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ORIGINAL ARTICLE

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Mechanical properties assessment of *Cunninghamia lanceolata* plantation wood with three acoustic-based nondestructive methods

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Abstract The objectives of this study were to establish the method of evaluating wood mechanical properties by acoustic nondestructive testing at standing trees and at logs of a Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) plantation, and to compare three acoustic nondestructive methods for evaluating the static bending modulus of elasticity (MOE), modulus of rupture (MOR), and compressive strength parallel-to-grain (σ_c) of plantation wood as well. Fifteen Chinese fir plantation trees at 36 years of age were selected. Each tree was cut into four logs, for which three values of dynamic modulus of elasticity, i.e., E_{sw}, of the north and south face based on stress waves to assume the measuring state of the standing tree, E_{fr}, longitudinal vibration, and E_{us}, ultrasonic wave, were measured in the green condition. After log measurements, small specimens were cut and air-dried to 12% moisture content (MC). Static bending tests were then performed to determine the bending MOE and MOR, and compressive tests parallel-to-grain were made to determine σ_c. The bending MOE of small clear specimens was about 7.1% and 15.4% less than E_{sw} and E_{us}, respectively, and 11.3% greater than E_{fr}. The differences between the bending MOE and dynamic MOE of logs as determined by the three acoustic methods were statistically significant ($P < 0.001$). Good correlation ($R = 0.77$, 0.57, and 0.45) between E_{sw}, E_{fr}, and E_{us} and static MOE, respectively, were obtained ($P < 0.001$). It can be concluded that longitudinal vibration may be the most precise and reliable technique to evaluate the mechanical properties of logs among these three acoustic nondestructive methods. Moreover, the results indicate that stress wave technology would be effective to evaluate wood mechanical properties both from logs and from the standing tree.

Key words Nondestructive method · Modulus of elasticity · Modulus of rupture · Compressive strength parallel-to-grain · *Cunninghamia lanceolata* plantation

Introduction

In 1998, following the implementation of the Natural Forest Conservation Program established by the Chinese government, the main supplies of wood resources have been shifting from natural forests to plantation forest stock. China now has the largest area of fast-growing plantation forests in the world. Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is one of the major commercial plantation species. It is mainly distributed within 17 provinces of the central and southern regions of China. The most recent national forestry survey indicates that the current distribution area of Chinese fir plantations is about 9.22 million ha.[1] To better understand the quality of plantation forests to provide fiber for use in value-added products, there is a need to assess how relevant wood properties are impacted by growth characteristics. Application of nondestructive evaluation (NDE) techniques to plantation-grown materials is an important step in understanding and learning how to improve the quality of plantation-grown materials and to identify optimal use by the forest products industry.

NDE techniques have been developed during the past several decades for many materials and have been extensively applied to predict the mechanical properties of different kinds of wood materials.[2,3] Recent research has focused on determining whether the portable and cost-

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Table 1. Basic characteristics of 15 sample trees

Characteristics	Mean	SD	Max	Min
Tree height (m)	18.8	0.99	20.4	17.8
Clean length (m)	8.94	1.98	11.9	6.25
DBH (cm)	24.1	2.68	28.8	20.0
MC of sapwood (%)	184	47.0	261	81.0
MC of heartwood (%)	57.0	13.0	104	38.0

SD, standard deviation; Max, maximum; Min, minimum; DBH, diameter at breast height; MC, moisture content

effective acoustic-based NDE techniques such as stress wave, longitudinal vibration, and ultrasonic wave could be applied to assess the quality of raw materials. Several studies have shown a good relationship not only between the acoustics-based modulus of elasticity (MOE) of logs and the static bending properties of lumber cut from logs,[4–7] but also between the acoustics-based MOE of standing trees and the elasticity properties of logs,[8–10] lumber,[10] or small specimens[11] cut from standing trees.

Although a few studies have been conducted on the strength properties of small clear specimens from Chinese plantations,[12,13] very little work has been focused on the wood properties assessment of plantation wood by using acoustic nondestructive methods.[14] The objective of this research is to tap the possibility of acoustic nondestructive methods to estimate the mechanical properties of Chinese fir plantation wood at the standing tree and logs. To achieve this objective, three nondestructive methods based on stress wave, longitudinal vibration, and ultrasonic wave were examined and compared. In addition, the predictive accuracy of wood quality was compared between different acoustic nondestructive methods in this study. Relationships between each of the three dynamic elastic properties measurements [dynamic modulus of elasticity based on stress wave (E_{sw}), dynamic modulus of elasticity based on longitudinal vibration (E_{fr}), and dynamic modulus of elasticity based on ultrasonic wave (E_{us})] of logs and the static bending MOE, the modulus of rupture (MOR), and compressive strength parallel-to-grain (σ_c) of small clear samples are revealed in this study.

Materials and methods

Fifteen sample trees were collected from a 36-year-old Chinese fir plantation in Shanxia Forestry Centre, Dagangshan of Jiangxi Province (Table 1). After noting the north- and the south-facing stem surfaces, each sample tree was cut into four logs 2.4 m in length at heights of 1.3 m, 3.7 m, 6.1 m, and 8.5 m from ground level. The ends of each log were coated with pitch to minimize moisture loss.

After all 60 marked logs were conveyed to the Chinese Academy of Forestry in Beijing, one 200-mm-thick disk, to be used for wood moisture content (MC) measurement, was taken from the butt end of each log. Green density of the 2.20-m log was determined by measuring bulk weight and volume and used for the calculation of dynamic elasticity properties.

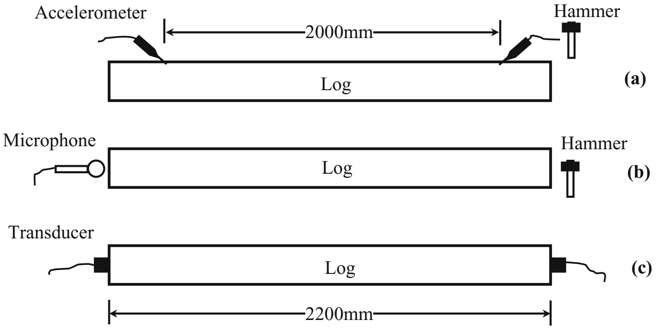

Fig. 1. Acoustic experimental setup. **a** Stress wave velocity measurement. **b** Measurement of fundamental frequency of longitudinal vibration. **c** Ultrasonic wave propagation time measurement

Two spikes from the accelerometer of the stress wave equipment (Fakopp FRS-06/00; 1 µs resolution) were nailed into the xylem at a 45° angle with the log axis on the north and south faces of the log to simulate the measuring state of the standing tree (Fig. 1a). The test was conducted by a hammer hitting the head of a spike with an accelerometer. The stress wave was detected by another accelerometer after wave propagation in the log. The dynamic modulus of elasticity, E_{sw}, of the log was then determined using Eq. 1. The average value from the north and south faces was assumed to be the dynamic elasticity property of the log based on stress wave.

$$E_{\mathrm{sw}} = \rho \times v_{\mathrm{sw}}^{2} \tag{1}$$

where E_{sw} is the dynamic modulus of elasticity of the log based on stress wave, ρ is the green density of the log, and v_{sw} is the stress wave velocity propagated in the log.

The longitudinal vibration of the log was driven by a hammer and the fundamental frequency was then measured by an FFT Analyser (AD-3542; 10 Hz resolution) (Fig. 1b). E_{fr} was determined using Eq. 2:

$$E_{\mathrm{fr}} = 4 \times \rho \times l^{2} \times f^{2} \tag{2}$$

where E_{fr} is the dynamic modulus of elasticity of the log based on longitudinal vibration, ρ is the green density of the log, l is the length of the log, and f is the fundamental frequency of longitudinal vibration of the log.

The ultrasonic wave apparatus [PUNDIT 6 (portable ultrasonic nondestructive digital indicating tester); 1 µs resolution] included a transmitting transducer and receiving transducer (Fig. 1c). For each log, transducers were placed in pairs at the sapwood and heartwood zone, respectively, of the two ends. Ultrasonic pulses started from the transmitting transducer and stopped at the receiving transducer after ultrasonic wave propagation in the log. E_{us} was calculated using Eq. 3. The average value from sapwood and heartwood zones was assumed to be the dynamic elasticity properties of the log based on the ultrasonic wave.

$$E_{\mathrm{us}} = \rho \times v_{\mathrm{us}}^{2} \tag{3}$$

where E_{us} is the dynamic modulus of elasticity of the log based on the ultrasonic wave, ρ is the green density of the log, and v_{us} is the ultrasonic wave velocity propagated in the log.

After the nondestructive measurements were completed, each log was divided into two parts: one 1-m top section used for lumber and one 1-m butt section for a small clear specimen. Each top and butt section was then cut into two halves along the east–west direction separately. From these, pieces of lumber (40 × 90 × 1000 mm) were produced from all halves of the top section to evaluation their bending strength.[14] Meanwhile, as many as possible small rough specimens (35 × 35 × 500 mm) were sawn from all halves of the butt section according to the sketch in Fig. 2. In total, 856 small rough specimens were obtained for further testing. After 4 months of air-drying, the small rough specimens were then planed and finished into 20 × 20 × 400 mm pieces. From these, a total of 648 pieces were selected and each piece was cut into one 20 × 20 × 300 mm for the bending test and one 20 × 20 × 30 mm small clear specimen for the compression test. The small clear specimens were conditioned to equilibrium moisture content (EMC) of approximately 12% by storing in a constant environment room maintained at 20°C and 65% RH.

For reasons of the limited log diameter and the presence of knots and other defects, the number of small clear specimens obtained from each log varied from 5 to 19 pieces. An average value from all 19 (or few) specimens was assumed to be the average properties of the log and was used for the comparison with dynamic MOE values obtained by three acoustic measurements on the logs. Static bending tests and compressive tests parallel-to-grain were conducted according to the procedure outlined by the Chinese Standard, respectively (Table 2). The loading method of the third point with 240-mm span was applied for the static bending MOE test. Two loading shoes with 80-mm span were set between two supports. An alloy aluminum frame with micrometer gauge was fastened on the neutral axis to measure the deflection between the supports.[15] However, midway loading between the supports was applied for MOR testing.[16] Compressive strength (σ_c) was measured in parallel-to-grain.[17] Following the destructive test, a wood block was immediately cut near the failure location from each specimen. Moisture content (MC) was then measured by the oven-drying method.

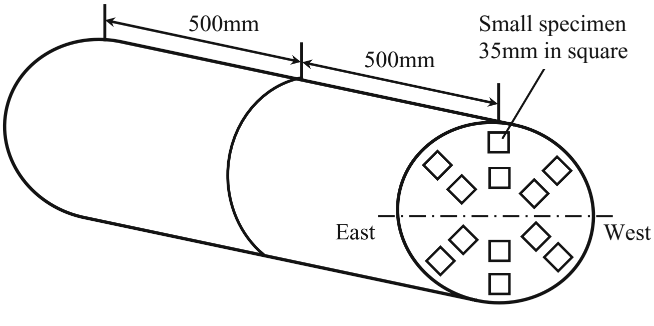

Fig. 2. Sawing pattern for extracting small specimens

Statistical analysis was performed using SAS programs (SAS Institute 8.0). One-way analysis of variance (ANOVA) was used for comparison analyses. Correlation coefficients between dynamic elastic properties (E_{sw}, E_{fr}, and E_{us}) of the log and mechanical properties (MOE, MOR, and σ_c) of the small clear specimens were also calculated to determine their relationships.

Results and discussion

Nondestructive evaluation test on logs

The average diameter at breast height (DBH) of the Chinese fir sample trees ranged from 20.0 to 28.8 cm. After removing the disks for MC measurement, the average diameters of the butt logs obtained from the trees ranged from 13.1 to 27.5 cm. For both sapwood and heartwood, the individual and average MC was above the fiber saturation point (about 30%). However, the MC of sapwood was much higher than that of heartwood in all logs. The individual MC values ranged from 81% to 261% for sapwood and from 38% to 104% for heartwood.

As shown in Table 3, the average velocity ranged from 3523 to 4440 m/s for stress wave and from 3573 to 4964 m/s for ultrasonic wave in green logs. The average velocity of the ultrasonic wave was about 4.4% greater than that of the stress wave. A significant difference was found between the velocity of ultrasonic waves and stress waves in the logs ($P < 0.01$). In this study, although the layout of sensors on the log differs between the ultrasonic wave and stress wave methods, the difference between the velocity of ultrasonic wave and stress wave is in agreement both with the results in green wood of standing *Cryptomeria japonica* trees reported by Chuang and Wang[18] and those in air-dried wood of *Pinus koraiensis* reported by Lin et al.[19] The variance between the propagation efficiency or relative energy loss[20] of the stress waves and ultrasonic waves traveling though the wood materials may result in the difference of their propagation velocity.

Table 2. Summary of test conditions for small clear specimens

Test	Standard	Specimen dimension (mm)	Loading	Span (mm)	Average time to failure (min)
Bending MOE	GB1936.2-91[15]	20 × 20 × 300	Third point	240	–
Bending MOR	GB1936.1-91[16]	20 × 20 × 300	Central point	240	1.5
Compressive strength parallel-to-grain (σ_c)	GB1935-91[17]	20 × 20 × 30	End face	30	2.0

MOE, modulus of elasticity; MOR, modulus of rupture

Table 3. Dynamic elasticity properties of green logs

Specimens	Mechanical properties	Mean	SD	Max	Min
60 green logs	Green density (kg/m^3)	728	43.2	841	659
	v_{sw} (m/s)				
	N	4065	265	4643	3521
	S	3815	257	4319	3117
	N/S	3940	252	4440	3523
	E_{sw} (GPa)				
	N	12.0	1.38	15.3	9.55
	S	10.6	1.31	13.5	7.22
	N/S	11.3	1.28	14.40	9.17
	f (Hz)	848	53.2	958	745
	E_{fr} (GPa)	9.43	0.82	11.22	7.78
	v_{us} (m/s)	4113	335	4964	3573
	E_{us} (GPa)	12.4	1.77	17.1	9.38

v_{sw}, stress wave velocity; N, north segment; S, south segment; N/S, average value of north and south segments; E_{sw}, dynamic modulus of elasticity based on stress waves; f, the resonant frequency in fundamental mode; E_{fr}, dynamic modulus of elasticity based on longitudinal vibration; v_{us}, ultrasonic wave velocity; E_{us}, dynamic modulus of elasticity based on ultrasonic waves

Table 4. Mechanical properties of small clear specimens

Specimens	Mechanical properties	Sample size	Mean	SD	Max	Min
Conditioned small clear specimens	Air-dried density (kg/m^3)					
	N	319	369	31.3	454	291
	S	329	368	30.5	459	293
	N/S	648	368	22.7	427	318
	MOE (GPa)					
	N	319	10.7	0.95	13.4	8.78
	S	329	10.3	0.98	12.7	8.63
	N/S	648	10.5	0.88	12.9	9.09
	MOR (MPa)					
	N	319	70.9	8.87	97.8	56.2
	S	329	70.8	8.04	93.6	53.2
	N/S	648	70.9	7.91	94.6	58.2
	σ_c (MPa)					
	N	319	31.5	3.79	42.2	25.6
	S	329	31.1	3.12	40.9	25.8
	N/S	648	31.3	3.30	40.8	26.0

MOE, modulus of elasticity based on static bending; MOR, modulus of rupture based on static bending; σ_c, compressive strength parallel-to-grain, N, north-facing segments; S, south-facing segments; N/S, average value of north- and south-facing segments

The coefficient of variation for the average E_{sw}, E_{fr}, and E_{us} in green logs was 11.3%, 8.7%, and 14.4%, respectively. The average value of E_{sw} was about 19.8% larger than that of E_{fr} and 8.5% less than that of E_{us}. The difference between the dynamic MOE of logs determined by the three acoustic methods was highly significant at the 0.001 level. For both v_{sw} and E_{sw}, the average value from the north-facing location half-circle was greater than that from the south-facing location. It was observed that the mean v_{sw} from the north segment was 6.6% greater than that from the south and that the mean E_{sw} from the north segment was 13.2% greater than that from the south. Significant variance was shown between both v_{sw} and E_{sw} from the north- and south-location segments of the log ($P < 0.01$).

Mechanical properties of small clear specimens

The air-dried density and mechanical properties of small clear specimens are shown in Table 4. The average air-dried density ranged from 318 to 427 kg/m^3 with a 8.5% coefficient of variation. The average value of bending MOE ranged from 9.09 to 12.9 GPa with a 8.4% coefficient of variation. The average MOE obtained from static bending was about 7.1% and 15.4% less than that from the stress wave and ultrasonic wave method, respectively, and 11.3% greater than that from longitudinal vibration. The ANOVA results showed that the differences between the bending MOE and dynamic MOE of logs by the three acoustic methods were statistically significant ($P < 0.001$). The difference between bending MOE from small clear specimens and E_{sw} of logs agrees with that between bending MOE from small clear specimens and E_{sw} of the standing tree.[11] Besides the variance in the principle of signal sending and receiving among the three acoustic methods, defects (such as knots) in the log and uneven sampling distribution of small clear specimens within a log may have caused the differences between the dynamic elasticity properties of log obtained by acoustic methods and the MOE average from small clear specimens.

It was also shown that the bending MOE measurement on the north-facing segments was 3.7% greater than that from the south-facing segments. The result was consistent with that of E_{sw} in the log based on stress wave. The average value of bending MOR ranged from 58.2 to 94.6 MPa with a 11.2% coefficient of variation, and that of σ_c ranged from 26.0 to 40.8 MPa with a 10.5% coefficient of variation. The bending MOR measurement on the north-facing segments was only 0.7% greater than that on the south, and σ_c on the north was 1.3% greater than that on the south.

There was significant difference between bending MOE on the north- and south-facing segments of the logs ($P < 0.05$). However, there was no significant variance between the measurements of air-dried density, MOR, and σ_c from the north and south location segments of logs ($P > 0.5$). Luo et al.[12] suggested that, in Chinese fir, no apparent conclusions for comparison of air-dried density and mechanical properties of small clear specimens between north and south sides were observed. On the other hand, Ren and Nakai[13] reported that only MOR and wood density (air-dried and oven-dried) had a statistically significant difference ($P < 0.05$) between north and south sides of Chinese fir. The difference of wood properties between the north and south sides of the trees used in this study might result from the growing conditions, such as stand slope direction of the sample trees, which would affect the natural growth in different sides of the standing tree. Moreover, the irregular log shape and uneven sampling distribution of small clear specimens within a log could also affect the results of testing the mechanical properties. Further research is needed to clarify the difference of wood properties between north and south sides in trees.

Regression analyses suggested that the correlation coefficient ($R = 0.85$) between bending MOE and MOR of small clear specimens was highly significant at the 0.001 confidence level. However, the mean bending MOR of 1-m lumber from the same logs in a previous report[14] was 32.4% less than that of the small clear specimens in this study. The result could be mainly affected by the growth defects randomly distributed in the 1-m lumber that have been removed in the small clear specimens.

Relationship between nondestructive evaluation and mechanical properties

Linear regression analyses were applied to quantify the relationship of dynamic elasticity properties of logs to mechanical properties of small clear specimens obtained from the logs (Table 5). The relationship between the average value of E_{sw} measured on the north- and south-facing segments of the logs, the average E_{fr} and E_{us} of the logs, and the bending MOE of small clear specimens are illustrated in Fig. 3a, 3b, and 3c, respectively. The MOE of the small clear specimens reported is computed from the average value of those small clear specimens obtained from the same log. The regression results indicated that the developed linear regression model between the E_{fr} of the logs and the MOE of small clear specimens taken from those same logs are significant at the 0.001 confidence level ($R = 0.77$). Weaker relationships ($R = 0.57$ and 0.45, respectively) were observed between the E_{sw} and E_{us} of the logs and the MOE of small clear specimens from those logs (Table 5). These results suggested that the average MOE for small clear specimens from the logs can be predicted by E_{fr}, E_{sw}, and E_{us} of those same logs. It was shown that E_{fr} based on the longitudinal vibration method can provide the best prediction of the static elasticity properties of the log.

Figure 3e shows the relationship between E_{fr} of logs and MOR of small clear specimens ($R = 0.76$) was also better than that between E_{sw} and E_{us} of logs and MOR of small clear specimens (Fig. 3d, Table 5). Moreover, Fig. 3f indicates the relationship between E_{fr} of logs and σ_c of small clear specimens ($R = 0.64$) was also better than those between E_{sw} and E_{us} of logs and σ_c of small clear specimens (Table 5). As the longitudinal vibration evaluation on logs showed better prediction for both the static bending MOE, MOR, and σ_c of small clear specimens than stress wave and ultrasonic wave evaluation on logs in this test, it is suggested that the longitudinal vibration measurements can provide a more reliable and accurate assessment of log mechanical properties. It has been reported that the resonance-based acoustic method is a well-established NDT technique for long and slender wood members.[4,5,9] In the measurement of resonance frequency in the longitudinal vibration method, many acoustic pulse reverberations stimulated in a log could resulting in a more repeatable and accurate measurement in comparison with the time-of-flight measurement along a single propagation path in the stress wave and ultrasonic wave methods. Furthermore, the much higher value and uneven distribution of MC in green logs would tend to introduce additional variability for stress wave and ultrasonic wave measuring,[21,22] which could result in a lower correlation coefficient with mechanical properties

Table 5. Relationship between dynamic elasticity properties and mechanical properties

Correlation coefficients (R)	Dynamic modulus of elasticity of green logs				
	E_{sw} (GPa)			E_{fr} (GPa)	E_{us} (GPa)
	N	S	N/S		
Conditioned small clear specimens					
MOE (GPa)	0.44**	0.61**	0.57**	0.77**	0.45**
MOR (MPa)	0.42**	0.56**	0.53**	0.76**	0.40*
σ_c (MPa)	0.34*	0.45**	0.40*	0.64**	0.32ns

*Significant at 0.01 level
** Significant at 0.001 level
ns, Not significant at 0.01 level

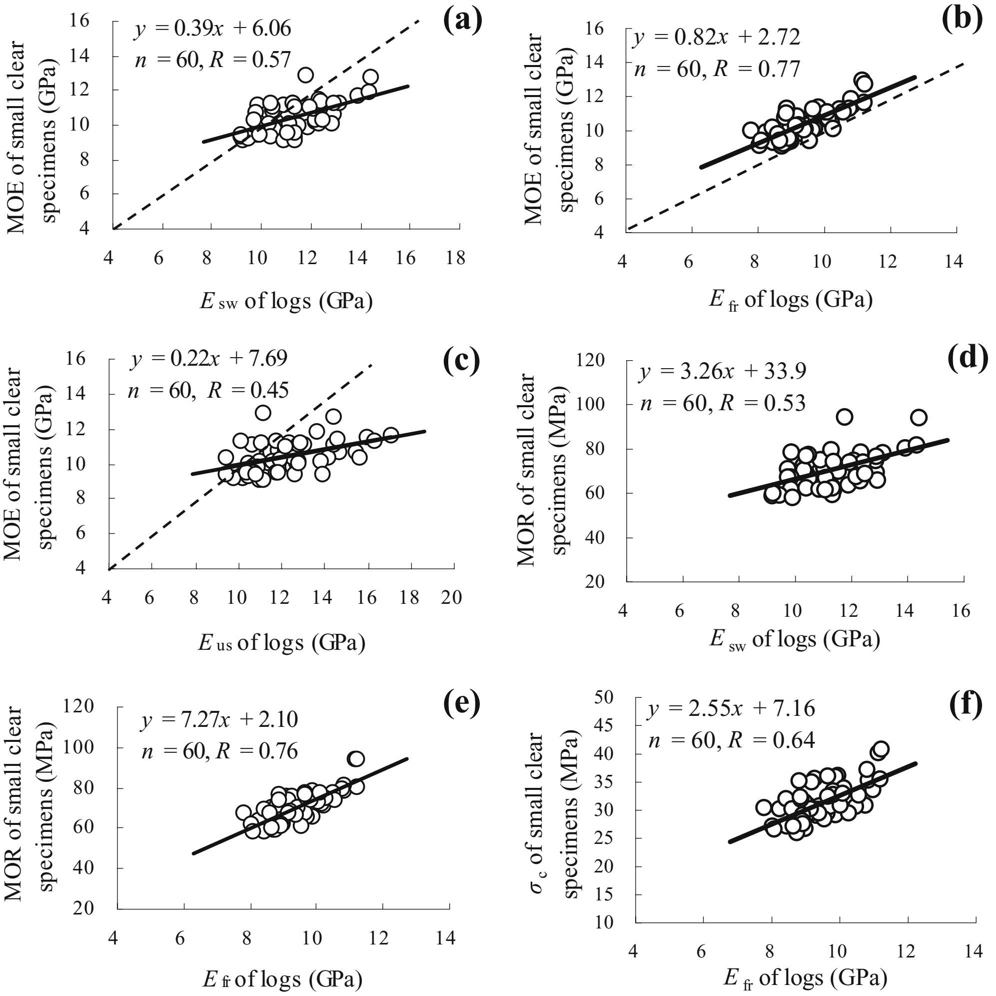

Fig. 3. Relationships between dynamic elastic properties and static mechanical properties of Chinese fir plantation wood. **a** Dynamic modulus of elasticity based on stress wave (E_{sw}) of logs and modulus of elasticity (MOE) of small clear specimens. **b** Dynamic modulus of elasticity based on longitudinal vibration (E_{fr}) of logs and MOE of small clear specimens. **c** Dynamic modulus of elasticity based on ultrasonic wave (E_{us}) of logs and MOE of small clear specimens. **d** E_{sw} of logs and modulus of rupture (MOR) of small clear specimens. **e** E_{fr} of logs and MOR of small clear specimens. **f** E_{fr} of logs and compressive strength parallel-to-grain (σ_c) of small clear specimens

of small clear specimens when air dried. However, the literature[22] indicates that E_{fr} based on longitudinal vibration remained nearly constant in a wide range of MC, although vibration frequency decreased with MC level. As a result of the relatively constant properties of E_{fr} with MC, better correlation was shown between longitudinal vibration measuring and wood properties of small clear specimens.

However, the currently developed devices are limited to apply longitudinal vibration on the standing tree. The equipment for longitudinal vibration and ultrasonic wave methods used in this study is not adaptable for standing tree evaluation because of boundary condition limitations. Therefore, the Fakopp tester was applied to conduct stress wave testing on fresh logs to provide the measurements on the standing tree. The correlation coefficient between the average dynamic modulus of elasticity on logs as determined by stress wave measurement and the bending MOE of small clear specimens was close to a published research result ($R = 0.66$) from tests on trees.[11] Recently, correlation models have been developed between the velocity of stress waves in standing trees of several conifer species and dynamic MOE based on longitudinal vibration in green logs cut from the same trees.[9] Additionally, Iki et al.[8] and Ishiguri et al.[10] also reported that the significant correlation between the stress wave velocity of standing trees and E_{fr} by longitudinal vibration was evident in *Abies sachalinensis* and *Larix kaempferi*. From this study, it was concluded that not only the average MOE but also MOR and σ_c of small clear specimens from the logs can be predicted well by E_{sw} and E_{fr} of those same logs. Therefore, our finding indicates that stress wave technology would be effective to evaluate the wood mechanical properties of both logs and the standing tree.

In the present research, the stress wave technique was practical to measure the propagation time on the north and south face of green logs to agree with the measurement state of the standing tree. The correlation between E_{sw} measured on the south-facing segments of the logs and the bending MOE and MOR of small clear specimens was slightly higher than that between the average value of E_{sw} from the north and south segments and MOE and MOR of small clear specimens, respectively. However, much lower correlations were observed between the E_{sw} from the north segments and the bending MOE and MOR of small clear specimens (Table 5). Although the stress wave evaluation on the south-facing segments showed slightly better prediction for both the bending MOE and MOR of small clear specimens than that on two locations in this test, it is

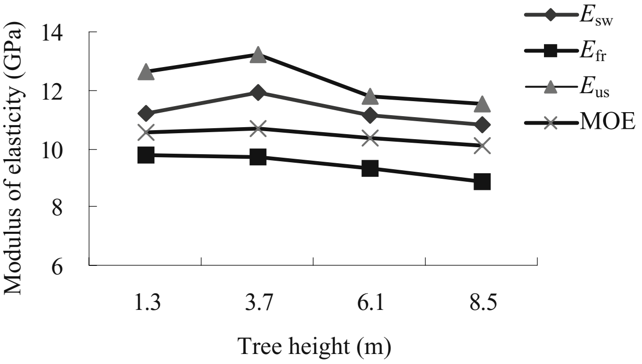

Fig. 4. Change in MOE along tree height

suggested that the stress wave measurements could be performed on two or more locations to reduce the influence of the growth characteristics of the trees and to provide a more reliable and accurate assessment on log and tree mechanical properties.

Nondestructive evaluation and static bending properties at different tree height

The effects of tree height (1.3, 3.7, 6.1, and 8.5 m from ground level) on dynamic moduli of elasticity of log by using three acoustic nondestructive methods and static MOE from small clear specimens were examined (Fig. 4). It was observed that the longitudinal changes of dynamic and static elasticity properties of logs showed similar tendencies along the tree stem. The E_{sw}, E_{us}, and bending MOE reached a maximum at the second height position (at 3.7 m) and then decreased with increasing height, although the average value of E_{fr} always decreased with height. Iki et al.[8] suggested that, in *Abies sachalinensis*, E_{fr} of the region from ground level to a height of 3 m could be used as an alternate value to the mean E_{fr}. However, in this study, E_{sw} and E_{us} at the first height (from 1.3 m to 3.7 m) were close to the mean values of E_{sw} and E_{us} averaged from logs at four heights. On the other hand, E_{fr} and bending MOE at the third height (between 6.1 m and 8.5 m) could be a substitute for their mean values from logs at four heights. The variation of dynamic and static MOE with tree height had a similar trend to that of the tracheid length and cell-wall thickness of earlywood and latewood[23]; however, it was not completely consistent with the variation of air-dried density and microfibril angle in the previous report.[13] Further study is required on the relationship between the wood elasticity and analytical properties along tree stems of Chinese fir.

It was shown that, with the changes of height in the tree, the changes in dynamic elasticity properties of logs determined by the acoustic methods almost followed that in the average bending MOE of small clear specimens. Therefore, these results suggested that the acoustic technique used in this study might be applied to track longitudinal changes of mechanical properties along the tree height span.

Conclusions

1. The average bending MOE of small clear specimens obtained from static bending was about 7.1% and 15.4% less than E_{sw} and E_{us}, respectively, and 11.3% greater than E_{fr}. The differences between the bending MOE and dynamic MOE of logs by the three acoustic methods were statistically significant ($P < 0.001$).
2. The significant correlation (R) between E_{sw}, E_{fr}, and E_{us} in green logs and static MOE in small clear specimens produced from these same logs were 0.77, 0.57, and 0.45, respectively ($P < 0.001$).
3. Longitudinal vibration is the most precise and reliable technique to evaluate the mechanical properties of logs among the three acoustic-based nondestructive methods.
4. Stress wave technology would be effective to evaluate the wood mechanical properties of both logs and the standing tree.
5. The acoustic-based technique might be applied to track the longitudinal changes of mechanical properties along tree height.

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