EFFECTS OF TEMPERATURE ON THE BENDING PERFORMANCE OF WOOD-BASED PANELS

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The effect of temperature in the range from 25 ºC to 175 ºC on the bending performance of plywood and medium density fiberboard (MDF) has been studied with the ultimate purpose of optimizing the post-processing using radio frequency heating and improving the quality of the final products. Static 3-point bending tests were conducted on a universal testing machine inside a computer-controlled chamber. Results show that the bending strength (MOR) and modulus of elasticity (MOE) of plywood and MDF decrease with the increase of the temperature from 25 ºC to 175 ºC. The bending strength of plywood and MDF decreases with the increase of the exposure time. However, the effects of exposure time on MOE of plywood and MDF are not obvious. Plywood and 2.6 mm thick MDF show a typical elasto-plastic behavior, while 12 mm thick MDF does not exhibit any plastic behavior. It is recommended that the post-processing procedure should be completed within 15 minutes for both MDF and plywood.

Keywords: Bending strength; Modulus of elasticity; Plywood; Medium density fiberboard

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INTRODUCTION

Wood-based panels encourage the use of undervalued materials and improve the economics of forest restoration projects because they can be made from a variety of materials: fiber and particles or flakes from small logs, especially those from invasive species and overgrown forests at risk of wildfire; post-industrial and post-consumer wood wastes; and other natural bio-fibers, such as wheat straw and corn straw. The nonstructural application of wood-based panels such as plywood and medium density fiberboard (MDF) for furniture has considerably increased in the last few years because of their favorable physical and mechanical properties, ease of machining, availability, and cost-effectiveness. In the panel furniture industry, thin plywood and MDF panels are often post-processed to produce thicker or curved laminated furniture components by means of cold or hot pressing with radio frequency heating. It is of great interest to understand the effects of hot-pressing temperature on mechanical behavior of these post-processed wood-based panels, and accordingly to optimize the hot pressing process and improve the quality of the final products. Several researchers have reported on the effects of temperature on the mechanical properties of wood (Gerhards 1982; Lenth and Kamke 2001; Young and Clancy 2001; Bekhta and Niemz 2003; Moraes *et al.* 2005; Green and

Evans 2008a, b; Kocaefe *et al.* 2008; Ayrilmis *et al.* 2009, Manriquez and Moraes 2010). They observed that the strength of lumber decreases as the temperature increases. There are some publications on the effect of temperature on mechanical properties of oriented strand boards (OSB), and plywood from the viewpoint of the structural application considering the change of the service environment and fire performance (Back and Sandstrom 1982; Yu and Ostman 1983; Suzuki and Saito 1987; Bekhta *et al.* 2003; Sonderegger and Niemz 2006; Bekhta and Marutzky 2007; Ayrilmis *et al.* 2010; Sinha *et al.* 2011). However, there is limited information about the effect of temperature used during post-hot processing using radio frequency heating on bending properties of plywood and MDF manufactured from thinner panels. Therefore, such knowledge is very important from a practical point of view.

The objective of the present study was to determine the effect of the temperature and exposure time on the bending performance of plywood and MDF, which are usually used as laminating stock to produce thicker and curved laminated furniture parts.

EXPERIMENTAL WORK

Commercially available MDF and 3-ply plywood, urea-formaldehyde (UF)-bonded, made from Eucalyptus species (*Eucalyptus* spp.), were provided by the Foursea Furniture Ltd. for this study. Moisture content and density were determined at the temperature of 25 ºC and 65% relative humidity. Static 3-point bending tests were carried out in an Instron 5582 universal test machine inside a Eurotherm 2408 temperature-controlled chamber. Specimens were prepared and cut according to ASTM D1037-06a (ASTM 2006). Loading and deflection were measured, and MOR and MOE were calculated according to Section 9 in ASTM D1037. Sizes of specimens were reduced due to the internal space limitation of the chamber, which had dimensions of 400 mm × 400 mm × 550 mm. Investigated temperatures were 25 ºC, 75 ºC, 125 ºC, and 175 ºC. Specimens were preheated in the chamber until they reached equilibrium with the target temperature. The preheating times shown in Table 1 were determined from preliminary experiments by an embedded thermocouple, and the prediction model was developed in a previous study (Zhou *et al.* 2012). The mechanical properties of the samples were tested in the chamber while being heated when the samples reached the target temperature. The experimental design is shown in Table 1.

Table 1. Experimental Factors and Levels

Materials	Sample size (mm^3)	Density ($kg \cdot m^{-3}$)	Moisture content before preheating (%)	Pre-heating time (min)				Span-to-depth ratio
				25 ºC	75 ºC	125 ºC	175 ºC	
Plywood	3.8×50.0×150	651	12.1	0	/	25	/	24
MDF	2.6×50.0×150	825	9.7	0	3	7	6	24
MDF	12.0×50.0×350	712	8.2	0	13	42	45	24
MDF	18.0×50.0×360	772	7.1	0	/	53	/	15

Different temperatures, dimensions of samples, and pre-heating times that the samples were kept in the heated environment after their core reached the target temperature, were considered. A total of 20 groups were tested. The test results are summarized in the Appendix Table. The number of replications adopted for each group was six.

RESULTS AND DISCUSSION

The 12.0 mm and 2.6 mm thick MDFs are often used as laminates for producing thicker and curved furniture parts. The effect of the temperature on the bending strength and MOE was studied to understand the bending performance of MDF samples of different thicknesses. Load-displacement curves of the 12 mm thick MDF samples obtained from the bending test under different temperatures are shown in Fig. 1. It can be observed that both the changes in bending strength (MOR) and MOE were not significant when the temperature was increased from 25 ºC to 75 ºC. The bending strength and MOE decreased by 28.3% and 29.7%, respectively. A monotonic, linear and decreasing relationship between the bending strength and the temperature from 20 ºC to 140 ºC with exposure time of 180 minutes has been reported (Bekhta *et al.* 2003). In this study however, both the bending strength and MOE did not change significantly when the temperature increased from 75 ºC to 125 ºC. Similar results have been obtained in previous studies on the effect of temperature on the embedding strength and compression strength of solid wood (Moraes *et al.* 2005; Manriquez and Moraes 2010). The softening or glass transition temperature of wood is thought to be one of the major reasons for these observations on mechanical properties of wood-based materials at elevated temperatures.

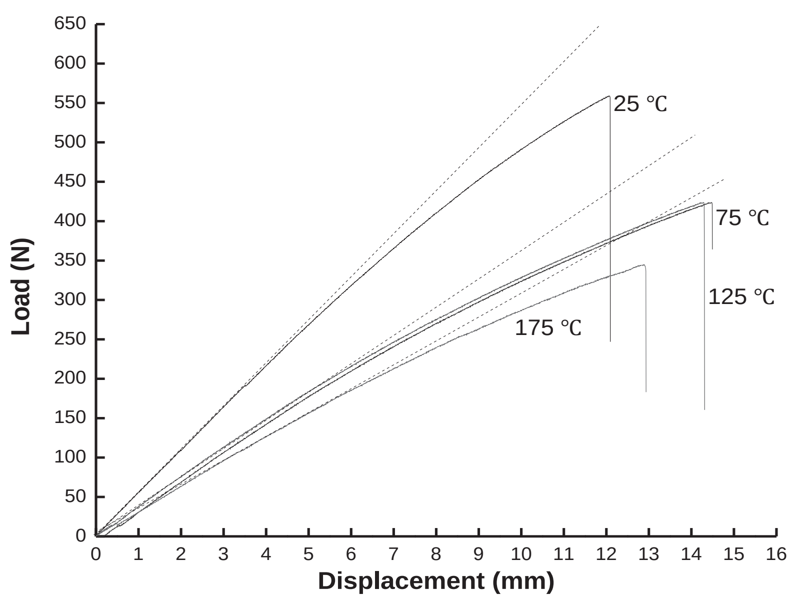

Fig. 1. Typical load-displacement curves of 12.0 mm MDF under different temperatures

Some researchers have reported that the glass transition temperature (T_g) of different solid wood at different moisture content is within the range of 60 ºC to 115 ºC (Becker and Noack 1968; Hoglund *et al.* 1976; Atack 1981; Irvine 1984; Salmen 1984; Kelley *et al.* 1987; Ostberg *et al.* 1990). The softening temperature of hemicelluloses and lignin is about 30 ºC and 70 ºC when the moisture content is approximately 10% (Kelley *et al.* 1987). Studies have shown that the thermal softening of wood occurs in the range 115 to 145 ºC (Blechschmidt *et al.* 1986). It can be deduced that the mechanical properties of wood-based materials are governed by a similar softening mechanism when the temperature is within the range of 75 ºC to 125 ºC. The bending strength and MOE decreased by 40.8% and 38.3% when the temperature was increased from 25 ºC to 175 ºC. The urea-formaldehyde (UF) resin used in the manufacturing MDF panels may have a major impact on the mechanical properties of wood-based panels, especially when the heating temperature exceeds 125 ºC. It can be also observed from Fig. 1 that there is the linear-elastic part of the load-deformation response and no obvious post-plastic part.

Load-displacement curves of 2.6 mm thick MDF samples under different temperatures are shown in Fig. 2. It can be observed that the bending strength was almost the same at different temperatures of 25 ºC, 75 ºC, and 125 ºC. However, MOE was decreased by 26.3 %, 28.4 %, and 57.5 %, respectively when the temperature was increased from 25 ºC to 75 ºC, 125ºC, and 175 ºC. Results of the ANOVA and multiple comparison statistics analysis for the temperature effect are shown in Table 2. The Sig. values for MOEs between 25 ºC and 75 ºC, 25 ºC and 125 ºC, 25 ºC and 175 ºC, 75 ºC and 125 ºC, 75 ºC and 175 ºC, and 125 ºC and 175 ºC were less than 0.05, indicating that the effects of different temperatures on MOE for these pairs are statistically significant. The significant values for MORs between 25 ºC and 175 ºC, 75 ºC and 175 ºC, and 125 ºC and 175 ºC are less than 0.05, indicating that the effects of temperature on MOR were statistically significant only when the temperature was raised to 175 ºC. The displacement at the maximum load point greatly increased with an increase in temperature.

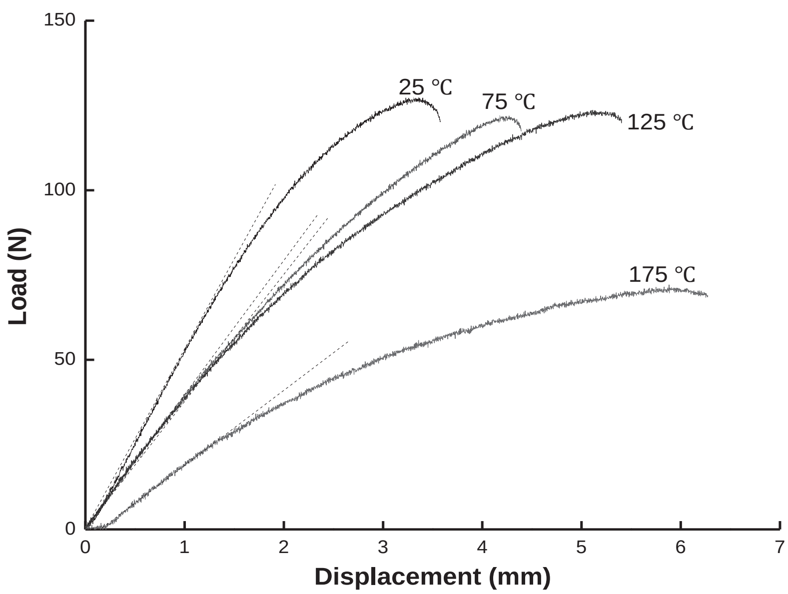

Fig. 2. Typical load-displacement curves of 2.6 mm MDF under different temperatures

The bending strength and MOE were decreased by 42.0% and 57.5%, respectively, when the temperature was raised from 25 ºC to 175 ºC. It is safe to draw a conclusion that the stiffness of the 2.6 mm thick MDF sample decreases with an increase in temperature. This finding explains why the thinner MDF is usually used as laminates to produce thicker and curved laminated furniture parts by the industry. It is also interesting to note that there exists an obvious plastic behavior in the load-displacement curves. It is very valuable to find that the deforming ability increases without the reduction of the bending strength when the temperature is below 125 ºC for the 2.6 mm thick MDF sample.

Table 2. Statistical Analysis of Effects of Temperature on MOR and MOE of 2.6 mm Thick MDF

Property	Sig.					
	25°C vs. 75°C	25°C vs. 125°C	25°C vs. 175°C	75°C vs. 125°C	75°C vs. 175°C	125°C vs. 175°C
MOR	0.430	0.990	0.000	0.423	0.000	0.000
MOE	0.000	0.004	0.000	0.000	0.000	0.001

Legend: The multiple comparisons for MOR and MOE at different temperature levels were computed by LSD and Tamhane methods based on the ANOVA test results using SPSS 19.0, respectively. N = 6 for each group.

Increasing temperature has two effects on a wood panel product: post-curing of the UF adhesive and increasing the deformability of wood during the radio frequency heating process. Exposure time and temperature play an important role. Bending stress-deflection curves of different exposure times for MDF and plywood when the temperature is 125 ºC are shown in Fig. 3. The 2.6 mm MDF samples, 12 mm MDF samples, and 3.8 mm plywood samples were pre-heated in the chamber to reach the equilibrium temperature. Samples were exposed to the heating up to the target temperature for 15 minutes, followed by 30 minutes at the target temperature before the bending test commenced. It can be observed that both 2.6 mm MDF and plywood samples exhibited a typical elastic-plastic behavior. The plastic behavior was much more obvious for plywood. The reason is thought to be that plywood is much closer to solid wood than MDF because of its layered structure.

Results of the ANOVA test on the exposure time effects are shown in Table 3. It can be observed that the Sig. values for MOE were less than 0.05 for both thicknesses of MDF. The Sig. value for MOR was less than 0.05 for 2.6 mm MDF, while the Sig. value was greater than 0.05 for 12 mm MDF. These findings indicate that the exposure time had a significant effect on MOR and MOE for 2.6 mm MDF while being heated. The bending strength of 2.6 mm MDF sample decreased with an increase in exposure time, while MOE showed an opposite trend. The exposure time had a negative impact on the bending performance of 2.6 mm MDF. The short-term effect of the exposure time on the bending strength and MOE of 12 mm MDF samples and plywood samples was not obvious.

Table 3. Statistical Analysis of Effects of Exposure Time on MOR and MOE

MAT	Mechanical properties	Sum of Squares	df	Mean Square	F	Sig.
2.6 mm MDF	MOR	47.0	2.0	23.5	5.5	0.025
	MOE	196417.8	2.0	98208.9	6.0	0.019
12 mm MDF	MOR	10.6	2.0	5.3	1.7	0.209
	MOE	128711.7	2.0	64355.9	13.0	0.001
Plywood	MOR	42.0	2.0	21.0	2.4	0.123
	MOE	104904.0	2.0	52452.0	0.6	0.552

Legend: The One Way ANOVA tests were conducted using SPSS 19.0. The p-value results between groups were generated.

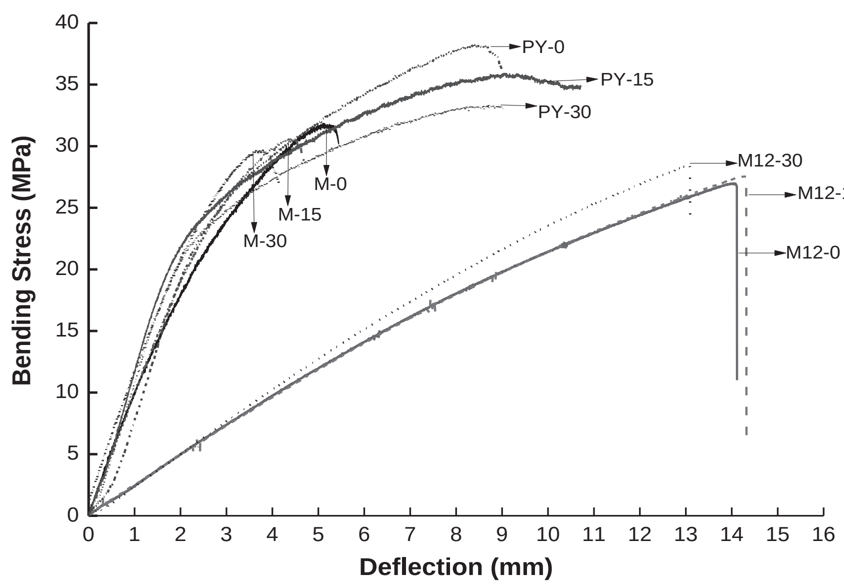

Fig. 3. Typical bending stress-deflection curves of different exposure times at 125 ºC. M-0, M-15, and M-30 represent different exposure times of 0min, 15min, and 30min for 2.6 mm MDF, respectively; PY-0, PY-15, and PY-30 represents different exposure times of 0 min, 15 min, and 30 min for plywood, respectively; M12-0, M12-15, and M12-30 represents different exposure times of 0 min, 15 min, and 30 min for 12 mm MDF, respectively.

The work reported in this paper was intended to develop preliminary values for process parameters to optimize the post hot pressing with radio frequency heating and to improve the quality of the final product. However, a systematic study is further needed to construct a constitutive model of the mechanism behind the heating of the wood-based panels and to well understand the transient and permanent impacts at various temperatures and exposure time for the better use of wood- based panels.

CONCLUSIONS

The effects of temperature on the bending performance of plywood and MDF were studied with the ultimate purpose of optimizing the post-hot-pressing of the final products with radio frequency heating and to improve their quality. The major findings are as follows:

1. The bending strength and MOE decreased with increasing temperature during the evaluation. However, it is not a simple monotonic, linear relationship between the mechanical properties and the temperature.
2. The exposure time has a negative impact on the bending performance of plywood and MDF samples. The post-hot-pressing process should be finished within less than 15 minutes when MDF or plywood is adopted as the laminate to produce a thicker and curved laminated furniture part.
3. The thickness of MDF has a negative impact on the bending performance. The thinner the panel, the better the bending properties.

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Appendix Table Mechanical properties of plywood and MDF under different experimental conditions

MAT	Thickness (mm)	Mechanical properties	25 °C		75 °C		125 °C								175 °C	
							Exposure time (min)									
							0		15		30		30-higher testing speed			
			Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)	Mean	SD (COV)
MDF	2.6	MOR (MPa)	31.5	2.4 (7.6%)	31.4 (-0.3%)	1.3 (4.1%)	32.3 (2.6%)	3.2 (9.9%)	31.3 (-0.7%)	2.2 (7.0%)	29.9 (-5.0%)	2.5 (8.4%)	32.1 (2.0%)	2.3 (7.2%)	18.3 (-42.0%)	1.0 (5.5%)
		MOE (MPa)	3129	116 (3.7%)	2307 (-26.3%)	139 (6.0%)	2240 (-28.4%)	310 (13.8%)	2372 (-24.2%)	203 (8.6%)	2482 (-20.7%)	149 (6.0%)	2481 (-20.7%)	223 (9.0%)	1331 (-57.5%)	108 (8.1%)
		DML (mm)	3.27	0.18 (5.5%)	4.42 (35.3%)	0.10 (2.3%)	5.08 (55.4%)	0.26 (5.1%)	4.40 (34.6%)	0.21 (4.8%)	3.97 (21.6%)	0.34 (8.6%)	4.14 (26.7%)	0.53 (12.8%)	6.58 (101.3%)	0.35 (5.3%)
	12	MOR (MPa)	35.9	2.0 (5.6%)	25.8 (-28.3%)	2.3 (8.9%)	27.0 (-24.7%)	2.4 (8.9%)	27.8 (-22.7%)	1.1 (4.0%)	27.8 (-22.5%)	1.3 (4.7%)	29.9 (-16.8%)	1.2 (4.0%)	21.2 (-40.8%)	1.2 (5.7%)
		MOE (MPa)	3768	75 (2.0%)	2648 (-29.7%)	98 (3.7%)	2887 (-23.4%)	138 (4.8%)	2809 (-25.4%)	68 (2.4%)	3067 (-18.6%)	29 (1.0%)	2970 (-21.2%)	65 (2.2%)	2326 (-38.3%)	163 (7.0%)
		DML (mm)	13.14	0.93 (7.1%)	14.27 (8.7%)	1.51 (10.1%)	13.61 (3.6%)	0.40 (2.9%)	14.10 (7.4%)	0.62 (4.4%)	12.75 (-2.9%)	1.05 (8.2%)	14.13 (7.6%)	0.63 (4.5%)	12.37 (-5.8%)	0.99 (8.0%)
	18	MOR (MPa)	33.7	2.5 (7.4%)	/	/	/	/	/	/	28.1 (-16.8%)	2.0 (7.1%)	/	/	/	/
		MOE (MPa)	3660	226 (6.2%)	/	/	/	/	/	/	2864 (-21.8%)	139 (4.9%)	/	/	/	/
		DML (mm)	7.57	0.46 (6.1%)	/	/	/	/	/	/	9.17 (21.2%)	0.48 (5.2%)	/	/	/	/
Ply-wood	3.8	MOR (MPa)	57.2	2.1 (3.7%)	/	/	36.4 (-36.4%)	2.9 (8.0%)	35.7 (-37.7%)	3.8 (10.6%)	32.7 (-42.9%)	1.9 (5.8%)	/	/	/	/
		MOE (MPa)	5941	137 (2.3%)	/	/	4612 (-22.4%)	310 (6.7%)	4246 (-28.5%)	423 (10.0%)	4454 (-25.0%)	128 (2.9%)	/	/	/	/
		DML (mm)	9.03	0.24 (2.7%)	/	/	9.73 (7.8%)	0.36 (3.7%)	9.19 (1.8%)	1.31 (14.3%)	9.25 (2.4%)	0.74 (8.0%)	/	/	/	/

Legend: MOR, the bending strength; DML, the displacement at maximum load; MOE, modulus of elasticity; The percentage within the bracket is calculated based on the values at 25℃; SD for standard deviation, COV for coefficients of variation.