Variation of Larch Wood Property Indexes Based on Nondestructive Testing Data

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To quickly evaluate the material properties of ancient wooden structure members on site, the larch species of northeastern China was used as the research object, and the nondestructive testing method of the stress wave and the micro-drill resistance meter were used to measure it. The variation laws of the larch wood's cross and longitudinal property indexes were determined. According to the variation law of material property indexes, the detection divisions under the nondestructive testing technology of stress wave and micro-drill resistance instruments were divided, which provides a basis for improving the accuracy of on-site nondestructive testing. From the comparison of shade and light side data, it was found that there was little difference in material properties indexes. According to the change trend of larch wood with density, the pith, juvenile wood, mature wood, and overmature wood were divided, which provided a reference value for the study of wood growth laws.

Keywords: Nondestructive testing; Variation; Property indexes; Stress wave; Micro-drilling resistance; Detection division

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INTRODUCTION

Ancient timberwork buildings are important cultural relics. According to the principle of "minimum intervention and protection of the status quo", nondestructive testing technology has become an important way to maintain and repair ancient buildings (Zhu 2012). Wood is the most important building material in ancient buildings, and it plays an important role in support and maintenance. Studying the changes in the wood properties has important implications for the life, bearing capacity, and durability of ancient timberwork buildings (Lu 2017). At the same time, it can provide a scientific basis for the condition assessment, safety limits, and performance maintenance of the ancient timber structure.

Wood properties are affected by many factors (Li *et al*. 2011), such as ring width (Jiang *et al*. 2012), moisture content (Montero *et al*. 2015), density (Liu and Gao 2014), age (Cavalli *et al*. 2016), direction of anatomical constituents (Wang *et al*. 2016), tree species (Mvondo *et al*. 2017), earlywood and latewood, temperature (Hu and Xue 2013), *etc*. Due to the growth mode of the wood and its characteristics of porosity and nonuniformity, its various properties change with the tree species, tree age, positions from the center of the heart, and directions of the fibers (Zhang 2017). The change of wood properties is closely related to the life of ancient timberwork buildings and is an inherent factors affecting the strength of timber structures.

Conventional testing of wood property indexes uses mechanical testing machines to load prescribed standard samples (Shi *et al.* 2019). However, this test method is time consuming, it has many restrictions, and the measurement method is destructive. In recent years, increased attention has been paid to the research of wood properties using nondestructive testing technology. Currently, many nondestructive testing technologies are used to test wood property, such as ultrasonic testing (Haseli *et al*. 2020), stress wave testing (Del Menezzi *et al*. 2014), resistance meter testing (Sun *et al.* 2012), radiographic inspection (Jiang *et al*. 2010), and microwave inspection (Wu 2018). Moreover, there are many instruments that can test the wood properties, such as SilviScan-3^{TM} (Xu *et al*. 2012) developed by the Federal Institute of Science and Industry of Australia; Pilodyn (Zhang *et al*. 2010) of Proceq, Switzerland; micro drills of Rinntech, Germany Resistograph (Zhu *et al*. 2011); and Fakopp Hungarian stress wave 2D and 3D measuring instrument (Liu *et al*. 2015). The first two can measure the density and the last two can measure the dynamic modulus of elasticity (E_d). There have been many related studies on various tree species, such as *Pinus koraiensis* (Zhu *et al*. 2013), *Pinus elliottii* (Zhang *et al*. 2017), *Robinia pseudoacacia* (Sun *et al*. 2018), larch (Tian *et al.* 2017), Chinese fir (Lin *et al*. 2000), *Machilus pauhiol* (Leng *et al*. 2018), and masson pine (Bao *et al*. 2001). At the sampling location of the test object, the material properties of heartwood and sapwood (Cao 2005; Zhu *et al*. 2011; Zhu 2018) were studied. In terms of object types, there are many studies on topics such as standing wood (Zhang 2014), log (Luo 2011), board (Huang 2013), sawn wood (Tian *et al*. 2017), and glued wood (Wang *et al*. 2013; Chen *et al*. 2014), old wood (Chen 2003), new wood (Lourenco *et al*. 2007; Zhu 2018), full-scale components (Yu *et al*. 2017; Guan *et al*. 2019), and standard components (Zhu 2018). In terms of detection targets, the literature consists of studies on density (Gao 2012), E_d (Carrasco *et al*. 2017), modulus of stress-resistograph, which means multiplying the value of the drilling (feeding) needle by the square of the stress wave propagation velocity (Zhu *et al*. 2011), compression strength parallel-to-grain, and bending strength (Huang *et al*. 2007).

The diameters of wooden members in ancient buildings are relatively large. For example, the maximum diameter of the pillars of the Forbidden City can be more than 100 cm. Considering the complexity of the wood structure and the anisotropy of the wood itself, when applying nondestructive testing technology to such timber structures, the technology must be performed according to the characteristics of the wood, so as to improve the speed and accuracy of the survey of the material condition of the ancient wooden structure's wooden components. Therefore, it is of great significance to precisely detect the wood property indexes for improving the accuracy of nondestructive or minimally destructive testing.

Recently, there have been some important studies on rapid determination of wood density. Williamson and Wiemann (2010) suggested an approach, using applied calculus to estimate the density when the form of radial variation is known. In theory, they thought the tree need only be bored to a specific point, to estimate density of the whole cross section. The study proposed a prediction method based on theory. As to the traditional increment borer methods, Gao *et al.* (2017) provided a comprehensive review of research development, the results of which showed that the choice of method for predicting wood density of major tree components was significant. It was thought that resistance drilling has emerged as a potential tool for more efficient and economical collection of wood density. José Tarcísio da Silva Oliveira *et al.* (2017) suggested that the average resistance amplitude of a half-diameter drilling (from bark-to-pith) is more advantageous for assessing the density of young eucalyptus trees than a whole-diameter drilling. Unlike previous researches, the density and some other properties were determined. Based on the experiment, a more reasonable detection range on cross and longitudinal section were determined. This study investigated the larch species of northeastern China as the object, and used the coupling effect of stress wave and micro-drilling resistance instruments to analyze the material properties of larch from the whole and part. It analyzed the variation laws of cross and longitudinal section performance indexes of larch. According to the variation laws of each material property index, the detection zones for using the stress wave tester and micro drilling resistance instrument were divided. The results of nondestructive testing provided the basis for improving the accuracy of on-site testing. At the same time, according to the change trend of larch wood with density, the pith, juvenile wood, mature wood, and over-mature wood were divided, which provided a reference value for the study of wood growth law.

EXPERIMENTAL

Materials

The experimental materials were selected from green larch materials and purchased from Qingdongling Timber Factory in Tangshan City, Hebei Province (China). The diameter of the base was 50 cm, and the top was 40 cm. The height was 400 cm. The green wood was approximately 300 to 400 years old. It was cut into eight sections from the base to the top by the following measurements: 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 300 cm, 350 cm, and 400 cm; the sections were labelled A, B, C, D, E, F, G, and H, respectively. Because one part of the wood was exposed to light and the other part was not during growing, the specimens were divided into two parts, the light part and shade part. According to GB 1929 (2009), the standard for selecting specimens, each section was sawn into 2 cm × 2 cm × 45 cm specimens. A total of 559 specimens were selected. The specimens were divided into 10 groups according to the actual depth (Fig. 1, Tables 1, 2).

Table 1. Cross-section Grouping and Depth Ratio

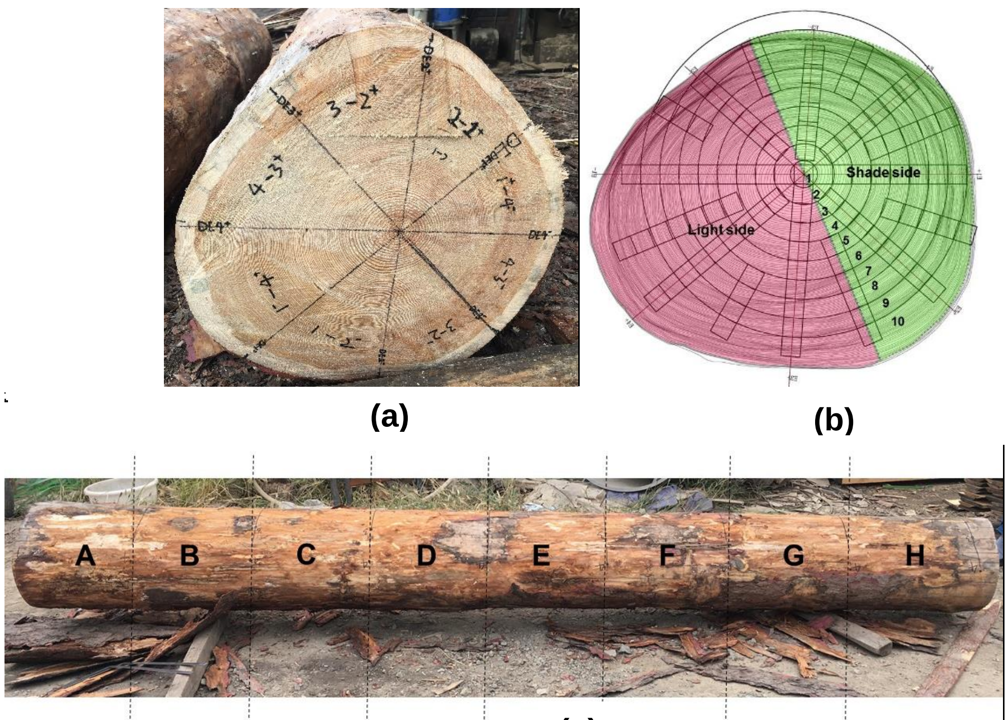
Name	Cross-section Depth and Ratio			
	Whole (cm)	Shade Side (cm)	Light Side (cm)	Depth Ratio (d)
Group 1	19.10	19.10	19.10	1/2
Group 2	16.98	16.72	17.24	9/20
Group 3	14.88	14.64	15.38	2/5
Group 4	12.71	12.53	12.89	1/3
Group 5	10.68	9.93	11.19	7/25
Group 6	8.06	7.54	8.55	1/5
Group 7	6.51	5.61	7.22	17/100
Group 8	4.40	3.52	5.16	6/50
Group 9	3.78	3.22	4.31	1/10
Group 10	2.88	2.12	3.40	2/25

Note: The method for determining the depth ratio (d) of the cross distance from the bark depth is the distance from the detection position to the bark divided by the diameter of the wood.

Table 2. Longitudinal Section Grouping and Height Ratio

Section Name	A	B	C	D	E	F	G	H
Height (cm)	50	100	150	200	250	300	350	400
Height Ratio (h)	1/8	1/4	3/8	1/2	5/8	3/4	7/8	1

Note: The method for determining the height ratio (h) of the longitudinal l distance from the bottom of the tree is the distance of the detection position from the bottom of the tree divided by 400 cm.



(a) (b) (c)

Fig. 1. Schematic diagram of cross-section (a, b,) and longitudinal section saw (c)

The equipment consisted of a Lichen Technology blast dryer box 101-3BS (Shanghai Lichen Electronic Technology Co., Ltd., Shanghai, China), Lichen Technology electronic precision balance JA1003 (Shanghai Lichen Electronic Technology Co., Ltd., Shanghai, China), vernier calipers (Guilin Guanglu Measuring Instrument Co., Ltd., Guilin, China), FAKOPP microsecond timer (FAKOPP Enterprise Bt., Ágfalva, Hungary), and an IML-RESI PD500 micro-drill resistance instrument (IML Co., Ltd., Wiesloch, Germany).

Methods and Steps

The propagation time of the stress wave in wood was measured with a stress wave tester (FAKOPP Enterprise Bt., Ágfalva, Hungary). Two transducers were coupled in the specimens' ends and measurements were made along the direction parallel to the fibers of the specimens. The angle between the two probes and the length of the specimens was not less than 45°, and the distance between the two measurement points was measured (Fig. 2). During the measurement, the reading of the propagation time of the first tap was invalid.

Starting from the second time, the average value of the propagation time obtained by continuously measuring three times was used as the final test result.

The micro-drilling resistance instrument 200/5000 was used to measure both ends of the specimens, and the resistance value of the material inside the wood was tested. A probe was drilled into the surface of the processed specimen at a uniform speed and perpendicular to the direction of the annual ring, and the test data was imported into the computer to calculate the resistance value.

The measured position was cut off, according to Fig. 2. The size of the specimens was tested with a vernier caliper (Guilin Guanglu Measuring Instrument Co., Ltd., Guilin, China). The mass of the specimens was recorded with a balance (Shanghai Lichen Electronic Technology Co., Ltd., Shanghai, China). The moisture content (MC) was tested with a dryer box.

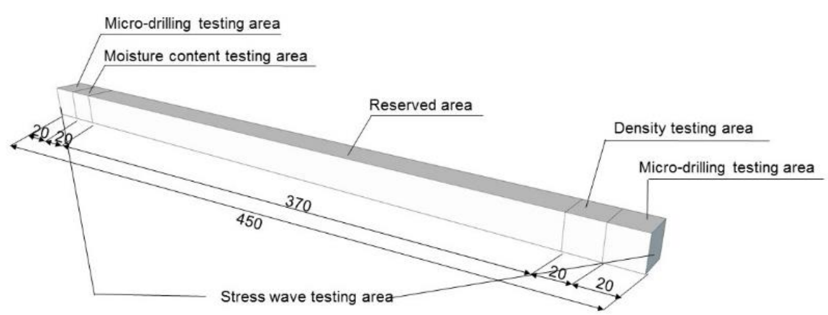


Fig. 2. Experimental specimen partition

Experimental Data Processing

According to Eq. 1, the density values of all the specimens was calculated,

$$\rho = \frac{M}{V} \tag{1}$$

where ρ is the density (g/cm^3), M is the mass (g) and V is the volume (cm^3).

The propagation velocity and E_d was calculated according to the application principle of the stress wave tester (Eq. 2and Eq. 3),

$$V_d = 10^6 \times \frac{L}{t} \tag{2}$$

where L is the distance between the two sensors of the stress wave tester (m), t is the time recorded between the two sensors of the stress wave tester (μs), and V_d is the stress wave propagation velocity in wood (m/s),

$$E_d = \rho V_d^2 \tag{3}$$

where E_d is the dynamic modulus of elasticity of wood (MPa).

The F_{drill} and F_{feed} were calculated according to the principle of the micro-drilling resistance instrument (Eq. 4 and Eq.5),

$$F_{drill} = f_{drill} V_d^2 \tag{4}$$

$$F_{feed} = f_{feed} V_d^2 \tag{5}$$

where F_{drill} is the modulus of stress-resistograph of the drilling needle (resi·km^2/m^2), f_{drill} is the rotational resistance value of the drilling needle (resi), F_{feed} is the modulus of stress-resistograph of the feeding needle (resi·km^2/m^2), and f_{feed} is the resistance value of the feeding needle (resi).

The micro-drilling resistance instrument started timing after being disturbed by the outside disturbance, and recorded data at a certain time interval. The needle advance speed of the impedance meter was a constant value, and the needle depth could be calculated according to Eq.6,

$$x = V \times t \quad (6)$$

where x is the needle depth (cm), V is the needle advance speed of the micro-drilling resistance instrument (cm/s), and t is the needle insertion time (s).

According to the data obtained by the micro-drilling resistance instrument software and the thickness of the actual specimen (2 cm), it was calculated that the micro-drilling resistance instrument recorded the data approximately every 0.01 cm.

Data and pictures were obtained by the micro-drilling resistance instrument software PD-Tools Pro (IML Co., Ltd., Wiesloch, Germany) (Fig. 3). The initial 0.2 cm was not suitable because of the small depth of needle insertion, angular deviation, and uneven surface of the specimen. The last 0.2 cm of the penetration specimen was subject to errors due to damage to the surface structure and the characteristics of the specimen. The selected point of the micro-drilling resistance instrument data was 0.6 to approximately 2.2 cm as the valid data range (Eq. 7),

$$f = \frac{\int_{0.6}^{2.2} \mathrm{y}\,\mathrm{dx}}{\int_{0.6}^{2.2} \mathrm{dx}} \quad (7)$$

where f is f_{drill} (resi) or f_{feed} (resi).

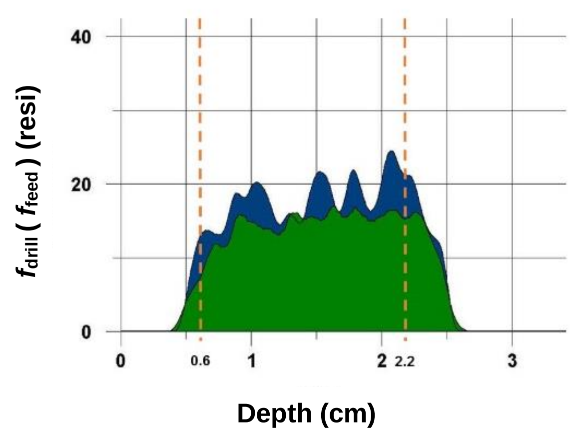


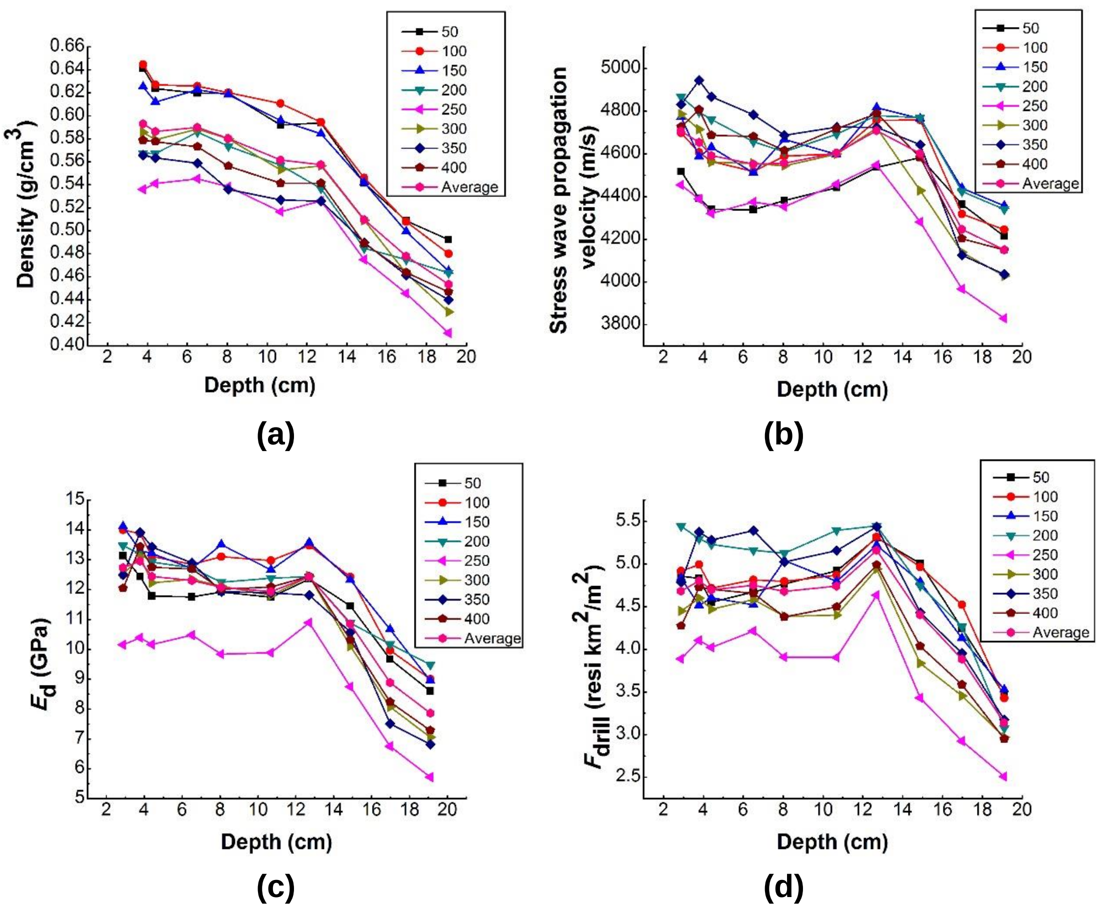
Fig. 3. Schematic diagram of micro-drilling resistance PD-Tools Pro data

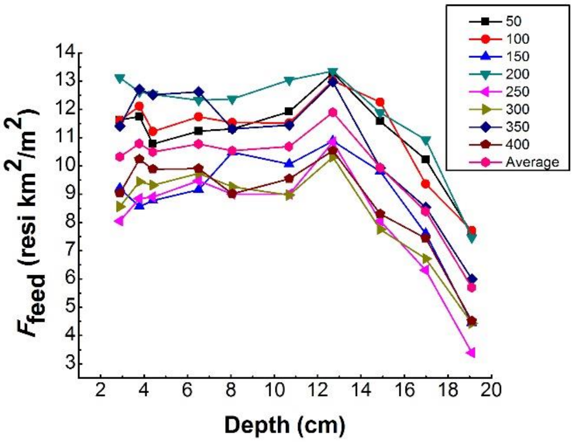
The MC of the specimens was determined according to GB 1931 (1991). Through the determination, the MC of the 559 specimens was in the range of approximately 4% to approximately 7%.

RESULTS AND DISCUSSION

Analysis of Wood Cross-section Variation

Figure 4 presents the average values of each property index at each ring depth, including the data of the shade and light side. Judging from the trend of larch wood property indexes with annual ring depth, at the same cross-section height, the index values were the smallest at the center of the annual ring at 19.10 cm (the ratio of 1/2). They gradually increased outward from the depth of 19.10 cm and became steady, which was 3.78 cm to 12.71 cm (the ratio of 1/10 to 1/3). Values became slightly lower at 2.88 cm (the ratio of 2/25) than 3.78 cm (the ratio of 1/10) (except for the trend chart of the stress wave propagation velocity), but the values were not much different (Fig. 4).





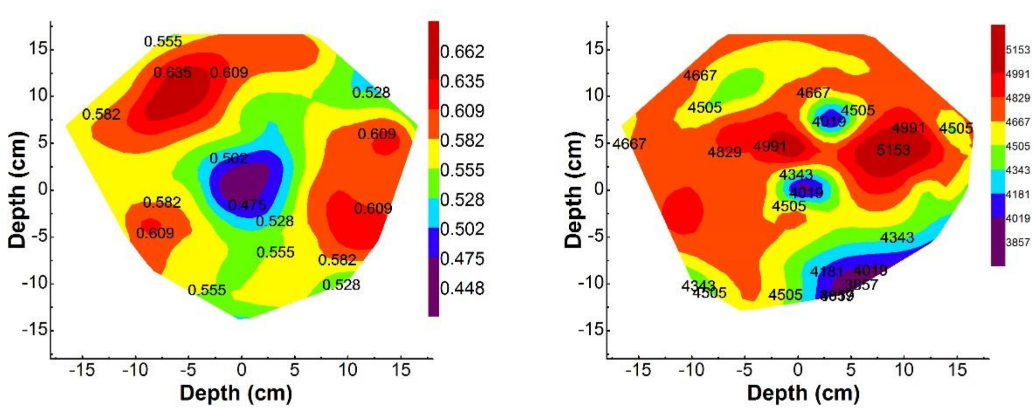
(e)

Fig. 4. Variation of cross-section figures of the five material property indexes: (a) density, (b) stress wave propagation velocity, (c) E_d, (d) F_{drill}, and (e) F_{feed}

This was consistent with the results of Cao's research on density variation (Cao 2005). The formation of this variation was related to the tracheid width, tracheid wall thickness, microfibril angle, *etc.*, which are important indexes affecting the wood properties. Trees have high levels of growth hormone from the early stages of growth to maturity, and accordingly the tracheid width of the meristem is larger, and the tracheid wall thickness is smaller. With the growth of trees and their biological properties, the hormones that inhibit cell growth gradually increase, the growth rate of tracheid width slows down, and gradually stabilizes. The tracheid wall thickness increases first and then decreases, and the microfibril angle decreases (Panshin *et al*. 1970).

It was found from the data analysis that the dispersion coefficients at all annual ring depths were very small. The density was 0.07 to 0.12, the stress wave propagation speed was 0.02 to 0.08, the E_d was 0.11 to 0.21, F_{drill} was 0.11 to 0.21, and F_{feed} was 0.11 to 0.25.

There are 8 sections of contour figures to reflect the variation trend of the cross-section. And the trend was similar. Eight sections are shown. Figure 5 represents the data of F. The x-axis and y-axis are represented by the pith center, which indicates the depth from the pith center to the bark. From the contour maps of the five material properties, the variation trend shown in Fig. 5(a) was consistent with Fig. 4(a). The variation trends of Fig. 5(b), Fig. 5(d), and Fig. 5(e) slightly deviated from those of Fig. 4(b), Fig. 4(d), and Fig. 4(e). This might have been related to the small errors in the fluctuation of the moisture content during the experiment and the influence of the experimental conditions.



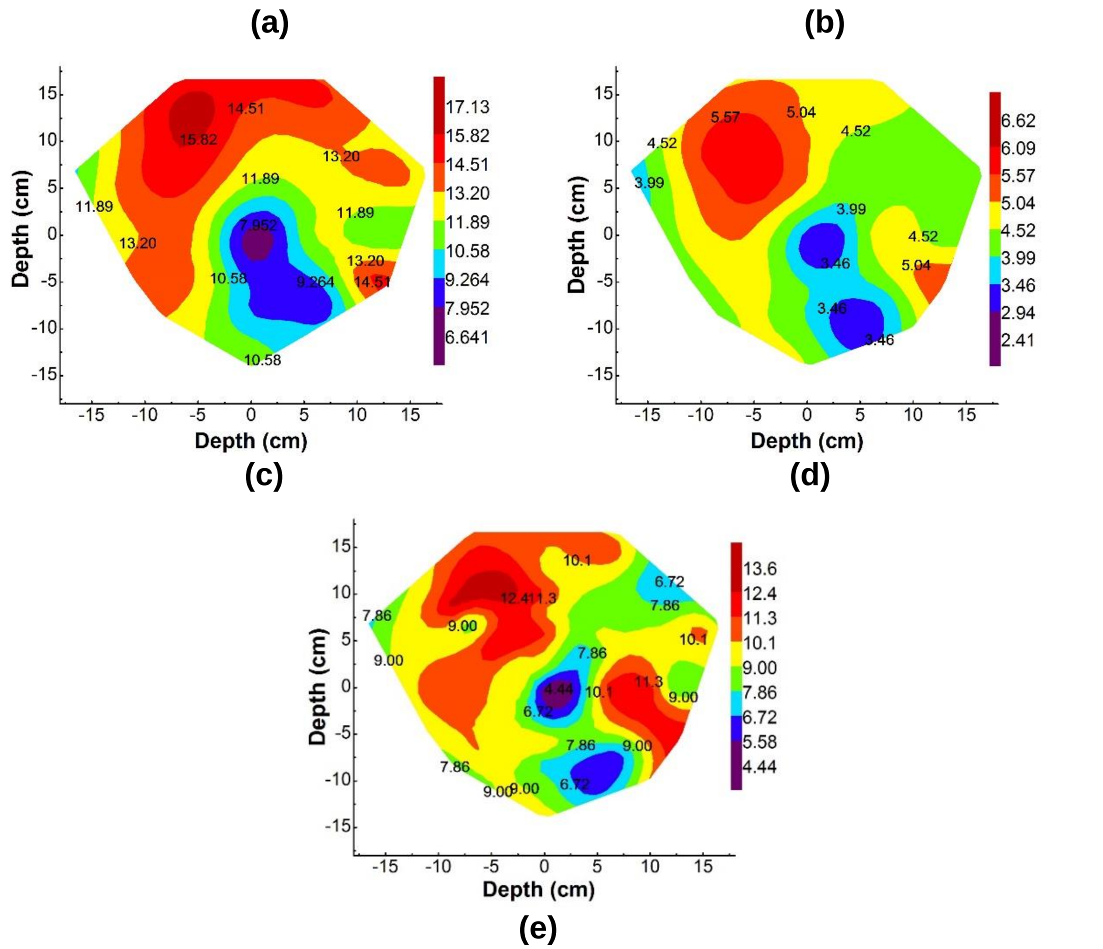


Fig. 5. Cross-section contour figures of the five material property indexes: (a) density, (b) stress wave propagation velocity, (c) E_d, (d) F_{drill}, and (e) F_{feed}

The variation trend formed in Fig. 5(c) was not obvious. This might have been related to the large deviation of the value at the height of 250 cm in Fig. 4(c). Overall, the contour map of each material property index was roughly consistent with the variation trend chart in Fig. 4. The reliability of the cross-section variation trend of Fig. 4 was further verified.

Through comparing the data of the shade side and light side of each material property index, it was found that overall, the shade side and light side had the same change trend and there was not much difference between them. Figure 6 shows the results of overall density, shade side and light side.

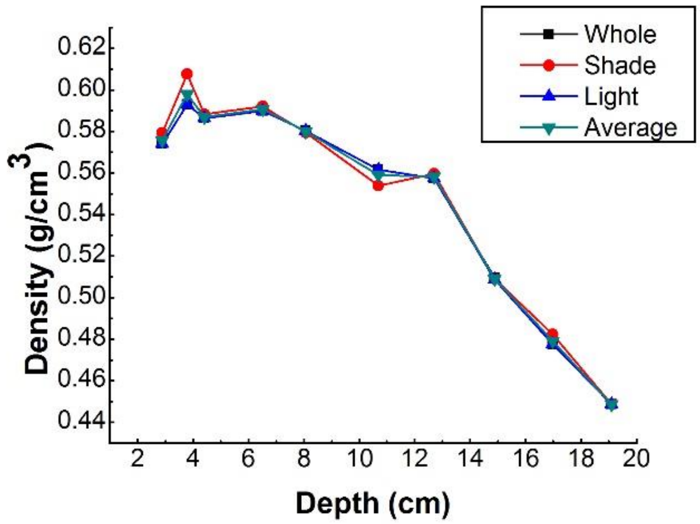


Fig. 6. Comparison of density in cross-section

Analysis of wood longitudinal section variation

The average depth of each of the property indexes in each annual ring is shown in Fig. 7. Judging from the trend of larch wood property indexes with section height, at the same cross-section height, the annual ring depth of each property indexes at 16.98 cm (the ratio of 9/20) and 19.10 cm (the ratio of 1/2) were smaller than the other depths. The density at 14.88 cm (the ratio of 2/5) was also smaller than other index values. This showed that in the years in which the three annual rings were located, the wood was affected by the growing environment; the nutrients, light, and moisture were different during the growth at that time. Based on the depth curves of other groups of rings, according to various property indexes, there was not a large difference between the values at the height of 150 cm (the ratio of 3/8), 200 cm (the ratio of 1/2), 300 cm (the ratio of 3/4), and 400 cm (the ratio of 1). Among them, except for the variation law of F_{feed}, the variation trends of other material property indexes were similar (Fig .7).

From the data analysis, it was found that the dispersion coefficients of the material property values at different cross-section heights and annual ring depths were small. Among them, the density was 0.05 to 0.09, the stress wave propagation speed was 0.02 to 0.08, the E_d was 0.06 to 0.17, F_{drill} was 0.06 to 0.22, and F_{feed} was 0.11 to 0.39.

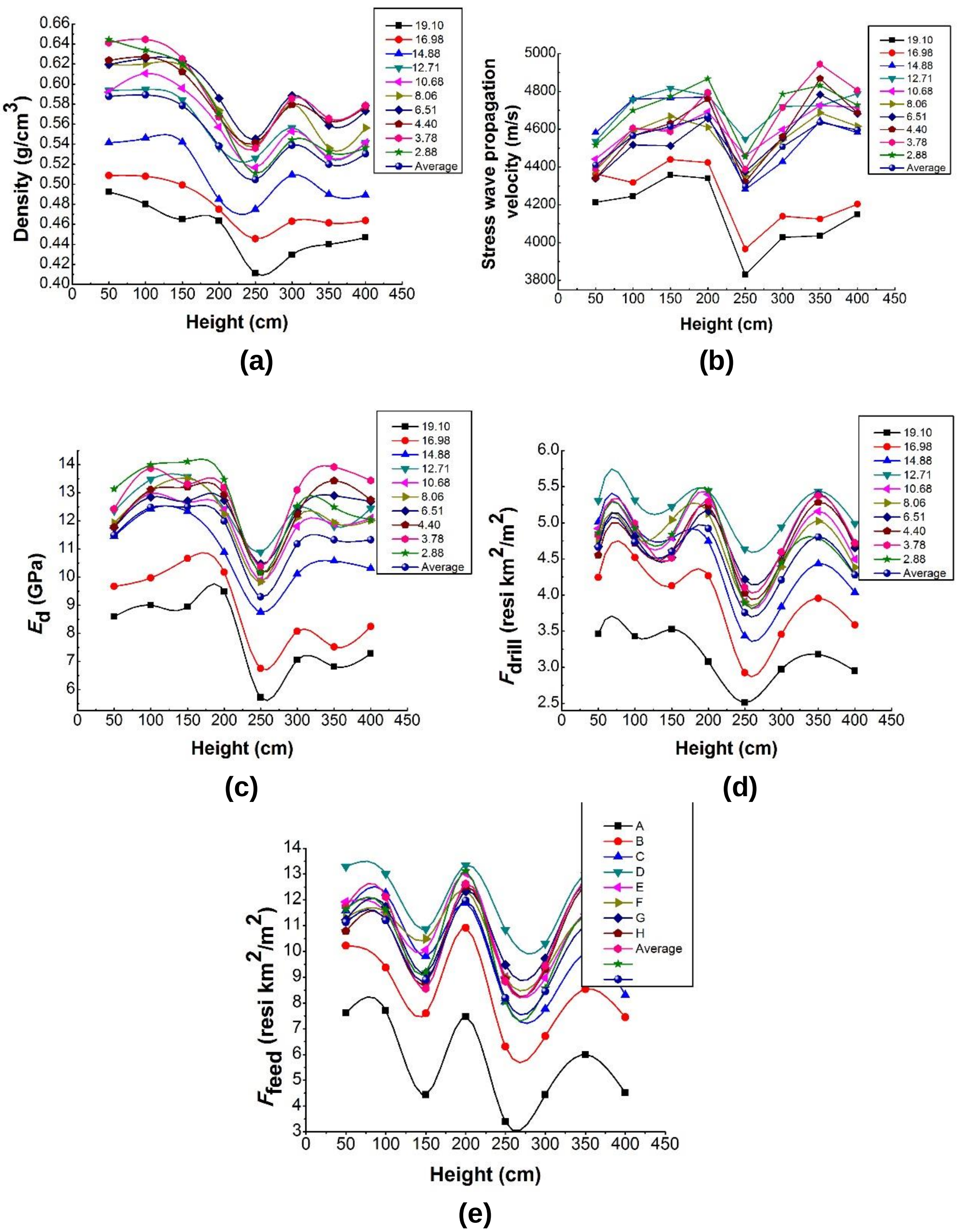


Fig. 7. Variation of longitudinal section figures of the five material property indexes: (a) density, (b) stress wave propagation velocity, (c) E_d, (d) F_{drill}, and (e) F_{feed}

There are 8 sections of contour figures to reflect the variation trend of the longitudinal section. And the trend was similar. Figure 8 represents the data of F. The x-axis represents the pith center as the origin and indicates the distance from the pith center to the bark. The y-axis represents the base of the tree as the origin and indicates the height from the base to the top of the tree. It can be seen from the contour maps of the five material properties that the contour map of each material property index was consistent with the variation trend chart in Fig. 7. The reliability of the variation trend of the longitudinal section in Fig. 7 was further verified.

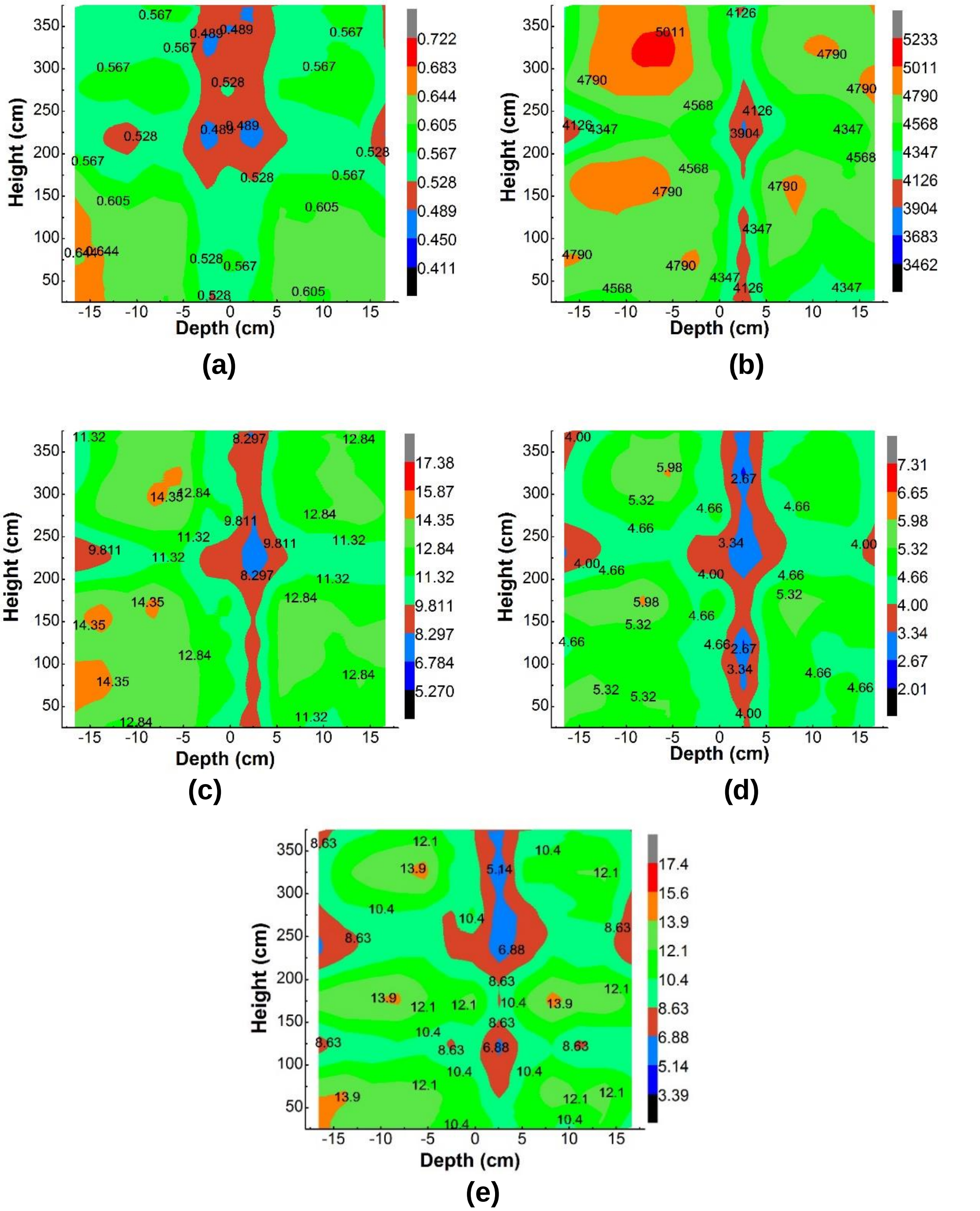


Fig. 8. Longitudinal section contour figures of the five material property indexes: (a) density, (b) stress wave propagation velocity, (c) E_d, (d) F_{drill}, and (e) F_{feed}

By comparing the data of the shade side and light side of each material property index, it was found that overall, shade side and light side had the same change trend and there was little difference between them. Figure 9 shows the results of overall density, for both shade side and light side.

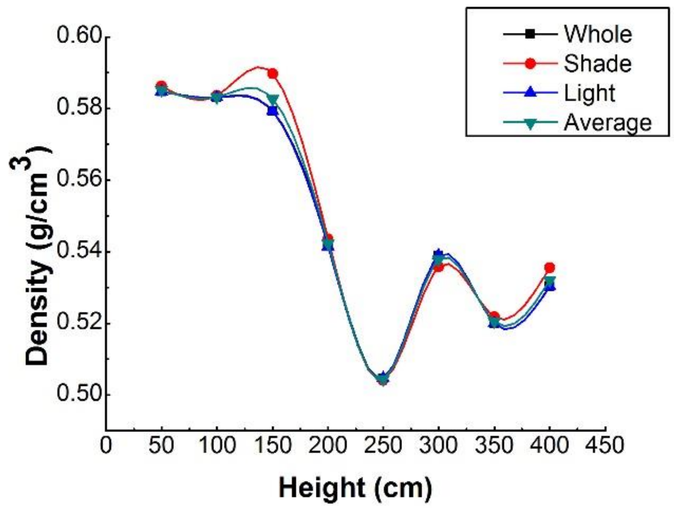


Fig. 9. The comparison of density in longitudinal section

Creating the detection division

When trees grow outward from the pith, the wood that is formed when the layer is younger is called juvenile wood. Within a certain range of age, it gradually transitions to maturity to produce mature wood. The wood properties of juvenile wood vary greatly, and the wood properties of mature wood are basically stable. Based on the definition of juvenile and mature timber in the study of larch wood anatomy, considering the on-site inspection of the wooden structure of ancient buildings, it is necessary to make a fast and an accurate judgment under nondestructive conditions. According to the variation laws of density, stress wave propagation velocity, E_d, F_{drill}, and F_{feed} in cross-section and longitudinal section divide the zones of larch using nondestructive testing. The comparative analysis was performed according to the different index values of the pith, juvenile wood, mature wood and over-mature wood, so as to improve the accuracy of the nondestructive test. This was shown in Table 3, and the dotted area in Figs. 10 and 11. Compared to Williamson and Wiemann (2010), for linear radial changes, the wood density at two thirds of the distance from pith to bark should equal the density of the whole disk, the results were coincident.

Table 3. Detection Divisions of Wood Property Indexes Under Nondestructive Testing Technology of Larch

Ratio and Detection Suggestion	Detection Division			
Ratio of cross-section distance to bark depth	Over-mature Wood	Mature Wood	juvenile Wood	Pith
	0 < d ≤ 1/10	1/10 < d ≤ 1/3	1/3 < d < 1/2	d = 1/2
Detection suggestion	Preference		Auxiliary Reference	Auxiliary Reference
Ratio of longitudinal section distance to base height	0 ≤ h < 3/8	3/8 ≤ h ≤ 1/2	1/2 < h < 3/4	h = 3/4, h = 1
Detection suggestion	Auxiliary Reference	Preference	Auxiliary Reference	Preference

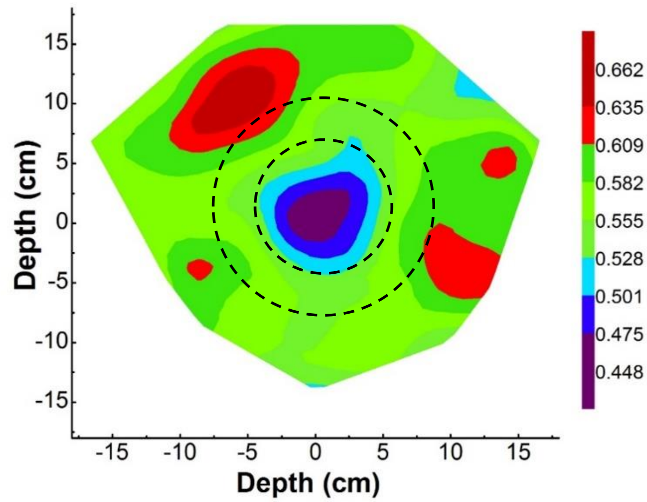


Fig. 10. Detection divisions of material property indexes (ρ, E_d, F_{drill} and F_{feed}) in cross-section

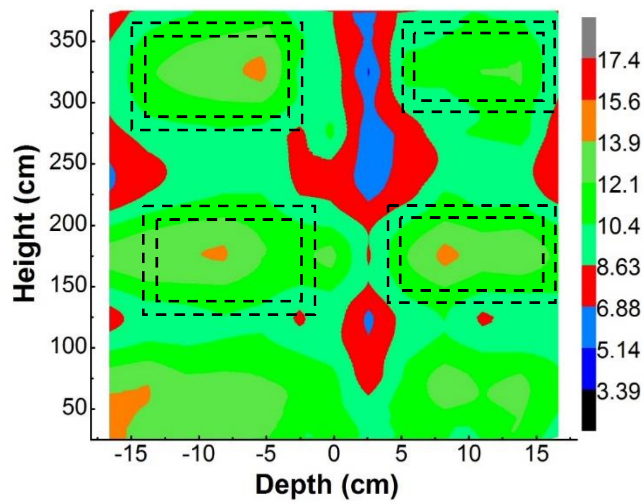


Fig. 11. Detection divisions of material property indexes (ρ, E_d, F_{drill} and F_{feed}) in longitudinal section

This study provides a reference value for other species and some related research. It has practical significance in establishing research ideas and methods for detection divisions

CONCLUSIONS

1. This work established the variation laws of larch's property indexes in cross and longitudinal sections based on nondestructive testing methods. The five property indexes included density, the stress wave propagation velocity, E_d, F_{drill}, and F_{feed}.
2. According to the variation laws of material property indexes, the detection divisions for nondestructive testing technology of stress wave and micro-drill resistance instrument were divided, which provided a basis for improving the results of nondestructive testing on site.

3. From the change trend of larch wood with density, it was found that the density of wood increased rapidly from the outer bark of the pith and flattened after a short transition until the bark was near the bark. Then, it decreased slightly near the bark. The use of variation rules to classify the pith, juvenile wood, mature wood, and over-mature wood also provided a reference value for the study of wood growth laws.

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REFERENCES CITED

Bao, F. C., Jiang, Z. H., Jiang, X. M., Lu, X. X., Luo, X. Q., and Zhang, S. Y. (2001). “Differences in wood properties between juvenile wood and mature wood in 10 species grown in China,” *Wood Science and Technology* 35(4), 363-375. DOI: 10.1007/s002260100099

Cao, Q. (2005). *Study on Variations of Physical and Mechanical Properties of Ancient Wood Structure in the Imperial Palace*, Master’s Thesis, Beijing Forestry University, Beijing, China.

Carrasco, E. V. M., Souza, M. F., Pereira, L. R. S., Vargas, C. B., and Mantilla, J. N. R. (2017). “Determination of modulus of elasticity of wood depending on the inclination of fibers using acoustic tomography,” *Matéria (Rio de Janeiro)* 22(Suppl. 1), 1-9. DOI: 10.1590/S1517-707620170005.0271

Cavalli, A., Cibecchini, D., Togni, M., and Sousa, H. S. (2016). “A review on the mechanical properties of aged wood and salvaged timber,” *Construction and Building Materials* 114(1), 681-687. DOI: 10.1016/j.conbuildmat.2016.04.001

Chen, G. (2003). “Research on timber material changing which affect buildings form in ancient architecture construction,” *Traditional Chinese Architecture and Gardens* 15(3), 49-52, +60.

Chen, Y., Wang, Z., Chang, L., and Fang, L. (2014). “Analysis on properties diversity of different species of poplar plantation and their effects on the bonding strength of plywood,” *China Forest Products Industry* 41(4), 11-14, +21. DOI: 10.19531/j.issn1001-5299.2014.04.004

Del Menezzi, C. H. S., Amorim, M. R. S., Costa, M. A., and Garcez, L. R. O. (2014). “Evaluation of thermally modified wood by means of stress wave and ultrasound nondestructive methods,” *Materials Science* 20(1), 61-66. DOI: 10.5755/j01.ms.20.1.3341

Gao, S., Wang, X., Brashaw, B. K., Ross, R. J., and Wang, L. (2012). “Rapid assessment of wood density of standing trees with nondestructive methods – A review,” in: *2012 International Conference on Biobase Material Science and Engineering (BMSE)*, Changsha, China, pp. 262-267. DOI: 10.1109/BMSE.2012.6466226

Gao, S., Wang, X., Wiemann, M., Brashaw, B., Ross,R., and Wang, L.(2017). “A critical analysis of methods for rapid and nondestructive determination of wood density in standing trees,” *Annals of Forest Science* 74(2). DOI: 10.1007/s13595-017-0623-4

GB 1929 (2009). "Method of sample logs sawing and test specimens selection for physical and mechanical tests of wood," Standardization Administration of China, Beijing, China.
GB 1931 (1991). "Method for determination of the moisture content of wood," Standardization Administration of China, Beijing, China.
Guan, C., Liu, J., Zhang, H., Wang, X., and Zhou, L. (2019). "Evaluation of modulus of elasticity and modulus of rupture of full-size wood composite panels supported on two nodal-lines using a vibration technique," *Construction and Building Materials* 218, 64-72. DOI: 10.1016/j.conbuildmat.2019.05.086
Haseli, M., Layeghi, M., and Hosseinabadi, H. Z. (2020). "Evaluation of modulus of elasticity of date palm sandwich panels using ultrasonic wave velocity and experimental models," *Measurement* 149, Article 107016. DOI: 10.1016/j.measurement.2019.107016
Hu, Y., and Xue, B. (2013). "Analysis of nondestructive testing for mechanical properties of LVL at different relative humidities based on fuzzy and classical mathematics," *BioResources* 8(2), 2839-2854. DOI: 10.15376/biores.8.2.2839-2854
Huang, R., Wang, X., and Li, H. (2007). "Quantitative analysis on the detected results by resistograph on inside wood decay of ancient architecture," *Journal of Beijing Forestry University* 29(6), 167-171. DOI: 10.13332/j.1000-1522.2007.06.036
Huang, Y. (2013). *Study on Detection and Analysis of Mechanical Properties for Thin Wood Composites*, Master's Thesis, Beijing Forestry University, Beijing, China.
Jiang, J., Lu, J., Ren, H., and Long, C. (2012). "Effect of growth ring width, pith and visual grade on bending properties of Chinese fir plantation dimension lumber," *European Journal of Wood and Wood Products* 70(1-3), 119-123. DOI: 10.1007/s00107-011-0529-z.
Jiang, Z., Shen, S., Zhai, Z., and Xu, X. (2010). "The present situation and development trend of non-destructive testing of wood," *Forestry Machinery & Woodworking Equipment* 38(2), 4-7. DOI: 10.3969/j.issn.2095-2953.2010.02.001
Leng, C., Yi, M., Zhang, L., Hu, S., Luo, H., Wen, T., and Lai, M. (2018). "Application of wood properties rapid assessment technology in prediction of wood density and modulus of elastic of standing tree of *Machilus pauhiol*," *Journal of Forestry Engineering* 3(6), 56-61. DOI: 10.13360/j.issn.2096-1359.2018.06.009
Li, H., Chen, Y., Li, D., Zhang, T., Wang, J., and Liu, X. (2011). "Influencing factors on the results of resistograph of wood components in historical building," *Wood Processing Machinery* 2, 19-21, +26. DOI: 10.13594/j.cnki.mcjgjx.2011.02.012
Lin, J., Zheng, Y., Dong, J., Nie, S., and Lin, S. (2000). "Study on the relation between mechanical properties and fiber morphology of Chinese fir wood from plantations," *Journal of Biomathematics* 15(3), 281-285. DOI: 10.3969/j.issn.1001-9626.2000.03.006
Liu, F., Zhang, H., Jiang, F., Fan, G., and Shi, R. (2015). "Research progress of stress wave-based non-destructive testing of plantation wood quality," *Forestry Machinery & Wood Working Equipment* 43(3), 8-12. DOI: 10.13279/j.cnki.fmwe.2015.0040
Liu, H., and Gao, J. (2014). "Effects of moisture content and density on the stress wave velocity in wood," *Journal of Beijing Forestry University* 36(6), 154-158. DOI: 10.13332/j.cnki.jbfu.2014.06.002
Liu, Y. (1997). "Differentiation of juvenile wood zone and effect of tree growth rate on increment of the juvenile wood," *Scientia Silvae Sinicae* 33(5), 418-426.

Lourenco, P. B., Feio, A. O., and Machado, J. S. (2007). "Chestnut wood in compression perpendicular to the grain: Non-destructive correlations for test results in new and old wood," *Construction and Building Materials* 21(8), 1617-1627. DOI: 10.1016/j.conbuildmat.2006.07.011

Lu, P. (2017). *Analysis of the Effect of Aging on Mechanical Behavior of Ancient Timber Structural Members*, Master's Thesis, Xi`an University of Architecture and Technology, Xi`an, China.

Luo, J. (2011). *Relationship between Log Mechanical Properties and Stress Wave Propagation Parameters*, Master's Thesis, Northeast Forestry University, Harbin, China.

Montero, M. J., De la Mata, J., Esteban, M., and Hermoso, E. (2015). "Influence of moisture content on the wave velocity to estimate the mechanical properties of large cross-section pieces for structural use of Scots pine from Spain," *Maderas. Ciencia y Tecnología* 17(2), 407-420. DOI: 10.4067/S0718-221X2015005000038

Mvondo, R. R. N., Meukam, P., Jeong, J., Meneses, D. D. S., and Nkeng, E. G. (2017). "Influence of water content on the mechanical and chemical properties of tropical wood species," *Results in Physics* 7, 2096-2103. DOI: 10.1016/j.rinp.2017.06.025

Oliveira, J., Wang, X., and Vidaurre, G. (2017). "Assessing specific gravity of young Eucalyptus plantation trees using a resistance drilling technique," Holzforschung 71(2), 137-145. DOI: 10.1515/hf-2016-0058

Panshin, A. J., Zeeuw, C. D., and Brown, H. P. (1970) *Textbook of Wood Technology*, McGraw-Hill, New York, NY, USA.

Shi, F., Tang, Q., and Wei, P. (2019). "Physical and mechanical properties of timber of *E. grandi* × *E. urophylla*," *Shaanxi Forest Science and Technology* 47(2), 15-18. DOI: 10.3969/j.issn.1001-2117.2019.02.004

Sun, H., Ji, X., Zhao, H., Yang, M., and Cong, X. (2018). "Physical and mechanical properties of *Robinia pseudoacacia* wood in artificial forests," *Journal of Beijing Forestry University* 40(7), 104-112. DOI: 10.13332/j.1000-1522.20180030

Sun, Y., Zhu, L., Wang, X., Yan, H., and Liao, C. (2012). "Research on rapid detection of larch wood modulus of elasticity based on micro-drilling resistance," *Hubei Agricultural Sciences* 51(11), 2348-2350. DOI: 10.14088/j.cnki.issn0439-8114.2012.11.014

Tian, Z., Wang, Z., Wang, J., Zhang, Z., Ge, P., Lv, Y., and Ren, H. (2017). "Classification in modulus of elasticity and mechanical properties of larch lumber in Mohe," *Journal of Northwest Forestry University* 32(3), 211-215. DOI: 10.3969/j.issn.1001-7461.2017.03.39

Wang, X., Chen, J., and Xia, D. (2013). "Research progress on elasticity modulus nondestructive examination of wood and glulam structures," *Journal of Central South University of Forestry & Technology* 33(11), 149-153. DOI: 10.14067/j.cnki.1673-923x.2013.11.005.

Wang, Z., Zhou, J., Gong, M., Chui, Y. H., and Lu, X. (2016). "Evaluation of modulus of elasticity of laminated strand lumber by non-destructive evaluation technique," *BioResources* 11(1), 626-633. DOI: 10.15376/biores.11.1.626-633

Williamson, G., and Wiemann, M. (2010). "Measuring wood specific gravity…correctly," *American Journal of Botany* 97(3), 519-524. DOI: doi:10.3732/ajb.0900243

Wu, F. (2018). "Research progress of microwave nondestructive testing technology for standing trees," *Forestry Machinery & Woodworking Equipment* 46(12), 9-14. DOI: 10.13279/j.cnki.fmwe.2018.0131

Xu, J., Lv, J., Bao, F., Xiao, J., Evans, R., Huang, R., and Xu, M. (2012). "Measuring wood properties by SilviScan-3^{TM} and its application in climate change research," *Progressus Inquisitiones de Mutatione Climatis* 8(2), 124-130. DOI: 10.3969/j.issn.1673-1719.2012.01.008

Yu, J., Chen, J., Shi, X., Niu, Q., Wan, J., and Li, T. (2017). "Research on the flexural performance of ancient wood based on the restoration of cultural relics," *Sciences of Conservation and Archaeology* 29(4), 62-66. DOI: 10.16334/j.cnki.cn31-1652/k.2017.04.008

Zhang, L. (2017). *Experimental Study on the Mechanical Properties of Wood and the Numerical Modeling Strategies of Wood*, Master's Thesis, Beijing Jiaotong University, Beijing, China.

Zhang, S., Luan, Q., and Jiang, J. (2017). "Genetic variation analysis for growth and wood properties of slash pine based on the non-destructive testing technologies," *Scientia Silvae Sinicae* 53(6), 30-36. DOI: 10.11707/j.1001-7488.20170604

Zhang, Y., Wang, J., Zhang, S., Zhang, J., Sun, X., and Zhu, J. (2010). "Relationship between the Pilodyn penetration and wood property of *Larix kaempferi*," *Scientia Silvae Sinicae* 46(7), 114-119.

Zhang, W. (2014). *Study on the Influence by Seasonal Changes to Mechanical Properties of Standing Tree Branches*, Master's Thesis, Northeast Forestry University, Harbin, China.

Zhu, L., Zhang, H., Sun, Y., and Yan, H. (2011). "Determination of mechanical properties of ancient architectural timber based on stress wave and micro-drilling resistance," *Journal of Northeast Forestry University* 39(10), 81-83. DOI: 10.13759/j.cnki.dlxb.2011.10.010

Zhu, L., Zhang, H., Sun, Y., and Yan, H. (2011). "Research status of non-destructive testing technology for wooden components of ancient architectures," *Forestry Machinery & Woodworking Equipment* 39(3), 24-27. DOI: 10.3969/j.issn.2095-2953.2011.03.005

Zhu, L. (2012). *Determining the Mechanical Properties of Ancient Architectural Timber with Stress Waves*, Master's Thesis, Beijing Forestry University, Beijing, China.

Zhu, L., Zhang, H., Sun, Y., Wang, X., and Yan, H. (2013). "Mechanical properties non-destructive testing of wooden components of Korean pine based on stress wave and micro-drilling resistance," *Journal of Nanjing Forestry University* (Natural Sciences Edition) 37(2), 156-158. DOI: 10.3969/j.issn.1000-2006.2013.02.028

Zhu, Y. (2018). *Experimental and Nondestructive Examination Studies on the Material Mechanical Properties of Chinese Fir Structural Timber*, Master's Thesis, Beijing Jiaotong University, Beijing, China.

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