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ORIGINAL ARTICLE

Screw-nail withdrawal and bonding strength of paulownia (*Paulownia tomentosa* Steud.) wood

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Abstract The effects of screw type, moisture content, and grain direction on the screw and nail withdrawal strength and bonding strength were investigated for paulownia (*Paulownia tomentosa* Steud.) wood grown in Turkey. The withdrawal strength was carried out according to the ASTM-D 143 and ASTM-D 1761 and Turkish Standard 6094 in three directions (tangential, radial, and longitudinal) on 60 samples. The moisture content of half of the samples was 12 % and that of the other half 28 %.The experiment of bonding strength (BS EN 205) was applied to both sanded surfaces jointed by poly-vinly acetate and Desmodur-VTKA adhesives. Results of the tests indicate that, the withdrawal strength values at 12 % moisture content were higher than the 28 % for screws whereas the withdrawal strength for 28 % moisture content was higher than 12 % for nails. The maximum withdrawal strength value was found in the chipboard screw. In the case of directions, the withdrawal strength values of radial direction were found to be higher than the others for all parameters. The lowest withdrawal strength values were found in the longitudinal directions for both nails and screws. For adhesive types, the highest bonding strength of D-VTKA was found to be 5.64 N mm^{-2} and it was higher than the bonding strength with PVAc (5.33 N mm^{-2}). However, there were no significant statistical differences between the two adhesive types. The results show that paulownia wood can be used for different purposes such as house construction, roof systems, and box cases as it possesses enough strength.

Keywords *Paulownia tomentosa* · Screw · Nail · Withdrawal strength · Bonding strength

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Introduction

Paulownia (*Paulownia tomentosa* Steud.) is an exotic species in Turkey and under favorable environmental conditions, it grows 4–5 cm in a year [1–3]. The average value of specific gravity of the air-dried and oven-dried paulownia wood has been reported as 0.32 and 0.29 g cm^{-3}, respectively, and the standard deviation is 0.021 on either side. It was also reported that paulownia wood grown in Turkey and China has similar mechanical properties [1].

The timber of Paulownia dries quickly in open-air conditions and does not cause serious drying defects. The wood has high strength compared to the lightness, for example its tensile strength parallel to grain is approximately 1660 times of its density. It has also excellent machining and finishing properties [2, 4–6].

Some factors of the wood, especially type and thickness, have some effects on the structural rigidity of the furniture elements. It is common practice to use screws and nails to connect members in furniture making. Therefore, the determination of these withdrawal strengths for some wood types is important since the results depend on the natural properties of wood such as density [7].

Akyildiz and Malkocoglu [8, 9] evaluated the screw and nail withdrawal strengths for five different tree species (beech, alder, chestnut, spruce, and pine). Tests were conducted in compliance with the Turkish Standard (TS)

6094 [10] and ASTM-D 143 [11] and ASTM-D 1761 [12] standards at two different moisture contents (MC) (12 and 30 %). The dimensions of screw were 4.5 mm in diameter and 40 mm in length. For common wire nail, the dimensions were 2.5 mm in diameter and 50 mm in length. The 12 % MC had significantly higher withdrawal strength (WR) than the 30 % for screws. In the case of nail withdrawal, the 12 % had significantly lower WR than the 30 %. The WR values of radial surfaces were found to be higher than the others. The least withdrawal strength values were found in the cutting ends. On the other hand, the highest screw and nail withdrawal strengths were obtained in the oriental beech, among the five tree species. The least withdrawal strength was found in pine and spruce for nail and screw, separately [8, 9, 13].

Ferah [14] performed screw and nail withdrawal strength tests for seven tree species and two different moisture contents (12 and 30 %). The WR experiments for tangential surfaces were conducted in compliance with TS 6094 and ASTM-D1761 standards on seven wood species. They reported that the Uludag fir had the lowest screw WR, while the sessile oak had highest. Beech, red pine, black pine, and Lebanese cedar followed them, respectively.

The shear strength as the reference parameter in evaluating the adhesive bond strength of solid wood is considered to be the most common interfacial stress encountered under conditions of use [15, 16]. When the lap joint test method is carried out in compliance with EN 302-1 [17], a main disadvantage is that, for a given bond quality, the shear strength may exceed the shear strength of wood, which may lead to wood failure [15].

The usage of synthetic resins needs to take account of different wood materials used in the dry and humid environments. The synthetic resins are suitable for use in the workshop. In order to achieve higher bonding strength, future research should continue to develop and find new usage areas of glue [18, 19].

The main objective of this study was to determine the screw-nail withdrawal strength and bonding strength and explore where paulownia wood can be used.

Experimental

Wood samples

Wood of paulownia was selected from Kargı in Çorum, Turkey. Wood materials were selected, at 350–400 m altitude, free from resin and features such as knots, zone line, reaction wood, decay, insects, etc. in compliance with TS 2476 [20] standard. The logs were cut at breast highest, and they were 5–6 years of age. The wood samples for using tests were cut parallel to grain directions in a sawmill in compliance with TS 4176 [21] and stored in a condition room with temperature of 20 ± 2 °C and 65 ± 3 % relative humidity for 2 months before planning and cut into small specimens.

Preparation of experimental samples

Then small clear specimens were cut into 50 × 50 × 150 mm pieces for withdrawal tests and 5 × 50 × 400 mm pieces for bonding strength tests. Afterwards, half of these specimens were conditioned at 10 ± 2 °C and 95 ± 5 % relative humidity to reach 28 % moisture content (MC), and the other half were dried and conditioned at 20 ± 2 °C and 65 ± 5 % relative humidity to reach 12 % MC in a conditioning cabin throughout 8 weeks [22]. Two different moisture contents were selected to compare the withdrawal strength of samples in different moisture conditions.

Screws were driven into pilot holes, 70 % of the core diameter of screw and 13 mm depth, drilled on the face of the specimens. Six nails and six wood screws (semi-chamfer) and six chipboard screws (whole chamfer) for each sample were used for withdrawal tests (Fig. 1). In practice, only one screw and nail was inserted at a time and the insertion was 30 mm for both.

Bonding strength test specimens with dimensions 10 × 20 × 150 mm and with an average moisture content of 12 % were prepared in compliance with BS EN 205 [23] (Fig. 2). The experimental design for nail and screw withdrawal strength and bonding strength tested is provided in Table 1.

Adhesives

Polyvinyl acetate (PVAc) adhesive is usually preferable for the joining process in the furniture industry. The material used in this study was supplied from a producer firm-Polisan, and was used in accordance with TS 3891 [24].

The Desmodur-VTKA (D-VTKA) adhesive, a single component, PU-based, solvent-free, was used for assembly process. D-VTKA is especially recommended for application in locations exposed to high levels of humidity [25]. Approximately 150–200 g m^{-2} adhesive was applied to the bonding surfaces. Application press pressure and time was 0.2 N mm^{-2} and 24 h, respectively.

The experiments

Withdrawal testing was carried out following the ASTM-D 143-94 [11] and TS 6094 [10] standards. The loading speed was 2.5 mm min^{-1} for nails and screws. The loading continued until a separation occurred on the screw or nail

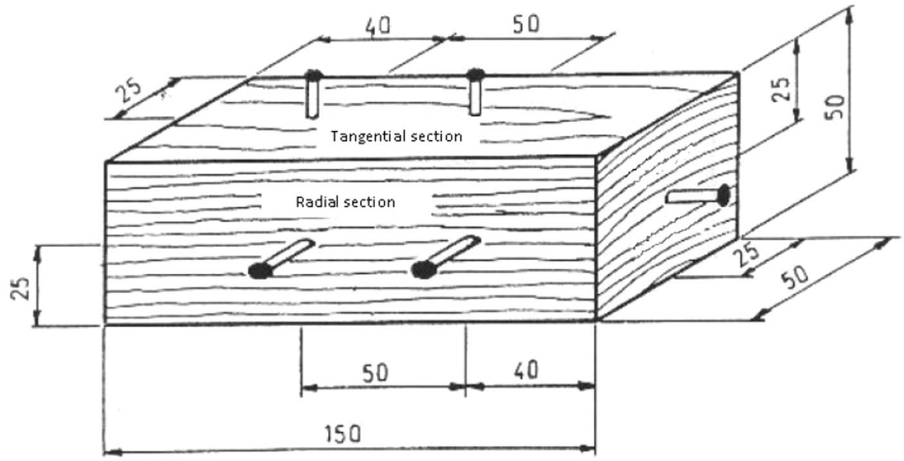

Fig. 1 Withdrawal strength test sample (mm)

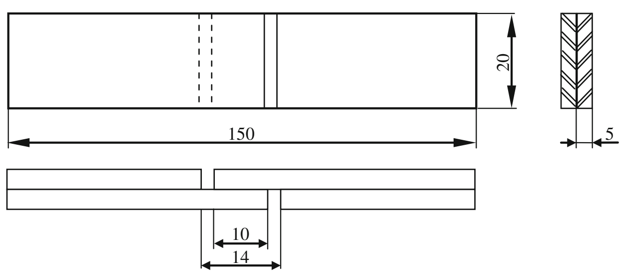

Fig. 2 Bonding test sample (mm)

of the test samples. The maximum values shown by the test machine were recorded as the withdrawal strength of the samples.

The test of bonding strength was conducted according to BS EN 205 [23] standard. The loading speed was 50 mm min^{-1} and was progressively increased until failure took place on the test samples. The bonding strength (σ_b) was computed by dividing the recorded load (F_{max}) at failure by the shear area (A, mm^2) as follows:

$$\sigma_b = F_{max}/A = F_{max}/(a \times l) \ \mathrm{N\,mm^{-2}}, \quad (1)$$

where a is the width of glued face (10 mm), and l is the length of glued face (20 mm).

Statistical analyses

For each default properties, the basic statistics were computed. Comparing the results between the screw types, the moisture contents and the surfaces were executed using multi-variant analyses. However, pair-wise least significant difference (LSD) comparisons, defining which of the groups were significantly different from one another, were included to determine the significant differences between the individual variables.

Results and discussion

Screw withdrawal strength

Results of screw withdrawal strength for three surfaces, 12 and 28 % moisture contents, and two screw types are presented in Table 2.

Table 1 The experimental design for nail and screw withdrawal strength and bonding strength

Name	Type	Dimensions (mm)		Pilot hole (mm)	Standards	Moisture Content (%)	Replicates
		Screws and nail	Specimens				
Withdrawal strength							
Screw	Flat head wood screw	4.5 × 50	50 × 50 × 150	2 × 13	TS 6094	12	10
					ASTM-D 1761	28	10
	Flat head chipboard screw					12	10
						28	10
Nail	Flat head steel	2.5 × 50		–		12	10
						28	10
Bonding strength	–	–	10 × 20 × 150	–	BS EN 205	12	11

Table 2 Average values of screw withdrawal strength (kgf)

Screw types	Wood screw (WS)			Chipboard screw (CS)		
Surfaces	Tangential (T)	Radial (R)	Transverse (Tr)	Tangential (T)	Radial (R)	Transverse (Tr)
Moisture contents (%)						
12						
$\overline{X}$	154.61	149.73	117.21	184.34	155.56	142.15
S	7.87	19.00	10.88	11.37	24.56	13.46
28						
$\overline{X}$	131.37	122.30	71.74	140.16	132.14	99.02
S	12.98	9.46	18.28	14.70	5.84	15.54

$\overline{X}$ arithmetical average, *S* standard deviation

Table 3 Mean comparisons and LSD results for screws

Parameters	Withdrawal strength (kgf)	HG[a]	LSD
Screw types			
CS	142.227	A	5.561
WS	124.487	B	
Moisture content (%)			
12	150.598	A	
28	116.116	B	
Surfaces			
T	152.617	A	6.811
R	139.932	B	
Tr	107.521	C	

[a] Different letters in the columns refer to significant change among screw type, moisture content, and surfaces at 0.001 confidence level

HG homogeneity groups

Table 4 Average values of nail withdrawal strength (kgf)

Statistic values	Wood surfaces		
	Tangential (T)	Radial (R)	Transverse (Tr)
Moisture contents (%)			
12			
$\overline{X}$	26.13	23.89	22.01
S	2.49	3.68	4.26
28			
$\overline{X}$	38.40	37.79	19.01
S	5.03	3.85	3.63

According to average values, the chipboard screws had a higher WR than wood screws at both 12 and 28 % moisture contents. This may be because the chipboard screws give less damage the wood fibres during screwing depends on their thread. Regarding moisture contents, the screw WR at 12 % MC was higher than at 28 % MC for both screw types. This result shows that wood have the more moisture contents the more soften. Tangential surfaces (radial direction) had a higher WR in both moisture contents than the other surfaces (Table 2). This may be caused by the arrangement of wood cell and fibre angle orientations. The effects of the screw type, moisture content, and surfaces on the screw WR were statistically significant ($p < 0.001$).

The results of the LSD test are given in Table 3. Statistical analysis confirmed the results given and explained above.

According to the results of the LSD test, the highest screw WR was detected for chipboard screw, 12 % MC, and tangential surface (radial direction) among screw types, moisture contents, and surfaces, separately.

The interactions between screw type and surface, and surface and moisture content were significant at 5 % coefficient level ($p < 0.05$) separately. According to the interaction between screw type and surface, while the highest screw WR was determined for chipboard screw at tangential surfaces, the lowest strength was determined for both screw types at the transverse surface. For interaction between moisture content and surface, while the highest value was determined for 12 % MC at tangential surface, the lowest WR was determined for 28 % MC at radial and transverse surfaces (Table 2). Increasing the MC in the wood screw WR decreased. While the highest screw WR has been obtained the tangential surface among the surfaces, screw WR decreased related to increasing MC. Accordingly, especially in a low degree of MC should be joined from the tangential surface.

Nail withdrawal strength

Results of nail WR for three surfaces and 12 and 28 % moisture contents are presented in Table 4.

According to average values, for MC, nail WR value of 28 % MC was higher than at 12 % MC at tangential and radial surfaces, except for the transverse surface. It can be explained that wood fibres are more soft at 28 % MC than at 12 % and so wood fibres do not fracture by driving of nails in parallel with nail WR for 28 % MC. In the case of surfaces, tangential surface had a higher nail WR in the

Table 5 Mean comparisons and LSD results for nail WR

Parameters	Withdrawal strength (kgf)	HG[a]	LSD
Moisture contents (%)			
28	31.733	A	2.129
12	24.014	B	
Surfaces			
T	32.266	A	2.607
R	30.842	A	
Tr	20.512	B	
Moisture contents (%) and surfaces			
28-T	38.399	A	3.687
12-R	37.790	A	
12-T	26.133	B	
12-R	23.894	BC	
12-Tr	22.014	C	
28-Tr	19.011	CD	

both MCs than the other surfaces. This could be explained by arrangement of wood cell and fibre angle orientations (Table 4).

The effects of the MC and surfaces on the nail WR were statistically significant ($p < 0.001$). It means that statistical analysis for moisture contents showed significant differences. The results of the LSD test defining that the difference is significant between which groups are given in Table 5.

As indicated in Table 5, the highest nail WR was detected for 28 % MC and tangential surface (radial direction) among MC and surfaces, separately. While the highest value was determined for 28 % MC at the tangential surface and 12 % MC at radial surface, the lowest WR was determined at transverse surface for both 12 and 28 % MC. These results can be explained the same commends given above.

Bonding strength

Table 6 summarizes the results of bonding test. Bonding strength values were almost the same for both adhesive types. The bonding strength of D-VTKA and PVAc were 5.64 and 5.33 N mm^{-2}, respectively. Similar results were given the literature. European linden (*Tilia cordata*) and Lombardy poplar (*Populus nigra* Lipsky) woods materials have approximate bonding strength values with paulownia [26]. According to the results of multiple analyses of variance with regard to the effects of adhesive types, there was no significant change in the bonding strength values of two different adhesives types. The differences between groups were not found to be significant.

Table 6 Results of bonding strength tests (N mm^{-2})

Statistic values	Type of adhesives	
	PVAc	D-VTKA
$\bar{X}$	5.33	5.64
S	0.91	0.74

Conclusions

This study investigated the effects of two different screws and nail at two different MC using three different surfaces on the withdrawal strength for paulownia wood. In addition to, effects of the two different adhesives was investigated on the bonding strength for paulownia wood.

Obtained experimental results of this research justify the following conclusions:

1. The screw WR was found to be higher than the ones in the nails. Among the screw types, the highest WR was obtained for chipboard screws at all combinations of moisture content and surface.
2. Among the surfaces, the highest WR was obtained at tangential surfaces (radial direction) in both screw types and nail, whereas the transverse surface (longitudinal direction) showed the lowest withdrawal strength for screws and nail.
3. For moisture contents, the WR at 12 % MC showed significantly higher WR than the ones at 28 % MC except for nail WR.
4. For WR of nail, the highest values were obtained at 28 % MC.
5. To the results of adhesive types showed that there was no significant difference among the bonding strength of two adhesive types.

According to these results, in connections involving screw or nail, a tangential surface (radial direction) connection with a screw should be preferred in such applications of paulownia wood as roof systems, packing cases. Utilization of screws and nails in longitudinal connections should be avoided. Although the nail WR at 28 % MC was higher than at 12 % MC, nails should be used at 12 % MC to avoid problems after drying, such as splitting, and shrinking. Both adhesive types could be used for connections of wood such as boxes, frames, etc.

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