Withdrawal Force Capacity of T-Type Furniture Joints Constructed from Various Heat-treated Wood Species

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The withdrawal force capacities were compared for T-type furniture joints made from heat-treated Siberian pine (*Pinus sibirica*), iroko (*Chlorophora excelsa*), and common ash (*Fraxinus excelsior*), which are commonly used in the construction of outdoor furniture. A total of 120 specimens that consisted of 3 wood species, 2 treatment processes (untreated and heat-treated), 2 adhesive types (polyurethane and polyvinyl acetate), and 2 joinery techniques (mortise and tenon, and dowel) were tested, with 5 replications for each condition. Half of the specimens were constructed from heat-treated wood materials, while the remaining half were prepared from untreated wood materials (control specimens). The joints constructed from common ash and iroko exhibited the highest withdrawal force capacity values. Overall, heat treatment reduced the withdrawal force capacity of joints by 25% compared with the joints constructed of control specimens. Mortise and tenon joints yielded 4 times higher performance than dowel joints. The polyurethane adhesive gave better results than the polyvinyl acetate adhesive. The best withdrawal force capacity values of heat-treated wood materials were obtained from the Iroko-polyurethane-mortise and tenon joint combination.

Keywords: Wood; Heat treatment; T-type joint; Withdrawal force capacity

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INTRODUCTION

Wood is a common structural material because of its advantageous properties. However, biotic and abiotic factors have significant effects on the physical and mechanical properties of wood materials. Many methods have been developed to decrease the negative effects of these factors, and heat treatment is one of the most popular methods employed in recent years. Heat-treated wood has a growing market in indoor and especially in outdoor applications, such as exterior cladding, window and door joinery, garden furniture, decking, and indoor applications such as flooring, paneling, kitchen furnishing, and interiors of bathrooms and saunas (Viitaniemi 2000).

Garden furniture, including tables, chairs, benches, *etc.*, that are used in the exterior conditions, are mostly constructed with wooden furniture frames and contain various kinds of joints. Mortise and tenon joints (MT) are commonly utilized to connect the wooden pieces. They are especially favored for furniture frame constructions.

The strength and rigidity of MT joints are effected by various factors including tenon size (length, width, and thickness), type of fit, shape of the plug and hole, thickness of the glue line, wood species, and adhesives used (Smardzewski 2002; Dzincic and Skakic

2012; Dzincic and Zivanic 2014).

There have been many studies on the effect of strength factors of MT joints. An estimation formula that includes the effect of wood species, adhesive type, and joint geometry on the strength was recommended by Erdil *et al.* (2005) for rectangular MT joints. Kasal *et al.* (2013) investigated the effect of wood species, adhesive type, and tenon width and length on the static bending moment capacity and the rigidity of T-shaped MT furniture joints, finding that joints became stronger and stiffer as either tenon width or length increased. Moreover, Eckelman *et al.* (2017) improved a statistical technique with the same data that can be used to determine reduction factors and impact of the selection of any given confidence-proportion levels on design values. Numerical analyses methods have been widely used to calculate the strength requirements for MT joints. Kasal *et al*. (2016) compared empirical tests and numerical analyses, and the results showed that the numerical analyses gave reasonable estimates of joint strength.

The dowel joint is another commonly used joint technique in furniture frame construction. Eckelman (1971) indicated that the ultimate bending moment capacity (M) of the joint could be estimated by the expression, $M = F \times d$, where F denotes the ultimate direct withdrawal strength of a single dowel and d represents the distance between resultant compression and tension force vectors. Zhang *et al.* (2001) investigated the bending moment capacity and moment-rotation characteristics of T-type two-pin dowel joints constructed from solid woods and wood composites. The joints constructed of red oak and plywood had the highest bending moment resistance, while the particleboard joints had the weakest bending resistance. The ultimate bending moment of the joint could be estimated by the formula $M = (d_1/2 + w/3 + e/3) \times T$, where T denotes the ultimate direct withdrawal strength of a single dowel, w represents the width of the rail, e denotes the distance from the rail centerline to the neutral axis, and d_1 is the spacing between two dowels. Hajdarevic and Martinovic (2016) investigated stress and strain analysis of double-dowel case-type furniture corner joint. They showed that dowel spacing, distance between the dowels, and edge of board have considerable impact on the stress state of the face and edge member; joints became stiffer when distance between the dowels and board edge were rationally defined.

MT and dowel joints are popular joint techniques that are commonly utilized for wooden furniture frame construction. Furniture frames, especially sitting furniture such as chairs, benches, sofas, *etc.*, mostly consist of three kinds of joints, namely, L-type (front leg to side rail), T-type (back leg to side rail), and H-type (back/front leg to side rail) joints. The joints are the most critical parts of the whole frame in terms of strength. Therefore, the joints should resist the loads that they are exposed to during service. The typical loading conditions of a simple chair joints are shown in Fig. 1.

When a chair frame is exposed to seat and backrest loading, the back leg to side rail and top/back rail to backrest joints are subjected to coercive withdrawal force. The withdrawal force capacities of the above mentioned joints are very important for the strength of the complete chair frame.

To increase the utilization of heat-treated timber in furniture frame constructions, the strength properties of these materials must be thoroughly examined. There have been many studies on the physical and mechanical properties of heat-treated wood materials; however, the information related to the strength of furniture joints constructed of heat-treated wood is very limited. Accordingly, the aim of this study was to investigate the effect of the heat treatment, wood species, joint types, and adhesive types on withdrawal force capacities of T-type furniture joints.

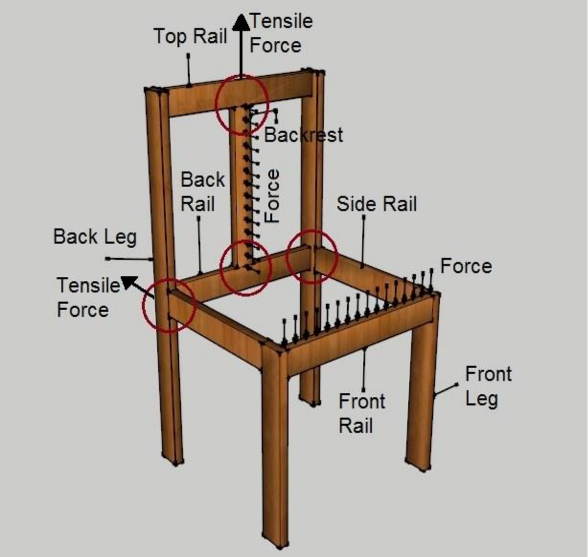


Fig. 1. T-type connection on a chair frame (Dizel *et al.* 2016)

MATERIALS AND METHOD

Materials

Siberian pine, iroko, and common ash were used as the wood materials in this study. All heat-treated and untreated wood materials were procured from Novawood Company in Gerede, Turkey. The heat-treated materials were processed at 212 °C for 3 h. However, the total heat treatment time was about 60 h because of a risk of cracks formed during drying. Heat treatment was applied following the Thermowood method (Thermowood Handbook 2003).

Untreated wood of the same species was used for control specimens. The control planks were dried in industrial drying kilns at approximately 70 °C and 65% relative humidity (RH), until they reach a moisture content of 11% to 15%. Special emphasis was given to selection perfect (with no defects) wood material. Prior to testing, both control and heat-treated specimens were conditioned at 20 ± 2 °C and 65 ± 3 % RH until an equilibrium was achieved. At the time of testing, untreated control specimens were 6% to 8% moisture content, and treated specimens were 3% to 5% moisture content.

Two type of adhesive, polyvinyl acetate (PVAc), and polyurethane (PU), were used to assemble the test specimens. According to product data of the suppliers, PVAc adhesive had specifications of viscosity 160 cps to 200 cps at 25 °C with a density of 1.09 g/cm^3, 50% solids content, liquid form, and water resistance (EN 204 D3). PU adhesive specifications were one component, with a viscosity of 3300 cps to 4000 cps at 25 °C with a density of 1.11 g/cm^3. The adhesives were applied at 150 ± 10 g/m^2.

Method

Physical and mechanical properties of wood materials

Moisture content and density of wood materials were evaluated in accordance with the procedures described in ASTM D 4442-92 (2001) and ASTM D 2395-14 (2015), respectively. Tensile strength and compression strength in parallel to grain and bending strength of wood materials were determined according to the test procedures described in ASTM D 143-94 (2000).

Withdrawal force capacity tests

A total of 120 T-type joint specimens were tested. The experimental design consisted of three wood species (Siberian pine, iroko, and common ash), 2 heat treatments (untreated and heat-treated), 2 adhesive types (PU and PVAc), and 2 joint techniques (MT and dowel), with 5 replicates for each test (Table 1).

Table 1. Experimental Design of the Study

Wood Species	Heat Treatments	Adhesive Type	Joint Technique	Replicates
Siberian Pine	Heat-treated	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
	Control	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
Iroko	Heat-treated	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
	Control	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
Common Ash	Heat-treated	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
	Control	PVAc	Dowel	5
			MT	5
		PU	Dowel	5
			MT	5
Total				120

Preparation of the T-type Joint Specimens

Each test specimen consisted of two structural elements, a post and a rail member. Dimensions of both members were 50×22×150 mm, as shown in Fig. 2a. The assembled specimens are shown in Fig. 2b.

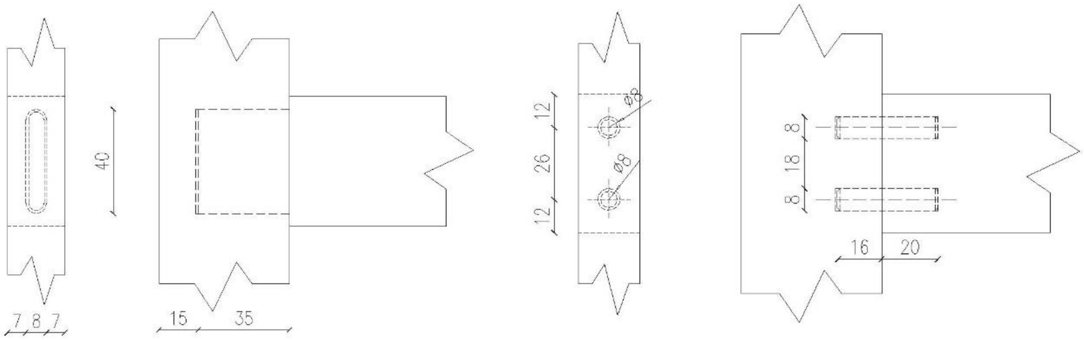
In the MT joint specimens, tenons measured 35×40×8 mm (length × width × thickness). The MT joint details are given in Fig. 3a. Mortising and tenoning machines were utilized for opening the mortises and cutting the tenons. A snug fit (average mortise-tenon clearance of 0.076 ± 0.025 mm) was obtained between tenons and mortises. The adhesive was liberally applied to all faces of the tenon and to the sides and bottom of the mortises. The adhesive was spread over an area of approximately 150 ± 10 g/cm^2. Pieces of wax paper were used between members to prevent them from adhering. Each specimen was assembled manually one by one with a clamp under firm pressure as described in adhesive product data sheet.

a b

Fig. 2. T-type specimens used in the study (dimensions in mm)

Multi-groove beech dowels (diameter, 8 mm; length, 36 mm) were utilized in the dowel joints. The depth of dowel embedment in the rail and post was 20 mm and 16 mm, respectively. The distance between the centerlines of two dowels was 26 mm. Dowel-hole clearances were not measured, but all dowels fit snugly into the holes. The depths of the holes in the end of the rail were carefully controlled to assure that the dowel pins penetrated exactly 20 mm deep into the end of the rail. A liberal amount of adhesive was spread over the sides of the holes and all faces of the dowels. Each specimen was assembled manually one by one with a clamp under firm pressure, as described in adhesive product data sheet. The details of dowel joints are given in Fig. 3b. Dowel withdrawal tests were carried out according to TS 4539 (1985).

Before the tests, to reduce minimum effects of moisture content variations, all the joint specimens were allowed to cure for a minimum of one month after assembly in an environmentally controlled conditioning room that was set to produce average MC of 12%.



a b

Fig. 3. Details of the MT (a) and dowel joints (b) (dimensions in mm)

Withdrawal Force Capacity Tests

Tests were conducted on a 50-kN capacity universal-testing machine (Mares 2007, Turkey) in the Physical and Mechanical Tests Laboratory of Wood Science and Industrial Engineering Department of Mugla Sitki Kocman University based on the accepted methods in previous studies (Erdil and Eckelman 2001; Efe *et al.* 2004; Efe *et al.* 2005; Dizel *et al.* 2016). The loading rate was 6 mm/min under static loading. Loading was continued until separation occurred on the intersection surfaces of the joints. Figure 4 illustrates the test set-up used in the withdrawal tests. The ultimate force monitored on T-type joint specimens was recorded as the withdrawal force in Newtons (N).

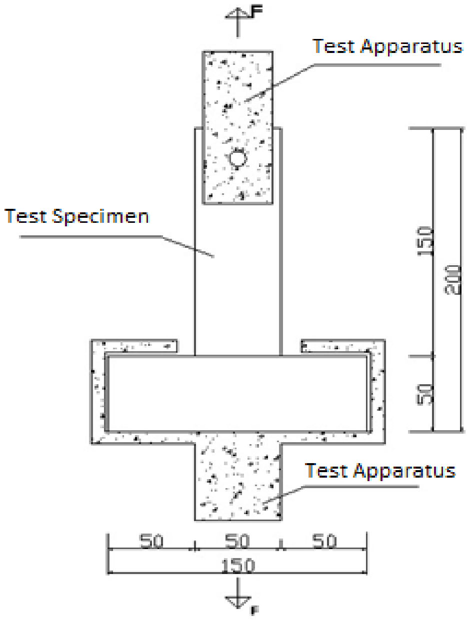


Fig. 4. Test set-up used for withdrawal force measurement (dimensions in mm)

Statistical Analysis

A four-way analysis of variance (MANOVA) general linear model procedure was performed for ultimate withdrawal force capacity data of T-type joints to analyze the main effects and interactions on the mean of the ultimate withdrawal force capacity. Statistically significant results were further analyzed by the least significant difference (LSD) multiple comparisons procedure at 5% significance level to determine the mean differences of withdrawal force capacity values of T-type joints tested considering the wood species, heat treatment, adhesive type, joint technique, and their four-way interactions. MSTAT-C statistical software (Michigan State University, USA) was used in statistical evaluations.

RESULTS AND DISCUSSION

Physical and Mechanical Properties of Wood Materials

The physical and mechanical properties of wood species determined in this study are given in Tables 2 and 3, respectively. The density of heat-treated wood materials decreased by 2.7%, 5.2%, and 6.7% for Siberian pine, iroko, and common ash, respectively, compared with the controls. Siberian pine had the lowest density of the heat-treated wood species. Normally, the MC values of heat-treated wood specimens are lower than the MC of control specimens. Some mechanical properties are shown in Table 3.

As shown in Table 3, the tensile strengths of all control specimens were higher than the heat-treated specimens. The tensile strength of Siberian pine, iroko, and common ash decreased by approximately 18%, 10%, and 3%, respectively, compared with the controls. Thus, heat treatment had a negative effect on tensile strength.

Table 2. Physical Properties of the Wood Materials

Wood Species	Treatment	Test Moisture Content (MC) (%)	Oven Dry Density (δ_0) (g/cm^3)	COV (%)	Density during the Test (δ_{MC}) (g/cm^3)	COV (%)
Siberian Pine	Heat-Treated	4.50	0.35	2.12	0.36	2.78
	Control	6.77	0.38	4.02	0.40	4.54
Iroko	Heat-Treated	3.71	0.54	2.48	0.56	2.28
	Control	7.54	0.57	3.01	0.61	2.59
Common Ash	Heat-Treated	4.24	0.55	2.26	0.57	2.24
	Control	7.04	0.59	3.65	0.63	3.86

COV: Coefficients of Variation

Table 3. Mechanical Properties of the Wood Materials

Wood Species	Treatment	Tensile Strength Parallel to Grain (N/mm^2)	COV (%)	Compression Strength Parallel to Grain (N/mm^2)	COV (%)	Bending Strength (N/mm^2)	COV (%)
Siberian pine	Heat-Treated	36.49	10.05	51.72	9.33	68.01	8.92
	Control	43.81	9.27	47.64	3.92	85.31	9.33
Iroko	Heat-Treated	51.54	10.07	69.72	8.38	88.29	8.58
	Control	57.78	5.66	56.70	6.27	87.51	8.21
Common ash	Heat-Treated	69.25	9.30	77.73	2.69	137.67	6.18
	Control	71.21	9.26	69.71	3.68	138.44	7.49

In the case of compression strength, contrary to expectations and common literature (Unsal and Ayrilmis 2005; Korkut *et al.* 2008), heat-treated specimens yielded higher values than control specimens. The ratios were 14%, 23%, and 9% for common ash, iroko, and Siberian pine, respectively. This controversial result may lead to further discussion as to improvement of compression strength after heat treatment. However, this study cannot solely provide conclusive results. Further research which focus only to mechanical properties might give more conclusive judgements. The highest bending strength values were obtained from common ash, while the lowest values obtained from Siberian pine. There were no significant differences between heat-treated and control specimens for common ash and iroko. However, the untreated Siberian pine specimens demonstrated approximately 20% higher bending strength values than the heat-treated specimens.

The mean withdrawal force capacity values of T-type joints with their coefficients of variation are given in Table 4.

In general, all joints failed completely between 60 to 90 seconds. Withdrawal capacities of joints declined after reaching their ultimate values. All specimens constructed with MT and dowel joints bonded PVAc and PU adhesive failed due to gluline fractures (Fig. 5) with two exceptions. These involved heat-treated specimens bonded with PU adhesive. One of the specimens failed due to splitting from the post and the other due to tenon fracture.

Table 4. Mean Ultimate Withdrawal Force Capacity Values of T-Type Joints with their Coefficients of Variation

Wood Species	Heat Treatment	Adhesive Type	Joint Technique	Mean (N)	COV (%)
Siberian pine	Heat-treated	PU	Dowel	1334	11.40
			MT	5299	3.03
		PVAc	Dowel	1415	4.53
			MT	4075	8.06
	Control	PU	Dowel	1012	9.63
			MT	5704	15.40
		PVAc	Dowel	1258	15.77
			MT	5466	10.70
Iroko	Heat-treated	PU	Dowel	1668	21.44
			MT	8698	5.35
		PVAc	Dowel	1268	14.05
			MT	6284	15.01
	Control	PU	Dowel	1882	15.11
			MT	11229	6.22
		PVAc	Dowel	718	2.03
			MT	9414	9.07
Common ash	Heat-treated	PU	Dowel	2131	13.67
			MT	6932	15.92
		PVAc	Dowel	1791	11.93
			MT	7340	22.85
	Control	PU	Dowel	3704	17.49
			MT	10218	5.59
		PVAc	Dowel	3235	14.52
			MT	9243	14.88

Fig. 5. Example of failure modes

According to the MANOVA results, the effect of wood species (WS), heat treatment (HT), adhesive type (AT), and joint technique (JT) on withdrawal force capacity were statistically significant at the 5% significance level. All of the two-way interactions were statistically significant except for the HT × AT and AT × JT at the 5% significance level. All three-way interactions were statistically significant, except for WS × HT × AT and HT × AT × JT. The four-way interactions of all factors were also statistically significant at 5% significance. The least significant difference (LSD) multiple comparisons were conducted at the 5% significance level for the main factors and four-way interactions to determine the mean differences on withdrawal force capacity of T-type joints.

Table 5 shows the mean comparisons of withdrawal force capacity values of T-type joints for wood species. The single LSD value of 353.8 was calculated based on the error mean square of the full model.

Table 5. Mean Comparisons for the Effect of Wood Species on Withdrawal Force Capacity of T-Type Joints

Wood Species	Withdrawal Force Capacity (N)	
	Mean (N)	HG
Siberian pine	3195	B
Iroko	5144	A
Common ash	5476	A

LSD ± 353.8, HG: Homogenous Group

Common ash and iroko exhibited the highest withdrawal force capacity. The differences between common ash and iroko were not statistically significant the 5% significance level. Siberian pine gave the lowest withdrawal force capacity values. In this context, common ash is approximately 6% stronger than iroko and 41% stronger than Siberian pine, whereas iroko is approximately 37% stronger than Siberian pine. A similar situation was observed with the densities of wood specimens, which were 0.63 g/cm^3, 0.61 g/cm^3, and 0.40 g/cm^3 for common ash, iroko, and Siberian pine, respectively.

Table 6 gives the mean comparisons of withdrawal force capacity values of tested T-type joints for heat treatment. The single LSD value of 288.9 was calculated based on the error mean square of the full model.

Table 6. Mean Comparisons for the Effect of Heat-Treatment on the Withdrawal Force Capacity of T-Type Joints

Heat Treatment	Withdrawal Force Capacity (N)	
	Mean (N)	HG
Heat Treatment	3954	B
Control	5257	A

LSD ± 288.9; HG: Homogenous Group

The joints constructed of heat-treated wood species gave lower withdrawal force capacity values than the control specimens. The withdrawal force capacities of the joints were reduced by approximately 25% compared with the control groups. Thus, the heat treatment process negatively affected the cellular composition of the wood materials.

The negative effects of the thermal process on the wood strength are well understood. The thermal process can result in strength loss, which is associated with thermal degradation and substance loss due to the applied temperature (Rusche 1973). The strength and hardness of wood materials decreases when heated but increases when cooled. According to Mitchel (1988), irreversible degradation of the mechanical and technological properties of wood are caused by thermal degradation.

Table 7 gives the mean comparisons for the effect of adhesive on withdrawal force capacity values of tested T-type joints. The single LSD value calculated was 288.9.

Table 7. Mean Comparisons for the Effect of Adhesive Type on the Withdrawal Force Capacity of T-Type Joints

Adhesive Type	Withdrawal Force Capacity (N)	
	Mean (N)	HG
PVAc	4292	B
PU	4919	A

LSD± 288.9; HG: Homogenous Group

The PU adhesive gave 13% higher values than the PVAc adhesive. PU is a thermosetting adhesive, which yields a very rigid material after curing; PVAc is a thermoplastic adhesive, which yields more elastic material after curing. These results suggest that PU performs better where mechanical adhesion is pre-eminent.

Table 8 gives mean comparisons of withdrawal force capacity values of tested T-type joints for the effect of joint technique. The single LSD value was 288.9.

Table 8. LSD Test Result of Joint Factor

Joint Technique	Withdrawal Force Capacity (N)	
	Mean (N)	HG
Dowel	1784	B
MT	7426	A

LSD± 288.9

Table 9. LSD Comparison Test Results of Four-Way Interactions

Wood Species	Heat Treatment	Adhesive Type	Joint Technique	Withdrawal Force Capacity (N)	
				Mean (N)	HG
Siberian Pine	Heat-Treated	PU	Dowel	1334	GHI
			MT	5299	E
		PVAc	Dowel	1415	GHI
			MT	4075	F
	Control	PU	Dowel	1012	HI
			MT	5704	E
		PVAc	Dowel	1258	GHI
			MT	5466	E
Iroko	Heat-Treated	PU	Dowel	1668	GHI
			MT	8698	C
		PVAc	Dowel	1262	GHI
			MT	6284	E
	Control	PU	Dowel	1882	GH
			MT	11230	A
		PVAc	Dowel	718.1	I
			MT	9414	BC
Common ash	Heat-Treated	PU	Dowel	2131	G
			MT	6147	E
		PVAc	Dowel	1791	GH
			MT	7340	D
	Control	PU	Dowel	3704	F
			MT	10220	B
		PVAc	Dowel	3235	F
			MT	9243	BC

LSD± 1001; HG: Homogenous Group

The MT joints yielded approximately 4 times more withdrawal force capacity than dowel joints. This result is explained by the fact that MT joints have a larger bonding surface area than dowel joints. Hence, using MT joints when possible would provide more strength than dowel joints in T-type furniture joints.

The mean withdrawal force capacity values along with the LSD comparison results for four-way interactions are given in Table 9. According to the four-way interaction tests, the highest withdrawal force capacity values were obtained with the iroko–control–PU–MT combination, while the iroko–control–PVAc–dowel combination gave the lowest withdrawal force capacity values. For the heat-treated wood specimens, the highest withdrawal force capacity was obtained from the iroko-PU-MT combination. Siberian pine and iroko specimens gave the best results with the PU–MT combination, while the common ash specimens performed best with the PVAc–MT combination. There was no significant difference between the common ash and Siberian pine specimens with the PU-MT combination and iroko specimens with PVAc–MT combination. As a result, these 3 combinations could substitute for each other. These results could provide economic and technical benefits for furniture engineers and producers.

CONCLUSIONS

1. Wood species, heat treatment, adhesive type, and joint type had significant effects on the withdrawal force capacity of T-type joints.
2. Iroko and common ash gave the highest withdrawal force capacity values, and there were no significant differences between these two wood species in this study.
3. The joint specimens constructed of heat-treated wood materials yielded withdrawal force capacity values that were approximately 25% lower than untreated specimens.
4. The joints assembled with PU adhesive had 13% higher withdrawal strength than the joints glued with PVAc.
5. MT joints carried four times more withdrawal force than dowel joints.
6. For the specimens constructed of heat-treated wood materials, the best results were observed from the iroko-PU-MT combination.

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