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RELATIONSHIP BETWEEN THE DYNAMIC AND STATIC MODULUS OF ELASTICITY IN STANDING TREES AND SAWN LUMBERS OF *Paulownia fortune* PLANTED IN IRAN

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ABSTRACT

This paper aims to introduce a relationship between the dynamic modulus of elasticity in healthy standing trees of *Paulownia fortune* (planted in Iran) and the static modulus of elasticity in sawn wood. For this reason, a stress-wave non-destructive testing technique was carried out in longitudinal and transverse directions in 14 trees into two diameter classes (25-31 cm and 32-38 cm) at breast height and in logs at different height of stem to measure the stress wave speed and consequently, dynamic modulus of elasticity. Then, static modulus of elasticity of samples was calculated using 3-point bending tests in the sawn wood. The results revealed that the stress-wave speed and dynamic modulus of elasticity in logs of Paulownia are more than those of standing trees in longitudinal direction. Also, the diameter of the tree can significantly affect the stress wave velocity in standing trees and logs of Paulownia. Finally, a high correlation coefficient exists between static modulus of elasticity and dynamic modulus of elasticity (r= 0,68) in this tree.

Keywords: Modulus of elasticity, non-destructive testing, Paulownia, standing trees, stress-wave.

INTRODUCTION

In Iran, the available forest area is exceptionally limited, and consequently, the commercial volume of trees and sawn wood (that are available for commercial purposes and industrial applications) has created a special challenge for many groups, including the government and private sectors. The Iranian government has therefore established some road maps to increase the source of cellulosic materials and forest areas. This aim can only be achieved by employing (1) scientific silviculture and forest management to control the size, age, and quality of trees; (2) technological properties of their proceed woods; and (3) sustainable forest resources (Baar *et al.* 2015, Ghanbari *et al.* 2014, Macdonald and Hubert 2002).

Paulownia is considered as a suitable alternative because of its ease of regeneration, rapid growth rates, nearly short-term harvesting cycle, continuous availability, and ecological compatibility (Miri Tari and Madhoushi 2013) (Figure 1). *Paulownia fortune*, which is a native species to China, Laos, and Vietnam, is imported to Iran, where limited studies during the last 20 years have shown its considerable properties and its ecological compatibility with conditions in Iran.

Non-destructive testing (NDT) techniques have contributed immensely to the control and management of wood quality and the health assessment of standing trees, helping to avert their cutting down

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and destruction (Seidel *et al.* 2011, Tomazello *et al.* 2008). One of the most commercial NDT techniques is the stress wave method, which has been developed to predict the mechanical properties and grading of timber and wood products (Guntekin *et al.* 2012, Guntekin *et al.* 2014); evaluate the strength of standing trees, logs, and lumber (Grabianowski *et al.* 2006), and enhance the scientific management of standing trees (Auty and Achim 2008).

The passing of stress waves within wooden materials is a dynamic phenomenon, and longitudinal, shear, and surface waves are different types of waves that can be released in wood and analyzed and affiliated with mechanical properties, namely the dynamic modulus of elasticity (Beall *et al.* 2001). Assessment of the MOE_d of trees or wood using stress wave NDT could be used to survey and follow the process of decay in trees, logs, and lumber. In comparison with sound wood, MOE_d is lower in decayed wood and decreases more with advanced stages of decay. The measurement of the MOE_d helps to determine the decayed parts of trees, logs, and lumber, and assists in the follow-up of the decay process (Brazee *et al.* 2011, Lawday and Hodges 2000, Schubert *et al.* 2009, Wang *et al.* 2004, Wang *et al.* 2005).

Previous research has demonstrated a good (0,44 to 0,89) (Madhoushi and Daneshvar 2016) or better correlation (Divos and Tanaka 2005) between the MOE_d in trees and logs than the MOE_s of the sawn wood. Moreover, the stress wave velocity of a standing tree might be higher or lower than in its logs or lumber (Wang 2013) depending on the species, direction of fiber (longitudinal or transverse), site, tree diameter, and measuring methods. For instance, the speed of the stress waves is generally higher in the longitudinal direction than in the transverse direction, and it is typically higher in hardwood than in softwood (Wang *et al.* 2005).

Given that primary studies on the stress wave measurement of standing trees have been extensively conducted on the area of the trees located at breast height (130 cm), the application and extension of the results to the whole stem is questionable. For example, a report published on *Populous deltoides* indicates that the amount of transverse MOE_d increases considerably at the upper part of stem, while the longitudinal MOE_d decreases slightly (Madhoushi and Daneshvar 2016). Nevertheless, the results of recent studies have demonstrated that the trend could not be universalized across all species (Hidayati *et al.* 2013, Ishiguri *et al.* 2013, Zhang *et al.* 2011). More research is therefore necessary to establish sufficient data on the variation of the MOE_d in the length of the tree stem.

This study aims to determine the MOE_d in standing trees and logs of 20 years *Paulownia fortune* (grown in Iran) and examine its relationship with the MOE_s of sawn wood. This relationship is investigated at three stem heights, from the base to the top, and the effect of the tree diameters will be demonstrated. This study also aims to introduce and expand this technique for forestry management and scientific silviculture in Iran.

MATERIALS AND METHODS

Standing tree measurement

To measure the stress wave parameters of standing trees, Shastkalateh forest, an educational and research area in Gorgan (northern part of Iran) was selected as the study site. Fourteen healthy standing trees of 20 years Paulownia (*Paulownia fortune*), were designated randomly into two diameter classes (25-31 cm and 32-38 cm) at the breast height. In this forest, Paulownia trees have been planted and grown under a controlled plan by the Gorgan University Department of Forestry. For this reason, all Paulownia trees have been identified with associated technical records, and older trees have greater diameters than the younger trees.

According to previous studies, the density of wood of these trees is 290 kg/m^3, with negligible differences among them, nevertheless, the density of wood was measured in all fourteen trees via unique samples for each tree.

Stress-wave velocities were measured in transverse and longitudinal directions using Electronic

Hammer IML® equipment, that included two probes, two electronic screws, and two electronic sensors (start and stop sensors), a portable two-channel digital analyser, and a handheld electronic hammer. In the longitudinal direction, sensors were inserted 50 cm above and below the breast height (130±50) (Figure 1a) and measurement was done in two northern side and southern side of the trees. To measure the stress-wave speed in the transverse direction, two probes were installed radially at breast height (Figure 1b, Figure 1c), and measurement were conducted in two directions, north-south and east-west.

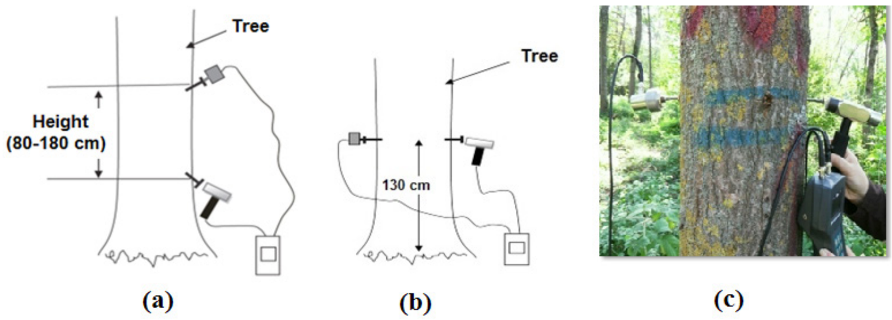

Figure 1: Schematic of tree measurement using stress wave NDT (a) longitudinal direction, (b) transverse direction and (c) real photo.

Measurement of logs

The measured standing trees were cut down and three logs in length of 100 cm were separated from each tree and defined as L1: 80-180 cm, L2: 180-280 cm, and L3: 280-380 cm. Measurement of logs was done nearly 2 weeks after trees cutting down and wave speed was evaluated in the middle of the logs in both the radial and longitudinal directions (Figure 2). Thereafter, the MOE_d was calculated for standing trees and logs according to Equation 1.

$$MOE_d = \rho V^2 \quad (1)$$

where MOE_d: dynamic modulus of elasticity (Pa), ρ: wood density (kg/m^3), and V: stress wave velocity (m/s).

For greater confidence, the density of the samples was measured which was equal to 290 kg/m^3.

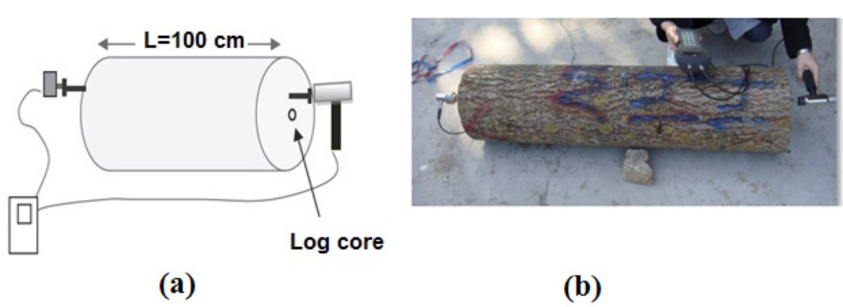

Figure 2: (a) Schematic and (b) real photo of log measurement using stress wave NDT.

Lumber measurement

The logs were then cut into small specimens with dimensions of 5×5×76 cm, followed by conditioning at 12% MC according to ASTM-D-143-94 (2007) standard. Several specimens were selected from each log in 4 geographical directions. The clear wood was selected with tangential patterns without defects and spiral grain. Finally, three-point bending tests were carried out on the samples to measure the modulus of elasticity (MOEs) using Equation (2):

$$MOE_s = \frac{P_{pl}L^3}{(4\Delta_{pl}bh^3)} \qquad (2)$$

where MOE_s: static modulus of elasticity, L: span (m), P_{pl}: proportional limit load (N), Δ_{pl}: proportional limit displacement (mm), b: width of sample (m), and h: thickness of sample (m).

RESULTS AND DISCUSSION

Stress-wave velocity

Table 1 shows the stress-wave velocities obtained from all standing trees. In general, the stress-wave speed in the longitudinal direction (2304 m/s) is greater than that in the transverse direction (1079 m/s), which might be attributed to the parallelism of the longitudinal wave with the fiber axis. These results are in line with the results of (Madhoushi and Daneshvar 2016) which showed that the particle oscillations are parallel to the direction of longitudinal wave propagation, whereas they are perpendicular to each other in transverse or shear waves.

Moreover, the speeds of both stress waves (longitudinal and transverse) in logs are greater than those in standing Paulownia trees (Figure 3, Table 1), which is consistent with previous report by (Madhoushi and Daneshvar 2016) and in spite of the other species such as the Scots pine (*Pinus sylvestris* L.), reported by (Auty and Achim 2008). This increase might be attributed to the moisture amount of wood in trees, which is naturally higher than that in logs. Previous findings reported that humidity is one cause of reduced wave speed in trees (Brashaw *et al.* 2004).

Moreover, the speed of stress wave in both longitudinal and transverse directions varies slightly from bottom to top of stem. It can be observed that the longitudinal stress wave increases at upper part of stem, however, the transversal stress wave after an increase in L1 decreases at upper parts. These results are consistent with previous results reported by (Ishiguri *et al.* 2013, Madhoushi and Daneshvar 2016), who demonstrated that speed of stress wave depends on the location of the stem. The reason for this variation in a transverse direction might be related to lower amount of wood materials at the upper parts of the stem.

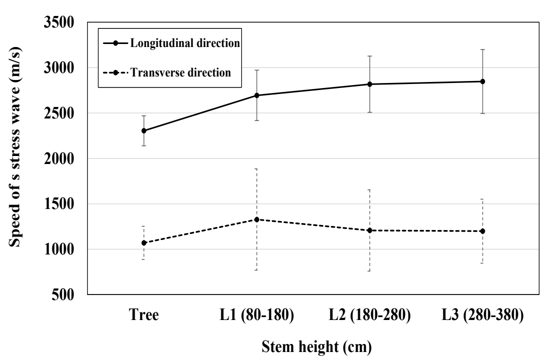

Figure 3: Stress wave velocity in trees and logs of Paulownia wood.

Table 1: Stress wave velocity (m/s) in standing trees and logs in longitudinal and transverse directions.

No.	Standing tree		L1		L2		L3	
	Long	Trans	Long	Trans	Log	Trans	Long	Trans
1	2409	1307	2683	1361	2855	861	3145	894
2	2101	1177	2551	1377	3008	1754	2959	1752
3	2407	1101	3107	2381	3223	2011	3138	1256
4	2276	1297	2865	1985	2983	1037	2889	1165
5	2482	735	3091	1900	2524	1956	3033	1796
6	2382	913	3075	1010	3193	833	2477	1588
7	2244	1083	2463	1392	3240	1227	3141	974
8	2017	1254	2332	978	2536	997	2531	893
9	2323	1090	2775	2089	2645	1737	3141	1643
10	2410	913	2506	902	2653	981	2540	960
11	2356	1015	2740	578	3146	839	3139	852
12	2286	1284	2423	964	2500	923	2646	956
13	2557	1013	2811	851	2538	877	2773	1206
14	2006	807	2291	1361	2388	870	2301	853
Averae	2304	1070	2694	1327	2817	1207	2847	1199
SD	165,2	±183	±278	±559	±309	±448	±298	±352

L1, L2, L3: Stem height, L1: 80-180 cm, L2: 180-280 cm, and L3: 280-380 cm.

Dynamic modulus of elasticity (MOE_d)

The results presented in Table 2 show that, in tree, the average amount of MOE_d in the longitudinal direction (1547 MPa) is higher than that in the transverse direction (359 MPa). Moreover, its magnitude in logs at the first height (S1) is significantly higher than that in standing trees, and its gradual increase can be seen at upper part of the stem. This trend can also be seen in transversal stress wave. The reason for this difference between tree and logs may be related to lower moisture content of logs (Wang *et al.* 2004), which in turns lead to higher speed of stress wave and MOE_d in logs compared to tree.

Table 2: Average dynamic modulus of elasticity (MPa) in standing trees and three heights of stem in Paulownia.

	Tree	L1	L2	L3
Longitudinal	1547 ± 216	2125 ± 437	2326 ± 509	2374 ± 482
Transverse	359 ± 128	633 ± 463	447 ± 364	268

L1, L2, L3: Stem height, L1: 80-180 cm, L2: 180-280 cm, and L3: 280-380 cm.

Effect of diameter

The mean value of the stress-wave speed is higher in logs of larger diameter (Figure 4) and this difference was statistically significant according to student's t-test. Thus, the MOE_d for diameter class 32-38 cm is more than that for diameter class 25-31 cm (Figure 5). This difference was also statistically significant. This might be due to large differences (wood amount) between two classes, and it is useful for practical purposes. These results are in line with those of (Wang *et al.* 2003, Wang *et al.* 2007), who found that the stress-wave speed increases in standing trees and logs with increase in diameter.

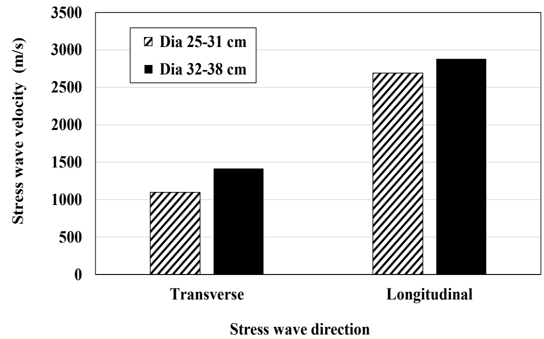

Figure 4: Effect of log diameter on stress wave velocity.

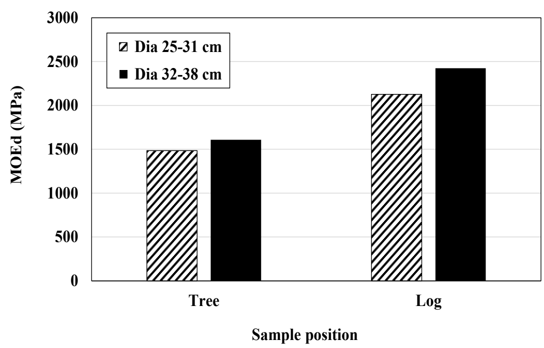

Figure 5: Effect of tree and log diameter on dynamic modulus of elasticity.

Static modulus of elasticity (MOE_S)

The results show that the mean value of modulus of elasticity of Paulownia wood is 5596 MPa (Figure 6). It shows that the strength of Paulownia is low and it can be considered as a weak wood. However, it is a fast-growing tree. It can be found that the modulus of elasticity increases slightly along the height of the stem. The reason for this variation in a transverse direction might be related to lower amount of wood materials at the upper parts of the stem. It might also may be affected by the diameter of the trees (Figure 7) because trees with larger diameters (32-38 cm) possess slightly higher MOE_s than trees with smaller diameters (25-31 cm). This finding shows that Paulownia trees planted in Iran require more time to grow to form a mature wood, is spite of poplar wood (Madhoushi and Daneshvar 2016). Generally, variation in the modulus of elasticity from bottom to top of stem depends on species, and in some species, there are similar trend, such as pine (Antony *et al.* 2011) and poplar (Madhoushi and Daneshvar 2016).

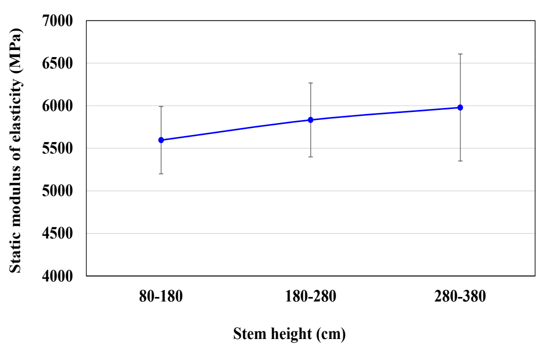

Figure 6: Modulus of elasticity in sawn wood of Paulownia.

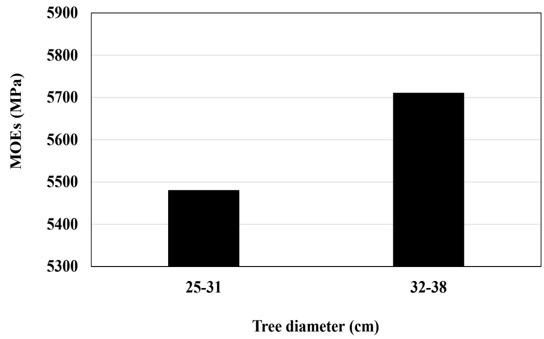

Figure 7: Effect of tree diameter on the static modulus of elasticity.

Relationship between MOE_d and MOE_S

Table 3 shows the degree of correlation between MOE_d in standing tree (as independent variable) and MOE_d in log at three levels (as dependent variable) in Paulownia. It can be found that the correlation between these two parameters is considerably strong only in longitudinal direction and in L1 (r=0,69) (Figure 8), and in transverse direction, all correlations are weak. It shows that NDT stress wave in transverse direction cannot be useful for prediction of properties. Strong correlation between these two dynamical parameters, which has also been reported for other species (Wang *et al.* 2000), can be very important from practical point of view, such as forest management and control of volume of wood production in trees.

Table 4 shows the degree of correlation between MOE_s (as dependent variable) of lumber and MOE_d in longitudinal direction (as independent variable) in standing tree of Paulownia. In addition, it can be observed that the general correlation between MOE_s of lumber and MOE_d in trees is considerably strong (r= 0,68) (Table 5). These results are consistent with the results of (Wang *et al.* 2004), who found that there is a good relationship between the MOE_d (in standing trees and logs) and MOE_s of lumber. This finding could be very useful for predicting MOEs by measuring MOE_d in the longitudinal direction in the standing tree.

It should be noted that the correlation between the MOE_d in tree (in transverse direction) and the MOEs was weak for all heights (Table 6). Therefore, this parameter cannot be useful for prediction of strength of lumber in Paulownia.

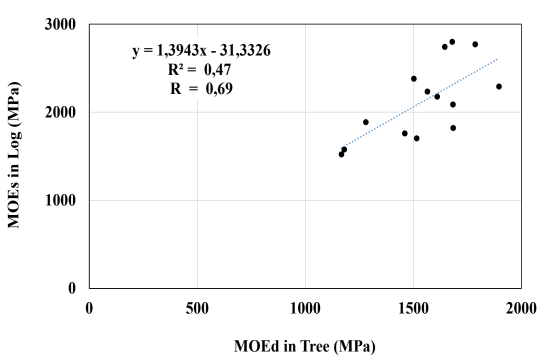

Figure 8: Relationship between MOE_d in tree and log (L1) in Paulownia.

Table 3: Correlation between MOE_d in standing tree and MOE_d in log at three levels in Paulownia.

Direction	MOE_d(x)	MOE_d(y)	$y = ax+b$	r^2	r
Longitudinal	Standing tree	L1	-1,394x+31,33	0,47	0,69
		L2	0,265x+1916	0,012	0,10
		L3	0,811x+1118	0,13	0,36
Transversal	Standing tree	L1	0,130x+585,7	0,001	0,031
		L2	-0,531x+667,5	0,034	0,18
		L3	-0,648x+682,6	0,095	0,30

L1, L2, L3: Stem height, L1: 80-180 cm, L2: 180-280 cm, and L3: 280-380 cm.

Table 4: Regression equations between MOE_d in longitudinal direction and MOE_s in Paulownia trough stem.

	$MOE_{d,l}$ (x)							
	Standing tree		L1		L2		L3	
MOEs(y)	r^2	r	r^2	r	r^2	r	r^2	r
L1	0,46	0,68	0,072	0,26				
	y= 1,25x+3665		y= 0,24x+5078					
L2	0,45	0,67			0,34	0,58		
	y= 1,36x+3725				y= 0,50x+4660			
L3	0,23	0,47					0,25	0,5
	y= 1,42x+3789						y= 0,66x+4415	

L1, L2, L3: Stem height, L1: 80-180 cm, L2: 180-280 cm, and L3: 280-380 cm.

Table 5: General relationship between MOE_d in longitudinal direction in tress and MOEs of lumber in Paulownia.

	Standing Tree		Log	
Lumber	r^2	r	r^2	r
	0,47	0,68	0,45	0,67
	y=1,342x + 3726		y=0,763x+4066 + 3726	

Table 6: Regression equations between MOE_d in transverse direction and MOE_s in Paulownia.

(x)	(y)	$y=ax+b$	r^2	r
MOE_d (tree)	MOE_d (log)	0,130x+585,7	0,001	0,032
MOE_d (tree)	MOE_s (lumber)	0,0957x+5630	0,001	0,032

CONCLUSIONS

The following conclusions could be drawn from this work in determining the correlation between the MOE_d in the logs and standing trees of Paulownia and the MOEs of lumber in both the transverse and longitudinal directions:

The stress-wave speed in logs (2125 m/s and 633 m/s) of Paulownia are more than that for standing trees (1547 m/s and 359 m/s) in both longitudinal and transvers direction, respectively.

The diameter of the tree can significantly affect the stress wave velocity and MOE_d in standing trees and logs of Paulownia. Results revealed that the stress-wave speed and consequently, MOE_d is statistically significant in trees and logs of larger diameter. As the MOEs of Paulownia is considerably low (approximately 5600 MPa), Paulownia can be considered as a wood that is low in weight and strength. Nevertheless, it is a fast-growing tree, which is an advantage for developing a forest area.

Paulownia trees (planted in Iran) with larger diameters (32-38 cm) possess higher MOEs, in comparison to trees with smaller diameters (25-31 cm).

The correlation coefficient between the MOE_d of the standing tree (in longitudinal direction) and the MOE_s of sawn lumber is considerably high (r= 0,68). This finding is useful for the silvicultural operations and forestry management of this species. In addition, a strong correlation exists between the MOE_d of the standing tree (in longitudinal direction) and logs of Paulownia. These findings can be used for assessing the mechanical properties of logs and lumber directly from the standing tree using the stress wave NDT. The correlation coefficient between the MOE_d of the standing tree (in a transverse direction) and the MOE_s of sawn lumber is considerably low (r=0,032), which shows that the stress wave NDT in a transverse direction cannot be considered useful for assessing the mechanical properties of logs and sawn wood in Paulownia.

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