Mechanical properties of heat-treated wooden material utilized in the construction of outdoor sitting furniture

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Mechanical properties of heat-treated wooden material utilized in the construction of outdoor sitting furniture

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Abstract: The present study examined the bending moment capacity and rigidity of T-type out-of-plane furniture joints and investigated the effects of heat treatment, wood species, and joint type factors on these joints. Heat treatment method clearly decreased the modulus of rupture (MOR) and the modulus of elasticity (MOE) of selected wood species. The bending strength of wood samples was reduced after the heat treatment, decreasing with increased loss of mass. For the heat-treated T-type joints, maximum bending strength values were obtained with Iroko (*Chlorophora excelsa*) for both mortise and tenon (MT) joints and blind MT (BMT) joints. The lowest reduction in bending strength was observed in Ash (*Fraxinus excelsior* L.) constructed with MT joints and with BMT joints. In general, the BMT joint had higher bending strength than MT joints. The best rigidity constant (7.21) was obtained with control Iroko BMT joints, while the worst rigidity constant (15.10) was obtained with control Oriental spruce (*Picea orientalis* L.) MT joints. In terms of heat-treated samples, the best rigidity constant (7.59) was obtained with Black pine (*Pinus nigra* L.) MT joints, while the worst rigidity constant (14.01) was obtained with Oriental spruce BMT joints. The maximum performance in joint stiffness was determined for Iroko sample BMT joints and Iroko MT joints. Lowest reduction in joint stiffness was observed in Scotch pine MT joints and Ash BMT joints. Heat treatment, wood type, and joint type had a significant effect on the bending strength of T-type MT post-rail joints. BMT joints produced from heat-treated Iroko wood can be considered as the most durable T-type joint for outdoor sitting furniture construction.

Key words: Bending moment capacity, joining, heat treatment, wood, rigidity

1. Introduction

Heat treatment of wood is one of the modification methods to improve the dimensional stability and biodurability of timber. This method reduces the equilibrium moisture content of wood (Jämsä and Viitaniemi, 2001; Gosselink et al., 2004; Metsä-Kortelainen et al., 2006), and improves its dimensional stability (Kollmann and Schneider, 1963; Boonstra et al., 1998; Epmeier et al., 2001; Bekhta and Niemz, 2003; Wang and Cooper, 2005) and its durability (Bourgois et al., 1998; Tjeerdsma et al., 1998; Militz, 2002). Wood species that have no commercial value can be heat-treated and, in this way, a new use can be found for these species. On the other hand, the major disadvantage of this method is the reduction of mechanical resistance (Kubojima et al., 2000; Reiterer and Sinn, 2002; Epmeier et al., 2004; Unsal and Ayrilmis, 2005; Korkut et al., 2008). Temperatures over 150 °C permanently modify the physical and mechanical properties of wood (Mitchell, 1998). The improved characteristics of heat-treated timber offer the furniture industry many potential and attractive

new opportunities, too. Because of its good weather resistance, heat-treated wood has a growing market in outdoor applications, like garden furniture, paneling, kitchen furnishing, and interiors of bathrooms and saunas (Viitaniemi, 2000).

It is believed that the most useful way to increase utilization of heat-treated timber in the area of furniture products is to expand the knowledge of strength properties. Different tree species can be utilized after employing proper construction approaches without any losses in strength values in furniture areas. No research has been done yet on the performance of heat-treated furniture used in outdoor applications.

The goal of this study was to investigate the effect of the heat treatment, wood species, and joint types on bending moment capacity and rigidity of T-type mortise and tenon (MT) joints prepared of Black pine (*Pinus nigra* L.), Scotch pine (*Pinus sylvestris* L.), Oriental spruce (*Picea orientalis* L.), Iroko (*Chlorophora excelsa*), and Ash (*Fraxinus excelsior* L.).

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2. Materials and methods

2.1. Wood materials, heat treatment process, and adhesive

In the tests, Black pine (*Pinus nigra* L.), Scotch pine (*Pinus sylvestris* L.), Oriental spruce (*Picea orientalis* L.), Iroko (*Chlorophora excelsa*), and Ash (*Fraxinus excelsior* L.) were used. They are the main wood species mostly used in the wood products industry in Turkey, and thus they are the potential wood species for industrial-scale heat treatment. Heat-treated and untreated timbers were provided from Nova ThermoWood in Gerede, Turkey. Prior to heat treatment, each plank (10 for each species) was cut into 2 pieces (each 2 m long) from the middle because the thermally modified and untreated samples were taken from the same planks. The planks that were used for control samples were then dried in industrial drying kilns at a temperature of approximately 70 °C and 65% relative humidity (RH), with a moisture content of 11%–15%. The other half of these planks were subject to ThermoWood heat treatment process. The heat treatment was applied according to the method described in the Finnish ThermoWood Handbook (Finnish ThermoWood Association, 2003). Planks were heat-treated at about 180 °C under steam. The total time of the heat treatment was 63 h, and the time of exposure to the highest temperature was 2 h. The heat treatment operation was performed quite slowly because of a risk of cracks forming while drying.

Prior to testing, both control and heat-treated specimens were stored in a conditioning room maintained at 23 °C and 65% RH until moisture equilibrium was achieved. The moisture content of the untreated control samples was around 10%–12% and that of the treated samples was around 6%–8%. Before the test, the dimensions of the samples were measured to the nearest 0.001 mm and their weights to the nearest 0.01 g. Static bending tests for bending strength and modulus of elasticity (MOE) were carried out accordance with TS 2474 and TS 2478, respectively (Turkish Standards Institution, 1976a, 1976b). Mass loss was determined in relation to dry wood. The changes in properties of the control and heat-treated samples were decided by calculating the property difference between heat-treated and untreated wood of the same species as a percentage of the untreated wood property.

All joints were assembled with polyurethane-based, solvent-free adhesive (Polisan, 1999). Adhesive was obtained from Wurth™. This is a one-component, solvent-free adhesive that is widely used for the assembly process in the furniture industry. Its viscosity was 14 ± 3 Pa s at 25 °C with a density of 1.11 ± 0.02 g/cm³. Its application is especially recommended in locations subjected to high level humidity. It is utilized because of its useful properties such as cold application, easy spreading, rapid drying, being scentless and fireproof, and being preferred in the production of the furniture products. Areas of application include wooden door and window frame construction, lamination of wood materials such as medium-density fiberboard, furniture construction, structural adhesion of garden furniture, bonding of mineral building boards, ceramic materials, and concrete.

2.2. Joint configuration

Each out-of-plane T-type joint specimen consisted of 2 structural elements (a post and a rail member) jointed together. In the joints, the post-and-rail member has 350 × 50 × 20 mm dimensions. The detail of specimens is presented in Figure 1 (MT joints) and Figure 2 (blind MT (BMT) joints). The rectangular end tenons had the following nominal dimensions: length = 20 mm, thickness = 10 mm, and width = 50 mm for MT joints; and length = 15 mm, thickness = 10 mm, and width = 50 mm for BMT joints. All specimens were then kept in an environment chamber until their weights became constant.

2.3. Testing method

Tests were conducted on a universal testing machine in the Wood Mechanics Lab of Bartın University, Turkey. All static-test materials and joint-test samples were tested using a screw-type test machine operated at a head speed of 6 mm/min. For static bending tests, samples were loaded to ultimate failure. For joint tests, the loading was continued until separation occurred on the surface of intersection area of the joints. The maximum bending resistance was identified as the load implemented to each specimen at the time of failure.

Joint displacements were measured with 2 linear variable differential transformers (LVDTs) attached to the wood members, and loads were obtained from the test machine's load cell. Loads and displacements were recorded on a personal computer (Figure 3). Most tests were concluded after the load decreased due to buckling or some other joint failure, but a few joint tests were continued to examine joint behavior beyond buckling.

2.4. Bending moments and rigidity analysis of joint construction

The strength of joints was identified by the bending moment value. Applied loads were converted to bending moment. The moment arm (L = 210 mm) was determined from the point of load application to the face of the post member. Bending moment capacity, M, was determined as:

$$M = F \times L \text{ (Nm)}, \tag{1}$$

Where F = applied load (N).

In mechanics of solids:

a) The deflection values of a one-end-fixed cantilever beam (Figure 4) under the concentrated load may be estimated by means of the following equation:

Figure 1. T-type MT joint (in mm).

$$y_1 = PL^3 / 48EI, \tag{2}$$

where P = maximum load (N), L = length of beam (mm), E = MOE (N/mm^2), and I = moment of inertia (mm^4).

b) The deflection values of a one-end-pinned cantilever beam (Figure 5) under the concentrated load may be estimated by means of the following equation:
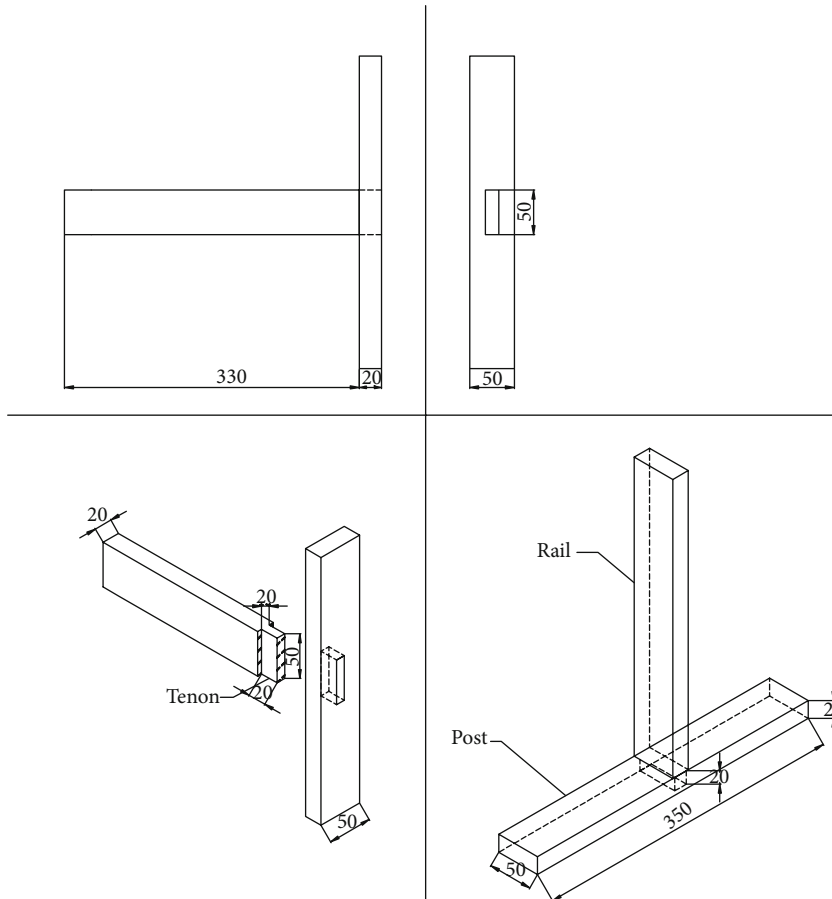
$$y_2 = PL^3 / 3EI \text{ (the symbols have the same meanings as previously given).} \tag{3}$$

The ratio of y_2 / y_1 is:

$$\frac{PL^3 / 3EI}{PL^3 / 48EI} = 16 \tag{4}$$

Based on the general beam deflection formulas of solid mechanics, a rigidity scale has been considered from 1 through 16, where 1 stands for most rigid and 16 stands for nonrigid. To express the degree of rigidity, the k (rigidity constant) value was formed:

$$Y_1 = PL^3 / kEI, \tag{5}$$

where Y_1 = deformation value obtained from LVDT (mm), k = rigidity constant (k = 1 for truly fixed end support, k = 16 for pin end support), and the other symbols have the same meanings as previously given.

2.5. Joint stiffness
The bending stresses were calculated by the following expression:

$$\sigma = 6M / wd^2, \tag{6}$$

where M = average maximum moment (N/mm), W = width of mortise (mm), and d = thickness of the mortise (mm).

Strain measurements were completed using strain gauges (2.12 gauge factor, PLW-60-11 gauge type, manufactured by TML Gages, Kenkyujo, Japan) that are accurate up to 5% maximum strain. In this study, strain gauges were bonded to the surface of wood joints using PS adhesive (a 2-component room-temperature-curing polyester adhesive, manufactured by TML Gages). The slope of the stress–strain curve in the elastic deformation region is the MOE. It shows the stiffness of the material
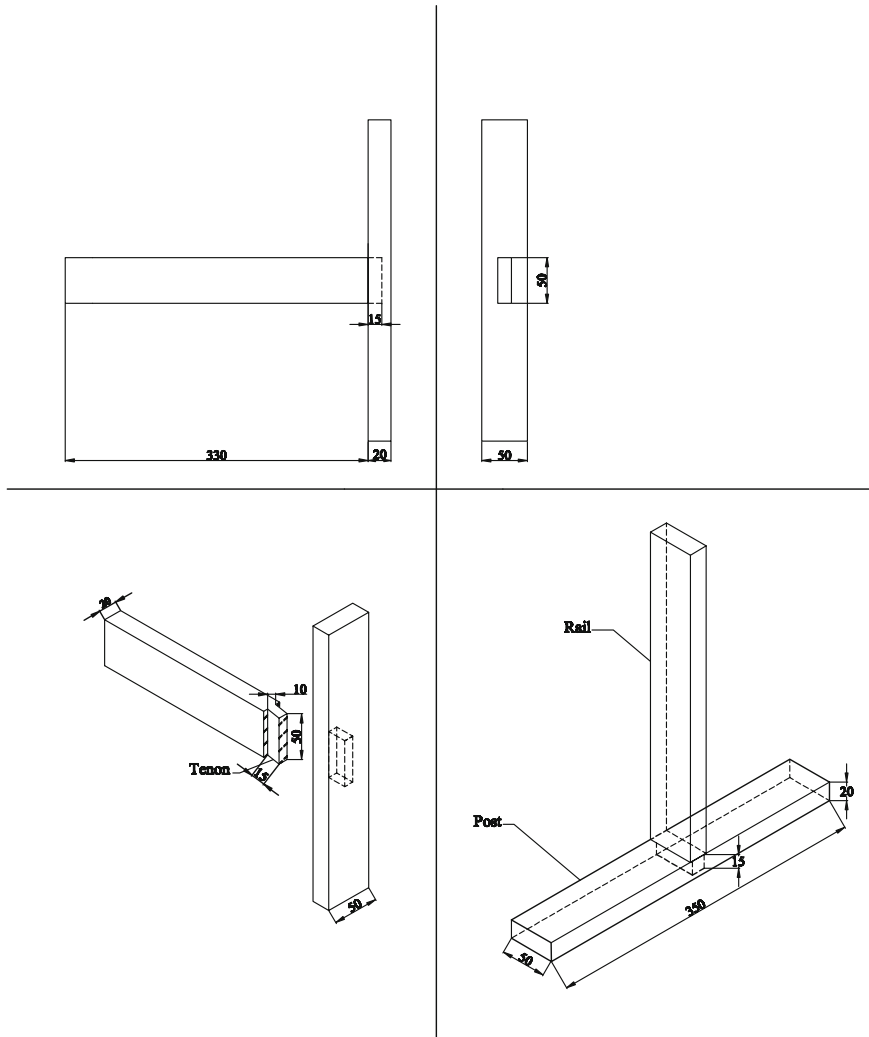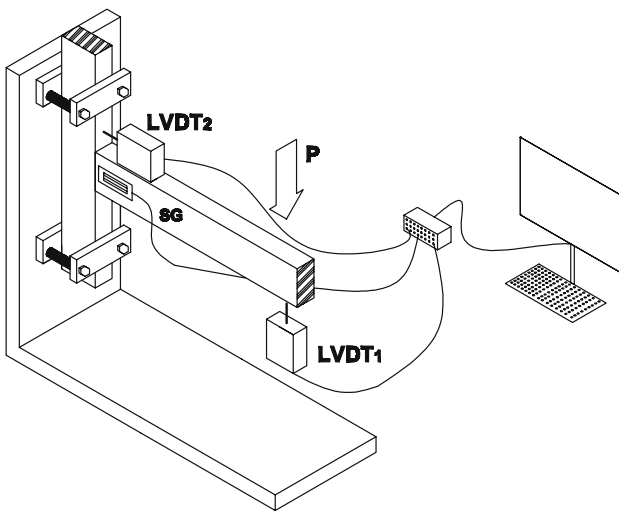
Figure 2. T-type BMT joint (in mm).

Figure 3. General configuration of the bending strength test set-up used in the study.

resistance to elastic strain. This definition was used in this study to calculate stiffness values of the joints.

2.6. Data analyses

By using 2 treatment types (untreated and heat treated), 5 different wood species (Black pine, Scotch pine, Oriental
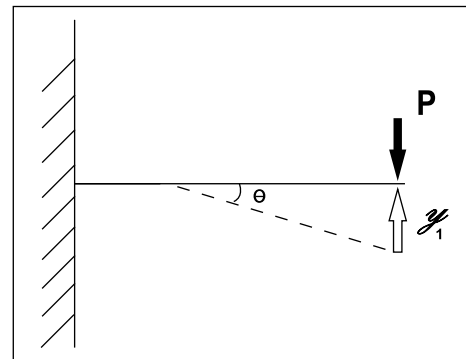

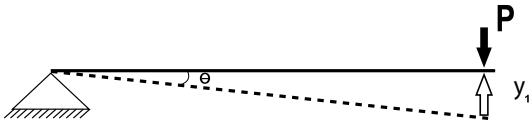**Figure 4.** Cantilever beam with a force at the free end.

Figure 5. One-end-pinned beam with a force at the free end.

spruce, Iroko, and Ash), and 2 joining methods (BMT and MT) for the bending tests, a total of 120 samples (2 × 5 × 2 × 6) were prepared having 6 T-type joint samples for each parameter. Multiple variance analysis was performed to determine the differences among the factors. Duncan's test was used to determine if there was a meaningful difference among the groups.

3. Results

3.1. Mechanical properties of woods and bending moment capacities of joints

The mean values of the measured properties of untreated and heat-treated wood species and the differences between them are presented in Table 1. Average equilibrium moisture content was 12.6% for untreated wood and 8% for heat-treated wood. The modulus of rupture (MOR) of heat-treated samples was smaller than that of the untreated wood and on average decreased with mass loss, as seen in Tables 1 and 2. Heat treatment processing influenced the correlation between MOE and MOR because of the physical changes occurring in the wood elements. In this study, heat treatment caused an average decrease in MOE of 19% and an average MOR reduction of 24%. The percentage of mass loss was determined in relation to the control-wood mass after treatment. It has been determined that among the types of wood species used in the study, the maximum mass loss was observed in Ash at 10.01%, and the minimum mass loss was observed in Oriental

spruce at 5.74%, as shown in Table 2. As seen in Table 2, the bending strength of wood was reduced by the heat treatment, decreasing with increasing mass loss.

The differences in the bending strengths of joints are presented in Figure 6. According to the results obtained in this study, the lowest reduction in bending strength was observed in Ash + MT joints and Ash + BMT joints. The mean ultimate moment capacities of T-type joints constructed with different wood species, treatment, and joining methods are presented in Figure 7. The bending moment capacity of Scotch pine joints ranked the highest, while Oriental spruce was lowest among the 5 wood species in terms of heat-treated samples.

3.2. Joint rigidity

Figure 8 shows the rigidity scale developed in this study. In analysis of joint rigidity, the best rigidity constant (7.21) was obtained with Iroko control samples constructed with BMT joints, while the worst rigidity constant (15.10) was obtained with untreated Oriental spruce MT joints. In terms of heat-treated samples, the best rigidity constant (7.59) was obtained with Black pine MT joints, while the worst rigidity constant (14.01) was obtained with Oriental spruce BMT joints. Thus, tested joints in this study were categorized as semirigid joints.

3.3. Stiffness of joints

A continuous stress–strain curve was generated for all joints in bending. The slope of the initial part of the curve indicated the stiffness. A typical example of the stress–strain curve for a joint constructed using Scotch pine is shown in Figure 9. Stiffness of joints determines the furniture's strength and rigidity. In terms of heat-treated samples, the maximum performance in joint stiffness was determined for Iroko BMT joints and Iroko MT joints. The lowest reduction in joint stiffness was observed in Scotch pine MT joints and Ash BMT joints.

Table 1. Mean values of untreated and heat-treated wood species and differences in their properties.

Property	Wood species	Number of samples	Control	Heat treatment	Difference (%)
Modulus of rupture (N/mm²)	Oriental Spruce	10	51.47 (5.17)*	47.25 (12.56)	19.80
	Scotch pine	10	77.77 (3.20)	63.55 (26.87)	18.28
	Black pine	10	105.85 (8.23)	70.23 (18.32)	33.65
	Iroko	10	126.49 (11.67)	97.21 (15.45)	23.15
	Ash	10	135.13 (10.45)	98.94 (22.43)	26.78
Modulus of elasticity (N/mm²)	Oriental Spruce	10	7502.61 (346.90)	6147.76 (365.19)	18.06
	Scotch pine	10	10,390.58 (503.67)	8530.48 (403.45)	17.90
	Black pine	10	13,843.95 (545.85)	10,365.06 (398.89)	25.13
	Iroko	10	12,791.50 (498.57)	10,012.11 (523.67)	21.73
	Ash	10	15,656.95 (598.65)	13,744.54 (601.56)	12.21

*: Standard deviation in parentheses.

Table 2. Mean mass loss values of the samples in the bending test.

Wood species	Untreated	Heat-treated	Mass loss (%)
Black pine	7.64 (0.33)*	7.25 (0.44)	6.15
Scotch pine	7.50 (0.30)	7.00 (0.47)	6.67
Oriental Spruce	4.71 (0.45)	4.44 (0.74)	5.74
Iroko	7.24 (0.28)	6.68 (0.37)	7.74
Ash	8.63 (0.33)	7.76 (0.40)	10.01

*: Standard deviation in parentheses.

In general, control samples yielded significantly higher stiffness characteristics than those of heat-treated samples. In terms of heat-treated samples, the maximum performance in joint stiffness was determined for Iroko + BMT joints (106.8 N/mm^2) and Iroko + MT joints (71.3 N/mm^2) (Figure 10). Obtained stiffness values comply with the results of bending strength values. According to Figure 11, the lowest reduction in joint stiffness was observed in Scotch pine + MT joints and Ash + BMT joints.

Using the data shown in Figure 7, MANOVA was carried out on data at the 0.05 significance level (Table 3). Results of this analysis show that there were significant differences in bending moment capacity of joints in terms of heat treatment, wood species, and joint type. However, the interacting effects of joint types and treatment types were not significant.

4. Discussion

The utilization of heat-treated wood material used to construct outdoor sitting furniture was investigated with the aid of engineering design principles. This study showed the design principles that should be employed to manufacture more durable sitting furniture. Furthermore,
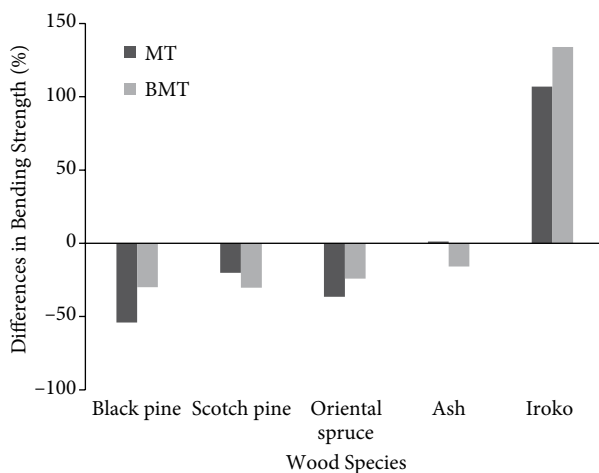

Figure 6. Differences in bending strength according to wood species. MT: mortise and tenon joints; BMT: blind MT joints.

the studied variables reveal worthwhile data related to the strength of specified sizes of T-type joints.

In terms of furniture manufacturing, bending strength appears to be an important material property of heat-treated wood. Heat treatment resulted in a decrease in MOE values by 19% and MOR values by 24%. There are some explanations for strength reduction based on earlier research, such as decreasing equilibrium moisture content of wood and volumetric expansion, degradation of wood components (cellulose and especially the hemicelluloses), and evaporation of extractives. In this study, MOE was less affected than bending strength, in agreement with the results of Bengtsson et al. (2002). The reduction in the MOR is mainly due to the degradation of hemicelluloses (Esteves et al., 2007). According to Dwianto et al. (1996), degradation of hemicelluloses causes the cross-linking reactions in the matrix substance and the crystallization of microfibrils, as well as the relaxation of stresses stored in microfibrils and matrix substances. Similar changes in MOE and MOR have been reported in the literature. Previous studies showed that heat treatment caused a decrease in MOR of from 1% to 72% and in MOE of from 1% to 40% (Johansson and Morén, 2006; Esteves et al., 2007; Shi et al., 2007; Korkut, 2008). In general, control samples yielded significantly higher bending strength values than those of heat-treated samples. The bending strength difference between untreated and treated samples was related to the modification of the wood by the heat treatment process.

Iroko was found to be different from the other wood types with its increase in bending strength after the heat treatment (Figure 6). It has been described that the heartwood of Iroko varies from a pale yellowish brown to dark chocolate brown with lighter markings associated with the vessel lines. The wood weighs about 640.738 kg/m^3. Iroko's mechanical properties are generally below those of White oak. Its heartwood is rated as very durable and permeable because of extractives and inorganic and nitrogen compounds (Kukachka, 1969; Ayensu and Bentum, 1974; Padayachee and Odhav, 2001; Shimizu et al., 2003). Fortin and Poliquin (1976) reported that Iroko
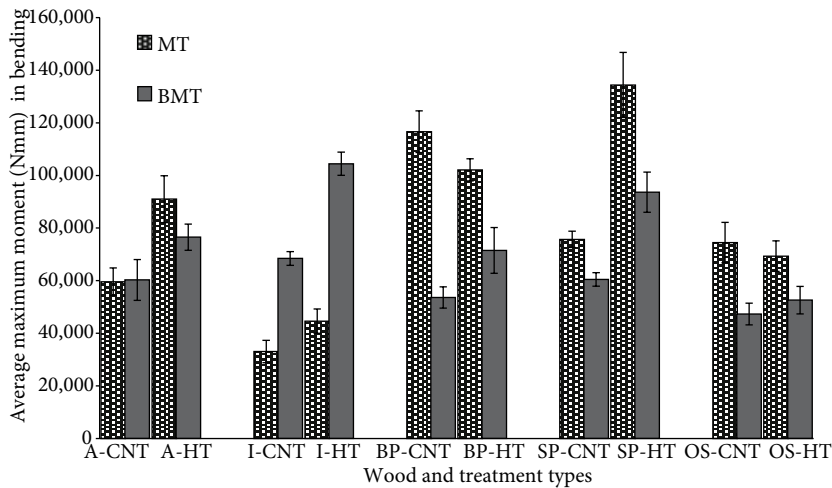
Figure 7. Effect of heat treatment, wood type, and joint type on average maximum moment in bending. MT: mortise and tenon joints; BMT: blind MT joints; CNT: control; HT: heat treatment; A: Ash; I: Iroko; BP: Black pine; SP: Scotch pine; and OS: Oriental spruce. Error bars represent ±1 standard deviation.

wood is classified as highly resistant, moderately resistant, or nonresistant depending on the sample provenance. It is well suited for many purposes where strength and inherent durability are prime requirements.

A decrease in the mass of specimens occurred because of heat treatment and thermal degradation. In terms of the heat-treated pine wood results, mass losses are not much different from those reported by previous researchers: for example, *Pinus sylvestris* had 5.7%–7.0% mass loss as found by Zaman et al. (2000). It was reported that the reason for the decrease of water adsorption after heat treatment is depolymerization of the carbohydrates and hemicelluloses, leading to a decrease of the total amount of hydroxyl groups (Tjeerdsma et al., 1998; Esteves et al., 2009).

In terms of heat-treated joint samples, the maximum value of bending moment capacity was obtained in Iroko for MT joints and BMT joints. The lowest reduction in bending moment capacity was observed in Ash samples for MT joints and Ash samples for BMT joints. It has been known that heat treatment cause changes in the chemical composition of wood, including the degradation of the hemicelluloses, cellulose, and lignin. Furthermore, it has been reported that strength changes were caused by increase of crystallinity and increased size of crystals. Thus, the strength of heat-treated wood material is dependent on density and moisture content (Finnish ThermoWood Association, 2003).

In general, BMT joints showed significantly higher bending strength values than those of MT joints. This can be explained by the increased gluing area of the joint, meaning that the bonding surface for the glue increases

and thus, the strength of BMT joints increases. Furthermore, for a larger gluing area, a higher bending moment should be expected. This study also confirms the findings of other researchers (Milham, 1949; Sparkes, 1968; Eckelman, 1971; Hill and Eckelman, 1973; Yang and Lin, 1986; Erdil et al., 2005; Güntekin, 2007; Derikvand et al., 2013) that the moment capacity of the MT joints is governed by different variables.

Joints are generally recognized as being the weakest point in construction, since the forming profiles of the joints prevent the development of the full strength of the material. The profiles, in addition to other factors, ultimately determine the load-bearing capacity and strength of the joint. Furniture joints are usually regarded as either pinned or fixed. In reality, the joint's behavior is in between: more semirigid. Strength properties can be enhanced by making the joints stiffer. For example, Tankut et al. (2003) indicated that round MT joints provided high rigidity for bookshelf frame construction.

Differences in moment capacities could be explained by the differences in shear strength parallel to the grain of the wood from which the joints were constructed. Tests have shown (Hill and Eckelman, 1973) that a positive linear relationship exists between the bending moment capacity of MT joints and the shear strength parallel to the grain of the wood from which the mortise is cut. Furthermore, joint strength is not related to the other mechanical properties of the wood species used in construction. Another explanation for these results has been the assumption that it is related to the bonding characterization and integration of the glue with wood
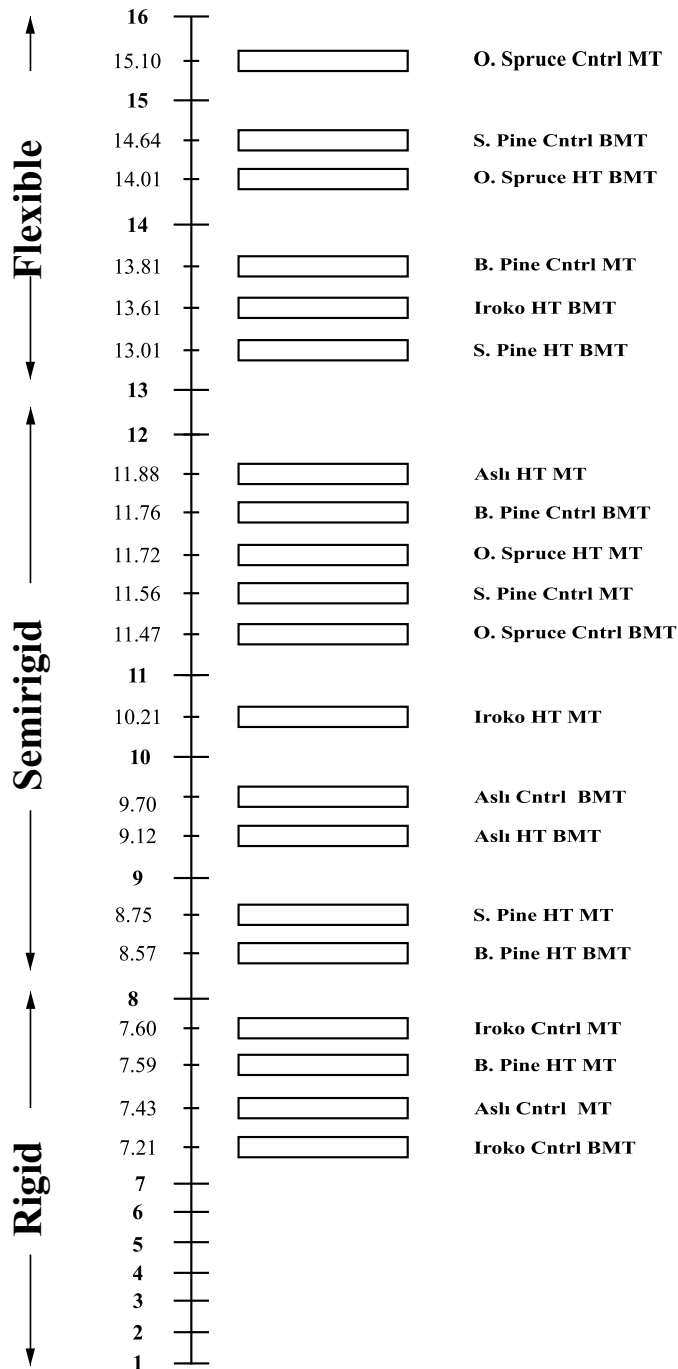
Figure 8. Rigidity scale developed for joint types. S. Pine: Scotch pine; B. Pine: Black pine (*Pinus nigra* L.); O. Spruce: Oriental spruce; MT: mortise and tenon joints; BMT: blind MT joints; Cntrl: control; and HT: heat treatment.

species. In this case, heat-treated Scotch pine has shown good performance with polyurethane-based adhesive.

For all connection types and variations of materials in terms of interaction, the best rigidity constant was obtained with Iroko control BMT joints, while the worst rigidity constant was obtained with Oriental spruce control MT joints. Previous researchers (Tankut et al., 2003) concluded that elastic deflections count on the geometry and mechanical properties of the rails, specifically their MOE, and the rigidity of the rail-to-post joints. In another
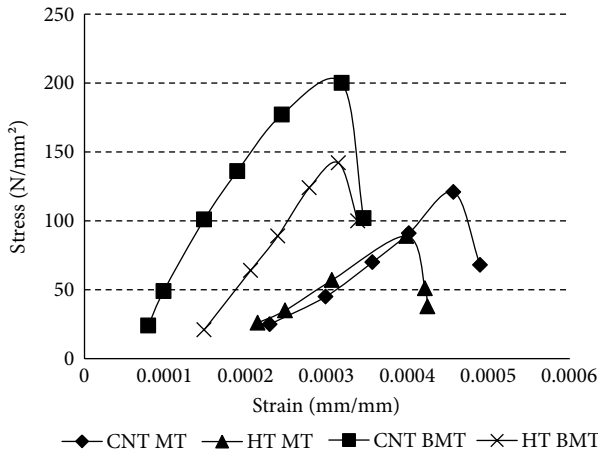
Figure 9. Stress-strain curve for a joint constructed using Scotch pine.

study, Tankut (2007) indicated that variations from planned dimensions will alter the thickness of the bond line. A tight fit between the tenon and mortise is necessary for the construction of durable joints, since a tighter joint produces a stiffer structure.

This study showed that heat-treated wood could be used for outdoor sitting furniture applications. Furthermore, heat treatment, wood type, and joint type had a significant effect on the bending strength of T-type MT joints. BMT joints produced from heat-treated Iroko wood can be considered as the most durable T-type joint for outdoor sitting furniture construction.

When the mechanical property results from this investigation are integrated with the anatomical data from future research, an even greater understanding of
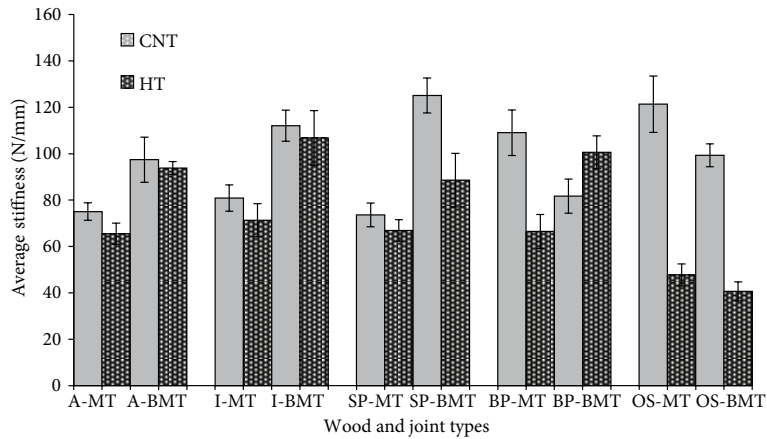

Figure 10. Effect of wood, treatment, and joint type on stiffness of joints. A: Ash; I: Iroko; SP: Scotch pine; BP: Black pine (*Pinus nigra* L.); OS: Oriental spruce; MT: MT joints; BMT: Blind MT joints; CNT: control; and HT: heat treatment. Error bars represent ±1 standard deviation.
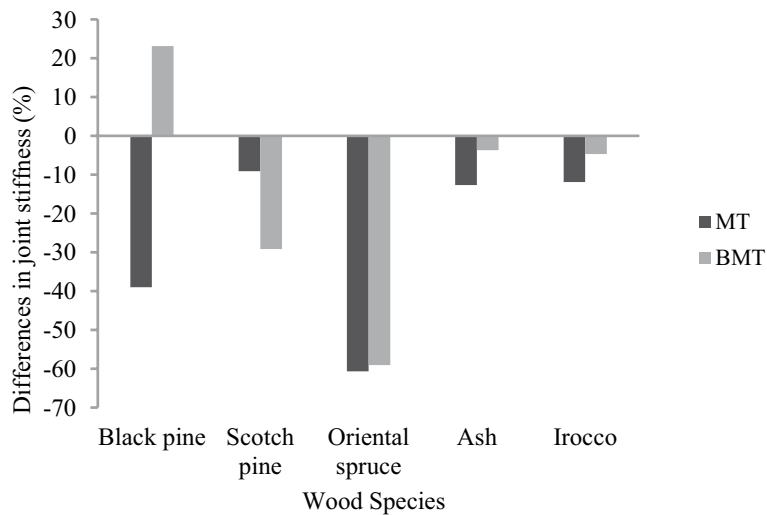

Figure 11. Differences in joint stiffness. MT: mortise and tenon joints; BMT: blind MT joints.

Table 3. Analysis of multivariance (MANOVA) of average maximum moment of T-type joint tests.

Source of variance	Sum of square	df	Mean square	F ratio	Level of significance
Between wood species	332,107.43	4	83,026.85	249.83	***
Between joint types	204,798.45	1	204,798.45	616.26	***
Between treatment types	113,590.53	1	113,590.53	341.80	***
Wood species × joint types	140,032.36	4	35,008.09	105.34	***
Wood species × treatment types	746,656.57	4	186,664.16	561.69	***
Joint types × treatment types	606.60	1	606.60	1.82	NS
Wood species × joint types × treatment types	128,711.95	4	32,177.99	95.82	***
Residual	32,232.26	100	332.32		
Total	1,599,736.28	120			

***: Highly significant with probability < 0.001; NS: not significant.

the strength reduction will be achieved. Further studies are suggested to minimize the strength loss that can occur due to different loadings and heat treatment conditions during furniture services. Different loading types and forces should be considered, especially in outdoor sitting furniture constructions.

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