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Unique characteristics of residual stress distribution of large-diameter keyaki (*Zelkova serrata*) logs and examination of their measurement method

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Abstract
Large-diameter keyaki (*Zelkova serrata* Makino) logs have long been used in Japan as high-quality material especially for traditional construction and furniture. However, unlike other major wood species in Japan, keyaki has been practically considered as a wood species of high difficulty when processing. Keyaki frequently shows processing defects due to sawing, such as warping, cracking, and so forth, which often reduces the production yield of logs. Furthermore, there are drastic differences in those behaviors between individual logs, so causing unexpected processing defects. A scientific approach is required to improve this situation, but data on the material characteristics of keyaki were scarce. This study aimed to characterize the radial pattern of the residual stress as one of the processing-related characteristics. The measurement method was also examined. This study used diametral planks obtained from large-diameter keyaki logs to measure released strain of residual stress from pith to the bark sides. The results showed the distribution of released strain often showed peculiar zig-zag patterns characterized with localized residual stress, unlike the smooth bell curve pattern seen in typical logs of other species. Because of the unique characteristics, some practical points related to the measuring methodology were investigated. The extent of influence of this residual stress in the longitudinal direction was limited to within 30 cm from the site of measurement of the strain. In addition, the length of log necessary to measure the released strain without being affected by crosscutting was more than four times the log diameter—greater than the diameter ratio theorized by previous studies.

Keywords Keyaki (*Zelkova serrata* Makino), Large-diameter log, Released strain of residual stress, Hardwood, Sawing

Introduction
Zelkova serrata Makino, which is also called “Japanese zelkova” or “keyaki,” has long been used as a building and furniture material in East Asia [1, 2]. Its use as a primary lumber began in Japan around the twelfth century. Compared to other domestic wood species in Japan, such as Japanese cypress (*Chamaecyparis obtusa* Endl.) and Japanese cedar (*Cryptomeria japonica* D. Don) keyaki has been preferred owing to the high strength, the ease of obtaining large-diameter logs, and the beauty of its grain [3]. Above all, it is highly sought after in the construction of traditional temples and houses as both structural

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and finishing materials owing to its good strength and large diameter (capable of creating large spaces inside of the constructions) and its highly decorative appearance (Fig. 1).

However, keyaki wood is susceptible to warping and cracking during sawing. This often reduces the utilization yield of harvested logs and frequently causes unexpected and irregular warping and cracking in the primary lumber. Furthermore, there are drastic differences in those behaviors between individual logs, and it is difficult to evaluate the log quality beforehand. For the moment, only highly skilled carpenters and craft persons can evaluate the quality of keyaki wood based on traditional experience and intuition. To maximize the use of the precious forest resource of keyaki wood, it is necessary to generalize the method for evaluating the quality. Therefore, an approach that is based on both experience and science is required.

Generally speaking, the growth stress that occurs with the formation of wood cell wall causes the residual stress in the log after the repetition of the secondary growth, leading to undesirable warping and cracking during sawing [4]. Curiously, keyaki frequently forms tension wood within the log regardless of whether the tree grows upright or inclined, while hard wood species generally generates tension wood on the upper side of their inclined trunk [5]. Tension wood is composed of Gelatinous (G-) fibers and has specific physical properties. It is considered that the occurrence of specific growth stresses at tension wood causes the disturbance of residual stresses [6–10]. Drying shrinkage in longitudinal direction is large at tension wood, which induces the irregular deformation [e.g., 11]. These characteristics could possibly contribute to the individual differences of keyaki. However, the true nature of inside characteristics of keyaki, such as residual stress, tension wood, and complex grain [12, 13], remains unclear.

Fig. 1 Keyaki wood used in traditional temple construction (Shogo-ji Temple, Miyazaki, Japan). Keyaki was used for main columns, beams with carving, and block and bracket clusters called Tokyou at the top of the columns

Even though keyaki wood is considered to have specific characteristics, there are not many studies on it possibly because keyaki wood has been used mainly in East Asia and its use has been owned by the traditional experience and intuition. Researches tried to establish the strength criterion for the effective use of keyaki wood [14–16]. However, as these studies are fragmentary data on material properties, the characteristics of keyaki wood, especially the distribution of the properties inside the logs, were still not clear. Yashiro et al. [17] measured the mechanical properties and chemical composition using a 5-cm-thick and 54-cm-diameter disk of keyaki wood. They defined the tension wood based on the measured values, and the area of tension wood in the disk was also determined. Using a tree of keyaki, Arakawa et al. [18] measured the surface growth stress, longitudinal Young's modulus, and drying shrinkage and their relationships. They revealed that G-layer contributed the specific properties of tension wood. Further, Abe et al. [19] investigated the effects of the proportion of G-fiber to normal fiber on the shrinkage of specimens owing to boiling and drying. On the residual stress of keyaki logs, Okuyama et al. [20] and Huang et al. [21] measured the distributions of released strain of residual stress (hereafter, "released strain") using large-diameter logs aiming to reduce the residual stress within the logs by heat treatment. The radial distributions of released strains in the logs, two samples from Okuyama et al. and one sample from Huang et al. [20, 21], showed unique shapes, not seen in other species. However, they did not mention in details on the results.

While there are some data regarding mechanical or chemical properties and how to solve material issues of keyaki wood (heat treatment, etc.) as mentioned above, there are few reports that comprehensively reveal the characteristics of keyaki wood, such as morphological structure, mechanical and chemical properties, residual stress, and the related issues, such as abnormal shrinkage, warping, cracking, and their variations among individuals. Due to the lack of research, there is little examination on measurement method for residual stress. Log-scale investigation using sufficient samples and the examination of measurement method are needed.

The final goal of this study is to scientifically characterize the various properties of keyaki wood as well as the reasons for individual differences in wood properties. In this paper, as the first step of a series of studies, the released strains of residual stresses were measured using diametral planks of large-diameter keyaki wood. The radial patterns of the residual stress and their diversity among individuals were characterized. In addition, measurement issues, such as length of the plank and cutting position, were discussed to establish the accurate method to measure the residual stresses of keyaki wood. Sixty-two large-diameter keyaki logs over 45 cm in top diameter, which had the sufficient sizes used as the primary building material in the construction of traditional temples and houses in Japan, were used as materials. With respect to quality of logs, this study primarily used logs with a certain degree of commercial value in the market, called *Kenta-zai.

*Kenta-zai: Market logs with approximately 2 m in length and at least 30 cm in top diameter. While large in diameter and long in log length, the wood may have knots, be curved, or be too long to log; therefore, these logs are cut down to lengths of 2 m and sold.

Materials and methods

Materials

This study used a total of 62 keyaki (*Zelkova serrata* Makino) samples that were harvested from across Japan: 4 standing trees and 58 logs (Fig. 2). The sample information is summarized in Table 1. Logs with a top diameter of 45 cm or greater were selected from the log market. These logs satisfied the quality for primary structural materials in traditional temples and houses, and for the purpose of experimenting with large quantities. The logs were cut during the dormant stage between autumn and spring and stored in the market field or warehouses for approximately six months until experiments. The moisture content of the logs was above a fiber saturation point during the storage and the experiments.

Preparation of diametral planks

Diametral planks were sawn from logs using a band saw so that the planks contained a pith and their diameter was as large as possible (Figs. 3 and 4a). As a result, the planks often contained tension wood when the planks contained eccentrically grown sections. Thickness of the planks was 5 cm in tangential direction. The planks were sawn as long as the log had no issues with branching, cracking, or rotting. In order to ensure a uniform thickness and to smooth the measurement surface, the surface of the planks was finished with an electric planer. Almost all the planks included the pith, but due to the slight pith winding along with the longitudinal direction, the pith was located nearby one side of the plank surfaces. The surface where the pith was located nearby was used as the measurement surface. The dimensions of each diametral plank after sawing are shown in Table 1. The preparation of the diametral planks and the measurements of the released strain were carried out on the same day. The saw mill work was conducted at Morijitsu Seizai lumber mill in Kakamigahara, Gifu prefecture.

(a) standing tree (Tochigi pref.)   (b) logs at the market (Gifu pref.)

Fig. 2 Example of standing trees and logs at the market used for the experiments. **a** Standing tree (sample No. 4.), **b** Logs (sample Nos. 5 and 6)

Table 1 Sample information

Form	Sample No.	Prefecture harvested	Harvesting date	Plank width (top/middle/bottom) (cm)	Plank length (cm)	Date of measurement	Experiment Fig. 3a	Experiment Fig. 3b	Experiment Fig. 3c	Experiment Fig. 3d	Experiment Fig. 3e
Tree	1	Tochigi	November 18th to 20th 2019	– / 62.5 / –	201	January 28th to 29th 2020			●		
	2	Tochigi		– / 89.0 / –	202				●		
	3	Tochigi		– / 76.0 / –	248				●		
	4	Tochigi		– / 78.0 / –	196				●		
Log	5	Tochigi	Mid. of February 2019	– / 71.0 / –	Approx.300	July 9th to 10th 2019			●		
	6	Tochigi	March 15th 2019	– / 57.6 / –	Approx.260				●		
	7	Saitama	Autumn 2019 to Spring 2020	– / 72.0 / –	Approx.180	May 19th 2020	●				
	8	Saitama		68.5 / 71.0 / 74.5	181		●				
	9	Saitama		66.0 / 63.0 / 64.0	177		●				
	10	Saitama		71.0 / 72.5 / 90.0	199		●				
	11	Saitama		58.5 / 58.5 / 64.5	215		●				
	12	Saitama		54.1 / 62.2 / 86.0	Approx.210		●				
	13	Saitama		61.0 / 65.3 / 72.6	232		●				
	14	Saitama		55.0 / 60.8 / 79.5	290			●			
	15	Ibaraki		62.3 / 64.3 / 62.4	175		●				
	16	Ibaraki		66.5 / 64.4 / 87.0	280		●				
	17	Ibaraki		69.0 / 71.3 / 98.2	209		●				
	18	Ibaraki		60.9 / 62.3 / 73.0	270			●			
	19	Ibaraki		58.4 / 54.5 / 58.3	228		●				
	20	Ibaraki		49.4 / 47.0 / 52.0	207			●			
	21	Ibaraki		69.0 / 61.0 / 61.5	170		●				
	22	Shimane		68.0 / 75.0 / 85.0	211		●				
	23	Gifu		62.1 / 59.8 / 60.4	210		●				
	24	Saitama	Autumn 2019 to Spring 2020	54.0 / 54.0 / 59.5	186	May 20th 2020	●				
	25	Saitama		51.5 / 49.8 / 51.5	144		●				
	26	Saitama		47.7 / 47.7 / 49.1	158		●				
	27	Saitama		51.2 / 53.1 / 59.4	215			●			

Table 1 (continued)

Form	Sample No.	Prefecture harvested	Harvesting date	Plank width (top/middle/bottom) (cm)	Plank length (cm)	Date of measurement	Experiment Fig. 3a	Experiment Fig. 3b	Experiment Fig. 3c	Experiment Fig. 3d	Experiment Fig. 3e
	28	Saitama		48.2 / 46.6 / 48.9	212		●				
	29	Ibaraki		50.1 / 50.2 / 50.1	194		●				
	30	Ibaraki		52.5 / 51.0 / 55.0	204		●				
	31	Ibaraki		49.0 / 49.0 / 52.5	164		●				
	32	Ibaraki		43.4 / 43.5 / 46.0	150		●				
	33	Ibaraki		64.0 / 63.6 / 67.5	261			●			
	34	Ibaraki		49.5 / 51.5 / 53.1	205		●				
	35	Ibaraki		46.8 / 47.0 / 46.8	201			●			
	36	Tochigi		69.1 / 68.8 / 69.2	248			●			
	37	Hyogo		49.4 / 47.0 / 49.7	233			●			
	38	Hyogo		49.8 / 52.0 / 56.3	221			●			
	39	Hyogo		50.6 / 50.7 / 62.2	230		●				
	40	Hyogo		49.0 / 49.0 / 51.1	186		●				
	41	Toyama		62.9 / 62.6 / 83.8	294			●			
	42	Saitama	Autumn 2019 to Spring 2020	57.8 / 57.6 / 71.0	210	June 16th to 17th 2020	●				●
	43	Saitama		69.0 / 71.0 / 82.6	216		●				●
	44	Saitama		62.6 / 66.9 / 71.0	206		●				●
	45	Saitama		66.6 / 68.0 / 70.0	402			●			●
	46	Saitama		64.3 / 70.6 / 90.5	229			●			●
	47	Saitama		66.0 / 68.0 / 73.5	193		●				●
	48	Shimane		61.5 / 63.3 / 62.6	172		●				●
	49	Saitama		72.0 / 78.4 / 81.0	173		●				●
	50	Saitama		61.5 / 66.8 / 83.6	215			●			●
	51	Saitama		58.0 / 54.8 / 56.6	323			●			●
	52	Saitama		65.6 / 63.0 / 66.0	192		●				●
	53	Saitama		56.2 / 59.0 / 61.4	202					●	●
	54	Saitama		58.0 / 59.5 / 65.6	201		●				●
	55	Shimane		64.6 / 67.3 / 79.0	234		●				●

Table 1 (continued)

Form	Sample No.	Prefecture harvested	Harvesting date	Plank width (top/middle/bottom) (cm)	Plank length (cm)	Date of measurement	Experiment Fig. 3a	Experiment Fig. 3b	Experiment Fig. 3c	Experiment Fig. 3d	Experiment Fig. 3e
	56	Ibaraki		70.2 / 68.5 / 74.6	187		●				●
	57	Ibaraki		66.0 / 67.1 / 73.5	206		●				●
	58	Chiba		61.0 / 59.0 / 66.8	208		●				●
	59	Gifu		49.5 / 54.1 / 66.0	314			●			●
	60	Hyogo		59.6 / 61.4 / 66.5	214		●				●
	61	Shimane		66.3 / 65.3 / 73.8	202		●				●
	62	Fukui	Spring 2019	44.6 / 45.7 / 47.0	216		●				●

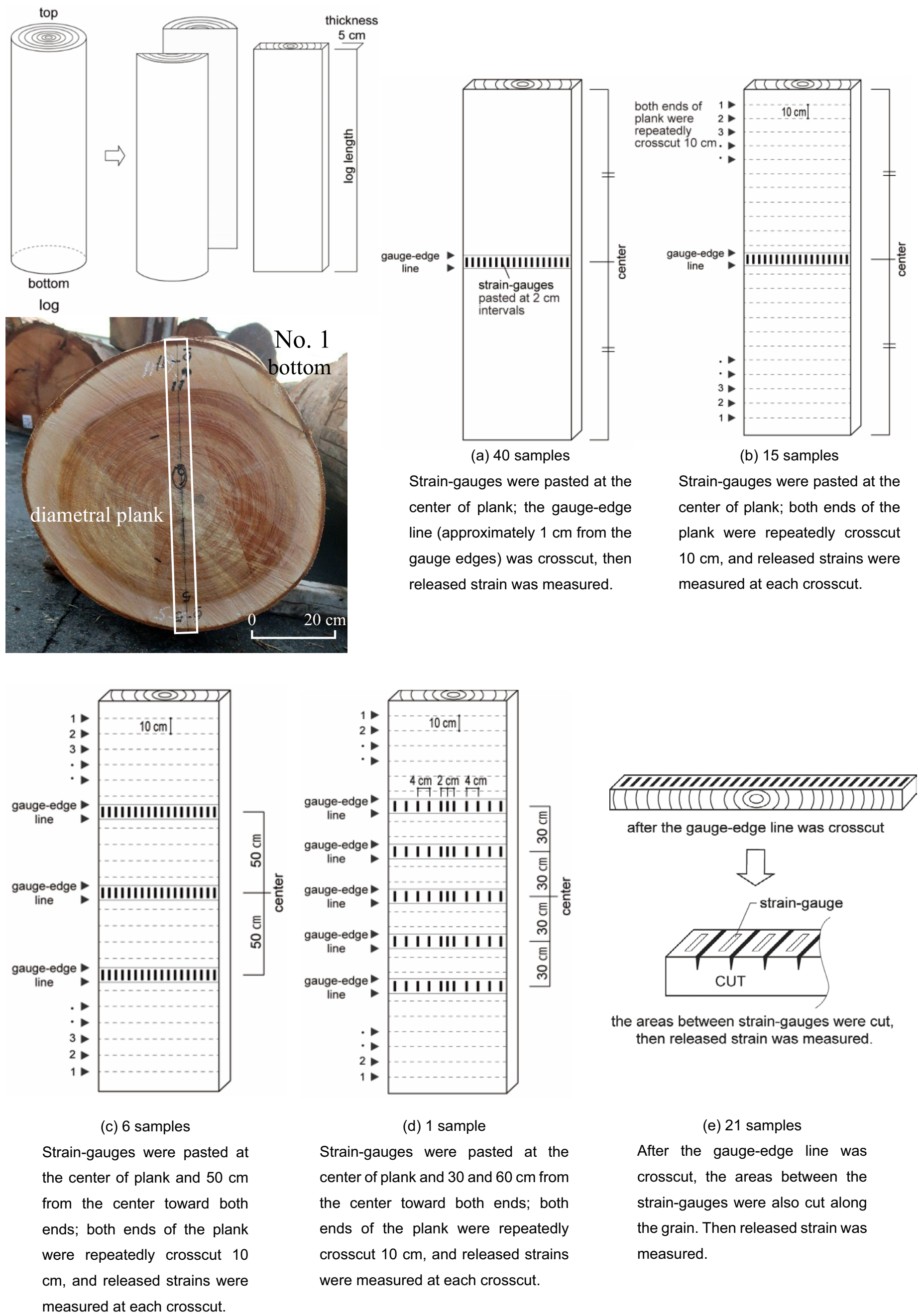


Fig. 3 Production procedure of diametral planks and five measurement patterns of released strain

Measurement of released strain

For all 62 samples, five measurement patterns, (a)–(e) in Fig. 3, were tried for each objective.

For 40 samples, a strain measurement position was set at the center of diametral plank, where strain gauges were pasted at 2-cm intervals from pith to each bark side (Fig. 3a). Crosscuts were made approximately 1 cm from both edges of the strain gauges (hereafter, "gauge-edge line"), and the released strain in the longitudinal direction was measured.

For 15 samples, the strain measurement position was set at the center of diametral plank (Fig. 3b). Both ends of the plank were repeatedly crosscut by 10 cm in length until approaching the gauge-edge line of the

(a) Saw-mill work

(b) After pasting strain-gauges

(c) Strain-gauges connected to data loggers

(d) Crosscutting a gauge-edge line

(e) Cutting between strain-gauges

Fig. 4 Sawing process of diametral planks and measurement of released strain

strain measurement position, and released strains were measured at each crosscutting. The relationship between the released strain and the distance from the strain measurement position to the crosscut end was examined.

For six samples, the strain measurement position was set at the center of diametral plank and 50 cm from the center toward both ends, where strain gauges were pasted at 2-cm intervals from the pith to each bark side (Fig. 3c). Gauge-edge lines of strain measurement positions were crosscuts, and the released strains were compared between the different strain measurement positions in the same diametral plank.

For one sample, five strain measurement positions were set at the center of diametral plank, and at 30 and 60 cm from the center toward both ends. At each measurement position, 3 strain gauges were pasted at 2-cm intervals around the pith and other strain gauges were pasted at 4-cm intervals toward each bark side (Fig. 3d).

For 21 samples from Fig. 3a and b, after the gauge-edge lines were crosscut, the areas between the strain gauges were also cut along the grain and measured to examine the effect on strain values by releasing the residual stress in the radial direction (Fig. 3e).

For all the patterns, the released strain was measured as follows:

At each strain measurement point, strain gauges (Kyowa Electronic Instruments KFGS-10–120-C1-11 L3M3R and L5M3R, three-wired, gauge length of 10 mm, cable lengths of 3 or 5 m) were pasted using cyanoacrylate quick-setting glue (Kyowa Electronic Instruments CC-33A) along the longitudinal direction (Fig. 4b). Strain gauges were connected to data loggers (Kyowa Electronic Instruments UCAM-65C-AC, EDX-10B, EDX-14A, DBS-120B-8), and initial strain values were measured (Fig. 4c). All types of crosscuts were made using an electric circular saw. Finally, crosscuts were made at the gauge-edge lines of the strain measurement positions (Fig. 4d). For pattern Fig. 3e, after crosscutting the gauge-edge lines, an electric reciprocating saw was used to cut between adjacent strain gauges with the depth of approximately 1.0–1.5 cm along the grain (Fig. 4e).

Results and discussion

Characteristics of residual stress

Characteristics of radial distributions of released strains in logs

Figures 5 shows examples of the distribution of released strain from the pith to both bark sides, measured in the center of each log. Other data of all logs are shown in supplementary information. The horizontal axis represents the distance of the strain measurement point from the pith (cm), with the pith is set at ± 0; the vertical axis represents released strain (microstrain) (hereafter, "μs"). Released strain is represented as positive with elongation owing to compressive stress release and negative with contraction owing to tensile stress release.

Generally speaking [22, 23], the distribution of released strain in a typical upright tree has a smooth bell shape (Fig. 5, Japanese cedar, "Smooth (No spike) and Bell shape" [24]), with the compressive stress reaching a maximum near the pith and mechanical neutrality (zero) at a distance of approximately two-thirds of the radius from the pith. The tensile stress increases approaching the bark. For the plank, the mechanical neutrality (zero) becomes at a distance of approximately one-third to half of the radius from the pith because residual stress in the

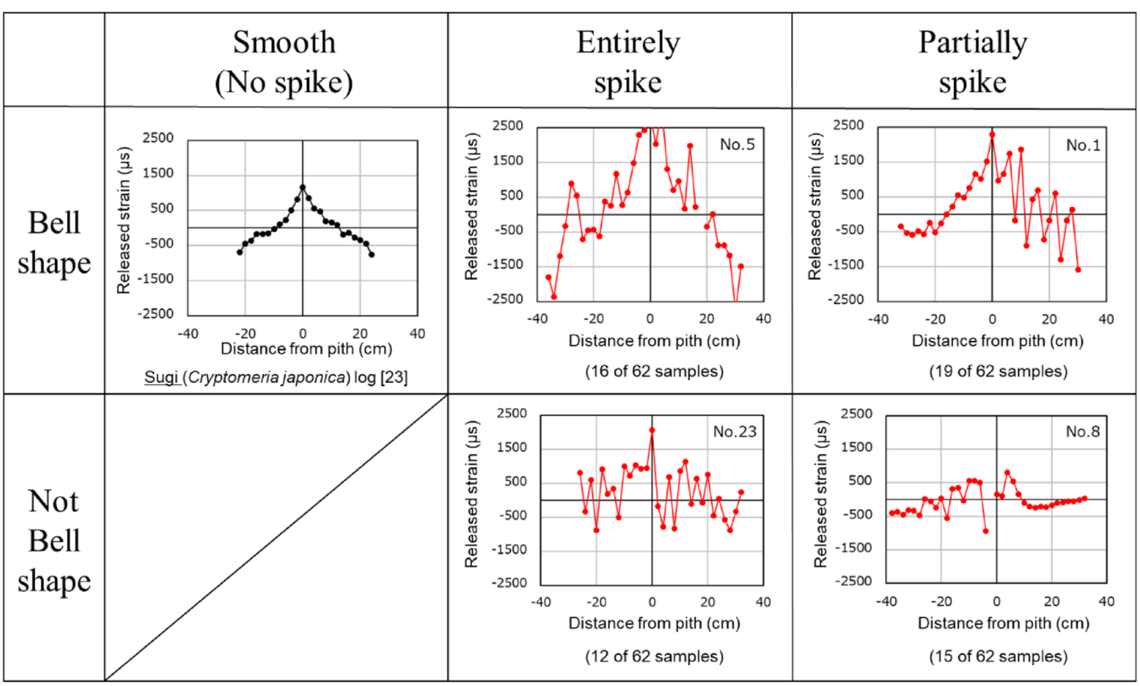


Fig. 5 Typical distribution of released stain in an upright tree of Japanese cedar (*Cryptomeria japonica* D. Don) [24]) and four representative types of distribution pattern of keyaki wood measured in this study (sample Nos. 1, 5, 8, and 23). Plus and minus signs of the horizontal axis were occasionally given depending on the experimental situation

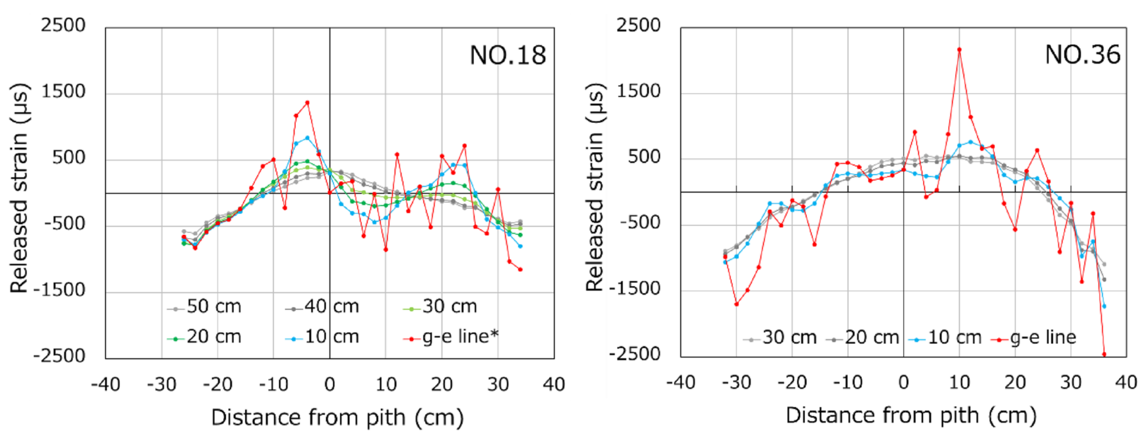
log would release slightly when sawing [25]. On the other hand, the distribution of released strain in keyaki exhibited various patterns, following not to a smooth curve, but rather a zig-zag pattern with spike-shaped released strains (hereafter, 'spike-shaped strain"), indicating generation of large, localized stresses (hereafter, "spike-shaped stress") (Fig. 5, sample Nos. 1, 5, 8, and 23). This pattern has not been reported with Japanese cedar, larch (*Larix* sp.) and Japanese cypress [20, 22, 24, 26] as well as buna (*Fagus crenata*), teak (*Tectona grandis*), mangium (*Acacia mangium*), and falcata (*Paraserianthes falcataria*) which were hardwoods [27–31], more difficult for processing than softwoods. This spike-shaped strain was considered to be distinguishing characteristics of keyaki wood.

Focusing on the overall shape of the distribution of released strain and the appearance of spike-shaped strain, four representative types were extracted from the results (Fig. 5 and Additional file 1: Fig. S1). The first type was that the overall shape was bell shaped and the spike-shaped strains appeared entirely over radial direction (Fig. 5 No.5). The second type also has a bell-shaped distribution but its spike-shaped strains appeared partially (Fig. 5 No.1). Other two types were not bell shaped and classified to the third type with the spike-shaped strains that appeared entirely (Fig. 5 No.23) and to the fourth type with the spike-shaped strains that appeared partially (Fig. 5 No.8). Some samples were intermediate between these types. This classification of the spike-shaped strain would be useful for discussing the variation among individuals and among the tree origins. To investigate the relationship between the distribution patterns and the tree origins, all the distributions were classified based on the prefecture harvested (Additional file 1: Fig. S2). The relationship was not so clear; however, it would be worth continuing the discussion. Spike-shaped strain would be also related to heterogeneous distribution of morphological structure or physical properties. Further observation and analysis of factors, such as local tension wood, interlocked grain, Young's modulus, annual ring width, and microfibril angle, were required.

Extent of the influence of spike-shaped stress in the longitudinal direction

For measurement patterns Fig. 3b and c, both ends of the plank were repeatedly crosscut by 10 cm in length until approaching the gauge-edge line of the strain measurement position with strain values recorded at every crosscut. Based on the changes in the strain values, it was discussed how far the effects of locally generated spike-shaped stresses reached in the longitudinal direction (Fig. 6). When the crosscut position has a sufficient distance from the strain gauges, the distribution of strain values assumed a smooth arched shape, with the absolute value of strain gradually increasing the closer the cutting position was to the gauge. However, when the distance from the gauge became less than 30 cm, spike-shaped strain began to appear, and after crosscuts were made at the gauge-edge lines, the spike shape completely appeared. The spike shape first appeared at 30 cm in two samples, 20 cm in four samples, 10 cm in 11 samples, and 1 cm (at the gauge-edge lines) in three samples. For one sample, the spike shape first appeared at a large distance of 60 cm.

Based on the above, spike-shaped strain appeared in locations close to strain measurement points. The extent of influence of spike-shaped stress in the longitudinal direction, which was the cause of the spike-shaped



*g-e line: gauge-edge line

Fig. 6 Typical examples showing longitudinal range of influence of spike-shaped stress. (Legends indicate the distance between the crosscutting position and the strain gauges.)

strain, could be limited to the area surrounding the strain measurement points. The extent of the effect of the spike-shaped stress would be related to the peculiar characteristics of tension wood. Further investigation is expected to reveal the reasons.

Difference of released strain distribution among different longitudinal positions in the same log

The results of measurement patterns Fig. 3c and d revealed the differences in released strain distribution at different longitudinal positions in the same plank (Fig. 7).

As indicated in each graph in Fig. 7, the distribution pattern "without spike" or "with spike," respectively, appeared in the similar radial area regardless of the longitudinal positions. Namely, the radial range where the spike-shaped strain appeared were always similar at different longitudinal positions, and the radial range where the spike-shaped strain "did not" appear were also similar. Within the range with spike-shaped strain, each measurement point where the spike-shaped strain appeared did not correspond completely at different longitudinal positions.

Based on the above, it was found that the radial pattern of residual stress in the same log was similar along longitudinal direction in the trunk, although it was not matched completely when focusing each local measurement point.

Methodology for residual stress measurement

Impact of between-gauge cuts on released strain

The results of measurement pattern Fig. 3e demonstrated that strain values slightly increased toward the compressed side in 10 of the 21 samples (Fig. 8a), with almost no change observed in strain values in the other 11 samples (Fig. 8b). In nine of the former 10 samples that showed an increase, values increased especially near the pith; in only one sample values increased throughout the radial distribution. In addition, the maximum strain value after the increase was 6145 μs (sample No. 49), followed by 4448 μs (No. 54)— only these two samples showed extremely high values (Fig. 8c). Except for these two samples, as no or slight change in strain was observed in most of the planks, it was reasonable to assume that the released strain could be measured with almost complete accuracy when crosscuts were made at the gauge-edge lines. Other data from 21 samples are shown in the Additional file 1: Fig. S3.

The reasons for which strain values increased near the pith may be deduced by the low longitudinal Young's modulus in the area around the pith. For example, the Young's modulus in Japanese cedar logs was lower near the pith than near the bark [32–34]. However, for keyaki, a clear decrease in Young's modulus near the pith was not confirmed [e.g., 14]. As there are few reports about the radial distribution of Young's modulus of large-diameter keyaki log, the measurement of Young's modulus and subsequent analysis will be necessary to discuss this issue.

Required log length for measuring released strain of the residual stress

Residual stress is completely released near the crosscut end of the log, and the residual stress distribution is disturbed at a position apart from the crosscut end in a certain distance: this is called "end effect" [23, 35]. Therefore, it is necessary to consider the length of the log required to measure the released strain of the residual stress without being affected by the "end effect."

Wilhelmy and Kübler [36, 37] not only predicted the change of distribution of the residual stress in a log due to crosscut using the finite element method (FEM) but also tried to verify obtained predictions based on an experiment using red oak (*Quercus rubra* L.). They introduced a parameter "L/D ratio" ($=L$ divided by D), where L is the distance from the crosscut end to the measurement position of the residual stress; D is the log diameter. They theoretically predicted that if the L/D ratio exceeded 1.3, the crosscut did not disturb the value of the residual stress. However, they also reported that based on the experiment an L/D ratio of approximately 2 was necessary to detect the residual stress without the end effect. Thereafter, Kübler and Chen [38] improved their calculation using FEM and finally concluded that an L/D ratio of approx. 1.5 was required.

In the present study, logs with various lengths and diameters were used, and the radial distribution of released strain of the residual stress was measured in the center of each log. It was considered that residual stress might have been partially released in some logs when the tree trunks were felled and logged. Then, the measurement patterns Fig. 3b and c were examined to determine the minimum log length that allowed the measurement without end effect.

Figure 9b shows the relationships between strain values and the L/D ratios, provided that the strain value before crosscut is set as 0. Measurements of strains were taken at each 10-cm crosscut at the selected five measurement points indicated in Fig. 9a [on the pith, bark sides (+, −), and the midpoint between them (+, −)]. The strain began to change obviously when the crosscut was made at a certain distance to the position of the strain gauges. In the present study, this position of L/D ratio was defined as "change point" (shown by a dashed line in Fig. 9b) and was detected for each sample. The relationship between the change point and the value of the initial L/D ratio, which is calculated as half of the plank length divided by

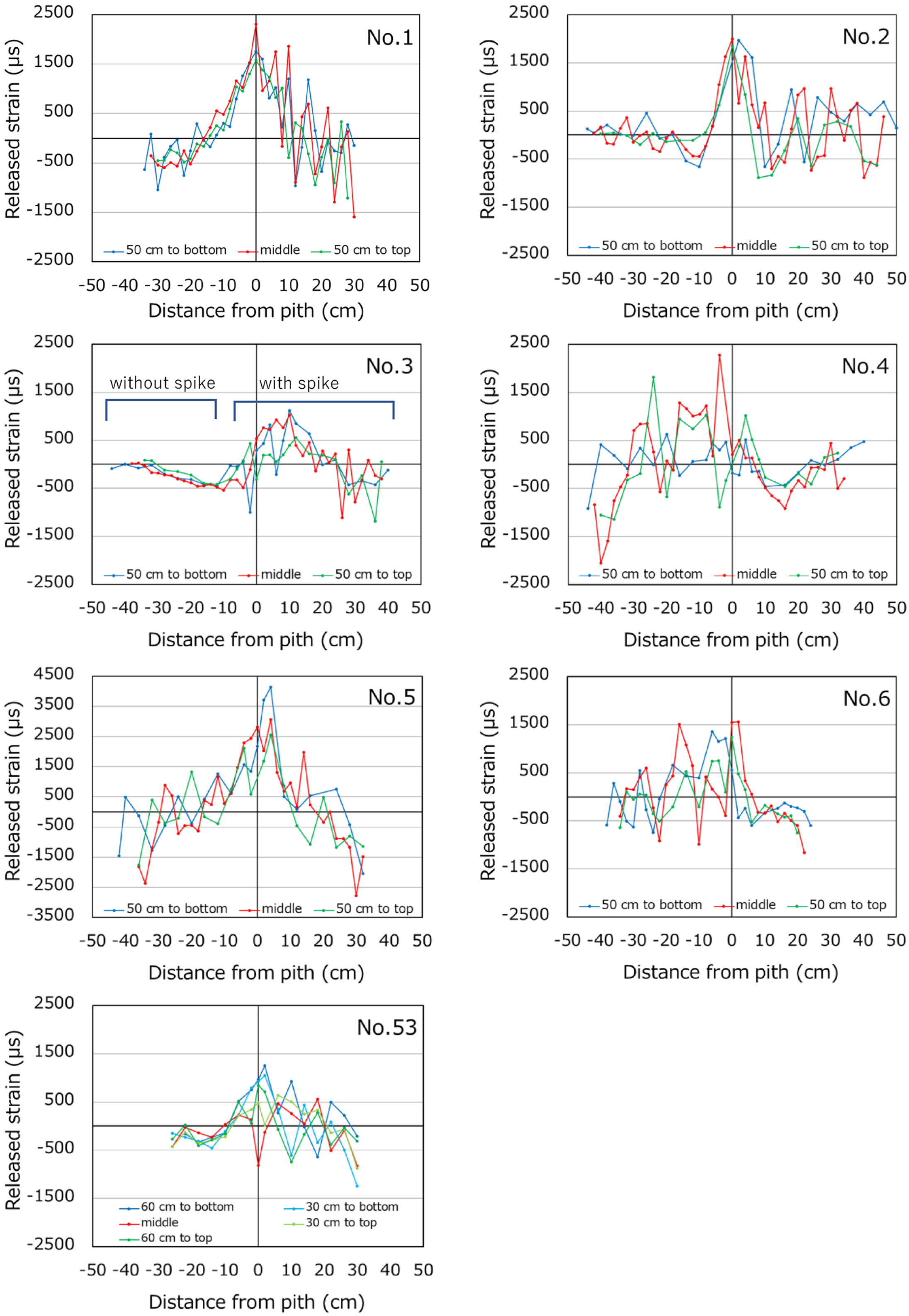
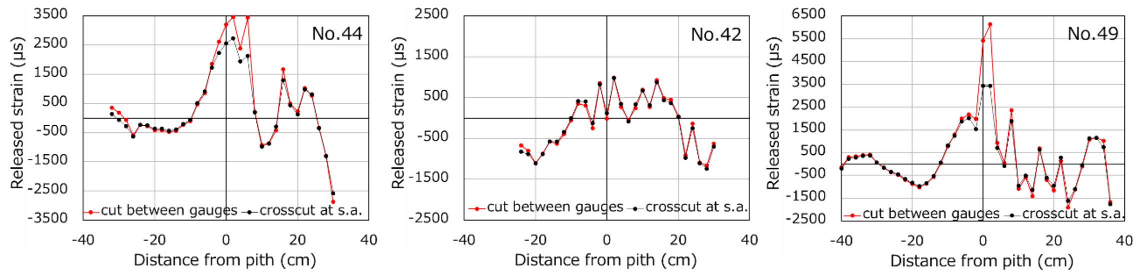


Fig. 7 Released strain distribution among different longitudinal positions in the same log. For sample No. 3, radial ranges with/without spike-shaped strain are indicated



(a) Strain increased near the pith (10 of 21 samples)

(b) Strain did not change (11 of 21 samples)

(c) Extremely high strain increased near the pith

Fig. 8 Changes in strain due to cutting between the strain gauges. (It is noted that the maximum values of the vertical axis are not the same)

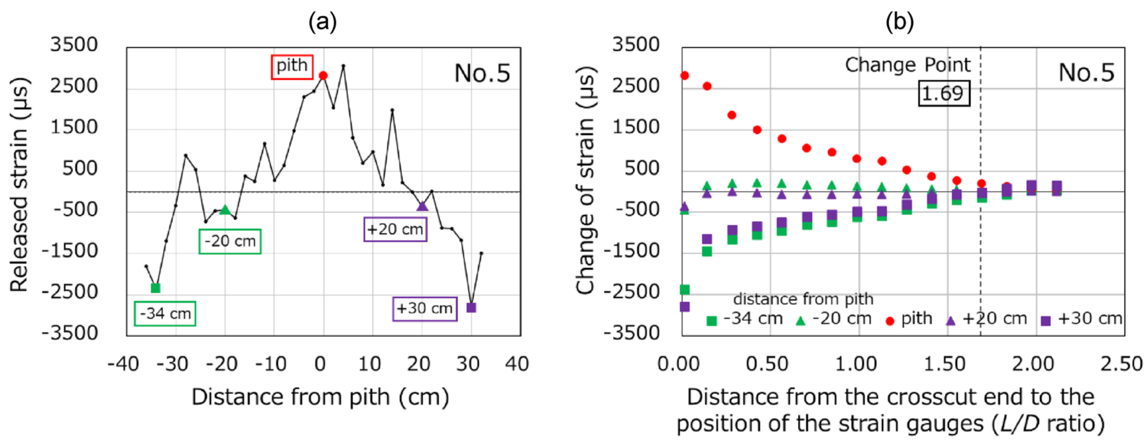


Fig. 9 Experiment to determine the minimum log length that allowed the measurement without end effect. **a** Strain measurement points on the pith, the outermost part of xylem, and the midpoints between them whose strain values were followed by 10-cm crosscutting (e.g., sample No. 5). **b** Change of strain values at the five strain measurement points. Change point: *L*/*D* ratio of crosscut position where the strain values began to change obviously

log diameter before crosscut, is shown in Fig. 10. The theoretically suggested “change point” value of 1.3 and 1.5 and an experimentally suggested “change point” value of 2.0 are also shown in Fig. 10 [36–38].

In the sample of which initial *L*/*D* ratio of the plank was smaller than 2.0, the correlation between the initial *L*/*D* ratio (x) and change point (y) theoretically should follow a straight line of $y=x$; however, measured change point was slightly smaller than the initial *L*/*D* ratio as shown in Fig. 10. This suggests that in the sample with an initial *L*/*D* ratio smaller than 2.0, some amount of residual stress had been already released when the tree trunk was logged. It was considered that in such a sample, the change point must coincide with the initial *L*/*D* ratio; however, the measured change point was underestimated by the first 10 cm crosscut.

In the sample of which initial *L*/*D* ratio was larger than 2.0, change point was between 1.5 and 2.0 regardless of the initial *L*/*D* ratio. The maximum value of change point seemed to converge to 2.0, suggesting that the log length is required to be larger than 4*D* to measure the released strain of the residual stress without end effect. These results could be understood by Saint–Venant’s principle [39]. Considering Saint–Venant’s principle, if a mechanically active position (*i.e.*, crosscut end) is enough apart at a certain distance from the position of interest (*i.e.*, the position of strain measurement), there is little mechanical effect on the position of interest. The samples in this study could be said to follow this theory and the certain distance was around $y=2.0$.

Even when initial *L*/*D* ratio was similar (*i.e.*, *L*/*D* ratios of 1.61–1.63 for four samples), there was a variation in the values of the change point. This possibly came from individual differences, such as the tension wood and interlocked grain.

Based on the above, it was clear that the length of the log required to measure the released strain without end effect was at least four times the diameter; *L*/*D* ratio was

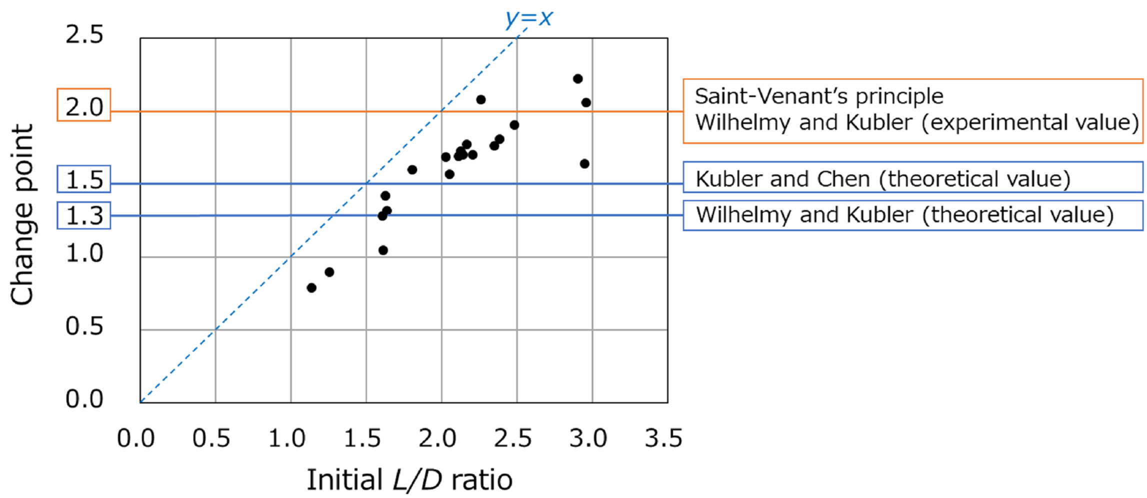


Fig. 10 Relationship between the change point (*y*) and the value of initial *L*/*D* ratio (*x*) and the comparison with the thresholds of previous researches [36–39]. Initial *L*/*D* was calculated as half of the plank length divided by log diameter

2.0. This agreed with the experimental results of red oak reported by Wilhelmy and Kübler [37].

Conclusion

The goal of this paper was to understand the characteristics of residual stress in large-diameter keyaki logs, which have so far been poorly understood. The measurement method for keyaki wood was also examined. The released strain of 62 sample logs from the pith to the bark sides was measured using diametral planks with pith. The variation in strain distributions of released strain revealed in this paper provided some insight into the nature of keyaki wood which were said to vary widely between individuals.

The detailed conclusions were as follows:

- One of the major characteristics was generation of the spike-shaped stress, which had never been reported in other wood species.
- Pattern of radial distribution of released strain was uniform in the same plank regardless of the positions relative to the longitudinal direction.
- The length of the log required to measure the released strain without being affected by the end effect was at least four times of the diameter.

In the future, it will be necessary to quantitatively characterize spike-shaped stress and to examine the origins of spike-shaped stress correlated with factors such as local tension wood, interlocked grain, Young's modulus, annual ring width, microfibril angle, and so forth.

Abbreviations

μs	Microstrain
FEM	Finite element method
L/*D* ratio	*L* Divided by *D*, where *L* is the distance from the cross-cut end to the measurement position of the residual stress; *D* is the log diameter
Initial *L*/*D* ratio	Initial *L* divided by *D*, which is calculated as half of the plank length divided by log diameter *D* before crosscut

Supplementary Information

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Additional file 1: Fig. S1. Results of the distribution of released strain obtained from all samples.The results were classified based on the 4 types of distribution patterns. **Fig. S2.** Results of the distribution of released strain obtained from all samples.The results were classified by the prefecture of tree origin. **Fig. S3.** Changes in strain due to cutting between the strain gauges.

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Author contributions

NK planned this study, conducted the experiment, analyzed the data, and wrote the manuscript. MM-U co-supervised this study, conducted the experiment, analyzed the data, and revised the manuscript. SC, JZ, and TI conducted the experiment and analyzed the data. MY co-supervised this study and provided the specific advices to this study. HY co-supervised this study, conducted the experiment, analyzed the data, and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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