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ORIGINAL ARTICLE

Effect of cross-sectional dimensions on bow and surface checking of sugi (*Cryptomeria japonica*) boxed-heart square timber dried by conventional kiln drying

**Kana Yamashita · Yasuhiko Hirakawa ·
Shuetsu Saito · Hiroshi Nakatani ·
Motoyoshi Ikeda · Masamitsu Ohta**

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Abstract The effect of cross-sectional dimensions on bow and surface checking were investigated, using the boxed-heart square timber of two sugi cultivars with dimensions 80, 120, and 140 mm and length 1.9 m taken at two different heights above the ground. The smaller cross-sectional timber tended to have larger bow, less surface checking, and larger dimensional shrinkage. However, the drying defects were different between the cultivars and sampling heights, depending on the shrinkage properties of the juvenile wood and the heartwood proportion in the core part of the stem. The bow was larger in the smaller cross-sectional timber in which the longitudinal shrinkage was large in the juvenile wood. Surface checking was more prominent in larger cross-sectional timber containing sapwood in its outer part, which suggested the surface checking was induced by drying stress, owing to large moisture gradients between the heartwood and sapwood. The cross-dimensional shrinkage of the timber was larger in timber with larger tangential shrinkage.

Keywords Sugi boxed-heart square timber · Conventional kiln drying · Bow · Surface check · Cross-sectional dimension

Introduction

The wood properties of sugi (*Cryptomeria japonica* D. Don) vary within and among trees. In order to supply quality-controlled timber and decrease wood processing costs, it is expected that logs will be sorted by their wood properties and processed in suitable ways. Sugi trees were planted in large numbers during 1950–1970 in Japan, and thinned trees have been used as boxed-heart timber for poles and beams in housing construction. The boxed-heart timber, which is symmetrical about the pith, has little distortion by growth-stress release during sawing. However, it sometimes has bow and is susceptible to surface checking during drying. The drying of the timber proceeds from the surface and begins to shrink, while the interior can still be quite wet and not shrink. The shrinkage of the surface-layer is restricted by the inner layer, so tension drying stress is induced in the surface layer, while compression drying stress is induced in the inner layer. Tangential shrinkage is free at the corners of the timber, but is restricted between the corners owing to the shrinkage anisotropy between the tangential and radial directions, which induces large tension drying stress [1]. When the stress overcomes the tension strength of the timber, surface checking is induced. Recently, to shorten the drying time and prevent surface checking, various kiln-drying methods have been developed [2]. However, there is little information on

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K. Yamashita (✉) · S. Saito
Forestry and Forest Products Research Institute, Tsukuba,
Ibaraki 305-8687, Japan
e-mail: zaikana@ffpri.affrc.go.jp

Y. Hirakawa
The Wood and Plywood Museum NPO, Tokyo 136-8405, Japan

H. Nakatani
Grandworks Inc., Toyama 936-0874, Japan

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

M. Ohta
Graduate School of Agricultural and Life Sciences,
The University of Tokyo, Tokyo 113-8657, Japan

Table 1 Properties of the sample logs

Cultivar	Sample	*N*	*H* (m)	NR_{log}		D_{log} (cm)		D_{HW} (cm)		MC_{HW} (%)		MOE_{log} (GPa)	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boka-sugi	B1	20	0.7–2.6	31	4	26.7	2.7	14.5	2.4	83.8	13.0	3.27	0.22
	B4	20	6.4–8.3	20	4	19.7	2.0	7.3	1.8	87.4	14.0	5.48	0.46
Ryuunohige	R1	10	0.7–2.6	49	1	24.9	3.1	16.8	2.8	99.6	18.2	7.73	0.68
	R4	10	6.0–7.9	37	2	19.6	2.1	11.7	1.7	52.3	4.4	9.34	0.54

N number of trees, *H* height above the ground of the timber source, NR_{log} number of growth rings, D_{log} log diameter, D_{HW} heartwood diameter, MC_{HW} moisture content of the heartwood, MOE_{log} modulus of elasticity of the green logs, *SD* standard deviation

why the drying defects such as bow and surface checking vary among timber that is dried together. The variations in the drying defects are considered to be induced by multiple wood-properties, which affect the water transportation, the deformation of the timber, and the surface checking occurrence and elongation. Therefore, the moisture content, density, shrinkage, and mechanical properties are suggested to be related to the bow and surface checking of the timber.

As for the variation of drying defects within sugi, Takeda et al. [3, 4] reported the bow and surface-checking of boxed-heart square timber were different between the sugi cultivars, tateyama-sugi and boka-sugi. Our previous studies showed that bow was large in the timber of sugi cultivars in which microfibril angle (MFA) and longitudinal shrinkage were large in the core part of the stem and declined outward [5, 6]. We also showed that timber with larger tangential shrinkage and more sapwood exhibited surface checks of longer lengths [7, 8]. The sapwood of the timber dries faster than the heartwood; therefore, the moisture-content gradient and the drying stress between the sapwood (surface) and heartwood (inside) would be large during drying.

In accordance with tree growth and user requirements, the timber products and sawing patterns are changing. In the 1970s and 1980s, the effect of cross-sectional dimensions on drying defects were examined, using boxed-heart timber with dimensions 30–105 mm taken from small thinned trees [3, 9–12]. They showed that bow was larger in smaller dimension timber, while surface checking was more prominent in larger dimension timber. One of the factors in the differences of the small and large dimensions is thought to be the variation of the wood properties from the core to the outer part of stem. Previous studies showed the juvenile wood portion exhibiting large MFA, large longitudinal shrinkage, and small tangential shrinkage, varied within trees and among trees [5, 7, 13–18]. Therefore, the size effects on the drying defects are expected to vary depending on the juvenile wood properties of the timber.

In this study, to examine the factors related to the bow and surface checking of sugi boxed-heart square timber, we used two cultivars with different wood properties such as shrinkage, density, and heartwood proportion. We kiln-dried the timber of different cross-sectional dimensions and compared the bow, surface-checking, and cross-dimensional shrinkage, and evaluated the relationships with the wood properties.

Materials and methods

Materials

Twenty trees of boka-sugi (B) were taken from a forest stand in Takaoka, Toyama prefecture, and ten trees of ryuunohige (R) were taken from a forest stand in Kikuchi, Kumamoto prefecture (Table 1). Logs of 1.9 m length were taken at two heights above the ground (lower height: “timber 1”; upper height “timber 4”) for boxed-heart square timber (Fig. 1). Disks were cut from both ends of the logs to estimate the wood properties.

Wood properties

The heartwood area percentage (HWP) on the transverse face of the boxed-heart square timber was calculated from the heartwood radius and timber dimensions. When the heartwood portion corresponded to the maximum inscribed

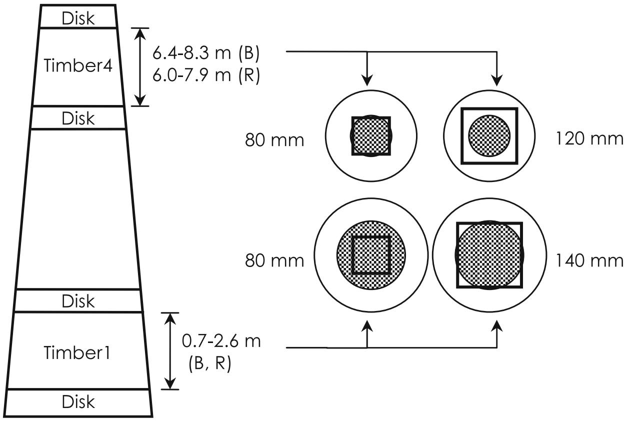

Fig. 1 Sampling heights above the ground and cross-sectional dimensions at each source height. *B* boka-sugi, *R* ryuunohige, shadow heartwood, white sapwood

circle, the HWP was 78.5 %. The moisture content of the heartwood (MC_{HW}) and the basic density (BD) were measured using small blocks cut at 20 mm intervals from the pith to the edge of the timber and then averaged. The longitudinal shrinkage (α_L), tangential shrinkage (α_T), and radial shrinkage (α_R) from the green to oven-dry condition were measured at 30–40 mm (*i*) and 60–70 mm (*ii*) from the pith (suffix *i* and *ii* indicate the distances from the pith) using small clear samples. The radial positions *i* and *ii* corresponded to the edge of the timber of dimensions 80 and 140/120 mm. The dimensions of the small clear samples were 5 (T) × 20–30 (R) × 50–60 (L) mm for α_L, and 20 (T) × 20 (R) × 5 (L) or 30 (T) × 30 (R) × 5 (L) mm for α_T and α_R. These properties were measured in two diametrically opposite directions, and averaged for each disk and each piece of timber. The α_L was measured at the small end of timber 1, and the large end of timber 4, because we could not take enough samples at the other ends.

The logs were sawn into boxed-heart square timber with the pith at the centers of both ends (Fig. 1). The cross-sectional dimensions were 80 and 140 mm for timber 1, and 80 and 120 mm for timber 4 (Fig. 1). The modulus of elasticity of the green logs (MOE_{log}) and the green timber (MOE_{GT}) were measured using the tapping method [6, 8, 19]. The rigidity (EI) was obtained from MOE_{GT} and dimensions of the green timber (D_{GT}) using Eq. (1).

$$EI = MOE_{GT} \times \frac{D_{GT}^4}{12} \quad (1)$$

Kiln-drying

The boxed-heart square timber was kiln-dried in three groups: (1) boka-sugi timber 1 of dimensions 80 mm ($B1_{80}$) and 140 mm ($B1_{140}$), (2) boka-sugi timber 4 of dimensions 80 mm ($B4_{80}$) and 120 mm ($B4_{120}$), and (3) ryuunohige timber 1 of dimensions 80 mm ($R1_{80}$) and 140 mm ($R1_{140}$), and timber 4 of dimensions 80 mm ($R4_{80}$) and 120 mm ($R4_{120}$) (Table 2). In addition, for comparison boxed-heart square timber of dimension 115 mm kiln-dried in two groups in our previous studies was used: (4) boka-sugi timber 1 ($B1_{115}$), and (5) ryuunohige timber 1 ($R1_{115}$) [6, 8]. The drying schedule was as follows: 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) (SKIF10LPT, Shinshiba).

Measurements of bow, surface checking, and dimensional shrinkage

After kiln-drying, the bow distortion was calculated as the sum of the maximum deflections of all the planes divided by the length of the green timber [6]. The length and number of surface checks on the four lateral faces were measured, summed, and divided by the length of the green timber as the total length of surface checks (TLSC), and the number of surface checks (NSC) [8]. The average length of the surface checks (ALSC) was obtained as the total length

Table 2 Properties of the boxed-heart square timber

Kiln group	Sample	D (mm)	N	HWP (%)		MC_{GT} (%)		MC_{DT} (%)		BD (kg/m^3)		MOE_{GT} (GPa)		EI (10^3 N m^2)	
				Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boka-sugi															
1	$B1_{80}$	80	10	100***	0	64.4	6.1	20.3	3.2	332	16	2.43	0.36	8.6	1.18
4	$B1_{115}$	115	21	95.8	7.8	87.3	11.5	19.4	4.3	338	23	3.71	0.83	54.1	12.08
1	$B1_{140}$	140	10	63.6	15.1	64.3	10.5	24.9*	5.8	340	11	3.39***	0.25	110.4***	8.86
2	$B4_{80}$	80	12	58.1*	25.1	81.1	14.0	13.2	5.5	334*	14	5.04	0.37	18. 5	1.19
2	$B4_{120}$	120	8	35.7	15.9	111.5***	12.3	16.1	5.9	320	14	5.69***	0.36	99.6***	7.15
Ryuunohige															
3	$R1_{80}$	80	6	100	0	78.7*	18.8	20.1	9.5	363	18	7.34	1.08	26.3	3.21
5	$R1_{115}$	115	10	99.2	2.5	65.7	18.5	23.2	6.0	356	19	8.94	0.72	129.8	10.75
3	$R1_{140}$	140	4	93.6	12.8	48.5	16.0	17.1	5.5	361	12	8.61*	0.90	260.9***	12.17
3	$R4_{80}$	80	5	100**	0	48.0*	8.1	15.6	3.6	376	8	8.90	0.87	31.7	2.65
3	$R4_{120}$	120	5	74.5	19.6	33.8	9.8	12.8	5.2	374	11	9.66	0.72	167.4***	9.99

Kiln groups 4 and 5 were from the previous study [8]

D cross-sectional dimension, *N* number of boxed-heart squares, *HWP* heartwood area percentage on the transverse face, MC_{GT} moisture content of the green timber, MC_{DT} moisture content of the dried timber, *BD* basic density, MOE_{GT} modulus of elasticity of the green timber, *EI* rigidity, *SD* standard deviation

Asterisks show significant differences between dimensions 80 and 140/120 mm at the same height for each cultivar (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$)

divided by the number of surface checks. The moisture content of the green timber (MC_{GT}) and dried timber (MC_{DT}) was obtained as a fraction of the oven-dry wood weight. The dimensions of the green timber (D_{GT}) and the kiln-dried timber (D_{DT}) were measured for the two sides and averaged. The dimensional shrinkage of the timber (α_D) was obtained from D_{GT} and D_{DT} using Eq. (2)

$$\alpha_D = (D_{GT} - D_{DT})/D_{GT} \times 100 \qquad (2)$$

The differences in bow, surface checking, and dimensional shrinkage were examined between the dimensions 80 and 140 mm for timber 1, and between 80 and 120 mm for timber 4. The differences between the dimensions were also examined by the Tukey–Kramer HSD test, in which the 115-mm dimension timber 1 was included. The difference between the source heights of the logs (timber 1 and timber 4) was examined for the small-dimension (80 mm) and large-dimension (140/120 mm) timber, respectively. The correlations of bow, surface checking, and dimensional shrinkage with the wood properties were examined using the timber of dimensions 80, 120, and 140 mm.

Results

Wood properties

The heartwood diameter of the logs (D_{HW}) was smaller for boka-sugi (B) than ryuunohige (R) at the same source heights (Table 1). The MC_{HW} was similar between the source heights for B, but higher for timber 1 than timber 4 for R.

The HWP was 100 % for $B1_{80}$, $R1_{80}$, and $R4_{80}$, but $B4_{80}$, $B1_{140}$, $B4_{120}$, $R1_{140}$, and $R4_{120}$ contained sapwood (Table 2). The heartwood portion of the timber $B1_{140}$, $B4_{120}$, and $R4_{120}$ was smaller than the maximum inscribed circle. The MC_{GT} was different for the samples, depending on the MC_{HW} and HWP. The MC_{DT} of B was a little higher for the 140/120-mm dimension timber than the 80-mm dimension timber. This might be because the interior of the large dimension timber was not well dried. On the other hand, the MC_{DT} of R was a little higher for the 80-mm dimension timber than the 140/120-mm dimension timber, which might because of the higher MC_{GT} of the small-dimension timber. The BD was higher for R than B, but was similar between the dimensions within each cultivar. The MOE_{GT} was higher for R than B, and higher for timber 4 than timber 1. The MOE_{GT} was higher for the larger dimension timber at the same source height, and the differences between dimensions were large for B (B1 and B4, $P < 0.001$), but small for R (R1, $P < 0.05$; R4, $P = 0.08$). The EI was higher for R than B, and for larger dimension than smaller dimension at both source heights for each cultivar ($P < 0.001$).

For B, the α_L was larger for the inner part (*i*) than the outer part (*ii*) and was larger for timber 1 than timber 4, while the α_T was larger for *ii* than *i* and larger for timber 4 than timber 1 (Table 3). For R, the α_L was larger for *ii* than *i*, while the α_T was larger for *i*, which was expected to be affected by that MFA was a little larger at the outer part of stem as shown in our previous studies [5, 6]. The difference between radial positions (*i*, *ii*) and between timber 1 and 4 were smaller for R than B. The α_L at *i* was larger for B than R, and α_T was larger for R than B.

Bow

The bow of the kiln-dried timber was larger for the 80-mm dimension timber than the 140/120-mm dimension timber,

Table 3 Shrinkage of the small clear specimens

Cultivar	Sample	Radial position	α_L (%)		α_T (%)		α_R (%)		α_T/α_R (%/%)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boka-sugi	B1	i	0.591***	0.418	5.59	0.44	2.32	0.23	2.43	0.20
		ii	0.269	0.184	5.82	0.23	2.63	0.20	2.29	0.14
	B4	i	0.235	0.140	6.36	0.23	2.61	0.14	2.46	0.10
		ii	0.180	0.039	6.50	0.17	2.64	0.11	2.47	0.08
Ryuunohige	R1	i	0.117	0.036	7.32*	0.19	2.81	0.18	2.63	0.17
		ii	0.234***	0.041	6.81	0.41	2.71	0.34	2.57	0.22
	R4	i	0.156	0.063	7.20	0.28	3.19	0.26	2.28**	0.18
		ii	0.239***	0.053	6.86	0.40	3.57***	0.20	1.95	0.18

α_L longitudinal shrinkage, α_T tangential shrinkage, α_R radial shrinkage, α_T/α_R tangential/radial shrinkage ratio, *SD* standard deviation

i 30 mm from the pith, *ii* 60–70 mm from the pith

Asterisks show significant differences between radial positions *i* and *ii* at the same height for each cultivar (*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$)

and intermediate for the 115-mm dimension timber. The difference between the dimensions was large for B, but small for R (Fig. 2; Table 4). For B, the differences between the dimensions were larger for timber 1 than timber 4 ($B1_{80}$ and $B1_{140}$, $P < 0.001$; $B4_{80}$ and $B4_{120}$, $P < 0.01$). The bow was larger for timber 1 than timber 4 ($B1_{80}$ and $B4_{80}$, $P < 0.001$; $B1_{140}$ and $B4_{120}$, $P < 0.001$). The percentage of timber with bow was high for timber 1 and the small-dimension timber ($B1_{80}$, 100 %; $B1_{140}$, 100 %; $B4_{80}$, 75 %; $B4_{120}$, 12.5 %). For R, on the other hand, the differences between the dimensions were small for both source heights ($R1_{80}$ and $R1_{140}$, $P = 0.28$; $R4_{80}$ and $R4_{120}$, $P = 0.07$). There was no significant difference between the source heights ($R1_{80}$ and $R4_{80}$, $P = 0.41$; $R1_{140}$ and $R4_{120}$, $P = 0.90$). The percentage of timber with bow was higher for large-dimension timber 1 ($R1_{80}$, 50 %; $R1_{140}$, 100 %; $R4_{80}$, 80 %; $R4_{120}$, 80 %).

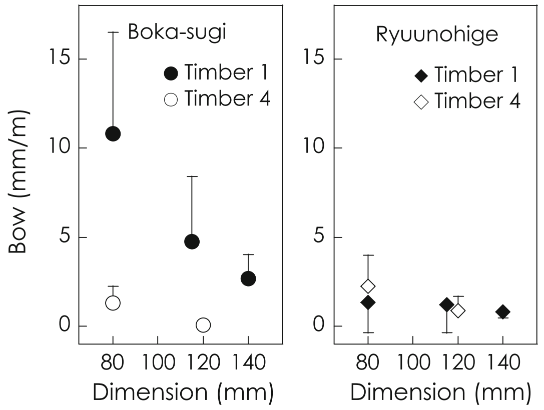

Fig. 2 Bow of the boxed-heart square timber of different dimensions. *Error bars* show the standard deviations

The bow of the kiln-dried timber was positively correlated with α_L ($r = 0.67$, $P < 0.001$) when both cultivars were included (Table 5; Fig. 3). Within each cultivar, the correlation of bow with α_L was significant for B ($r = 0.67$, $P < 0.001$), but not for R ($r = -0.29$, $P = 0.22$).

The results suggest the variation of bow with the timber dimensions and source heights was affected by the variation of α_L within the stems. For B, the small-dimension timber exhibited large bow, while the large-dimension timber exhibited small bow. This might be because the small-dimension timber is occupied with the portion of the stem with the large α_L, while the large-dimension timber included in the outer part the portion of the stem with the small α_L (Table 3). The difference in bow between the dimensions was larger for timber 1 than timber 4, which might be because the α_L in the juvenile wood and the portion of the stem with large α_L were larger at the bottom of the stem [5]. For R, on the other hand, the bow was small for all the dimensions and at both source heights, which might be because the α_L was small within the stem.

The bow of the kiln-dried timber was negatively correlated with MOE_{GT} and the specific MOE_{GT}/BD

Table 4 Bow, surface checking, and dimensional shrinkage for the timber of different dimensions

Sample	*D* (mm)	Bow (mm/m)		Surface checks							Dimensional shrinkage (%)	
				Total length (mm/m)		Number (count/m)		Average length (mm)		Max. length		
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	(mm)	Mean	SD
Boka-sugi												
$B1_{80}$	80	$10.8^{a,***}$	5.7	2^{b}	5	0.1^{b}	0.2	30^{a}	0	30	1.86^{a}	0.55
$B1_{115}$	115	4.7^{b}	3.7	134^{b}	202	0.9^{b}	1.1	151^{a}	111	640	–	–
$B1_{140}$	140	2.7^{b}	1.3	$380^{a,***}$	258	$3.3^{a,***}$	1.9	144^{a}	109	900	1.62^{a}	0.36
$B4_{80}$	80	$1.3^{a,**}$	0.9	191^{b}	178	0.9^{b}	0.7	192^{b}	86	610	3.65^{a}	0.90
$B4_{120}$	120	0.1^{b}	0.2	$1198^{a,***}$	410	$2.6^{a,**}$	1.4	$534^{a,***}$	229	1730	3.24^{a}	0.53
Ryuunohige												
$R1_{80}$	80	1.3^{a}	1.7	204^{a}	141	0.9^{a}	0.8	278^{a}	155	540	$4.48^{a,***}$	0.61
$R1_{115}$	115	1.2^{a}	1.6	102^{a}	190	0.4^{a}	0.8	311^{a}	233	1005	2.35^{b}	1.02
$R1_{140}$	140	0.8^{a}	0.3	279^{a}	283	0.7^{a}	0.5	512^{a}	453	970	2.46^{b}	0.57
$R4_{80}$	80	2.3^{a}	1.7	87^{a}	142	0.4^{b}	0.6	195^{a}	156	480	3.58^{a}	0.50
$R4_{120}$	120	0.9^{a}	0.8	335^{a}	326	$1.8^{a,**}$	0.6	190^{a}	198	980	2.91^{a}	0.91

The mean and SD of the average length of surface checks was obtained for the timber with surface checking

D cross-sectional dimension, *SD* standard deviation

Asterisks show significant differences between dimensions 80 and 140 mm for timber 1, and 80 mm and 120 mm for timber 4, for each cultivar (*** $P < 0.001$, ** $P < 0.01$)

[a,b] Significant differences among dimensions within each cultivar and source height (B1, B4, R1, R4) by the Tukey–Kramer HSD test ($P < 0.05$)

Table 5 Correlation coefficients between bow and the wood properties

	N	HWP[a]	$\mathrm{MC}^{a}_{\mathrm{DT}}$	BD[a]	α^{b}_{L}	$\mathrm{MOE}^{a}_{\mathrm{GT}}$	$\mathrm{MOE}_{\mathrm{GT}}/\mathrm{BD}^{a}$	EI[a]
All samples	60	0.388**	0.200	−0.222	0.666***	−0.523***	−0.564***	−0.364**
Boka-sugi	40	0.635***	0.233	−0.064	0.674***	−0.714***	−0.687***	−0.448**
Ryuunohige	20	0.263	−0.163	0.268	−0.288	−0.025	−0.088	−0.317

N number of boxed-heart squares

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

[a] See Table 2

[b] See Table 3

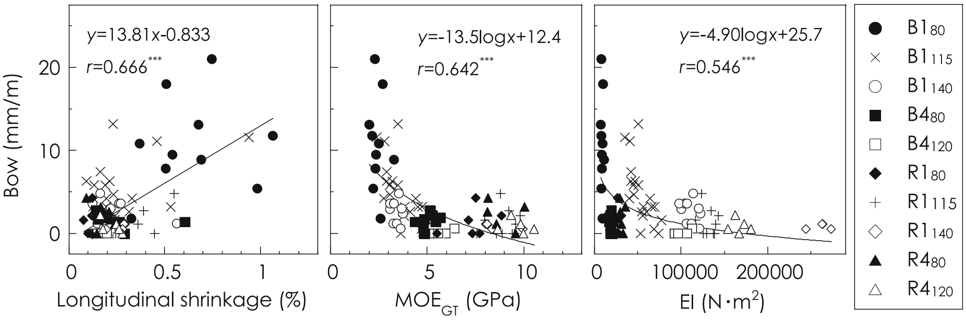

Fig. 3 Relationships between the bow, longitudinal shrinkage, $\mathrm{MOE}_{\mathrm{GT}}$, and EI. $\mathrm{MOE}_{\mathrm{GT}}$ and EI see Table 2. ***$P < 0.001$. The regression equations were obtained using the samples kiln-dried in this study, without $\mathrm{B1}_{115}$ and $\mathrm{R1}_{115}$

($P < 0.001$) (Table 5; Fig. 3), which is consistent with the results of our previous study [6]. The bow was negatively correlated with EI ($P < 0.01$) (Table 5; Fig. 3).

Surface-checking

The TLSC and NSC were different for the dimensions, source heights, and cultivars (Fig. 4; Table 4). The trends with the dimensions were similar for the TLSC and NSC. For B, the 140/120-mm dimension timber exhibited longer TLSC and larger NSC than the 80-mm dimension timber ($\mathrm{B1}_{80}$ and $\mathrm{B1}_{140}$, $P < 0.01$; $\mathrm{B4}_{80}$ and $\mathrm{B4}_{120}$, $P < 0.01$). For R4 also, the larger dimension timber exhibited longer TLSC and larger NSC ($\mathrm{R4}_{80}$ and $\mathrm{R4}_{120}$, TLSC $P = 0.08$, NSC $P < 0.01$). In these samples, the percentage of timber with surface checking was higher for the larger dimension timber ($\mathrm{B1}_{80}$, 10 %; $\mathrm{B1}_{140}$, 90 %; $\mathrm{B4}_{80}$, 75 %; $\mathrm{B4}_{120}$, 100 %; $\mathrm{R4}_{80}$, 40 %; $\mathrm{R4}_{140}$, 100 %). On the other hand, for R1, the TLSC and NSC were not significantly different between the dimensions ($\mathrm{R1}_{80}$ and $\mathrm{R1}_{140}$, TLSC $P = 0.30$, NSC $P = 0.31$), and the percentage of timber with surface checking was similar ($\mathrm{R4}_{80}$, 83 %; $\mathrm{R4}_{120}$, 75 %).

The average lengths of the surface checks were longer for the larger dimension timber for all samples, except R4. The maximum lengths of the surface checks were also longer for the larger dimension timber for all the samples.

For the small dimension timber of B and the large dimension timber of both cultivars, timber 4 exhibited longer TLSC and larger NSC than timber 1 ($\mathrm{B1}_{80}$ and $\mathrm{B4}_{80}$, TLSC $P < 0.01$, NSC $P < 0.001$; $\mathrm{B1}_{140}$ and $\mathrm{B4}_{120}$, TLSC $P < 0.001$, NSC $P = 0.43$; $\mathrm{R1}_{140}$ and $\mathrm{R4}_{120}$, TLSC $P = 0.79$, NSC $P = 0.02$). On the other hand, for the small-dimension timber of R, timber 1 exhibited longer TLSC and larger NSC than timber 4, although the difference was not significant ($\mathrm{R1}_{80}$ and $\mathrm{R4}_{80}$, TLSC $P = 0.20$, NSC $P = 0.31$).

The correlations between surface checking and wood properties were similar between TLSC and NSC. When all the samples were included, the TLSC was negatively correlated with HWP ($r = -0.49$, $P < 0.001$) and BD ($r = -0.38$, $P < 0.01$) (Table 6; Fig. 5). Within each cultivar, the relationships were also negative for HWP (B, $r = -0.47$, $P < 0.01$; R, $r = -0.43$, $P = 0.06$) and BD (B, $r = -0.35$, $P < 0.05$; R, $r = -0.51$, $P < 0.05$). The correlations of TLSC with α_{T} and α_{R} were not significant either for all the samples ($\alpha_{\mathrm{T}}, r = -0.07, P = 0.59$; $\alpha_{\mathrm{R}}, r = 0.07, P = 0.61$), or within each cultivar (B, α_{T}, $r = 0.26$, $P = 0.11$, α_{R}, $r = 0.31$ $P = 0.05$; R, α_{T}, $r = 0.19$, $P = 0.43$, α_{R}, $r = 0.17$, $P = 0.48$). There was no significant correlation between surface checking and the transverse shrinkage ratio ($\alpha_{\mathrm{T}}/\alpha_{\mathrm{R}}$), either. When the correlations were examined for timber containing only heartwood (HWP100 % from $\mathrm{B1}_{80}$, $\mathrm{R1}_{80}$, and $\mathrm{R4}_{80}$), the TLSC was positively correlated with α_{T} ($r = 0.50$, $P < 0.001$), but the correlation with BD was not significant ($r = 0.16$, $P = 0.46$).

The difference in surface checking among the samples in this study might be explained by the difference in the HWP. When all the samples were included, the HWP

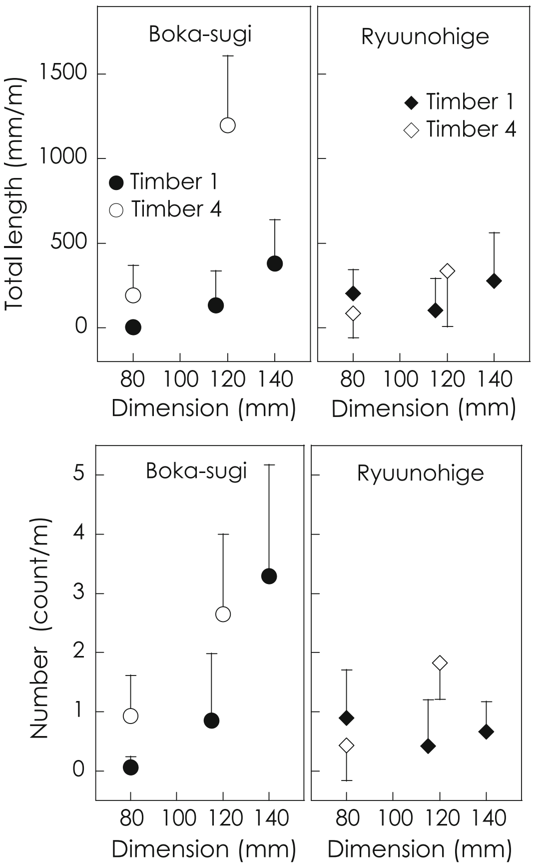

Fig. 4 Total length and number of surface checks for boxed-heart square timbers of different dimensions. *Error bars* show the standard deviations

exhibited the highest correlations with the TLSC and NSC among the wood properties examined. In the timber that contained sapwood on the outside, the drying stress would be large between the dry sapwood at the surface and the wet heartwood on the inside. The larger dimension timber contained more sapwood and had more prominent surface checking for B1, B4, and R4. For R1, both the small- and large-dimension timbers were mostly occupied with the heartwood and exhibited similar levels of surface checking. The $R1_{140}$ timber had sapwood only at the corners (HWP was 94 %), which might not have affected the drying stress between the corners. When surface checking was compared between source heights, timber 4 contained more sapwood and exhibited more prominent surface checking than timber 1, except that $R4_{80}$ was occupied with the heartwood and exhibited similar level of surface checking with $R1_{80}$.

The correlation analysis showed the BD and α_T also affected the variation in the surface checking variation. In the timber of low BD, the transverse strength would be low and the timber would be susceptible to the formation and elongation of surface checks. Among the samples, the surface checking was the most prominent for $B4_{120}$, in which the BD was the lowest. In the timber with large α_T, the drying stress in the tangential direction would be large. The surface checking was more prominent for B4 than B1, and for $R1_{80}$ than $R4_{80}$, which suggested it was affected by the larger tangential shrinkage of B4 and $R1_{80}$.

When all the samples were included, the TLSC was not significantly correlated with MOE_{GT} ($r = 0.09$, $P = 0.52$) and the specific MOE_{GT} ($r = 0.18$, $P = 0.17$) (Fig. 5; Table 6). For the timber containing only heartwood, the TLSC was positively correlated with MOE_{GT} ($r = 0.43$, $P < 0.05$) and the specific MOE_{GT} ($r = 0.47$, $P < 0.05$) (Table 6).

Dimensional shrinkage

The dimensional shrinkage of the kiln-dried timber was larger for the 80-mm dimension timber than the 140/120-mm dimension timber, although there was no significant difference between the dimensions except for R1 (Table 4). It might be attributed to shrinkage that was not homogeneous from the surface to the center of the timber, with the outside of the timber having shrunken more than the inside.

Among the samples, the dimensional shrinkage was the largest for $R1_{80}$. It was larger for B4 than B1. The large dimensional shrinkage of $R1_{80}$ might be attributed to the large α_T at the radial position i in R1 (Table 3). The larger dimensional shrinkage for B4 than B1 might be attributed to the larger α_T for B4 (Table 3). The dimensional shrinkage had a negative correlation with MC_{DT} and a positive correlation with α_T (Table 6; Fig. 6), which suggested it was affected by the degree of drying and the tangential shrinkage. The correlation of dimensional shrinkage with BD was not significant (Table 6). This suggested the factors affecting the dimensional shrinkage do not coincide with those of surface checking, which was significantly correlated with BD.

The dimensional shrinkage of the timber was positively correlated with MOE_{GT} and the specific MOE_{GT} (Table 6; Fig. 6). This might be because MOE_{GT} and the specific MOE_{GT} were correlated with α_T ($P < 0.001$).

Relationships between bow, surface-checking, and dimensional shrinkage

The bow was negatively correlated with the TLSC ($r = -0.40$, $P < 0.01$), the NSC ($r = -0.33$, $P < 0.01$), and the dimensional shrinkage ($r = -0.44$, $P < 0.001$) (Table 7). The TLSC was positively correlated with the NSC ($r = 0.60$, $P < 0.001$). The results are consistent with those of our previous study using 115-mm dimension timber [8]. There was no significant correlation between the surface checking and dimensional shrinkage.

Table 6 Correlation coefficients between surface checking, dimensional shrinkage, and the wood properties

	N	HWP^a	MC^a_{DT}	BD^a	α^b_T	α^b_R	α_T/α^b_R	MOE^a_{GT}	MOE_{GT}/BD
Total length of surface checks (TLSC)									
All samples	60	−0.490***	0.096	−0.376**	−0.072	0.067	−0.147	0.085	0.181
Boka-sugi	40	−0.466**	0.020	−0.351*	0.257	0.310	−0.188	0.574***	0.615***
Ryuunohige	20	−0.428	0.316	−0.508*	0.189	0.169	−0.156	0.191	0.342
HPW100 %	25		0.246	0.155	0.498*	0.297	0.136	0.428*	0.469*
Number of surface checks (NSC)									
All samples	60	−0.346**	0.351**	−0.267*	−0.145	0.126	−0.272*	−0.072	−0.027
Boka-sugi	40	−0.257	0.392*	−0.171	0.147	0.377*	−0.272	0.219	0.241
Ryuunohige	20	−0.511*	0.143	−0.162	0.003	0.391	−0.471	0.260	0.298
HPW100 %	25		0.217	0.219	0.505*	0.390	−0.090	0.470*	0.503*
Dimensional shrinkage									
All samples	60	−0.043	−0.336**	0.192	0.457***	0.312*	0.076	0.442***	0.467***
Boka-sugi	40	−0.426**	−0.599**	−0.069	0.314*	0.368*	−0.166	0.669***	0.638***
Ryuunohige	20	0.437	0.344	−0.311	0.364	−0.161	0.326	−0.641**	−0.611**
HPW100 %	25		−0.015	0.498*	0.779***	0.674***	−0.014	0.624***	0.635***

HWP 100 % timber contained only heartwood

N number of boxed-heart squares

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

[a] See Table 2

[b] see Table 3

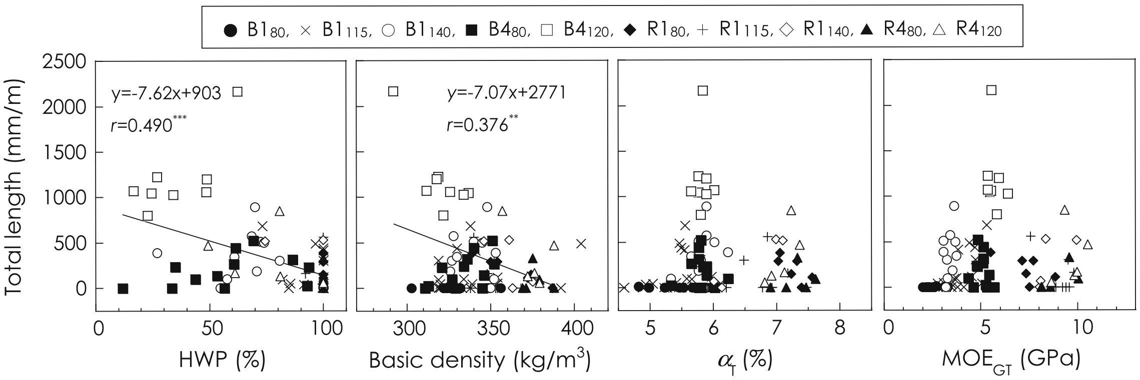

Fig. 5 Relationships between the total length of the surface checks and the wood properties. HWP and MOE_{GT} see Table 2. α_T see Table 3. ***$P < 0.001$, **$P < 0.01$

Discussion

Factors affecting the drying defects

Sagioka et al. [9] compared the boxed-heart square timber of tateyama-sugi with dimensions of 50, 70, and 100 mm and showed that the bow and twist decreased with the dimensions, while the number and total length of the surface checks increased. Saito et al. [10] compared the boxed-heart square timber of boka-sugi with dimensions of 45 and 70 mm and showed that the bow and twist decreased with the dimensions, while the number of surface checks increased. Takeda et al. [3] compared the boxed-heart square timber of tateyama-sugi and boka-sugi with dimensions of 70 and 90 mm and showed that the bow and twist were larger for the smaller dimension timber, while the total length of the end checks and the surface checks were longer for the larger dimension timber. Nakano and Saito [11] examined the boxed-heart square timber with dimensions 30–105 mm and showed that the percentage of timber ranked in the high grade for bow and twist increased with the dimensions, while that for surface checking decreased. These studies showed the common trend that the smaller dimension timber had larger bow and twist and less prominent surface checking. This study showed the same results for bow and surface checking with

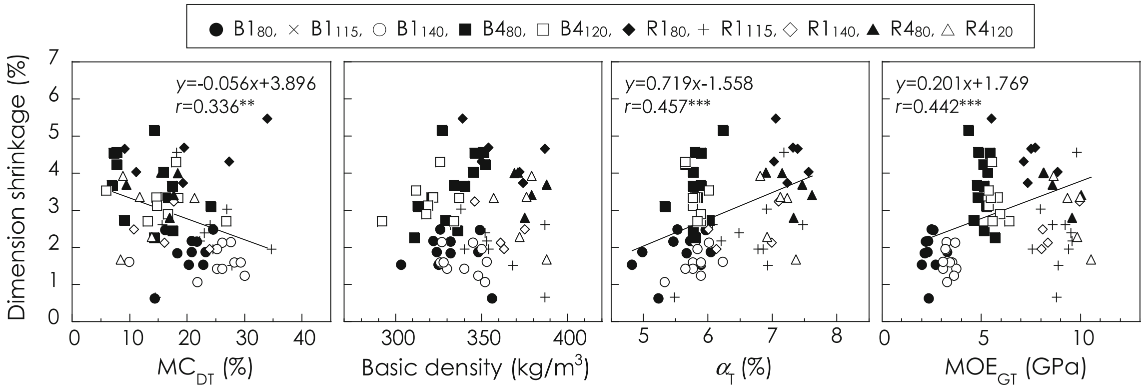

Fig. 6 Relationships between the dimensional shrinkage and the wood properties. MC_{DT} and MOE_{GT} see Table 2. α_T see Table 3. ***$P < 0.001$, **$P < 0.01$

Table 7 Correlation coefficients between bow, surface checking, and dimensional shrinkage

	TLSC	NSC	Dimensional shrinkage
Bow	−0.397**	−0.334**	−0.435***
TLSC		0.595***	0.056
NSC			−0.193

TLSC and NSC see Table 6. 60 boxed-heart squares were used

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

boxed-heart square timber dimensions of 80 and 140/120 mm. Twist was not observed, which might be because the dimensions were larger than those in the previous studies.

This study showed the dimension effect of the boxed-heart square timber on the bow was different for the cultivars and source heights. This depended on the α_L of the juvenile wood, which is highly affected by the MFA [5]. The bow of the boxed-heart square timber is considered to be caused by the radial growth not being eccentric and the longitudinal shrinkage not being completely symmetrical with respect to the pith. The side of the timber with larger longitudinal shrinkage will shrink more than the other side, and when the longitudinal shrinkage is large, the difference between the sides will be larger. The bottom of the tree stems tend to bend and grow with eccentricity, and have the compression wood. Takeda et al. [4] compared the boxed-heart square timber with dimensions of 70 mm taken from straight trees and bent trees and showed that the bow with drying was larger for the bent trees, while the end checking was longer for the straight trees. They also reported that the tree growth was more eccentric for the bent trees than the straight trees and that the compression wood is present not only in the bent trees, but also in the straight trees, and the bow with drying increased with the compression wood area percentage. Yamada et al. [1] showed that the eccentricity affected the tension drying stress and the surface checking of the sugi boxed-heart timber. If the trees contained compression wood, the shrinkage eccentricity would be larger.

This study showed the dimension effect on the surface checking was different for the source heights and cultivars, depending on the proportion of heartwood and sapwood. It is suggested that a high proportion of sapwood induced more surface checking, because the drying stress between the sapwood and the heartwood would be larger when the timber contains more sapwood. In order to confirm the effect of the heartwood proportion on the drying checks, the moisture gradient, shrinkage, drying stress and stress relaxation, and occurrence of drying checks will need to be monitored with different heartwood proportions. To understand the variation of surface checking, not only the variation of the moisture content [20–22] and shrinkage [5, 7], but also the variation of the tangential strength [23] and viscoelasticity [24–26] will need to be studied. A desirable drying schedule for timber containing a large portion of sapwood would reduce the moisture content gradient from the surface to the interior of the timber. For example, Noji et al. [27] showed that a local steam explosion treatment reduced the moisture gradient through the thickness during drying, and the drying stress, and surface checks.

Our previous study using 115-mm dimension timber showed the effect of tangential shrinkage on the surface checking [8]. However, in this study the effect of the tangential shrinkage was observed only when the HWP was 100 %. The large variation of the HWP might have affected surface checking strongly. The transverse shrinkage ratio had no observed effect, as shown in our previous study [8].

The effect of the growth conditions on the drying defects is a subject of future research. Even in the same cultivars, the wood properties might be different due to the growth. If the initial tree growth is fast, the portion of the juvenile wood will be larger. If the growth is fast, ring width and the proportion of earlywood with low density and high MFA will be larger [28]. Site quality and crown volume could possibly vary the heartwood diameter[29].

Indicator for timber sorting

Saito et al. [10] pointed out that the main drying defect was surface-checking for tateyama-sugi in which the MOE was high, but it was bow for boka-sugi in which the MOE was low. In our previous study [6] and this study, the timber with lower MOE exhibited larger bow. These results suggested that the timber which is susceptible to large bow can be sorted before drying by the MOE. Furthermore, this study examined the effect of rigidity and showed that the rigidity was much lower for the smaller dimension timber, which exhibited larger bow. The softening of green wood at high temperature might reduce the rigidity, which might also affect timber deformation during kiln-drying. The variation of wood properties relating softening is a future study.

The significant correlations between the surface checking and HWP for all the samples, and between the surface checking and MOE for timber with 100 % HWP suggested that the HWP and MOE could be useful indicators for sorting the timber that is susceptible to surface checking. The moisture content (MC) of the green wood has large variation within sugi, especially in the heartwood [20–22], and the initial MC of the timber before drying is highly correlated to the final MC of the timber after drying [30]. Therefore, to reduce the variation in the final MC of the timber, sorting the timber by the initial MC before drying is effective [30–32]. Nakashima [30] and Sugimori et al. [32] suggested that not only the initial MC, but also the heartwood proportion affected the final MC of the timber. Kawabe et al. [33] showed that the heartwood MC affected the distribution of the internal stresses and moisture content during drying. This study suggested that the heartwood proportion affected not only the drying speed and final MC, but also the surface checking.

In order to increase the yield and decrease the processing energy, it is desirable for the finishing thickness to be the minimum. This study showed significant correlations between the dimensional shrinkage of the timber and the MOE, which suggested that the MOE could be an indicator to predict dimensional shrinkage.

Conclusions

The larger dimension boxed-heart square timber of sugi exhibited smaller bow, more prominent surface checking, and less dimensional shrinkage; however, the dimension effect was different for the cultivars and the source heights of the logs. The dimension effect on bow depended on the α_L of the juvenile wood, while the dimension effect on surface checking depended on the heartwood proportion and the α_T. The dimension effect on dimensional shrinkage depended on the α_T. The MOE which is related to the α_L and α_T, and the heartwood proportion which is related to moisture distribution might be useful indicators of these drying defects.

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