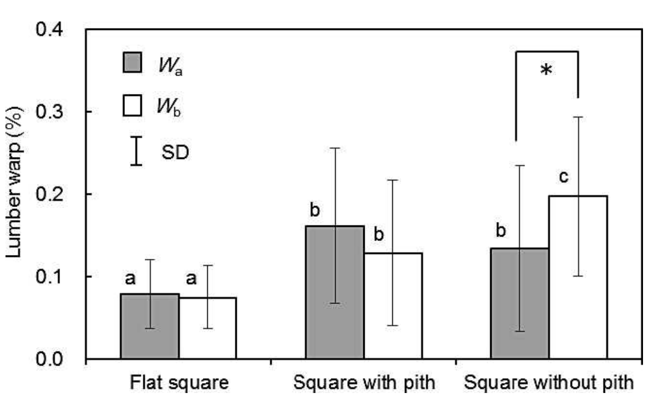

Figure 6.—Warp of lumber in Sawing Patterns 1, 2, and 4. Bars and error bars indicate mean values and standard deviations, respectively. Different letters (a, b, c) show significant differences using the Tukey-Kramer test (P $<$ 0.05) among sawing patterns. The asterisk (*) shows significant differences by analysis of variance (P $<$ 0.05).

Conclusions

This study was intended to examine the influence of sawing patterns on lumber quality of large sugi logs and involved us investigating the relationship between logs and lumber qualities in several sawing patterns.

The volume yield of large sugi logs tends to be high in sawing patterns producing large dimension lumber such as flat square. The value yield also showed a similar tendency.

A significant correlation was observed between the E_{fr} of logs and main products. The result shows that sorting logs by E_{fr} would be useful for the efficient production of reliable sawn lumber from large sugi logs, with especially large dimensions of main products. Conversely, it is important to note the variation of E_{fr} in logs when several main products were sawn, as in SP3, especially when lumber strength is required.

Lumber warp was affected by the sawing patterns rather than the log sweep, because of growth stress or their grain. Using a sawing pattern taking the variation of lumber warp into consideration for the processing accuracy of finishing might improve the sawing yield.

There is the potential to produce reliable lumber by considering the variation of E_{fr} within a log and the difference of lumber warp according to sawing patterns.

Acknowledgments

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