Original article

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Inheritance of static bending properties and classification of load-deflection curves in *Cryptomeria japonica*

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Abstract: To clarify inheritance of static bending properties in relation to elastic and plastic regions, air-dry density, microfibril angle of the S_2 layer in latewood tracheid (MFA), and static bending properties (modulus of elasticity [MOE], modulus of rupture [MOR] and bending work) were examined for juvenile wood of 18 full-sib families in 20-year-old *Cryptomeria japonica*. Heritability of all traits ranged from 0.12 (bending work) to 0.51 (air-dry density). Based on the results from principal component analysis (PCA) and cluster analysis, the families were classified into four groups with different types of load-deflection curves, suggesting that both elastic properties and deflection in plastic region differed among families. Furthermore, families included in a group were produced from specific parents, suggesting that deflection in plastic region as well as elastic property is inheritable. It can be concluded that mating parents may affect elasticity and plasticity of offspring.

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Keywords: air-dry density; bending property; inheritance; load-deflection curve; MFA.

1 Introduction

Tree breeding programs in Japan were firstly established at 1950s with the aim of improving growth characteristics, such as stem diameter, tree height, straightness, and disease resistance. In the programs, many individuals were selected as elite trees. Progeny test stands were established using these selected trees. Under the programs, inheritance of many traits was evaluated through heritability, breeding values, and other criteria (Fujisawa et al. 1992, 2000; Kurahara and Kato 2005; Kuramoto et al. 2007; Sato et al. 2016). Heritability is a parameter to determine the degree of resemblance between relatives (Falconer and Mackay 1996). The breeding value refers to values that determine their influence on the next generation (Falconer and Mackay 1996) and is an important function in selecting individuals for tree breeding programs.

Cryptomeria japonica D. Don (sugi in Japanese, and Japanese cedar in English) is one of the plantation species in Japan (Forestry Agency 2017) and has been subjected to the tree breeding program in Japan. There are many studies on the inheritance of growth traits for this species (Kuramoto et al. 2007; Sato et al. 2016). In addition, inheritance of wood quality traits, such as wood density, microfibril angle, and Young's modulus, has also been investigated in *C. japonica* elite trees planted in progeny test stands established in the1950s (Fujisawa et al. 1992, 2000; Hirakawa and Fujisawa 1995; Nakada et al. 2003). As a result, it has been reported that the wood quality of this tree is genetically controlled because of high heritability (Fujisawa et al. 1992, 2000, Kurahara and Kato 2005). In tree breeding programs, the genetic parameters of wood properties are needed to improve wood properties for commercial utilization of this species.

Static bending properties, such as modulus of elasticity (MOE), modulus of rupture (MOR), and bending work, are important for evaluating wood quality, because wood is often subjected to bending load in cases where it is used as structural lumbers in constructions. Elastic property, such as MOE, is resistance to deformation caused by load that is completely recovered after unloading (Kollmann and Côté 1984). Bending strength, MOR, is a parameter to assess maximum stress to loadings until the wood breaks. Bending work is the amount of energy absorbed until wood is broken by bending load. Wood with higher bending work has more toughness, showing resistance to failure (Bodig and Jayne 1982). These parameters were calculated by load-deflection curve, which was obtained in static bending tests. The shape of the load-deflection curve is important to understand the elastic and plastic properties of the wood. Sasaki et al. (1983) tested static bending properties of full-size lumber of 36 cultivars in *C. japonica*, and they found that load-deflection curves in each cultivar could be classified into three types: type I displayed higher load at proportional limit and smaller deflection in plastic region, type II displayed intermediate load at proportional limit and deflection in plastic region between type I and III, and type III displayed lower load at proportional limit and larger deflection in plastic region. Thus, load-deflection curves differed among cultivars, suggesting that both the elastic property and deflection in plastic region of wood might be heritable. Therefore, there is a need to clarify the differences of load-deflection curves between genetic sources.

It is known that static bending properties are related to wood properties, such as wood density and microfibril angle of the S_2 layer of tracheid (MFA) in some softwood species (Ishiguri et al. 2009; Kubojima et al. 2000; Lachenbruch et al. 2010; Steffenrem et al. 2007). The MFA is negatively correlated with MOE (Hirakawa and Fujisawa, 1995; Kijidani et al. 2012; Nakada et al. 2003; Steffenrem et al. 2007), whereas MOR is affected by air-dry density rather than MFA in softwood species (Koizumi et al. 2003; Lachenbrush et al. 2010). Thus, if the tree breeding objectives include producing wood with higher bending properties, the individuals with higher wood density and lower MFA should be selected as trees with higher bending properties.

In the present study, to clarify the possibility of improving bending properties, heritability and breeding values of bending properties were examined for small-clear specimens obtained from the juvenile wood of 206 trees that originated from 18 full-sib families produced from control-crossing with 12 parental clones of elite trees in *C. japonica*. In addition, classification of the families based on load-deflection curves was conducted using cluster analysis and principal component analysis (PCA).

2 Materials and methods

2.1 Materials

A total of 206 trees of 20-year-old *C. japonica* D. Don were used in the present study. The trees were originated from 18 full-sib families control-crossed by 12 parental plus tree clones using a randomized block design with six replicates and were planted in the Forest Tree Breeding Center, Forestry and Forest Products Research Institute, Hitachi, Ibaraki, Japan (36°41′31″N, 140°41′26 ″E). Table 1 shows the mating combinations of seed and pollen parents for the families used in the present study. Mean values and standard deviation of stem diameter at 1.2 m above ground and tree height in all trees were 15.0 ± 3.7 cm and 11.9 ± 2.0 m, respectively (Table 1). After cutting the trees, logs were collected from 1.2 to 1.6 m above ground. Bark to bark radial boards (3 cm in thickness) were prepared from the logs. The boards were air-dried under laboratory conditions without air conditioning for six years. Then, the boards were planed down to a 20 mm thickness.

2.2 Static bending properties

Static bending tests were conducted according to the Japanese Industrial Standard (JIS) Z 2101–2009 (Japanese Industrial Standards 2009). A small-clear specimen (20 (R) × 20 (T) × 320 (L) mm) was prepared from each board. All specimens were prepared at the same radial position to eliminate the effects of radial positions on bending properties: The 4th annual ring from the pith was located in the center of the radial surface of a specimen in cross-section, because small-clear specimens with fourth annual ring could be collected from all individuals. A total 206 specimens were prepared. Static bending tests were conducted using an universal testing machine (MSC-5/500-2, Tokyo Testing Machine, Tokyo, Japan). Load was applied to the center of radial surface of the specimen at 5 mm/min with 280 mm of span. The data regarding the load and deflection were recorded using a personal computer. The following bending properties were calculated: MOE, MOR, and bending work (Figure 1). After the static bending tests, a small block was collected from each specimen for measuring air-dry density and moisture content of the small-clear specimen. Mean value and standard deviation of moisture content were 12.6 ± 1.4%.

2.3 Microfibril angle

Microfibril angle of the S_2 layer in latewood tracheid (or the MFA) was measured as the angle of the slit-like pit aperture of boarded pits in latewood tracheids (Cookrell 1974; Donaldson 1991; Hirakawa and Fujisawa 1995). Small-wood blocks containing the 4th annual ring from the pith were obtained from the small-clear specimens after the static bending test. Tangential sections of 20 μm in thickness containing latewood of the 4th annual ring from the pith were obtained from the blocks with a sliding microtome (ROM-710, Yamatokohki, Saitama, Japan). These sections were stained with 1% safranine and then dehydrated using graded ethanol. The dehydrated sections were dipped into xylene and mounted on the slides with bioleit (Okenshoji, Tokyo, Japan). Photomicrographs of tangential sections were taken using a light microscope (CX-41, Olympus Corporation, Tokyo, Japan)

Table 1: Mating combinations of seed and pollen parents of families used in the present study.

Seed parent	Pollen parent	Family ID	*n*	D (cm)	TH (m)
A3	F5	1	11	14.5 ± 3.3	11.6 ± 1.9
A3	E1	2	13	13.3 ± 3.5	10.4 ± 1.8
A3	G6	3	13	14.8 ± 3.4	12.1 ± 1.8
A12	C3	4	10	16.7 ± 3.1	12.5 ± 1.8
A12	D16	5	13	15.2 ± 3.4	12.5 ± 1.6
A12	G3	6	14	17.2 ± 4.3	13.3 ± 2.4
A18	A20	7	11	12.4 ± 3.5	9.7 ± 2.8
A18	F6	8	13	15.6 ± 3.8	11.8 ± 2.0
B12	A18	9	10	15.1 ± 3.6	12.2 ± 1.8
A20	F6	10	5	13.5 ± 1.0	11.5 ± 1.4
B12	A20	11	9	12.8 ± 2.7	11.1 ± 2.3
C3	D16	12	13	14.9 ± 3.0	12.7 ± 1.9
C3	G3	13	15	16.5 ± 4.1	12.1 ± 1.7
D16	G3	14	10	15.9 ± 4.2	12.3 ± 2.2
E1	F5	15	10	13.8 ± 3.4	11.6 ± 1.5
F5	G6	16	8	14.6 ± 2.3	11.7 ± 0.9
B12	F6	17	10	16.0 ± 4.6	12.8 ± 2.6
E1	G6	18	18	14.9 ± 3.8	12.1 ± 1.4
Mean/Total			206	15.0 ± 3.7	11.9 ± 2.0

n, number of sample trees; D, stem diameters at 1.2 m above the ground; TH, tree height.

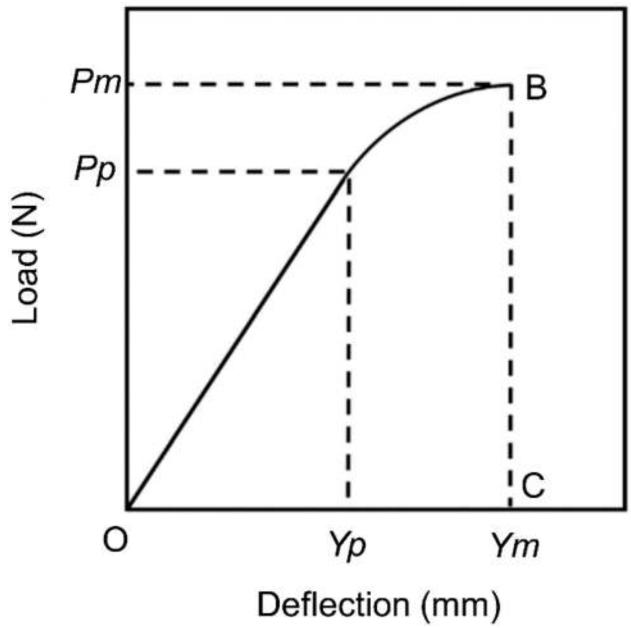

Figure 1: Calculation of static bending properties from load-deflection curve of static bending test. *Pm*, maximum load; *Pp*, load at proportional limit; *Ym*, maximum deflection; *Yp*, deflection at proportional limit. MOE and MOR were determined by the following equations: MOE (GPa) = $Ppl^3/4Ypbh^3$, MOR (MPa) = $3Pml/2bh^2$ where *l* is the span, *b* is the width of the specimen, *h* is the height of the specimen, bending work is an area enclosed with OBC in this graph.

equipped with a digital camera (E-300, Olympus Corporation, Tokyo, Japan). The angle of the slit-pit aperture in the bordered pits of latewood tracheids to longitudinal direction was measured as MFA using ImageJ (National Institute of Health, Bethesda, MD, USA). Thirty tracheids were measured in each tree.

2.4 Data analysis

Statistical analysis was conducted using the R open-source statistical package (R Core Team 2017). The correlation coefficients between properties were determined as Pearson correlation coefficients.

The variance component of each trait was estimated using residual maximum likelihood estimation (REML) methods using a software (ASReml, VSN International). The linear mixed model used for the estimation of breeding value and variance components was expressed in matrix form Equation (1);

$$y = Xb + Z_1 g + Z_2 s + e \quad (1)$$

where, y is the vector of measured values, X is the incidence matrix of the fixed effects, b is the vector of fixed effect parameters of block, Z_1 and Z_2 are the incidence matrices of the random effects, g is the vector of random additive genetic effects, which equates to the breeding value, s is the vector of random specific combining ability (SCA) effects and e is the vector of random residuals. The random effects are assumed to be distributed as follow Equation (2);

$$\mathrm{Var}\begin{pmatrix} g \\ s \\ e \end{pmatrix} \sim \mathrm{MVN}\left(\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} G & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & R \end{pmatrix}\right) \quad (2)$$

where, G, S and R are the variance-covariance matrices of g, s and e, respectively. The random effects are estimated by best linear unbiased prediction (BLUP), which is calculated by solving the mixed model equations, given by Equation (3);

$$\begin{bmatrix} X'R^{-1}X & X'R^{-1}Z_1 & X'R^{-1}Z_2 \\ Z_1'R^{-1}X & Z_1'R^{-1}Z_1 + G^{-1} & Z_1'R^{-1}Z_2 \\ Z_2'R^{-1}X & Z_2'R^{-1}Z_1 & Z_2'R^{-1}Z_2 + S^{-1} \end{bmatrix} \begin{bmatrix} b^{\circ} \\ \hat{g} \\ \hat{s} \end{bmatrix} = \begin{bmatrix} X'R^{-1}y \\ Z_1'R^{-1}y \\ Z_2'R^{-1}y \end{bmatrix} \quad (3)$$

The narrow-sense heritability of each trait was estimated using following Equation (4):

$$h^2 = \frac{\sigma_g^2}{\sigma_g^2 + \sigma_s^2 + \sigma_e^2} \quad (4)$$

where, h^2 is narrow-sense heritability, and σ_g^2 and σ_s^2 are variance components of the additive genetic effects and the SCA, respectively, and σ_e^2 is the residual variance.

PCA and cluster analysis were performed to categorize the family or mating parents. Principal component scores were calculated using correlation matrix with four variables: simple arithmetic mean values of individuals for each family in load and deflection at proportional limit and maximum load and deflection. Using 1st and 2nd principal component scores from PCA as variables, cluster analysis using Ward hierarchical clustering algorithm was performed for categorization of families. In addition, cluster analysis with breeding values of air-dry density, MFA, MOE, MOR and bending work in each mating parent as variables was performed as well as case of categorization of families, to clarify characterization of influences of mating parents on wood properties of their progenies.

3 Results and discussion

3.1 Mean values of wood properties

Table 2 shows the mean values and standard deviations of air-dry density, MFA, and bending properties at the 4th annual ring from pith in each family. The mean values of air-dry density and MFA in all specimens were 391 kg/m^3 and 32.3°, respectively. Hirakawa and Fujisawa (1995) reported that mean air-dry density ranged from 317 to 421 kg/m^3 (from 0.317 to 0.421 g/cm^3) for juvenile wood within the 20th annual ring from pith in approximately 24-year-old six clones trees of *C. japonica*. The MFA in *C. japonica* rapidly decreased from pith to approximately the 20th annual ring from pith, and the maximum MFA values were found around the pith ((Hiraiwa et al. 2014; Hirakawa and Fujisawa 1995; Iizuka et al. 2007; Ishidoh et al. 2009; Ishiguri et al. 2009; Nakada et al. 2003; Yamashita et al. 2000; Zhu et al. 2005). Ishidoh et al. (2009) reported that MFA of the 3rd annual ring was 31.6 ± 3.6 for 45-year-old *C. japonica* trees. The mean values in air-dry density and MFA obtained in the present study were similar to those in the previous reports (Hiraiwa et al. 2014; Hirakawa and Fujisawa 1995; Iizuka et al. 2007; Ishidoh et al. 2009; Ishiguri et al. 2009; Kubojima et al. 2000; Yamashita et al. 2000; Zhu et al. 2005). Iizuka et al. (2007) reported that the mean value of MOE and MOR in 26-year-old *C. japonica* trees ranged from 3.79 to 3.80 GPa, and from 47.9 to 49.3 MPa, respectively. In the present study, mean values of all specimens were 3.28 GPa and 54.1 MPa for MOE and MOR, respectively (Table 2). These results obtained in the present study were similar to those for juvenile wood of *C. japonica* reported by other researchers (Hiraiwa et al. 2014; Hirakawa and Fujisawa 1995; Iizuka et al. 2007; Ishidoh et al. 2009; Ishiguri et al. 2009; Kubojima et al. 2000; Zhu et al. 2005). The mean value of bending work in all specimens was 19.0 Nm (Table 2). Ishiguri et al. (2009) investigated bending properties of juvenile wood and mature wood in 55-year-old *C. japonica* trees. They reported that mean values of bending work of juvenile wood was 8.7 Nm. Mean bending work obtained in the present study was larger than that reported by Ishiguri et al. (2009).

3.2 Relationships between radial growth rate and wood properties or static bending properties

Fujisawa et al. (1992) reported that in elite clone trees of 21, 23 and 26-year-old *C. japonica*, there was no relationship between stem diameter at 1.2 m above ground and Young's modulus of logs. In the present study, as shown in Table 3, correlation coefficients between stem diameter at 1.2 m above ground and all properties obtained were significant but lower values, suggesting that trees with both higher growth rate and superior wood properties can be selected in the tree breeding programs for *C. japonica*.

3.3 Relationships between air-dry density or MFA and static bending properties

In *C. japonica*, it was reported that mechanical properties such as MOE and MOR in juvenile wood were lower than those in mature wood (Hiraiwa et al. 2014; Ishiguri et al. 2009; Zhu et al. 2005). Thus, improvement of mechanical properties in juvenile wood is necessary through tree breeding programs. It is known that MFA is negatively correlated with MOE in softwoods (Hirakawa and Fujisawa 1995; Kijidani et al. 2012; Lachenbrush et al. 2010; Steffenrem et al. 2007). On the other hand, several researchers have discovered that air-dry density affected MOR rather than MFA in softwood species (Ishiguri et al. 2009; Koizumi et al. 2003; Kubojima et al. 2000; Lachenbruch et al. 2010). These tendencies are also true for *C. japonica* (Hirakawa and Fujisawa 1995; Ishiguri et al. 2009; Nakada et al. 2003; Yamashita et al. 2000). Figure 2 shows the correlation coefficients between air-dry density or MFA and static bending properties. In MOE, absolute values of correlation coefficients with MFA were significantly higher (r = −0.677) than those with air-dry density (r = 0.209) (Figure 2). On the other hand, air-dry density was highly correlated with MOR and bending work (r = 0.456 and 0.289, respectively) compared to MFA (Figure 2). Based on these results, both air-dry density and MFA can be used as selection criteria for improving some mechanical properties in juvenile woods of *C. japonica*.

3.4 Heritability and breeding values of mating parents

Table 4 shows heritability and breeding values of mating parents for all traits. In the present study, the highest narrow-sense heritability (h^2 = 0.51) was obtained in air-dry density. Kurahara and Kato (2005) reported that narrow-sense heritability for basic density in 21 full-sib families of 17-year-old *C. japonica* was 0.20. They also reported that narrow-sense heritability of Young's modulus of logs was

Table 2: Mean values and standard deviations of air-dry density, microfibril angle, and static bending properties in each family.

Family ID	*n*	Air-dry density (kg/m³)	MFA (°)	MOE (GPa)	MOR (MPa)	Bending work (Nm)
1	11	411 ± 41	33.8 ± 3.4	3.29 ± 0.26	57.3 ± 5.3	17.5 ± 8.1
2	13	382 ± 24	34.0 ± 2.1	3.11 ± 0.31	54.6 ± 5.3	25.3 ± 13.5
3	13	404 ± 45	31.5 ± 3.2	3.75 ± 0.89	54.9 ± 15.0	15.3 ± 13.0
4	10	369 ± 27	31.7 ± 3.5	3.22 ± 0.54	51.3 ± 6.6	14.5 ± 5.2
5	13	371 ± 31	26.2 ± 5.2	3.67 ± 0.58	54.0 ± 7.2	13.7 ± 6.7
6	14	377 ± 35	31.8 ± 2.6	3.65 ± 0.60	55.8 ± 8.0	17.9 ± 7.5
7	11	391 ± 25	33.6 ± 3.1	3.40 ± 0.69	55.1 ± 7.3	22.0 ± 16.1
8	13	426 ± 53	35.3 ± 5.6	3.09 ± 0.67	54.7 ± 9.6	20.7 ± 12.5
9	10	412 ± 30	34.5 ± 2.2	3.55 ± 0.55	61.1 ± 6.2	25.6 ± 7.3
10	5	442 ± 31	34.7 ± 2.0	2.99 ± 0.62	57.2 ± 4.5	28.5 ± 14.5
11	9	412 ± 34	33.3 ± 2.8	3.73 ± 0.72	61.1 ± 7.7	27.4 ± 16.5
12	13	370 ± 28	31.5 ± 3.7	3.18 ± 0.79	52.6 ± 11.4	18.1 ± 8.9
13	15	361 ± 36	31.5 ± 2.4	2.90 ± 0.54	47.3 ± 7.2	14.7 ± 7.8
14	10	360 ± 32	30.8 ± 6.5	3.36 ± 0.81	52.6 ± 6.9	14.6 ± 3.8
15	10	360 ± 23	33.5 ± 1.8	2.92 ± 0.58	50.5 ± 7.6	18.2 ± 10.1
16	8	419 ± 28	32.0 ± 2.6	3.46 ± 0.74	57.8 ± 3.1	21.1 ± 11.6
17	10	427 ± 37	33.9 ± 2.5	3.22 ± 0.45	55.6 ± 8.9	21.3 ± 10.4
18	18	394 ± 39	35.1 ± 6.2	2.84 ± 0.72	49.6 ± 7.9	19.5 ± 11.9
Mean	206	391 ± 41	32.3 ± 4.4	3.28 ± 0.68	54.1 ± 8.7	19.0 ± 10.6

n, number of specimen; MFA, microfibril angle; MOE, modulus of elasticity; MOR, modulus of rupture.

Table 3: Correlation coefficients between stem diameter at 1.2 m above the ground and wood properties or bending properties.

Factor	*r*
Air-dry density	-0.247^{**}
MFA	0.082^{ns}
MOE	-0.183^{**}
MOR	-0.204^{**}
Bending work	-0.173^{*}

number of specimens = 206; *r*, correlation coefficient; MFA, microfibril angle; MOE, modulus of elasticity; MOR, modules of rupture; **, significant at 1% level; *, significant at 5% level; ^{ns}, not significant.

0.17. In the present study, narrow-sense heritability of MOE displayed a higher value (h^2 = 0.38) compared with their result.

To assess mating parents, breeding values of all parents for each trait were estimated. Breeding values mean the value of individuals, judged by mean value of their progeny (Falconer and Mackay 1996). The highest breeding value for stem diameter at 1.2 m above ground was found in G3. In tree height, breeding values ranged from −1.37 (A20) to 0.71 m (A12). Parents exhibiting the highest breeding values for air-dry density and MFA were F6 and E1, respectively. In breeding values of bending properties, B12 showed relatively higher values compared with other parents. Of the mating parents subjected in the present study, A12 and G3 were superior in growth traits. Furthermore, results suggested that bending properties may be improved if B12 was selected as mating parent. Cluster analysis based on breeding values of growth characteristics (tree height and stem diameter) and wood properties (air-dry density, MFA and bending properties) as variables were conducted. As shown in Figure 3, twelve mating parents were divided into five groups (group i, group ii, group iii, group iv and group v). Mating parents of group i (A12) showed positive breeding values for growth characteristics, MOE and MOR and negative breeding values for air-dry density and MFA. In mating parents belonged into group ii (C3, D16, E1, and G3), breeding values of air-dry density and bending properties were negative values. Mating parents F6 in group iii showed positive breeding values for growth characteristics and air-dry density, but negative breeding values for MOE and MOR with positive breeding value for MFA. All mating parents in group iv (A3, A18, A20, and F5) showed negative breeding values for growth characteristics. Positive breeding values in both growth characteristics and bending properties were obtained in mating parents belonged into group v (B12 and G6). From these results, it is considered that, characteristics of influence of mating parents on progeny was different among parents, and some mating parents such as A12, B12, and G6 may produce the progeny with good growth characteristics and strength properties.

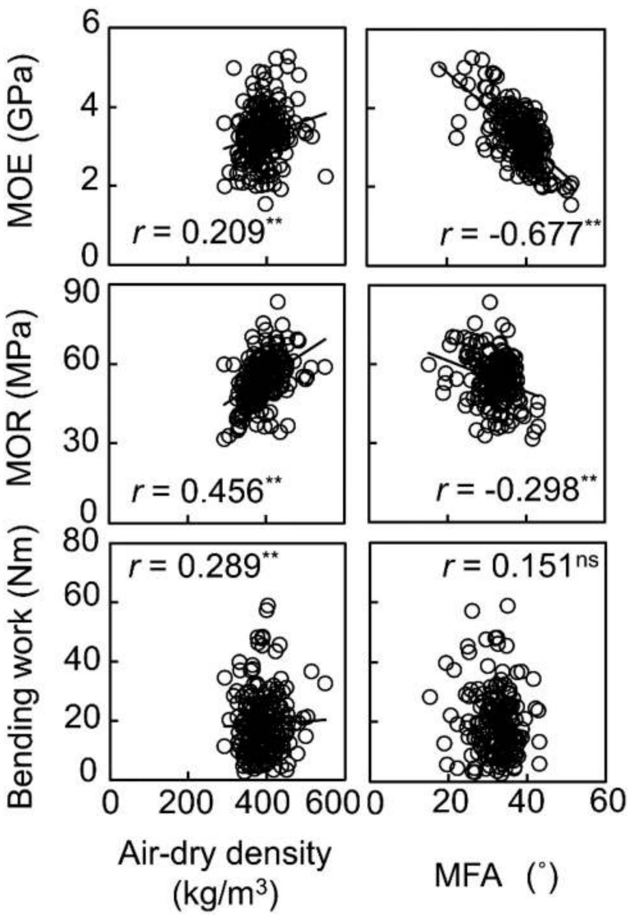

Figure 2: Relationships between air-dry density or MFA and static bending properties. Number of specimens = 206; *r*, correlation coefficient; **, significant at 1% level; ns, not significant; MFA, microfibril angle; MOE, modulus of elasticity; MOR, modulus of rupture.

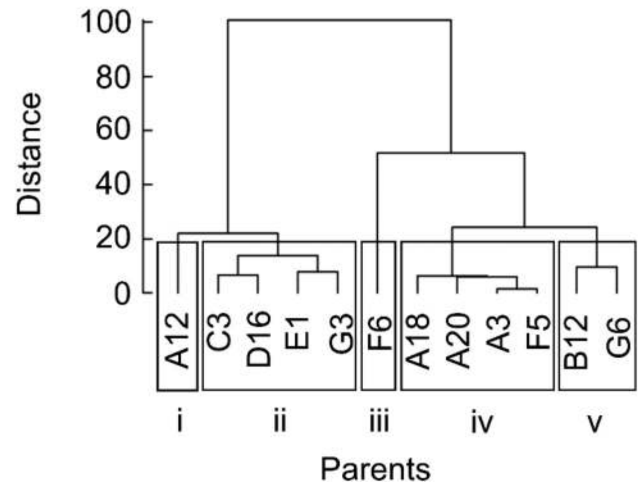

Figure 3: Cluster dendrogram using Ward hierarchical clustering algorithm based on breeding values of air-dry density, MFA and bending properties. The vertical axis shows the distance between families based on Euclidean distance.

3.5 Inheritance of load-deflection curves

Sasaki et al. (1983) investigated bending properties in full-size lumbers of 36 cultivars in *C. japonica*. They found that load-deflection curves obtained through bending test differed among cultivars, and the curves were classified into three types: type I showed higher load at proportional limit and smaller deflection in plastic region, type II exhibited intermediate load at proportional limit and deflection in plastic region between type I and III, and type III exhibited lower load at proportional limit and larger

Table 4: Heritability and breeding values of all parents.

Parents	D (cm)	TH (m)	Air-dry density (kg/m³)	MFA (°)	MOE (GPa)	MOR (MPa)	Bending work (Nm)
A3	−0.54	−0.42	8	−0.04	0.34	2.22	−0.37
A12	1.10	0.71	−11	−3.01	0.50	1.26	−2.93
A18	−0.19	−0.54	3	1.10	0.05	1.61	1.49
A20	−2.12	−1.37	8	0.70	0.16	2.30	4.17
B12	0.22	0.59	19	−0.64	0.36	4.96	3.96
C3	0.25	0.05	−22	1.05	−0.45	−4.37	−2.40
D16	−0.36	0.31	−24	−3.58	0.21	−0.22	−2.80
E1	−0.54	−0.31	−34	2.91	−0.72	−4.54	2.35
F5	−0.52	−0.32	8	0.58	−0.11	0.98	−0.76
F6	0.87	0.41	51	2.26	−0.42	−0.41	1.45
G3	1.65	0.59	−30	−0.28	−0.05	−2.64	−2.63
G6	0.19	0.28	24	−1.05	0.13	−1.16	−1.52
h^2	0.15	0.22	0.51	0.29	0.38	0.19	0.12

D, stem diameters at 1.2 m above the ground; TH, tree height; MFA, microfibril angle; MOE, modulus of elasticity; MOR, modules of rupture; h^2, narrow-sense heritability.

Table 5: Loading of principal components of PCA for 18 families.

Variables	PC1	PC2
Load at proportional limit	−0.576	0.406
Deflection at proportional limit	−0.186	−0.703
Maximum load	−0.663	0.207
Maximum deflection	−0.441	−0.545

PC1 and PC2, first and second principal components, respectively.

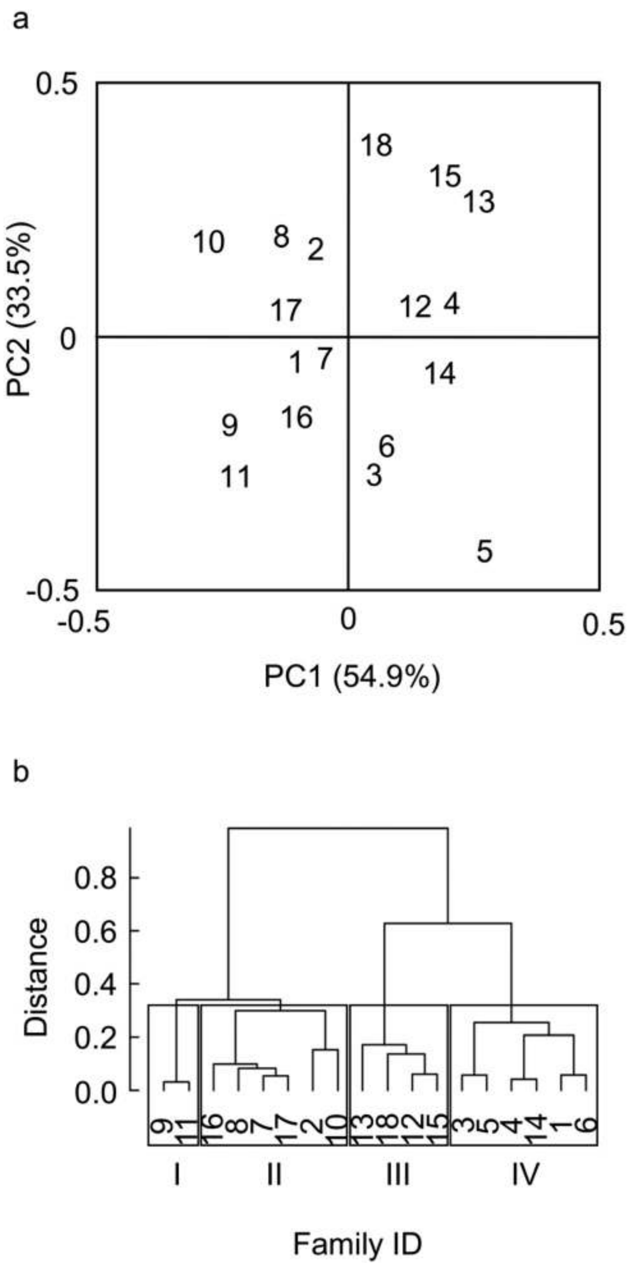

Figure 4: A plot of principal component scores and cluster dendrogram using Ward hierarchical clustering algorithm based on load and deflection at proportional limit and maximum load and deflection: (a) PC1 and PC2; first principal component and second principal component. (b) The vertical axis shows the distance between families based on Euclidean distance. I, II, III, and IV shows group I, group II, group III, and group IV, respectively.

deflection in plastic region (Sasaki et al. 1983). Results revealed that of the 36 cultivars, 17, 11, and eight were type I, type II, and type III, respectively (Sasaki et al. 1983). Thus, types of load-deflection curves in static bending tests may differ among cultivars, clones, and families in *C. japonica*. In the present study, families were classified by cluster analysis and PCA using load and deflection at proportional limit and maximum load and deflection as variables. Table 5 shows loading of principal components of PCA for 18 families. The 1st and 2nd principal components included the information on load (at proportional limit and maximum) and deflection (at proportional limit and maximum), respectively. As the results, eighteen families were grouped into four groups: group I (9 and 11 in Family ID), group II (2, 7, 8, 10 16, and 17 in Family ID), group III (12, 13, 15 and 18 in Family ID) and group IV (1, 3, 4, 5, 6, and 14 in Family ID) (Figure 4). In addition, typical load-deflection curves in static bending test were identified in each group (Figure 5). The families in group I showed higher load at proportional limit and larger deflection in plastic region. The families having intermediate load at proportional limit and larger deflection in the plastic region were group II. On the other hand, lower load at proportional limit and smaller deflection in plastic region were found in group III, whereas load-deflection curves in the group IV families exhibited higher load at proportional limit with smaller deflection in plastic region. Based on the

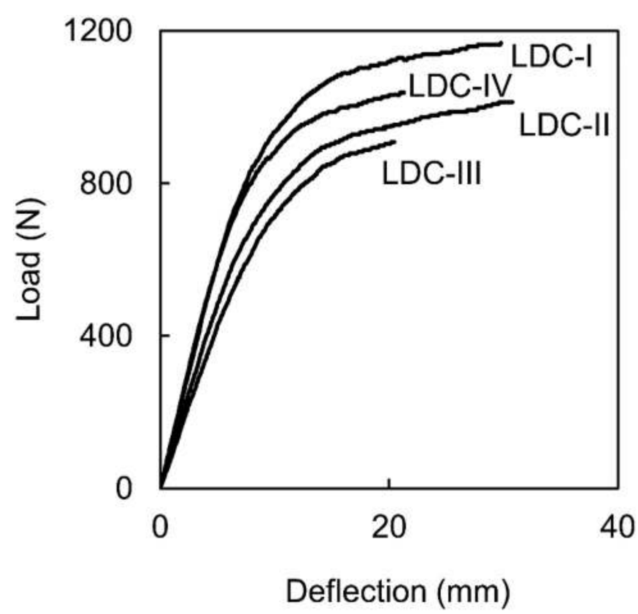

Figure 5: Shape of typical load-deflection curves in each group. Each load-deflection curve was obtained from a selected specimen showing mean MOE, MOR, and bending work in each group. LDC-I, II, III, and IV indicated families classified into group I, II, III, and IV, respectively. Load-deflection curves of LDC-I, II, III, and IV in this figure were obtained from family ID 9, 7, 15, and 5, respectively.

results, typical load-deflection curve in each group obtained in the present study was defined as LDC-I, LDC-II, LDC-III, and LDC-IV, respectively (Figure 5). Our results obtained in the present study were similar to those obtained by Sasaki et al. (1983). For example, LDC-IV in the present study might correspond to type I classified by Sasaki et al. (1983).

To assess the effect of mating parents on load-deflection curves, mating parents including into each group were investigated. Two families belonged into group I was produced by mating parents B12 as seed parent. Mating parents of four families in group II were A18, A20 or F6. Seed parent of group III were C1 or E1. In addition, families belonged into group IVwas produced by mating combination using A3, A12, and G3. Young's modulus is an elastic property of wood and one of the heritable characteristics (Acquah et al. 2018; Fujisawa et al. 2000; Kumar et al. 2006; Miyashita et al. 2009). Results obtained in the present study also strongly supported the inheritance of Young's modulus. In addition, load-deflection curves could be classified due to mating parents, suggesting the possibility of producing wood with desirable bending properties by combination of mating parents in *C. japonica*.

4 Conclusions

Inheritance of wood properties and static bending properties in juvenile wood were examined for 18 full-sib families of 20-year-old *C. japonica*. Relationships were clarified between tested properties. Correlation coefficients between stem diameter and all properties tested in the present study were significant but low, suggesting that the tree with faster growth rate and superior wood properties could be selected in tree breeding programs. The results of comparison in absolute values of correlation coefficients between air-dry density or MFA and each wood property revealed that air-dry density mainly affected MOR and bending work, whereas MFA mainly affected MOE. The highest narrow-sense heritability was found in air-dry density. Mating parents A12 and G3, and B12 showed higher breeding values for growth traits and bending properties, respectively. Based on the results of cluster analysis in combination with PCA, 18 families used in the present study were classified into four groups with different types of load-deflection curves in static bending test. In addition, typical load-deflection curves of families in each group were affected by mating parents. It can be concluded that not only elastic properties but also deflection in plastic region in juvenile wood of *C. japonica* can be improved through tree breeding programs. Therefore, it is concluded that improvement of both growth characteristics and bending properties in progeny was possible by the selection of mating parents.

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