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Article

Maturation Stress and Wood Properties of Poplar (*Populus × euramericana* 'Zhonglin46') Tension Wood

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Abstract: Understanding maturation stress and wood properties of poplar tension wood are critical for improving lumber yields and utilization ratio. In this study, Released Longitudinal Maturation Strains (RLMS), anatomical features, physical and mechanical properties, and nano-mechanical properties of the cell wall were analyzed at different peripheral positions and heights in nine inclined, 12-year-old poplar (*Populus×euramericana* 'Zhonglin46') trees. The correlations between RLMS and wood properties were determined. The results showed that there were mixed effects of artificial inclination on wood quality and properties. The upper sides of inclined stems had higher RLMS, proportion of G-layer, bending modulus of elasticity, and elastic modulus of cell wall but lower microfibril angle than the lower sides. At heights between 0.7 m and 2.2 m, only the double wall thickness increased with height, RLMS and other wood properties such as fiber length and basic density fluctuated or changed little with height. RLMS was a good indicator of wood properties in the tension wood area and at heights between 0.7 m and 1.5 m. The results of this study present opportunities to identify and select better quality wood in poplar trees.

Keywords: released longitudinal maturation stresses; wood properties; *Populus × euramericana* 'Zhonglin46'; tension wood; peripheral positions; heights

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1. Introduction

Tree growth stress is a result of cell wall maturation during growth, helping keep trees up-right against disturbance by gravity or wind [1]. 'Abnormal' cell growth enhances the strength of tree trunks and controls their growth orientation [2,3]. Growth stress also act as a pre-stressing system which can reduce the risk of axial buckling of fiber [4].

The thickening in the secondary cell wall generates mechanical stresses at the periphery of the trunk mostly along the stem axis [5]. When reaction wood is produced in inclined stems and/or branches, the distribution of stress across the cross section is heterogeneous [6–8] whereby greater stress on one side generates a bending moment to facilitate gravitropism in stems [9]. Eccentric growth and stiffness heterogeneity help to optimize this process [10]. In angiosperms, tension wood is generated on the upper side to restore the trunk to the upright position [11]. Some temperate-zone hardwood species such as *P. euramericana* contain a gelatinous (G) layer with the characteristics of high tensile growth stresses and low microfibril angle (MFA) values [12] which in turn affects wood strength properties and quality.

Growth stress affects timber production, causing problems such as radial splitting at the log edges and bowed/twisted sawn planks [13,14]. Reaction wood can cause serious defects which can cause economic losses across the lumber industry [3]. Understanding tree growth stresses and reaction wood, their distribution, wood properties are interesting not only for ecophysiology but also necessary in the field of wood quality, timber conversion and engineering.

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Numerous studies have highlighted the influence of growth stress levels on the properties of tension wood in Poplar [15], Beech [16], Eucalyptus [17], and Chestnut [18], with most focusing on the microscopic and macroscopic level. Very few studies were reported on the relationship between growth stress and properties of wood at the nanometer level of tension wood. Nanoindentation can be used to characterize mechanical properties of wood such as elastic modulus and stiffness of cell wall [19–21].

Poplars (*Populus* sp.) are the most common in commercially important hardwoods in China [22], several species such as *P. euramericana* 'Zhonglin46' are commonly used in the plywood, solid wood, and paper industries [23,24]. But their stems are susceptible to tension wood formation [15,25]. It is therefore necessary to assess the levels and distribution of growth stresses to increase sawn lumber yields and utilization ratio. Growth stress can be easily measured experimentally using the release method [26]. In this study the Released Longitudinal Maturation Strains (RLMS), anatomical features, physical and mechanical properties, and nano-mechanical properties of the cell wall were examined in leaning trees of *P. euramericana* 'Zhonglin46'. The objectives of this research were to (1) Identify the changes in maturation stresses and related wood properties along peripheral and vertical positions, (2) Determine and discuss the correlations between RLMS and wood properties.

2. Materials and Methods

2.1. Study site and tree information

The experimental site was located at Anhui Agricultural University in Hefei City, Anhui province, China (31°87′ N, 117°26′ E), with a subtropical humid climate and monsoon influence. The site is 20 m–40 m ASL, annual temperature range of 13°C–22°C, average annual temperature of 15.7°C, annual rainfall range of 794 mm–1523 mm, and average annual rainfall of 1000 mm. The sampled *P. euramericana* 'Zhonglin46' trees were spaced in a 3 m × 3 m configuration in a monoculture planted on a north-facing slope with soil type being yellow-brown soil.

In January 2021, a total of nine well-developed 12-year-old trees were selected for sampling. Figure 1 shows typical trees sampled. The trees were planted in 2009 and were artificially inclined to 15–60° for about one year to test the growth stress of seedings for another experiment. After the first year, the trees were allowed to grow naturally. The average tree height, DBH, and tilted angle of sampled trees are listed in Table 1.

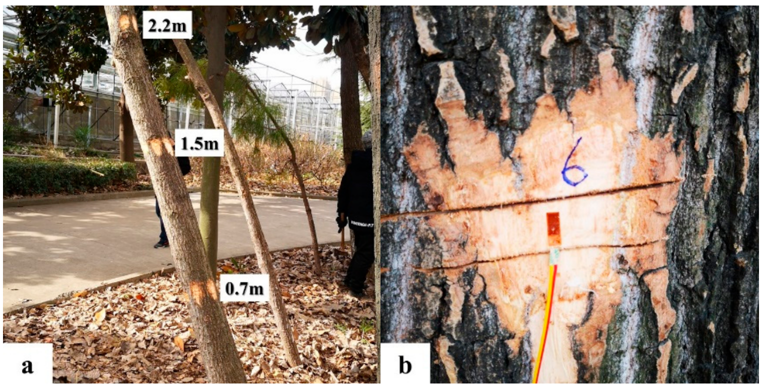

Figure 1. Image of sampled trees. **a.** Measuring points at three different heights of tree 5; **b.** Maturation strains released by strain gauges of tree 6.

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Table 1. Sample information of nine studied trees.

Tree number	Tree height (m)	DBH (cm)	Tilt angle from vertical position (°)
1	19.6	38.8	27
2	21.7	51.2	11
3	18.5	35.6	17
4	16.5	23.8	15
5	15.9	18.4	24
6	14.3	15.2	18
7	16.2	21.0	13
8	14.1	14.7	16
9	15.8	19.1	20

DBH: diameter at breast height.

2.2. Released Longitudinal Maturation Strains

RLMS was estimate using strain gauges [26,27] on seven measuring points of the leaning tree at three different heights vis. 0.7 m, 1.5 m, and 2.2 m from the ground (Figure 1a). In each sampled tree, the uppermost side was set as position 0°, seven positions were numbered in clockwise sequence at 50–60° intervals as 0°, 50°, 100°, 150°, -160°, -110°, and -60° around the trunk (Figure 2).

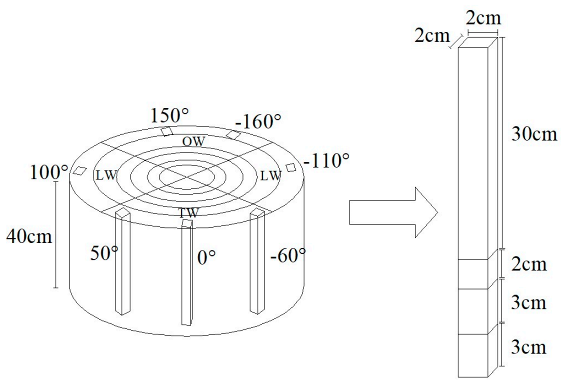

Figure 2. Schematic of measurement positions. TW: tension wood area (0°, 50°, and -60°); LW: lateral wood area (100° and -110°); OW: opposite wood area (150° and -160°).

Before testing, bark and cambium was removed using a knife and axe to expose fresh and smooth xylem zone with a size of about 5 cm × 5 cm. A 10 mm long electric-wire strain gauge (Sigmar Co., BSF120-6AA-T, Jinan, China) was glued securely to the exposed zone and was connected to a strain meter (Sigmar Co., ASMB2-16, Jinan, China). Then grooves with 5 mm depth were cut with a saw above and below gauges 5 mm (Figure 1b), RLMS values were recorded until the changed strain values remain stable.

2.3. Sampling of felled trees

After RLMS measurement all sample trees were felled for wood properties sampling. Eccentricity in diameter was calculated as:

$$\text{Eccentricity} = \frac{T_{TW}-T_{OW}}{T_{TW}+T_{OW}} \quad (1)$$

Where T_{TW} was the radius of the TW area, T_{OW} was the radius of the OW area.

Seven locations beneath the RLMS measurement positions at three different heights were marked on the trunk surfaces for further studies with 21 wood properties samples cut from each tree. Rectangular wood strips measuring 380 mm (longitudinal direction, L) × 20 mm (radial direction, R) × 20 mm (tangential direction, T) were cut along the axial of the stem. Specimens measured for

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standard physical and mechanical properties according to Chinese National Standard GB/T 1929-2009 [28]. Bending modulus of rupture (MOR) and bending modulus of elasticity (MOE) was measured on specimens measuring 300 mm (L) × 20 mm (R) × 20 mm (T) and basic density (BD) specimens were 20 mm (L) × 20 mm (R) × 20 mm (T). Two 30 mm (L) × 20 mm (R) × 20 mm (T) samples were cut to test compressive strength (CS) and anatomical features of the wood at each location.

2.4. Anatomical features

Fiber length (FL) was determined from 30 measurements of macerated fibers at each location. The specimens used to assess wood anatomical features measured 20 mm (L) × 10 mm (R) × 10 mm (T) and were pre-softened by microwaving for 5–10 min. Transverse sections 20 μm in thickness were sliced using a rotary microtome (Leica, RM 2265, Wetzlar, Germany) and double-stained with safranine and Astra-blue. This double-stained method can detect G fibers in tension wood (Figure 3). Sections were observed and thirty measurements each for double wall thickness (2WT) were made on each transverse section. The proportion of G-layer (PG) were counted and calculated on 20 randomly selected areas.

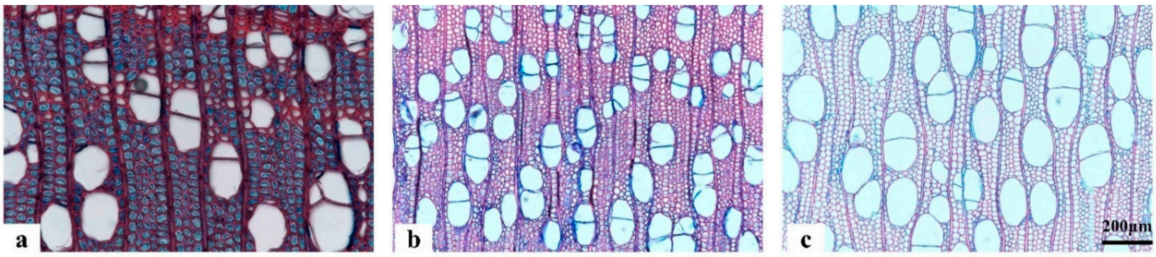

Figure 3. Light microscope view of anatomical sections of poplar tension wood. **a**. TW area; **b**. LW area; **c**. OW area.

MFA were measured through X-ray diffraction, with the size of 30 mm (L) × 0.5 mm (R) × 10 mm (T). The recorded data were then processed using the 0.6 T method [29].

2.5. Physical and mechanical properties

BD of wood specimens (20 × 20 × 20 mm^3) was measured following Chinese National Standard GB/T 1933-2009 [30].

MOR and MOE were tested on specimens measuring 300 × 20 × 20 mm^3 according to Chinese National Standard GB/T 1936.1, 1936.2-2009 [31,32]. Specimens measuring 30 × 20 × 20 mm^3 (LRT) were tested for CS according to Chinese National Standard GB/T 1935-2009 [33]. The mechanical properties were tested using a universal mechanical testing machine (Instron, 68TM-5, Boston, USA).

2.6. Nanoindentation test

The elastic modulus of cell walls (EC) was tested at different areas and heights. Three peripheral position specimens were chosen at a height of 1.5 m: TW specimen from position 0°, LW specimen from position 100°, and OW specimen from position -160°. Positions 0° was sampled at three heights: 0.7 m, 1.5 m, and 2.2 m.

Small wood blocks measuring 3 mm × 1 mm × 1 mm (LRT) were cut and equilibrated to -12% MC [21]. The blocks were then embedded in Spurr resin (SPI-Chem, USA). Then the blocks were cut to a pyramid shape and the top portion was polished by a semi-thin microtome (Leica, RM 2265, Wetzlar, Germany) using a glass knife and a diamond knife (SYM6050H, Japan). The nanoindenter (Bruker, Dimension ICON, Massachusetts, USA) and the Peak Force Quantitative Nanomechanical Mapping (PF-QNM) mode was used. A load-shift curve was obtained using the Derjaguin-Muller-Toporov (DMT) contact model [34]. The elastic modulus distribution of S1, S2, and G layers were obtained using Nanoscope Analysis software.

2.7. Statistical analyses

Statistical software SPSS 19.0 (IBM, NY, USA) was used to conduct ANOVA to determine significant differences in wood properties among peripheral positions and tree heights, followed by Duncan's means comparison tests at the 5% significance level. Correlation coefficients between RLMS and wood properties were calculated by correlation analysis.

3. Results

3.1. Released Longitudinal Maturation Strains

The RLMS values in all nine trees were negative meaning that longitudinal maturation stress was always tensile (Table 2). From Table 2 average RLMS values for positions and heights ranged from -0.16% and 0.00% with an overall mean of -0.04% (±0.03SD). Variation between peripheral positions and heights was large with an overall CV of 75%. ANOVA analysis detected significant differences in the RLMS among different peripheral positions ($p<0.001$), but no significant differences among different heights ($p>0.05$). Distribution of RLMS with peripheral positions and heights is shown in Figure 4. The upper sides (0° locations) had the largest RLMS, and the lower sides (corresponding to 150° or -160°) had the smallest values. Mean RLMS values changed little with height in trees.

Table 2. Basic statistics for measured parameters

Parameters	n	Average	SD	Max	Min	CV%
RLMS (%)	189	-0.04	0.03	-0.16	0.00	75.0
FL (μm)	7990	1302	227.71	2343	508	17.5
2WT (μm)	8698	5.73	1.34	11.69	2.50	23.4
MFA (°)	294	14.90	6.83	34.10	0.10	45.8
PG (%)	189	20.3	22.5	68.8	0.0	110.9
BD (g/cm^3)	189	0.37	0.03	0.50	0.31	8.1
MOE (MPa)	189	4224	444.80	5776	3273	10.5
MOR (MPa)	189	49.42	5.47	64	24	11.1
CS (MPa)	189	35.52	4.29	47	22	12.1

n: number of samples; SD: standard deviations; Max: maximum value; Min: minimum value; CV%: coefficient of variation. RLMS: Released Longitudinal Maturation Strains; FL: fiber length; 2WT: double wall thickness; PG: proportion of G-layer; MFA: microfibril angle; BD: basic density; MOE: bending modulus of elasticity; MOR: bending modulus of rupture; CS: compressive strength.

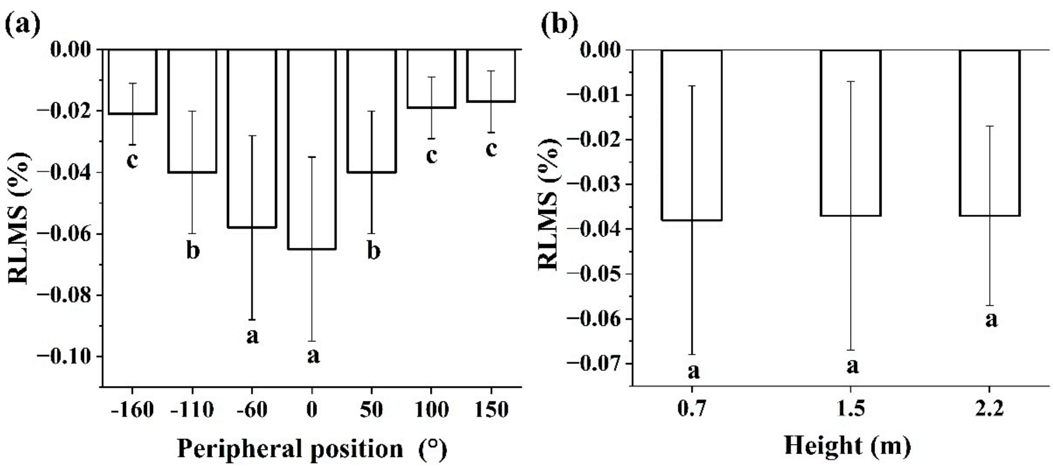

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Figure 4. Distributions of RLMS with peripheral positions (**a**) and heights (**b**). Different letters indicate significant differences according to Duncan's means comparison tests in p<0.05. RLMS: Released Longitudinal Maturation Strains.

3.2. Anatomical properties

The anatomical parameters from the nine sampled trees are listed in Table 2. The minimum value of MFA was 0.1° which was much lower than the average values. CV for MFA was 45.8%. The mean values of PG ranged between 0.0% and 68.8%, with highest CV of 110.9%. There was significant variation in FL, 2WT, MFA, and PG (p<0.001) with peripheral position around the trunk (Figure 5). MFA was significantly lower on the upper side of the trunk than the underside. The upper side of the trunk showed a high proportion of PG. FL and 2WT did not show any specific trends with position.

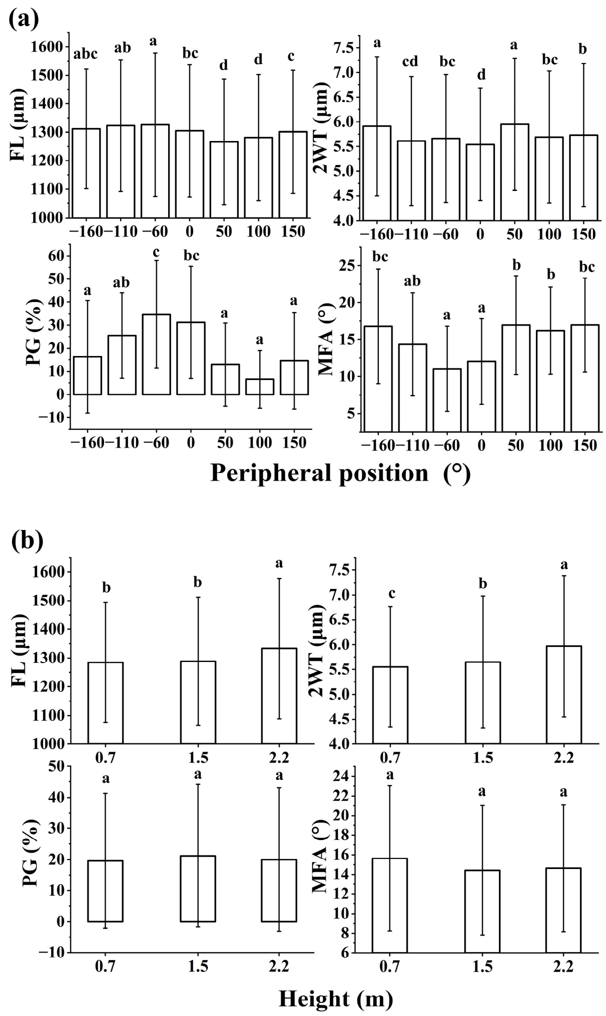

Figure 5. Distributions of anatomical measured parameters with peripheral positions (**a**) and heights (**b**). Different letters indicate significant differences according to Duncan's means comparison tests in p<0.05. FL: fiber length; 2WT: double wall thickness; MFA: microfibril angle; PG: proportion of G-layer.

There was significant variation in FL and 2WT (p<0.01) with height except in MFA and PG (p>0.05). At heights between 0.7 m and 2.2 m, 2WT increased with height, but other anatomical parameters fluctuated or changed little with height.

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3.3. Physical and mechanical properties

The physical and mechanical properties of wood from the sampled trees are listed in Table 2. There were significant differences in MOE among positions ($p<0.001$) but no significant differences in BD, MOR, and CS ($p>0.05$). MOE values were significantly higher on the upper sides of the stem (Figure 6). BD, MOR and CS fluctuated or showed little change with positions. With the increase of height, BD, MOE, MOR, and CS showed little variation. There were no significant differences in BD, MOE, MOR, and CS among heights ($p>0.05$).

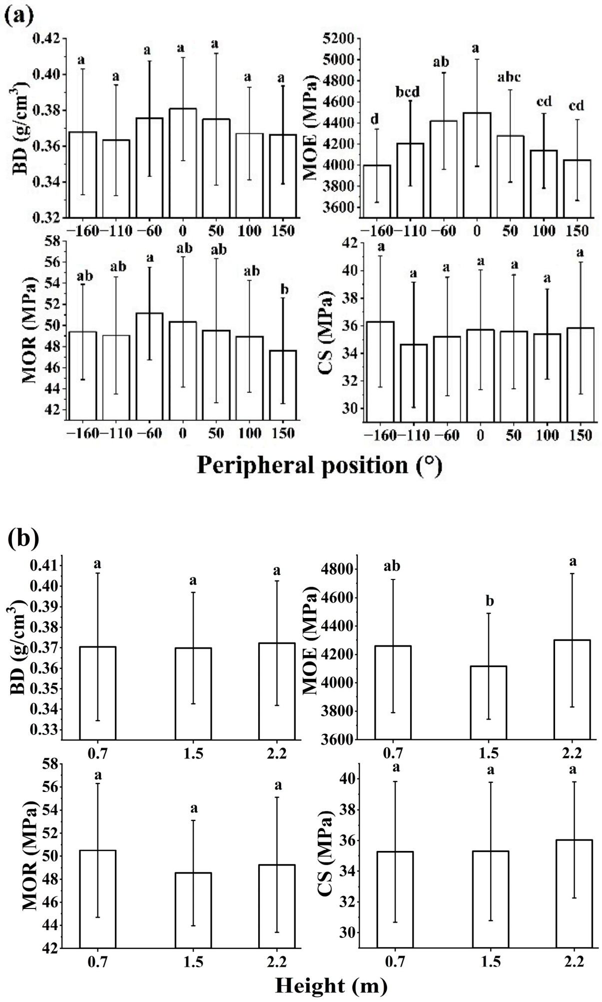

Figure 6. Distributions of physical and mechanical properties with peripheral positions (**a**) and heights (**b**). Different letters indicate significant differences according to Duncan's means comparison tests in $p<0.05$. BD: basic density; MOE: bending modulus of elasticity; MOR: bending modulus of rupture; CS: compressive strength.

3.4. Elastic modulus of cell wall

The elastic modulus of each wall layer in wood fiber cells in the TW-tension wood area, LW-lateral wood area, and OW-opposite wood area was characterized by AFM using the PF-QNM mode. As can be seen in Figure 7, the fibers of TW and LW contained a G-layer, but no G-layer was found in OW cells. There were clear differences in elastic modulus among three layers (Table 3, Figure 7). In TW and LW areas the average elastic modulus of the G-layer was higher than S2 and S1 layer. In the OW where the G-layer was absent the average elastic modulus of the S2 layer was larger than the S1 layer. The average elastic modulus of TW area was higher (13.9 GPa) than LW area (13.3 GPa) and the OW area (10.4 GPa). Cell wall elastic modulus was significantly different between TW, LW and OW areas ($p<0.05$).

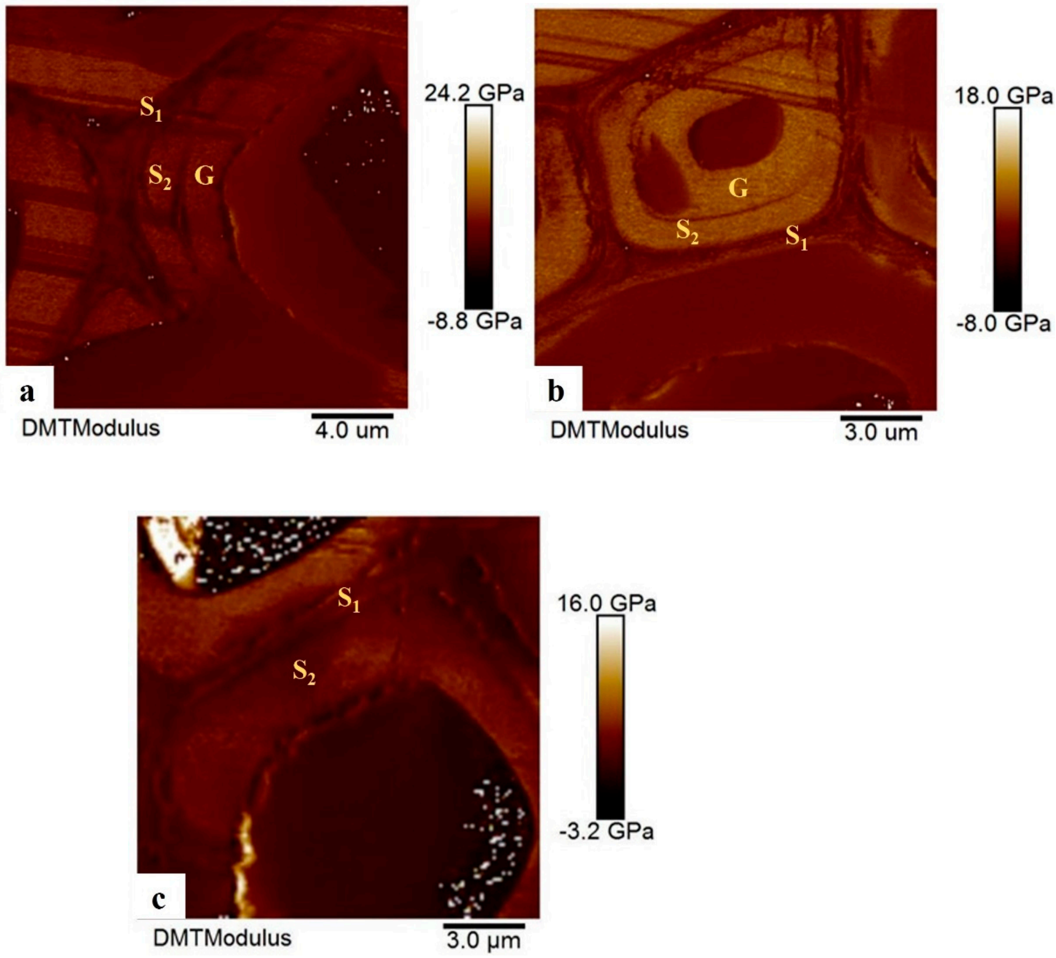

Figure 7. Elastic modulus of cell wall layer in DMT mode. **a**. TW area, **b**. LW area, **c**. OW area.

Table 3. Means and standard deviations of elastic modulus (in GPa) of cell wall at different areas.

	TW	LW	OW
S1	9.5±1.41 [a]	9.4±1.24 [b]	8.6±1.52 [c]
S2	15.6±2.51 [a]	15.1±2.53 [b]	12.2±2.60 [c]
G	16.6±3.15 [a]	15.5±2.98 [b]	N.A.

Different letters indicate significant differences according to Duncan's means comparison tests in $p<0.05$.

The elastic modulus of the cell walls at different heights: 0.7 m, 1.5 m, and 2.2 m are shown in Figure 8, and the elastic modulus values for each wall layer are summarized in Table 4. Since these samples were chosen from position 0° the G-layers could be observed. There was variation among S1, S2, and G-layer, and average elastic modulus of cell walls at 0.7 m was slightly higher than 1.5 m and 2.2 m, but the difference was not significant between heights ($p>0.05$).

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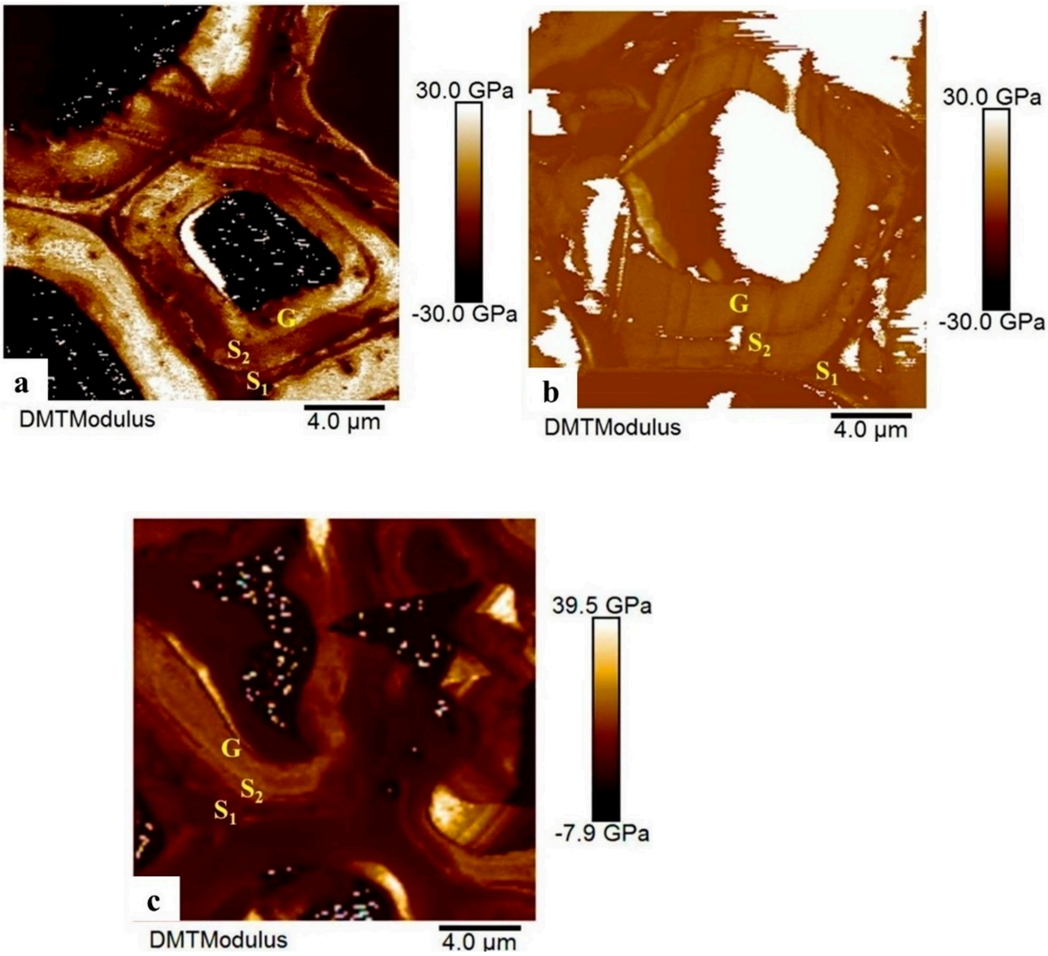

Figure 8. Elastic modulus of cell wall layer in DMT mode. **a**. 0.7 m, **b**. 1.5 m, **c**. 2.2 m.

Table 4. Means and standard deviations of elastic modulus (in GPa) of cell wall at different heights.

	0.7 m	**1.5 m**	**2.2 m**
S1	9.4+1.98 [a]	9.3+1.59 [a]	9.2+1.43 [a]
S2	12.1+2.35 [a]	11.3+2.44 [a]	11.6+2.53 [a]
G	13.1+3.21 [a]	12.8+2.38 [a]	13.0+2.57 [a]

Different letters indicate significant differences according to Duncan's means comparison tests in $p<0.05$.

3.5. Relationships between Released Longitudinal Maturation Strains and wood properties

Pearson correlation coefficients between RLMS and wood properties for peripheral positions were calculated and listed in Table 5. In the TW zone a positive correlation was found between RLMS and PG, BD, MOE, MOR and EC and a significant negative correlation was found between RLMS and MFA. In the LW zone a significant positive correlation was found between RLMS and FL and BD and a significant negative correlation was found between RLMS and CS. In the OW zone a significant positive correlation was found between RLMS and MFA and a significant negative correlation was found between RLMS and PG. There were no significant correlations between RLMS and other wood properties.

Table 5. Results of correlation analysis between RLMS and wood properties among different peripheral positions.

	TW (0°, 50°, -60°)			LW (100°, -110°)			OW (150°, -160°)		
	p	**Sig.**	**df**	**p**	**Sig.**	**df**	**p**	**Sig.**	**df**
FL	-0.071	ns	81	0.270	*	54	0.185	ns	54
2WT	0.14	ns	81	0.146	ns	54	0.176	ns	54
PG	0.386	**	81	0.234	ns	54	-0.290	*	54
MFA	-0.482	**	81	-0.078	ns	54	0.323	*	54
BD	0.267	*	81	0.340	*	54	-0.169	ns	54
MOE	0.322	**	81	0.205	ns	54	0.144	ns	54
MOR	0.303	**	81	0.144	ns	54	0.159	ns	54
CS	0.027	ns	81	-0.269	*	54	-0.137	ns	54
EC	0.955	**	9	0.523	ns	9	0.643	ns	9

RLMS: Released Longitudinal Maturation Strains; FL: fiber length; 2WT: double wall thickness; PG: proportion of G-layer; MFA: microfibril angle; BD: basic density; MOE: bending modulus of elasticity; MOR: bending modulus of rupture; CS: compressive strength; EC: elastic modulus of cell wall; ns: Non-significant; *: Significant at 0.05 level; **: Significant at 0.01 level.

Pearson correlation coefficients between RLMS and wood properties at different heights were calculated and listed in Table 6. At the height of 0.7 m, a significant positive correlation was found between RLMS and 2WT, PG, BD, MOE, and MOR, and a significant negative correlation was found between RLMS and MFA. At the height of 1.5 m, a significant positive correlation was found between RLMS and FL, PG, BD, MOE, and MOR. At the height of 2.2 m, a significant positive correlation was found between RLMS and MOE, a significant negative correlation was found between RLMS and EC. There were no significant correlations between RLMS and other wood properties.

Table 6. Results of correlation analysis between RLMS and wood properties among different heights.

	0.7 m			1.5 m			2.2 m		
	p	**Sig.**	**df**	**p**	**Sig.**	**df**	**p**	**Sig.**	**df**
FL	-0.081	ns	63	0.265	*	63	-0.059	ns	63
2WT	0.345	**	63	0.065	ns	63	0.023	ns	63
PG	0.312	*	63	0.393	**	63	0.24	ns	63
MFA	-0.393	**	63	-0.179	ns	63	-0.075	ns	63
BD	0.258	*	63	0.338	**	63	0.159	ns	63
MOE	0.429	**	63	0.497	**	63	0.352	**	63
MOR	0.444	**	63	0.252	*	63	0.066	ns	63
CS	-0.109	ns	63	-0.105	ns	63	-0.04	ns	63
EC	0.647	ns	9	0.005	ns	9	-0.773	*	9

RLMS: Released Longitudinal Maturation Strains; FL: fiber length; 2WT: double wall thickness; PG: proportion of G-layer; MFA: microfibril angle; BD: basic density; MOE: bending modulus of elasticity; MOR: bending modulus of rupture; CS: compressive strength; EC: elastic modulus of cell wall; ns: Non-significant; *: Significant at 0.05 level; **: Significant at 0.01 level.

4. Discussion

Wilson and Gartner [35] reported that growth stress increased with lean on the top side and Yoshida et al. [36] found growth stress increased from 0° (vertical) to 20°. As shown in Figure 9a the effect of inclination angle on maturation stress in artificially inclined poplar trees is limited ($p>0.05$), which was in contrast to previous studies. Analysis of the relationship between the mean RLMS on a tree and its eccentricity reveals significant relationships ($p<0.05$), as shown in Figure 9b. This means

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that eccentric growth increases the magnitude and heterogeneity of tensile RLMS. Eccentric growth, rigidity, and growth stress all increase the efficiency of controlling the orientation of tree axes [8,36]. Our results support the idea that gravitropism (ability to restore upright growth) in poplar trees is caused by synergistic effects of increased tensile growth stress and promotion of secondary growth on the upper side of the inclined stem [37]. The mean values of RLMS (-0.16%–0.00%) here are similar to those found in other studies on *Populus×euramericana* [15] and *Eucalyptus grandis-urophylla* [38].

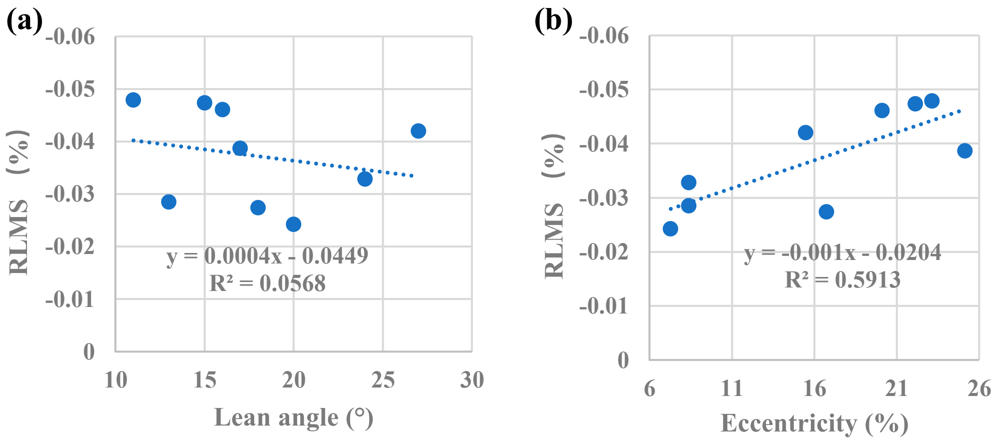

Figure 9. (**a**) Relationship of RLMS to lean angle in inclined trees, regression coefficients were not significant (p=0.53). Mean lean angle and SD=17.9°±5.11. (**b**) Relationship of RLMS to eccentricity in leaning trees, regression coefficients were significant (p=0.01). Mean eccentricity and SD=16.3%±6.90.

RLMS were significantly different between peripheral positions, which is interpreted as an adaption enabling them to re-orient the stem to vertical growth [37]. The effect of sampling height was not significant which consistent with findings by Li et al. [25] for *Populus × euramericana* cv. '74/76' trees. Huang et al. [39] also found no obvious relationship between height in tree and measured surface strains in the axial direction in *Zelkova serrata*. Other studies suggest growth stresses do vary with sampling height e.g., Omonte and Valenzuela [40] found that growth stress indicators at different height were highly variable in the case of *Eucalyptus nitens*. Naghizadeh and Wessels [38] reported that growth strains decreased from 1.4 m to 11.4 m in *Eucalyptus grandis-urophylla* trees.

Results from this study found no significant difference in fiber length between tension wood and normal wood, in accord with findings by Scurfield and Wardrop [41]. Fang et al. [15] reported the cell wall thickness increased in mild and severe tension wood areas. However, in this study, 2WT in the upper side tension wood were similar to those in wood cells from the other positions. MFAs range from 15°–30° in S2 layer, and 0°–2.5° in G-layer [42]. Our results accordingly showed low MFAs on the upper side and larger MFAs on the lower side of the poplar trunks. The smaller the microfibril angle, the larger the longitudinal tensile stress [7,43,44]. PG has been shown to be greater on the upper side, which can trigger big tensile stress for the vertical recovery of stems [2,45].

In accord with previous works, our findings showed BD remains unchanged between tension and normal wood [46]. Higher MOE, MOR, and CS on the upper side has been observed in *Picea asperata*, *Cecropia sciadophylla* [19,44]. In this study only MOE followed the same trend but MOR and CS showed minimal change. The higher wood MOE and elastic modulus of the cell wall in TW area are believed to be related to the characteristics of the G-layer which include higher cellulose content and crystallinity, and lower microfibril angles [21].

Li et al. [47] found that with the axial height from 0 m to 11.3 m in *Catalpa bungei* trees, fiber wall thickness decreased. Wu et al. [20] found in triploid hybrids of *Populus tomentosa* that fiber length decreased with height between 2 m and 6 m. De Boever et al. [48] observed an increase in MOE, MOR, and density with tree height in hybrid poplar from 1.2 m, 6.5 m and 11.5 m which they attributed to changes in the ratio of heartwood to tension wood. Kijidani and Kitahara [49] found the MOE of *Cryptomeria japonica* wood to be greater and the MFA lower at 5 m height compared to at 1.5 m, while the wood BD and latewood tracheid length did not change with height. Lima Jr. et al. [50] found that MOE of *Eucalyptus grandis* wood increases with height of 3 m, 6 m and 9 m from the base. Himes et al. [51] found density, MOR and MOE of hybrid poplar lumber samples generally increased with height from 0 m to 10 m. In this study, lower heights (0.7 m, 1.5 m, and 2.2 m from the ground) were selected for RLMS and wood properties than other studies due to restricted electric-wire length and operational safety of measuring RLMS in living trees. Here only 2WT was found to increase with height, while FL and MOE fluctuated with no particular relationship with height, while RLMS, MFA, PG, BD, MOR, CS, and elastic modulus of cell wall did not change with sampling height in tree. Increased 2WT with height may be attributed to the thinning treatment over the 12-year growth period [52].

Many researchers have reported the correlations between growth stress/growth strain and wood properties [25,53], but the effects and correlations among different peripheral positions and heights are seldom reported or discussed. Correlations in the TW zone were stronger than in other zones. It should also be noted that the correlations at the different heights were quite different, there were significant correlations between RLMS and wood properties at 0.7 m and 1.5 m, while at 2.2 m correlations weakened considerably. Therefore, RLMS could be considered a good indicator of wood properties in the TW area of the bole below 1.5 m height.

5. Conclusions

The influence of peripheral positions and heights on Released Longitudinal Maturation Strains (RLMS), anatomical features, physical and mechanical properties, and nano-mechanical properties of the cell wall were assessed in this work. Correlations between RLMS and wood properties were also analyzed. The results showed that upper sides of the inclined trunks had higher RLMS, proportion of G-layer, bending modulus of elasticity, and elastic modulus of cell wall but lower microfibril angle than the other sides. These differences may be related to the existence of the G-layer in tension wood area. Sampling height in trunk had little effect on measured wood and cell characteristics, except for double wall thickness which tended to be lower closer to the base of trees (0.7 m, 1.5 m, and 2.2 m from the ground). RLMS showed strong correlations with wood characteristics in the tension wood zone and with height up to around 1.5 m.

In general, the artificial inclination in the trees had mixed effects on wood properties and quality. The variation observed in this study could be used to improve the conversion value of poplar logs by identifying which parts of the lower trunk produce better wood quality suitable for higher value or higher demand products such as plywood, solid lumber or certain paper products when isolated from the rest of the tree. Additional studies are required to evaluate the variability in longitudinal maturation strains and wood characteristics higher up in the trunk for appropriate selection strategies.

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