J Wood Sci (2011) 57:363–370
DOI 10.1007/s10086-011-1194-x

ORIGINAL ARTICLE

Kana Yamashita · Yasuhiko Hirakawa · Shuetsu Saito
Hiroshi Nakatani · Motoyoshi Ikeda

Bow variation in kiln-dried boxed-heart square timber of sugi (*Cryptomeria japonica*) cultivars

Received: January 31, 2011 / Accepted: April 11, 2011 / Published online: July 18, 2011

Abstract To evaluate the bow variation in boxed-heart square timber of sugi (*Cryptomeria japonica*), bows from kiln-dried timber for five sugi cultivars with different longitudinal shrinkage trends were compared for two stem heights. Two general trends were observed, depending on the cultivar: (1) either the bow was larger at the lower than at the upper part of the stem, or (2) the bows at the lower and the upper parts of the stem were similar. In timber that had larger bow values, the gradients of longitudinal shrinkage were large across the radius and along the length of the timber. There was a positive relationship between the bow and longitudinal shrinkage. These results suggest that the bow variation between the timbers was caused by a variation in longitudinal shrinkage, which was affected by the microfibril angle. Furthermore, the bow was inversely proportional to the modulus of elasticity, which suggests that timber with a low modulus of elasticity is susceptible to a large bow due to large longitudinal shrinkage.

Key words *Cryptomeria japonica* · Boxed-heart square timber · Kiln drying · Bow · Longitudinal shrinkage

Introduction

Sugi (*Cryptomeria japonica* D. Don) is a major plantation species in Japan, of which thinned trees are sawn into boxed-heart timber and used as structural timber such as posts or beams. Recently, dried timber has been required to prevent dimensional change during and after construction. In order to shorten drying times and reduce checking, a variety of kiln-drying methods, including high-temperature drying, have been developed.[1]

Regarding longitudinal deformation, the warp on sawing due to the release of residual stresses in the tree is highly restrained in timber with centrally boxed pith.[2,3] The warp on drying results from the anisotropic shrinkage of wood. The twist influenced by the grain is quite small in sugi because the grain is straight. However, bowing due to cellulose microfibril orientation cannot be neglected in long timber. Boxed-heart timber contains the juvenile wood with large gradients of microfibril angle (MFA) and density across the radius and along the length of the timber, which affects the magnitude and anisotropy of the shrinkage.

Our previous studies showed that longitudinal shrinkage of small clear samples varied within trees and among cultivars, especially in the juvenile wood due to the large variation in MFA.[4] Longitudinal shrinkage was correlated with the modulus of elasticity (MOE), because both are related to MFA. Therefore, the longitudinal deformation of timber is expected to vary within trees and among cultivars and to be related to MOE. However, only a few reports have examined the variation of bowing in sugi timber.[5–7]

In this study, the bow variation in boxed-heart square timber of sugi was evaluated using conventional and high-temperature kiln-dried timber taken at different heights along the stem for five cultivars with different longitudinal shrinkage trends. The relationships between bow and longitudinal shrinkage, density, and MOE were examined.

Materials and methods

Materials

The five sugi cultivars were: boka-sugi, aya-sugi, ryuunohige, yabukuguri, and kumotooshi (Table 1). The sample trees of these cultivars were used in our previous studies on

---

K. Yamashita (✉) · Y. Hirakawa · S. Saito
Forestry and Forest Products Research Institute, Tsukuba 305-8687, Japan
Tel. +81-29-829-8300; Fax +81-29-874-3720
e-mail: zaikana@ffpri.affrc.go.jp

H. Nakatani
Toyama Prefectural Agricultural, Forestry & Fisheries Research Center, Forest Products Research Laboratory, Imizu, Toyama 939-0311, Japan

M. Ikeda
Forestry Research and Instruction Station of Kumamoto Prefecture, Kumamoto 860–0862, Japan

---

Part of this article was presented at the 60th Annual Meeting of the Japan Wood Research Society, Miyazaki, Japan, March 2010

Table 1. Sample logs

Cultivar	Sample	N	H (m)	NR_{Log}		D_{Log} (cm)		D_{HW} (cm)		MC_{HW} (%)	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boka-sugi	B1	42	0.7–2.6	33	1	25.4	2.4	14.4	2.1	84.1	14.5
	B4	42	6.4–8.3	21	3	19.1	2.0	7.6	1.7	77.4	10.9
Aya-sugi	A1	30	0.6–2.4	46	1	30.8	2.3	20.5	1.7	47.6	2.8
	A4	30	6.0–7.8	37	2	24.6	1.7	15.4	1.4	40.4	1.9
Ryuunohige	R1	18	0.7–2.6	50	1	23.1	1.7	15.3	1.3	94.2	19.3
	R4	18	6.0–7.9	37	2	18.3	1.3	10.6	1.0	48.2	4.8
Yabukuguri	Y1	20	1.5–3.5	37	1	28.0	2.1	21.4	1.9	89.1	9.5
	Y4	20	6.1–8.1	32	1	22.2	1.5	15.5	1.5	67.9	6.7
Kumotooshi	K1	20	1.5–3.5	53	1	24.6	2.4	15.7	2.0	151.6	9.7
	K4	20	6.1–8.1	41	3	20.8	2.0	12.2	1.7	108.4	16.3

NR_{Log}, D_{Log}, D_{HW}, and MC_{HW} are the average of both ends of the timber

N, number of trees; H, height above ground of the timber source; NR_{Log}, number of rings of log; D_{Log}, diameter of log; D_{HW}, diameter of heartwood; MC_{HW}, moisture content of heartwood; SD, standard deviation

shrinkage.[4] Logs were taken at two heights above the ground, and disks were cut from both ends of the logs to estimate wood properties. The logs were sawn without backsplitting into boxed-heart square timber of cross-sectional dimensions 115–120 mm and length 1.8–2.0 m and included the pith at the centers of both ends. The lower logs of yabukuguri and kumotooshi were taken above 1.5 m height in order to exclude basal bending. Half of the trees of each cultivar underwent conventional drying and the other half underwent high-temperature drying.

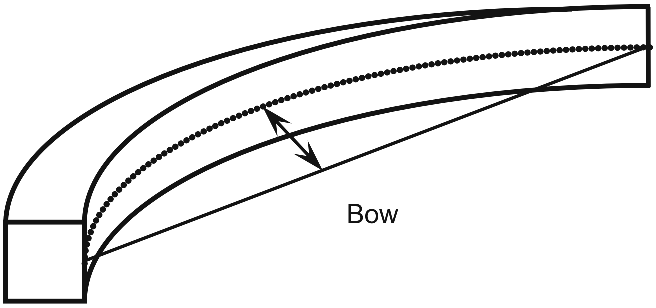

Fig. 1. Measurement of bow

Wood properties

The heartwood content (HWC) on the transverse face of timber was calculated from the heartwood radius and timber dimensions. Longitudinal shrinkage from the green to oven-dry condition (α_L) was measured at two radial positions using small clear samples: (i) 30 mm from the pith and (ii) 60 mm from the pith. The small clear sample dimensions were: 5 (T) × 30 (R) × 60 (L) mm for most trees. The dimensions of yabukuguri and kumotooshi that underwent conventional drying were: 5 (T) × 20 (R) × 55 (L) mm. Basic density (BD) was measured from small blocks cut at 20 mm intervals from the pith to the edge of the timber, and then averaged. The wood properties in the two diametrically opposite directions were averaged for each disk, and the disks at both ends of timber were averaged for each piece of timber. The modulus of elasticity of green timber (MOE_{GT}) was measured by using the tapping method.[8]

Kiln drying

The timber was kiln dried in four groups: (1) boka-sugi, (2) aya-sugi, (3) ryuunohige, and (4) yabukuguri and kumotooshi. Timber from different heights and/or cultivars were arranged alternately in the layers of the stack in the kiln (SKIF10LPT, Shinshiba) installed in the Forestry and Forest Products Research Institute. The conventional drying schedule was: steaming (85°C dry bulb, 85°C wet bulb, 8 h), drying (85°–95°C dry bulb, 81°–82°C wet bulb, 136 h), and conditioning (95°C dry bulb, 91°C wet bulb, 24 h). The high-temperature drying schedule was: steaming (90°C dry bulb, 90°C wet bulb, 8 h), drying (120°C dry bulb, 90°C wet bulb, 88 h), and conditioning (95°C dry bulb, 91°C wet bulb, 24 h).

After kiln drying, the maximum deflection from the plane connecting the ends of the timber was measured (Fig. 1). The deflections of all planes were added and divided by the green timber length as bow. The moisture content of green timber (MC_{GT}) and dried timber (MC_{DT}) were obtained as a fraction of the oven-dry wood weight.

Statistical analysis

The differences in wood properties and bow between samples from different source heights were examined using a paired t test for each cultivar. The differences among the samples of yabukuguri and kumotooshi (Y1, Y4, K1, K4), which were kiln-dried together, were examined using the one-way analysis of variance (ANOVA) and the Tukey-Kramer honestly significant difference (HSD) test. The relationships between bow and wood properties were examined by correlation analysis.

Table 2. Heartwood content (HWC) on the transverse face of timber and moisture content of green timber (MC_{GT}) and dried timber (MC_{DT})

Kiln group	Cultivar	Sample	*N*	HWC (%)		MC_{GT} (%)		MC_{DT} (%)	
				Mean	SD	Mean	SD	Mean	SD
Conventional drying									
1	Boka-sugi	B1	21	95.8***	7.8	87.3	11.5	19.4***	4.3
1		B4	21	35.4	18.0	120.9***	18.5	14.3	4.9
2	Aya-sugi	A1	15	100	0.0	23.0	4.5	13.7	4.7
2		A4	15	99.9	0.3	27.7**	2.2	16.5	2.3
3	Ryuunohige	R1	10	99.2***	2.5	65.7**	18.5	23.2**	6.0
3		R4	10	69.5	14.7	44.4	3.2	15.3	2.2
4	Yabukuguri	Y1	10	100	0.0	32.0	3.8	16.1	3.9
4		Y4	10	99.5	1.6	30.3	4.4	14.9	3.7
4	Kumotooshi	K1	10	96.1***	7.7	77.4***	22.7	32.7**	9.1
4		K4	10	69.5	17.6	43.8	14.7	21.0	6.5
High-temperature drying									
1	Boka-sugi	B1	21	95.8***	8.5	78.3	11.0	6.6	3.6
1		B4	21	37.1	16.4	125.6***	18.6	9.5*	4.6
2	Aya-sugi	A1	15	100	0.0	41.4	5.5	7.6	3.2
2		A4	15	98.8	4.5	44.9*	3.9	13.0***	2.9
3	Ryuunohige	R1	8	100***	0.0	50.4*	15.9	4.2	2.0
3		R4	8	65.5	10.3	32.9	6.9	5.3	3.1
4	Yabukuguri	Y1	10	100	0.0	58.1***	12.9	7.4	2.3
4		Y4	10	99.8	0.7	40.4	6.6	6.4	1.7
4	Kumotooshi	K1	10	100*	0.0	110.0**	31.6	6.0	2.2
4		K4	10	87.6	15.6	66.3	10.1	9.1**	1.5

Asterisks show significant differences between timber 1 and timber 4 within cultivars using a paired *t* test (***$P < 0.001$, **$P < 0.01$, *$P < 0.05$)

Results

Wood properties

The moisture content of heartwood (MC_{HW}) varied among the sugi cultivars (40%–152%) (Table 1). Timber 1 of ryuunohige (R1) and timbers 1 and 4 of kumotooshi (K1, K4) exhibited high MC_{HW}.

The heartwood content (HWC) on the transverse face of timber 1 was 100%, except for boka-sugi and kumotooshi (B1, K1), which contained sapwood at the corners (Table 2). The HWC of timber 4 varied among the cultivars.

The moisture content of green timber (MC_{GT}) varied among the cultivars (23.0%–126%) (Table 2), and was determined by MC_{HW} and HWC. The MC_{GT} was higher in timber 4 than timber 1 due to the higher content of sapwood for boka-sugi and aya-sugi, and higher in timber 1 due to the higher MC_{HW} for ryuunohige, yabukuguri, and kumotooshi.

For conventional drying, the moisture content of dried timber (MC_{DT}) varied among the cultivars (13.7%–32.7%) (Table 2). Timber 1 of ryuunohige and kumotooshi exhibited high MC_{DT} because their MC_{HW} was high and drying was slow. For high-temperature drying, the MC_{DT} was lower and less varied (4.2%–13.0%) than in conventional drying.

Longitudinal shrinkage (α_L) varied within the stems and among the cultivars (0.009%–0.967%) (Table 3). It had gradients across the radius of the timber, with larger values at 30 mm from the pith (α_Li) than at 60 mm from the pith ($\alpha_L$ii) for boka-sugi, aya-sugi, and yabukuguri, whereas the differences between α_Li and $\alpha_L$ii were small for ryuunohige and kumotooshi. Comparisons according to the height showed that timber 1 had larger α_L than timber 4 for boka-sugi, aya-sugi, and yabukuguri, whereas the differences were small for ryuunohige and kumotooshi. Comparisons among the cultivars showed that boka-sugi and yabukuguri had large α_L, especially for timber 1, and ryuunohige and kumotooshi exhibited small α_L.

Basic density (BD) also varied between the heights and among the cultivars (322–405 kg/m^3) (Table 3). Comparisons according to the height above ground of the source of the timber showed that BD was higher in timber 1 for boka-sugi, whereas it was higher in timber 4 for aya-sugi, ryuunohige, and yabukuguri. There was no significant difference in BD between the two source heights for kumotooshi. Comparisons among the cultivars showed that aya-sugi had high BD and boka-sugi exhibited low BD.

The modulus of elasticity of green timber (MOE_{GT}) varied among the timber samples (2.7–10.4 GPa) (Table 3). Comparisons according to the source heights showed that the MOE_{GT} was lower in timber 1 for boka-sugi, aya-sugi, ryuunohige, and yabukuguri ($P < 0.001$). Comparisons among the cultivars showed that boka-sugi and yabukuguri had low MOE_{GT} and ryuunohige and kumotooshi exhibited high MOE_{GT}.

Bow

On sawing the logs into boxed-heart square timbers, warp from the release of residual stress was not observed. After drying, some timber samples did not exhibit bow, but some timber samples exhibited a large bow. The mean bow ranged

Table 3. Longitudinal shrinkage (α_Li, $\alpha_L$ii), basic density (BD), and the modulus of elasticity of green timber (MOE_{GT})

Cultivar	Sample	α_Li (%)		$\alpha_L$ii (%)		BD (kg/m^3)		MOE_{GT} (GPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Conventional drying									
Boka-sugi	B1	0.719***	0.349	0.447***	0.186	338	23	3.71	0.83
	B4	0.225	0.126	0.190	0.041	328	12	6.01***	0.41
Aya-sugi	A1	0.583***	0.250	0.268***	0.101	362	14	4.83	0.71
	A4	0.265	0.095	0.126	0.039	403***	12	6.89***	0.59
Ryuunohige	R1	0.158	0.030	0.276	0.064	356	19	8.94	0.72
	R4	0.161	0.028	0.237	0.020	376*	11	10.18***	0.61
Yabukuguri	Y1	0.955 a***	0.316	0.500 a***	0.140	348 b	8	3.09 c	0.60
	Y4	0.375 b	0.143	0.178 b	0.038	363 a**	13	5.58 b***	0.63
Kumotooshi	K1	0.163 c	0.028	0.251 b	0.053	356 ab	13	9.74 a	0.59
	K4	0.184 bc*	0.015	0.217 b	0.046	353 ab	12	10.35 a*	0.63
High-temperature drying									
Boka-sugi	B1	0.967***	0.357	0.434**	0.247	343***	16	3.32	0.54
	B4	0.199	0.068	0.200	0.098	322	14	6.02***	0.26
Aya-sugi	A1	0.559***	0.149	0.244***	0.108	373	15	4.44	0.62
	A4	0.272	0.094	0.120	0.035	405***	9	6.69***	0.45
Ryuunohige	R1	0.156	0.042	0.217	0.029	356	7	8.33	0.65
	R4	0.145	0.023	0.244	0.024	373**	10	10.13***	0.38
Yabukuguri	Y1	0.813 a***	0.134	0.397 a***	0.100	340 b	11	2.66 c	0.23
	Y4	0.326 b	0.128	0.172 b	0.059	358 a**	11	4.98 b***	0.38
Kumotooshi	K1	0.043 c**	0.019	0.123 bc*	0.041	350 ab	10	9.48 a	0.34
	K4	0.009 c	0.020	0.081 c	0.027	346 ab	9	9.60 a	0.44

Different letters show significant differences using the Tukey-Kramer HSD test ($P < 0.05$)

Asterisks show significant differences between timber 1 and timber 4 within cultivars using a paired *t* test (***$P < 0.001$, **$P < 0.01$, *$P < 0.05$)

α_Li and $\alpha_L$ii: longitudinal shrinkage at 30 mm and 60 mm from the pith

There were significant differences among the samples Y1, Y4, K1, and K4 for MOE_{GT}, α_Li, and $\alpha_L$ii ($P < 0.001$), but not for BD (conventional drying: $P = 0.051$, high-temperature drying: $P = 0.064$), using ANOVA

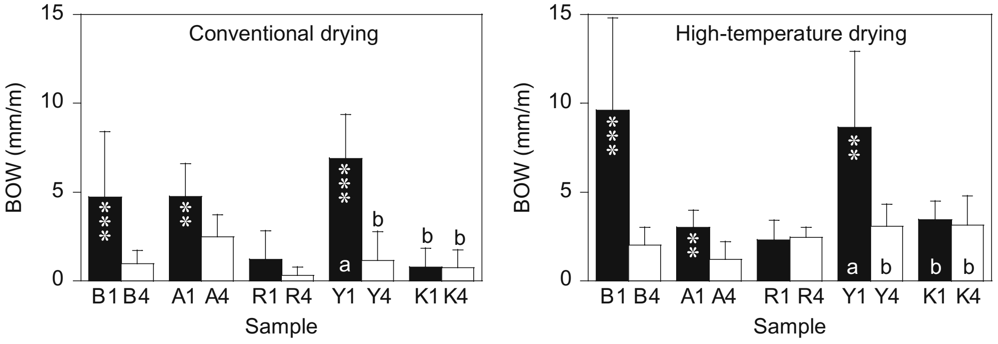

Fig. 2. Mean and standard deviation of bow. *Asterisks* show significant differences between timber 1 and timber 4 (from different source heights) within cultivars using a paired *t* test (***$P < 0.001$, **$P < 0.01$). There were significant differences among the samples of Y1, Y4, K1, and K4 using ANOVA ($P < 0.001$). *Different letters* show significant differences, using the Tukey-Kramer HSD test ($P < 0.05$)

from 0.32–6.90 mm/m in conventional drying and 1.20–9.63 mm/m in high-temperature drying (Fig. 2). Comparisons according to the source heights showed that timber 1 had a larger bow for boka-sugi, aya-sugi and yabukuguri under both types of drying ($P < 0.001$). On the other hand, there were no significant differences between the source heights for ryuunohige and kumotooshi ($P > 0.05$). Among the timber samples of yabukuguri and kumotooshi dried in the same kiln (Y1, Y4, K1, K4), Y1 exhibited a larger bow than the others ($P < 0.001$).

The bow was larger in high-temperature drying than in conventional drying for most timber samples, except for aya-sugi, and the differences were significant ($P < 0.01$), except for R1 and Y1. For aya-sugi, bow was larger in conventional drying, both for timber 1 and timber 4 ($P < 0.01$).

Relationships between bow and wood properties

The bow was directly proportional to longitudinal shrinkage for conventional and high-temperature drying ($P < 0.001$) (Fig. 3, Table 4). On the other hand, correlations with basic density were not significant. The bow was inversely proportional to MOE_{GT} and MOE_{GT}/BD ($P < 0.001$) (Fig. 4, Table 4). The relationships were curvilinear for lower MOE_{GT} and MOE_{GT}/BD values, and the correlation coefficients were higher in curvilinear regression than in linear regression.

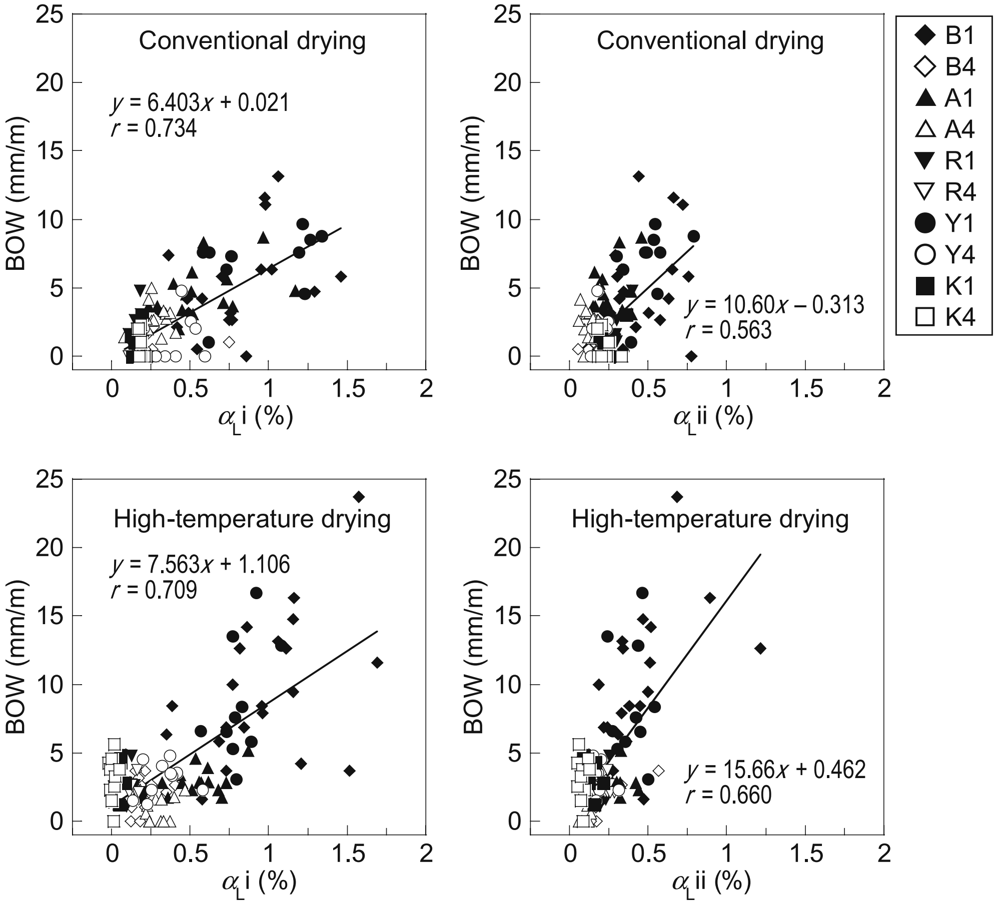

Fig. 3. Relationship between bow and longitudinal shrinkage at different radial positions (α_Li, $\alpha_L$ii)

Table 4. Correlation coefficients of linear regression between bow and wood properties

	α_Li	$\alpha_L$ii	BD	MOE_{GT}	MOE_{GT}/BD
Conventional drying					
Five cultivars	0.734***	0.563***	–0.004, $P = 0.97$	–0.656***	–0.682***
Yabukuguri and kumotooshi	0.828***	0.786***	–0.320*	–0.737***	–0.720***
Timber 1	0.701***	0.490***	0.033, $P = 0.79$	–0.707***	–0.729***
Timber 4	0.250*	–0.382**	0.320**	–0.275*	–0.363**
High-temperature drying					
Five cultivars	0.709***	0.660***	–0.146, $P = 0.10$	–0.512***	–0.496***
Yabukuguri and kumotooshi	0.687***	0.587***	–0.095, $P = 0.56$	–0.541***	–0.534***
Timber 1	0.668***	0.623***	–0.127, $P = 0.32$	–0.523***	–0.514***
Timber 4	–0.147, $P = 0.25$	0.146, $P = 0.25$	–0.250*	0.122, $P = 0.34$	0.206, $P = 0.10$

***$P < 0.001$, *$P < 0.01$

The MOE_{GT} was negatively correlated with longitudinal shrinkage ($P < 0.001$) (Fig. 5).

Discussion

Bow differences between source heights and among cultivars

Tooya[5] showed that the bow of small timber with dimensions of 20 × 20 × 800 mm was larger in the inner part of the stem (within 10 rings from the pith) than in the outer part, and the bow in the inner part decreased with the height at which the timber was located in the tree stem for measa-sugi. Masuda et al.[6] showed that the bow of boxed-heart square timber was larger in yabukuguri than obi-sugi.

This study examined the bow of boxed-heart square timber from different heights in the stem, and found that there were two patterns in the height direction depending on the cultivars. One was that the bow was considerably larger at the bottom of the stem than the upper part, as was the case for boka-sugi, yabukuguri, and aya-sugi (Fig. 2). The other was that the bow was small both at the lower and the upper parts, such as for ryuunohige and kumotooshi. This study also showed that the differences among the cultivars

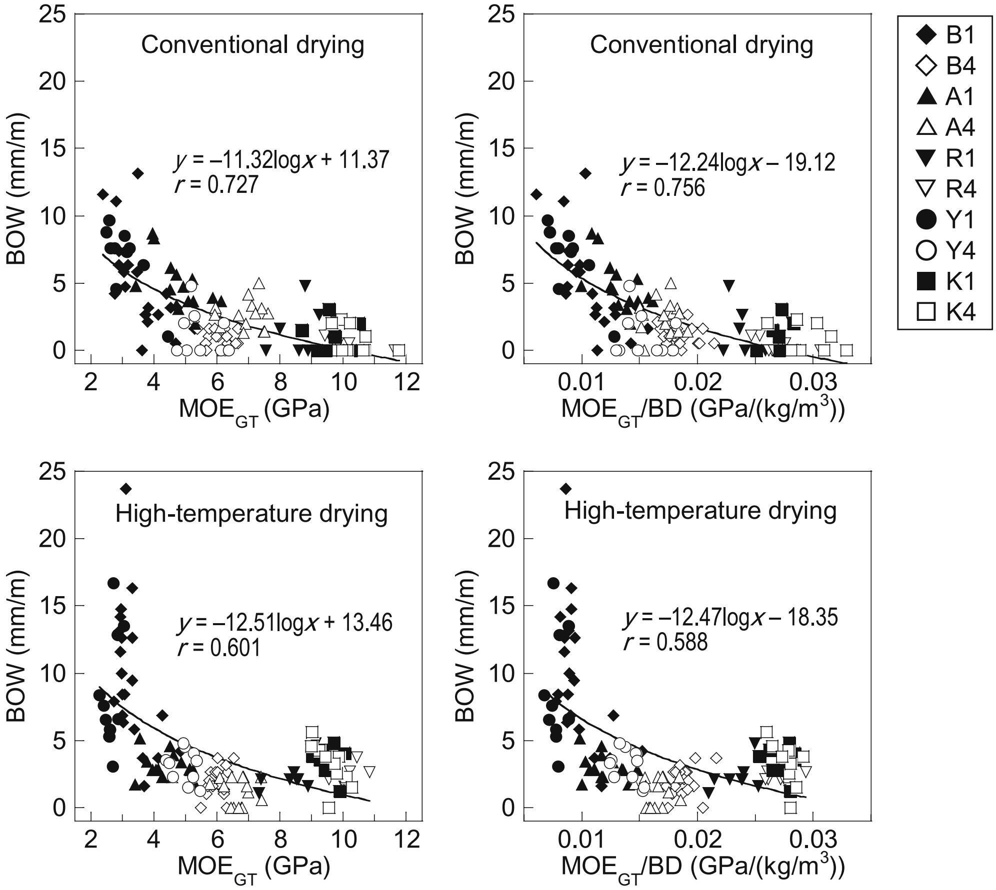

Fig. 4. Relationship between bow and the modulus of elasticity of green timber (MOE$_{GT}$) and the specific modulus of elasticity of green timber (MOE$_{GT}$/BD)

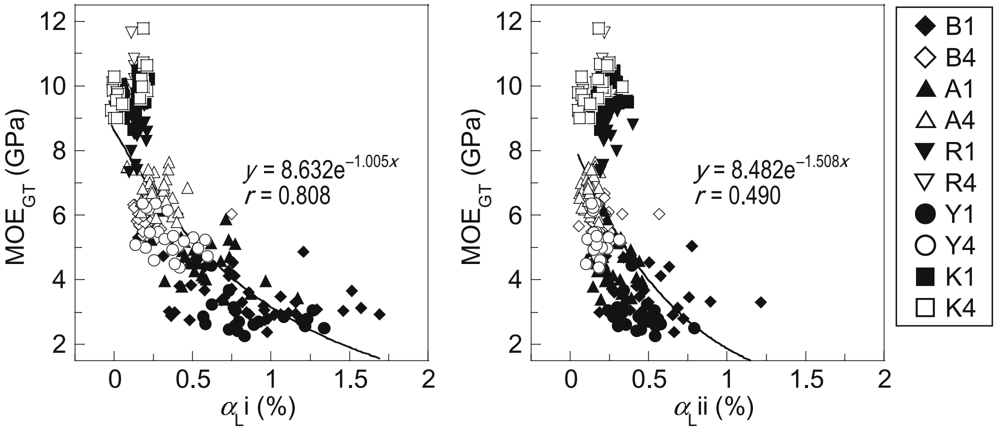

Fig. 5. Relationship between the modulus of elasticity of green timber (MOE$_{GT}$) and longitudinal shrinkage (α_Li, $\alpha_L$ii)

were prominent at the bottom of the stem, but small for the upper part.

Factors affecting bow

The bow differences between the source heights and among the cultivars were similar for both conventional drying and high-temperature drying. Therefore, the differences were thought to have been caused by the wood properties and not by the drying method. In *Pinus* spp., degradation from crook and bow is most severe in butt logs and near the pith because there is a steep, axial shrinkage gradient in this zone where the MFA is changing over the range from 50° to 30°; the effect is far less significant further up the tree where the initial MFA is lower, below the critical value of 30°.[9] This is because longitudinal shrinkage is negligible when the MFA is less than 25°–30°, but as the angle increases above this region there is a very rapid increase in longitudinal shrinkage.[10] For sugi, the MFA in the initial growth rings is large, especially at the lower part of the stem, and this results in a low modulus of elasticity (MOE) and large longitudinal shrinkage.[11,12] The portion of the stem with large MFA is different among sugi cultivars, which affects the variation of the MOE and longitudinal shrinkage.[4,13,14] In this study, the bow was large in the timber taken at the lower part of the stem for boka-sugi, aya-sugi, and yabukuguri, where the longitudinal shrinkage and MFA were large and had large gradients across the radius and along the length of timber[4] (Fig. 2, Table 3). On the other hand, the bow was small in timber taken at the lower part of the stem for ryuunohige and kumotooshi and at the upper part for most of the cultivars where the longitudinal shrinkage and MFA were small and their gradients within the timber were small[4] (Fig. 2, Table 3). Furthermore, there was a positive relationship between the bow and longitudinal shrinkage (Fig. 3, Table 4). These results suggest that the bow variation among the timber samples was caused by longitudinal shrinkage variation, which is itself affected by MFA. The bow variation within the stem of measa-sugi[5] and between yabukuguri and obi-sugi[6] is also expected to be caused by longitudinal shrinkage variation within the stem and between the cultivars.

Timber warping is due to shrinkage anisotropy and shrinkage asymmetry within the timber. If the longitudinal shrinkage is symmetrically distributed about the pith, timber with centrally boxed pith might not bow. However, some boxed-heart square timber does bow, which might be attributable to wood properties that are not perfectly symmetric about the pith, and have gradients within the timber. Longitudinal shrinkage gradients across the radius and along the length of the timber are expected to be large in trees with large MFA gradients. In this study, the timber was sawn to include the pith at the center of both ends; however, the bow will be larger if the pith position is not centered. In addition, tree growth patterns are not concentric, especially at the bottom of the stem where there is basal sweep because of sloping land or the weight of snow. In such cases, one side of the timber might form compression wood and have longitudinal shrinkage that is larger than that of the other side.

The bow was larger for high-temperature drying than for conventional drying, except for aya-sugi (Fig. 2). This difference can be attributed to the higher level of drying in high-temperature drying, as shown by the lower MC_{DT} values (Table 2). The faster drying might be due to the high temperature and internal checks, which would become pathways for heartwood moisture. Timber which is not dried enough during kiln drying will undergo deformation during later drying, and the magnitude might be larger in timber with larger longitudinal shrinkage. In addition, the bow is expected to be different between drying methods because the shrinkage varies with temperature.[15,16]

Predicting bow before drying

Aratake et al.[7] described a significant negative relationship between bow and MOE. This study also showed that bow was inversely proportional to MOE and specific MOE (Fig. 4, Table 4). In addition, the MOE was negatively correlated with longitudinal shrinkage (Fig. 5). These results suggest that timber with a low MOE is likely to have a large bow due to large longitudinal shrinkage and will thus require resawing to remove the bow. The MOE is useful for sorting because it can be measured nondestructively using the tapping method.

The bow will not be the same in timber sawn to different dimensions or taken from different locations within the stem, and future research should investigate optimized sawing patterns for trees of large diameter. Timber with large dimensions is expected to exhibit smaller bow due to the restraining effect of more mature wood, but it will be slower to dry and susceptible to drying checks. Timber without the pith will not be susceptible to drying checks, but will exhibit larger bow due to the shrinkage gradients across the timber, especially when it is taken around the core. In those cases, the bow is expected to be different depending on the source height and cultivar because the juvenile wood portion of the timber with large MFAs and longitudinal shrinkage will be different.

Conclusions

The bow of boxed-heart square timber tended to be larger at the bottom of the stem than at the upper part of the stem, but some sugi cultivars exhibited a small bow even at the bottom of the stem. The bow was caused by large longitudinal shrinkage and its gradients within the timber, which were affected by MFA. Timber having a low MOE is likely to have a large bow due to large longitudinal shrinkage and MFA.

Acknowledgments We thank Dr. Trevor Jones, Dr. Naohiro Kuroda, and Dr. Mario Tonosaki for suggestions regarding the manuscript.

References

1. Kuroda N (2007) Development of fundamental research on drying of boxed-heart square timber of Sugi (*Cryptomeria japonica*) (in Japanese with English summary). Mokuzai Gakkaishi 53:243–253
2. Watanabe H (1974) Growth ring (in Japanese). Tokyonogyodaigaku Mokuzaikougaku Kenkyukai, Tokyo, pp 63–75
3. Kuber H (1987) Growth stresses in trees and related wood properties. Forest Prod Abstr 10:31–119
4. Yamashita K, Hirakawa Y, Ikeda M, Nakatani H (2009) Longitudinal shrinkage variations within trees in sugi (*Cryptomeria japonica*) cultivars. J Wood Sci 55:1–7
5. Tooya R (1977) Variation in the height direction of sugi wood quality: measa-sugi plantation trees (in Japanese). Bull Kyushu Branch Jpn Forest Soc 30:323–324
6. Masuda T, Kanda T, Kamei J (1992) Studies on drying of timber: drying of sugi structural timber by natural energy (in Japanese). Res Rep Oita Prefect Forest Res Inst 17:1–24
7. Aratake S, Arima T, Sakoda T, Nakaura Y (1993) Effects of season crack on mechanical properties of sugi structural lumbers: modulus of rupture and modulus of elasticity in bending (in Japanese with English summary). Wood Ind 48:166–170
8. Sobue N (1986) Measurement of Young's modulus by the transient longitudinal vibration of wooden beams using a fast Fourier transformation spectrum analyzer. Mokuzai Gakkaishi 32:744–747
9. Keey RB, Langrish TAG, Walker JCF (2000) Kiln-drying of lumber. Springer-Verlag, Berlin, Heidelberg, New York, pp 139–169
10. Meylan BA (1968) Cause of high longitudinal shrinkage in wood. Forest Prod J 18:75–78
11. Watanabe H, Tsutsumi J, Kojima K (1963) Studies on juvenile wood. I: Experiments on stems of sugi trees (*Cryptomeria japonica*

D. Don) (in Japanese with English summary). Mokuzai Gakkaishi 9:225–230

12. Watanabe H, Tsutsumi J, Matsumoto T, Ohta S (1964) Studies on juvenile wood. II: On distribution of specific compressive strength and specific modulus of elasticity in stems of sugi (*Cryptomeria japonica* D. Don) (in Japanese with English summary). Mokuzai Gakkaishi 10:125–130
13. Hirakawa Y, Yamashita K, Nakada R, Fujisawa Y (1997) The effects of S_2 microfibril angles of latewood tracheids and densities on the modulus of elasticity variations of sugi (*Cryptomeria japonica*) logs (in Japanese with English summary). Mokuzai Gakkaishi 43: 717–724
14. Yamashita K, Hirakawa Y, Fujisawa Y, Nakada R (2000) Effects of microfibril angle and density on variation of modulus of elasticity of sugi (*Cryptomeria japonica*) logs among eighteen cultivars (in Japanese with English summary). Mokuzai Gakkaishi 46:510–522
15. Skaar C (1988) Wood-water relations. Springer-Verlag, Berlin, Heidelberg, New York, pp 122–176
16. Saito S (1995) High-temperature kiln-drying of sugi (*Cryptomeria japonica* D. Don) boards (in Japanese). Bull Kanto Branch Jpn Forest Soc 47:137–138