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Possibilities of tree breeding for wood quality of *Abies firma* to produce wooden frame-construction lumber

モミ（*Abies firma*）における材質育種および枠組壁工法用部材生産の可能性

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ABSTRACT

The stress-wave velocity of trees, dynamic Young's modulus of logs, and bending properties of lumber were examined in *Abies firma* trees, which might be regarded as valuable species for producing lumber for wooden frame construction systems. Naturally-grown *A. firma* trees in a *Pinus* plantation were used in the present study. The mean values of the stress-wave velocity of stems was 3.05 km/s. Dynamic Young's modulus of logs ranged from 5.79 to 10.09 GPa. The logs collected from 1.2 to 3.2 m above ground showed higher dynamic Young's modulus value than those collected from 3.2 to 7.2 m above ground. Mean values of modulus of elasticity and modulus of rupture (MOR) in static bending of lumber were 7.16 GPa and 47.7 MPa, respectively. In addition, preliminary estimated 5% lower tolerance limits with a 75% confidence level of the MOR was 35.1 MPa, suggesting that the lumber for wooden frame construction system can be produced from this species. A high correlation coefficient was not found between stem diameter and stress-wave velocity of the tree. Significant differences among trees were found in dynamic Young's modulus. Based on the results, lumber with high Young's modulus for wooden frame-construction systems can be obtained by conducting tree breeding for wood quality in this species.

Keywords: *Abies firma*, wooden frame-construction system, dynamic Young's modulus, tree breeding

要　旨

本研究では，枠組壁工法用部材生産のために，天然に生育したモミ（*Abies firma*）の立木の応力波伝播速度，丸太の動的ヤング率および板材の曲げ物性を調査した．立木の応力波伝播速度の平均値は，3.05 km/s であった．また，丸太の動的ヤング率は，5.79 ～ 10.09 GPa の範囲を示した．また，地上高 1.2 ～ 3.2 m において得られた丸太の動的ヤング率は，地上高 3.2 ～ 7.2 m 以上で得られた丸太と比較して高い値を示した．板材の平均曲げヤング率および曲げ強さは，7.16 GPa および 47.7 MPa であった．また，予備的に求めた MOR の信頼水準 75% の 95% 下限許容限界値は 35.1 MPa であり，十分な強度性能を持つ板材が生産できる可能性が示唆された．立木の応力波伝播速度と幹直径の間には，高い相関関係は認められなかったが，丸太の動的ヤング率には個体間で有意な差が認められた．このことから，モミにおいては，材質育種によって，ヤング率の高い枠組工法用部材の生産が可能であることが示唆された．

キーワード：モミ，枠組壁工法，動的ヤング率，林木育種

1. Introduction

In recent years, wooden house construction systems have been diversifying, and the number of buildings produced by wooden frame-construction systems has increased in addition to buildings produced by the conventional post and beam structural system. Although lumber imported from overseas and laminated timber are used for members such as posts and beams used in the conventional structural system, much lumber is produced from domestic plantation trees, such as *Cryptomeria japonica* and *Chamaecyparis obtusa*. On the other hand, lumber used in the wooden frame-construction system are softwoods such as *Pinus*, *Tsuga*, *Picea*, and *Abies*, many of which are imported from overseas. Recently, lumber for wooden frame-construction systems has been developed using *C. japonica* and *Abies sachalinensis*, using domestic plantation timber (Takizawa et al. 1995; Yamazaki et al. 1999, 2000; Ohashi et al. 2003; Shiiba et al. 2012; Ido et al. 2017).

Most Japanese plantation forests are composed of *C. japonica* or *C. obtusa*, except in some areas in the cold regions of Hokkaido and Honshu. In the cold regions of Hokkaido and Honshu, *Larix kaempferi* is used as a plantation species, while *A. sachalinensis* and *Picea glehnii* are also used in Hokkaido. On the other hand, as mentioned above, the wooden frame-construction system usually uses lumber from *Pinus*, *Tsuga*, *Picea*, and *Abies*, and these species are rarely planted in Japan, except in Hokkaido. Even when wood resources of these species are obtained from natural or secondary forests, they are rarely used as members of wooden frame-construction systems. Therefore, it can be said that there is a space for effective wood utilization of these species. It is necessary to reconsider using wood from species such as *Pinus*, *Tsuga*, *Picea*, and *Abies*, if the quality of wood from these species is sufficient to produce members for wooden frame-construction systems. In that case, it may be possible to use these species for afforestation in Japan.

In the present study, *Abies firma* (momi in Japanese, Momi fir in English), one of the *Abies* species widely distributed in Honshu, was considered a promising tree species for the future production of members for wooden frame-construction systems. However, it is rarely used as structural timber. We investigated the stress-wave velocity of trees, dynamic Young's modulus of logs, and bending properties of lumber of naturally grown *A. firma* trees in the Funyu Experiment Forest, School of Agriculture, Utsunomiya University. Based on the obtained results, the possibility of tree breeding for the wood quality of this species was also discussed.

2. Materials and methods

Abies firma that had been naturally regenerated in the F_1 test site of *Pinus thunbergii* No.26 in the Funyu Experiment Forest, School of Agriculture, Utsunomiya University, was used. This site was established in 1952. Until the first half of the 1970s, it was frequently managed, and all species except *P. thunbergii* and *Pinus densiflora* were removed from the site. However, in the late 1970s, *P. thunbergii* grew, and silvicultural management became less frequent. As a result, *A. firma* seeds from the surrounding secondary forests, which consisted mainly of broad-leaved trees, were introduced, and finally, many standing trees of *A. firma* were found in the test site. Field experiments for this study were conducted in 2004; therefore, most of the *A. firma* trees are estimated to be about 30 years old.

The stress-wave velocity of the stem was measured for 70 trees in the test site by a handheld stress wave timer (FAKOPP, Fakopp Enterprise) according to the method described in the previous report (Ishiguri et al. 2008b).

Of 70 trees, ten trees having similar stem diameters with a mean stem diameter of 70 trees were harvested for the following experiments. After measuring the tree height, three logs (2 m in length) in each tree were obtained from 1.2 m to 7.2 m above the ground. The diameter in both ends, length, and weight were measured to determine the green density of logs. The first resonance frequency of longitudinal vibration created by tapping of logs was measured with a handheld FFT analyzer (AD3527, A&D) and an accelerometer (PV-85, Rion). Dynamic Young's modulus of logs was calculated from the green density and the first resonance frequency created by tapping (Sobue 1986).

As many as possible number of lumber (50 by 100 mm in cross section and 1800 mm in longitudinal direction) was obtained from the logs. As a result, a total of 54 lumber were obtained. The lumber was air-dried in the laboratory without any air conditioner. After air-drying, lumber was planed into 38 by 89 mm in cross-section. Dynamic Young's modulus of the air-dried lumber was measured by the tapping method described above. Static bending test was conducted using a universal testing machine (DCS-5000, Shimazu). The load was applied to the center of edge-wise direction of the lumber with 1600 mm of span and a load speed of 10 mm/min. The modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated by the data analyzer (Dataledy 401, Shimazu). The mean value of moisture content at the bending test was 12.5%.

The 5% lower tolerance limits with a 75% confidence level ($TL_{75\%,95\%}$) of the MOR were preliminary calculated using the following formula (Japan Housing and Wood Technology Center 2011):

$$TL_{75\%,95\%} = \mu - K\sigma$$

where μ is the mean value, K is a constant (1.804, n = 54), and σ the standard deviation.

3. Results and discussion

3.1 Stress-wave velocity of trees

Table 1 shows the stem diameter and stress-wave velocity of the stem. Mean stem diameter and stress-wave velocity values were 16.8 cm and 3.05 km/s, respectively. Iki et al. (2006) reported that the mean value of stress-wave velocity was 4.57 km/s in 43-year-old plus tree clones of *A. sachalinensis*. On the other hand, the stress-wave velocity of *C. japonica*, which is a significant plantation softwood species, was 2.42 km/s for 26-year-old thinned trees originating seedlings (Iizuka et al. 2006) and 2.89 km/s for 14-year-old trees from 745 clones (Mishima et al. 2011). In other softwood species, stress-wave velocity was 3.55 and 3.63 km/s for 43- and 51-year-old *Picea koyamae* (Tanabe et al. 2013), 3.20 to 3.35 km/s for 33-year-old *C. obtusa* (Ishiguri et al. 2013), and 3.54 km/s for 59-year-old *P. densiflora* (Ishiguri et al. 2011). Although the tree age differed, the mean value of stress-wave velocity in this study showed relatively lower values than *A. sachalinensis*

Table 1 Statistical values of stem diameter and stress-wave velocity of stems in naturally grown *A. firma* trees

	Stem diameter (cm)	Stress-wave velocity (km/s)
Mean	16.8	3.05
Standard deviation	3.9	0.20
Minimum	10.4	2.60
Maximum	26.8	3.57

Note: Number of trees = 70. Stem diameter was measured at 1.2 m above the ground.

but higher than *C. japonica*. In general, the stress-wave velocity of the tree is positively correlated with dynamic Young's modulus of logs (Ikeda and Arima 2000; Ishiguri et al. 2008b). Thus, it is considered that *A. firma* will produce lumber with higher Young's modulus compared to those from *C. japonica*.

It has been reported that Young's modulus of wood is independent on growth characteristics because no significant or weak significant negative correlations were found between stem diameter and stress-wave velocity of stems in conifer species (Koizumi et al. 1990; Ikeda and Arima 2000; Ishiguri et al. 2008b). In the present study, a significant negative correlation (r = –0.258) was recognized between stem diameter and stress-wave velocity of stems in *A. firma* (Figure 1), suggesting that Young's modulus of this species is also independent of growth characteristics. Thus, when we use *A. firma* as a plantation species, trees with good growth characteristics and higher stress-wave velocity values should be selected as mother trees in *A. firma*.

3.2 Dynamic Young's modulus of logs

Table 2 shows the dynamic Young's modulus of logs. The dynamic Young's modulus of logs ranged from 5.79 to 10.09 GPa. The mean value of 10 logs collected from 1.2 to 3.2 m above the ground was 9.14 GPa (ranging from 7.85 to 10.09 GPa). Iki et al. (2006) reported that dynamic Young's modulus of logs from 43-year-old *A. sachalinensis* ranged from 7.1 to 11.9 GPa, and the mean value was 9.5 GPa. Irrespective of the tree ages, dynamic Young's modulus of logs in *A. firma* might show relatively lower values than those in *A. sachalinensis*.

When logs were corrected from 1-m intervals from base to top of *A. sachalinensis* trees, dynamic Young's modulus decreased toward the tree top after showing the maximum value at specific height positions, which differed among clones or families (Iki et al. 2006). On the other hand, Yamashita et al. (2000) examined the longitudinal variation of dynamic Young's modulus of logs (2 m in length) which were corrected from 1.5 m above the ground toward the tree top in 18 clones of 30 to 34-year-old *C. japonica*. As a result, they found several types of longitudinal patterns in dynamic Young's modulus: i) almost no variation (stable from base to top), ii) increase as increasing the height position from base to a certain height, and iii) logs obtained from 1.5 to 3.5 m height position showed lower values but other height showed stable value. In addition, they also pointed out that the lowest dynamic Young's modulus in mean values of all 18 clones was found in the logs obtained from 1.5 to 3.5 m above the ground. In the present study, with a few exceptions, logs obtained from 1.2 to 3.2 m showed the highest dynamic Young's modulus compared to those obtained from other height positions (Table 2).

An analysis of variance test was applied to clarify the among individual variations in the dynamic Young's modulus of logs. A significant difference (p < 0.05) was found among individuals (Table 2). These results suggest that selecting trees with higher Young's modulus is essential to produce structural lumber from this species.

3.3 Bending properties of lumber

Air-dry density, dynamic Young's modulus, and static bending properties of lumber are listed in Table 3. Mean values were 0.41 g/cm^3 in air-dry density, 8.97 GPa in dynamic Young's modulus, 7.16 GPa in MOE, and 47.7 MPa in MOR, respectively. Range from minimum to maximum values were from 5.48 to 8.55 GPa for MOE and from 33.9 to 62.4 MPa for MOR. Table 3 also shows the bending properties of 59-year-old *P. densiflora* and *P. thunbergii* (Ishiguri et al. 2011), 36-year-old *L. kaempferi* (Ishiguri et al. 2008b), 26-year-old *C. japonica* (Ishiguri et al. 2008a), and 33-year-old *C. obtusa* (Ishiguri et al. 2013) obtained by almost the same testing conditions. Comparing the bending properties of *A. firma* with other softwoods, MOE and MOR in *A. firma* lumber showed higher values than 26-year-old *C. japonica* lumber and similar values with 59-year-old *P. densiflora* lumber.

Characteristic values of the MOR in 2 by 4 lumber were listed in "Matters to determine the standard strength of wood

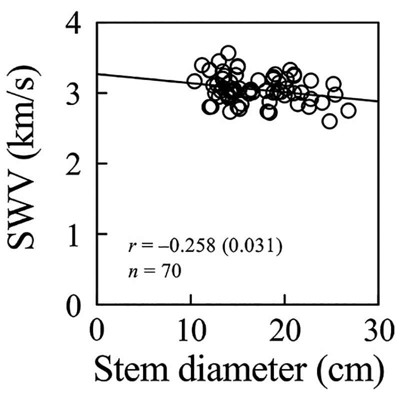

Figure 1 Relationship between stem diameter and stress-wave velocity of stem

Note: SWV, stress-wave velocity; r, correlation coefficient; n, number of trees. Value in parenthesis is p-value.

Table 2 Longitudinal variation in dynamic Young's modulus of logs

Tree code	1st log	2nd log	3rd log	Mean of a tree	Standard deviation	Significance among trees
A	9.67	9.24	8.93	9.29	0.38	
B	8.92	9.04	8.60	8.85	0.23	
C	9.95	9.16	9.03	9.38	0.50	
D	8.51	7.35	8.72	8.19	0.74	
E	8.71	9.57	7.72	8.67	0.93	*
F	9.17	8.38	8.30	8.62	0.48	
G	10.09	8.44	9.85	9.46	0.89	
H	8.66	7.31	7.13	7.70	0.84	
I	9.90	7.77	8.70	8.79	1.06	
J	7.85	7.96	5.79	7.20	1.23	
Mean	9.14	8.42	8.28	8.61	–	
SD	0.74	0.81	1.14	0.73		

Note: *, significance at 5% level. 1st, 2nd, and 3rd logs were collected from 1.2 to 3.2 m, 3.2 to 5.2 m, and 5.2 to 7.2 m above the ground, respectively.

Fc, *Ft*, *Fb*, and *Fs*" in Notification of Ministry of Land, Infrastructure, Transport and Tourism No. 910 (Japan 2 × 4 Lumber JAS Council 2020). For the S-P-F species group (*Picea engelmannii*, *Pinus sylvestris*, *Abies balsamea*, and others), Characteristic value of the MOR in 2 by 4 lumber was 30.0 MPa in Select structural (SS), 22.2 MPa in No. 1, 21.6 MPa in No. 2, and 12.6 MPa in No. 3, respectively (Japan 2 × 4 Lumber JAS Council 2020). In the present study, as shown in Figure 2, value of $TL_{75\%,95\%}$ was 35.1 MPa based on the mean and standard deviation. Thus, it is concluded that structural lumber with appropriate strength properties can be produced from this species.

3.4 Relationship between the stress-wave velocity of the tree and bending properties of lumber

A significant positive correlation was found between the stress-wave velocity of trees and the bending properties of lumber in several softwoods: bending properties can be estimated by the stress-wave velocity of trees (Ikeda and Arima 2000; Wang et al. 2001; Ishiguri et al. 2008b). Figure 3 shows the relationship between the stress-wave velocity of the tree and the bending properties of lumber in *A. firma*. For the calculation of correlation coefficients, mean values of bending properties were calculated by averaging those values in each tree. Significant positive correlations were found between them, suggesting that the stress-wave velocity of trees can be used for non-destructive estimation of bending properties of lumber and can be used as selection criteria in tree breeding for the wood quality of this species.

4. Concluding remarks

In the present study, the stress-wave velocity of the tree, dynamic Young's modulus of logs, and bending properties of lumber were examined for *A. firma*, which is considered an alternative candidate species for the production of structural lumber for wooden frame-construction systems. The mean value of the stress-wave velocity of the tree was 3.05 km/s. The value was smaller than that in 43-year-old *A. sachalinensis* but higher than in thinned 26-year-old *C. japonica*. Dynamic Young's modulus of logs was 8.61 GP in the mean value of 10 harvested trees. With a few exceptions, logs collected from 1.2 to 3.2 m above the ground showed the highest dynamic Young's modulus compared to those obtained from higher height positions of the stem. Mean MOE and MOR in lumber were 7.16 GPa and 47.7 MPa, respectively. Compared to the MOE and

Table 3 Comparison of strength properties of *A. firma* lumber with those of other Japanese softwoods

Species	Age	*n*	AD (g/cm³)		DMOE (GPa)		MOE (GPa)		MOR (MPa)	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
Abies firma (Present study)	UK	54	0.41	0.02	8.97	0.95	7.16	0.64	47.7	7.00
Pinus densiflora (Ishiguri et al. 2011)	59	24	0.54	0.30	9.57	2.79	7.31	2.19	49.8	24.7
Pinus thunbergii (Ishiguri et al. 2011)	59	36	0.55	0.26	11.53	2.48	8.73	1.77	58.6	20.8
Larix kaempferi (Ishiguri et al. 2008b)	36	84	0.50	0.03	11.22	1.96	11.20	1.22	56.8	9.5
Cryptomeria japonica (Ishiguri et al. 2008a)	26	114	0.40	0.03	5.98	1.05	5.38	0.98	41.4	5.4
Cryptomeria japonica (Ishiguri et al. 2008a)	26	87	0.39	0.03	5.79	1.19	5.15	0.88	39.9	5.6
Cryptomeria japonica (Ishiguri et al. 2008a)	26	47	0.41	0.03	6.26	1.10	5.56	1.02	42.7	6.5
Chamaecyparis obtusa (Ishiguri et al. 2013)	33	25	0.50	0.03	8.02	1.53	7.30	1.25	61.0	8.1
Chamaecyparis obtusa (Ishiguri et al. 2013)	33	30	0.49	0.03	7.08	1.41	6.34	1.08	55.1	8.4

Note: *n*, number of lumber; AD, air-dry density; DMOE, dynamic Young's modulus; MOE, modulus of elasticity; MOR, modulus of rupture; UK, unknown.

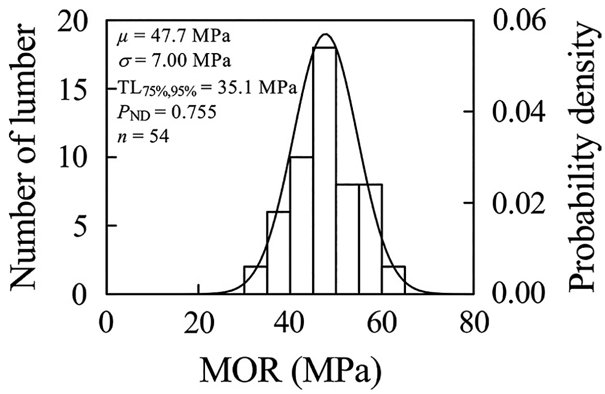

Figure 2 Distribution of the MOR of lumber
Note: *n*, number of lumber; MOR, modulus of rupture; *μ*, mean value; σ, standard deviation; $TL_{75\%,95\%}$, the 5% lower tolerance limit with a 75% confidence level; P_{ND}, probability obtained by Shapiro-Wilk test as test of normality of normal distribution (ND).

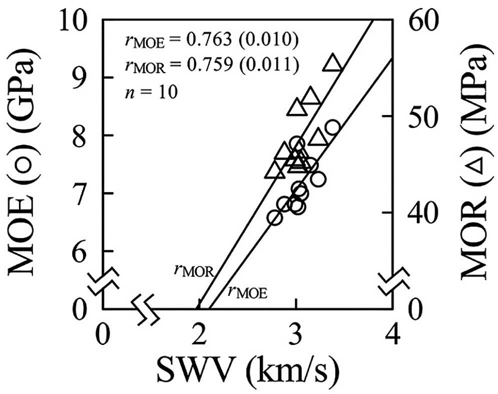

Figure 3 Relationships between the stress-wave velocity of stem and static bending properties of lumber
Note: SWV, stress-wave velocity; MOE, modulus of elasticity; MOR, modulus of rupture; r_{MOE}, the correlation coefficient between SWV and MOE; r_{MOR}, the correlation coefficient between SWV and MOR; *n*, number of trees. Values in parenthesis are *p*-value. Each symbol indicates the mean value of MOE or MOR of lumber produced from a tree.

MOR in other softwoods determined by the same method in the present study, MOE and MOR values in *A. firma* were higher than those in thinned *C. japonica* and similar to those in *P. densiflora*. In addition, $TL_{75\%,95\%}$ values of MOR preliminary determined in the present study (35.1 MPa, Figure 2) exceeded the characteristic values of MOR in 2 by 4 lumber of SS grade in S-P-F species group listed in "Matters to determine the standard strength of wood *Fc*, *Ft*, *Fb*, and *Fs*" in Notification of Ministry of Land, Infrastructure, Transport and Tourism No. 910 (Japan 2 × 4 Lumber JAS Council 2020). These results suggest that structural lumber with appropriate strength properties might be produced from this species. Significant positive correlations were found between the stress-wave velocity of the tree and the MOE or MOR of lumber. There was no significant correlation between stem diameter and stress-wave velocity of trees. In addition, a significant difference among individuals was found in dynamic Young's od logs. Based on the results, it is concluded that when mother trees of this species are selected as plantation species for structural lumber production, trees with good growth characteristics and high Young's modulus should be selected. In addition, stress-wave velocity of trees and dynamic Young's modulus of logs are useful non-destructive indicators for estimating the bending properties of lumber in this species.

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