Aluminum-laminated Panels: Physical and Mechanical Properties

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Aluminum lamination was performed to improve the physical and mechanical properties of several wood-based composite panels. The panels were aluminum-laminated on two faces in a hot press at 689 kPa and 120 °C for 6 min. Four types of wood-based composites were used as cores, and aluminum 3003 alloy sheets were used for face laminations. Polyurethane adhesive ensured bonding strength between the wood-based composite and the aluminum sheets. The objective was to assess sandwich composite panels made of wood-based composites as a core layer with aluminum-laminated faces. This study evaluated the physical and mechanical properties of these panels. The results show that aluminum-laminated panels had higher dimensional stability (thickness swelling and linear expansion values). Bending properties such as the apparent modulus of elasticity (E_{app}) and the modulus of rupture (MOR) were significantly increased with face-lamination. Medium-density fiberboard (MDF) laminate presented an increase of 554% for E_{app} and 570% for MOR in comparison with non-laminated MDF panels. The shear edgewise strength for oriented strand board and plywood increased by 44% and 77%, respectively. The results confirm that aluminum-laminated panels have the potential to be used as structural panels in future applications.

Keywords: Wood-based composite; Aluminum alloy sheets; Thickness swelling; Water absorption; Apparent modulus of elasticity; Modulus of rupture

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INTRODUCTION

Wood-based composites are used in a number of structural and non-structural applications. Performance criteria are directly related to the end use of these composites. Knowledge of their physical and mechanical properties is of critical importance to their future applications (Cai and Ross 2010). Traditional wood-based composites offer desirable properties for their main applications – oriented strand board (OSB) and plywood are used as structural material for construction, whereas particleboard and medium-density fiberboard (MDF) with laminating paper are used in cabinetry, furniture, and mouldings (Maloney 1993). Certain weaknesses, such as their mechanical properties, poor water resistance, dimensional stability, and durability, limit their use in applications involving exposure to wet environmental conditions. In the last decades, several studies attempted to improve the performance and structural efficiency of wood-based composites (Xu *et al.* 1998a; Biblis and Canino 2000; Cai 2006; Bouffard and Amiotte 2011). Reinforcement has been beneficial for improving physical and mechanical properties, decreasing variations, and improving durability. Reinforcement with materials of high strength and stiffness, such as fiberglass, carbon fiber, kevlar, natural fibers, and metal, has been used to increase the flexural and shear properties of wood-based composites. These reinforcements have been placed between the veneers or on the faces of plywood, OSB, high-density fiberboard (HDF), and MDF. Xu *et al*. (1998b) used bamboo fiber and jute fiber as reinforcements to make fiber-reinforced plywood with increased mechanical properties. Other research using various types of reinforcement between veneers or fiber layers presented a similar increase in mechanical properties (Xu *et al*. 1998a; Borysiuk *et al*. 2007; Kishi and Fujita 2008; Abdul Khalil *et al*. 2010; Cerbu *et al.* 2010; Mohebby and Tavassoli 2011).

Laminated panels, also called sandwich panels, have a wide range of utilization. They have been widely used in aircraft, automotive, marine, and other structural applications for a long time. Laminated panels are a special group of laminates that most frequently consist of three laminae, of which the core is much thicker and lower in stiffness and rigidity than the faces (Bodig and Jayne 1993). Recent applications have demonstrated that laminated panels can be effectively and economically used in engineering infrastructure (Manalo *et al.* 2010). Laminated panels offer high bending stiffness and high strength-to-weight ratios, which are achieved when the face and core interact in an optimal way (Belouettar *et al*. 2009). Several types of face and core material have been used in the design of laminated panels. Frequently used face materials include aluminum alloys, steel, fiberglass, hardboard, and gypsum, while frequent core materials include polyurethane, polyisocyanurate, expanded polystyrene, extruded polystyrene, mineral wool, and balsa wood (Pokharel and Mahendran 2003). In a laminated panel, the top and bottom layers (face materials) carry bending moments as tensile or compressive stresses, while the core materials transfer the transverse forces as shear stresses and support the faces against buckling and wrinkling (Shipsha 2013). Laminated panels may offer other properties such as good durability, lightness, and high acoustic and/or thermal insulation.

Among the development of wood-based laminated panels with enhanced properties, Biblis and Carino (2000) evaluated the mechanical properties of 3-ply and 5-ply southern pine plywood laminated with fibreglass-reinforced plastic. The results showed considerable improvement in the stiffness and strength of plywood panels with face-lamination on both sides with layers of thin fibreglass-reinforced plastic. Similarly, Cai (2006) evaluated the mechanical and physical performance of MDF and flakeboard laminated with fibreglass. Fibreglass lamination improved the apparent modulus of elasticity (E_{app}) and modulus of rupture (MOR), as well as resistance to water absorption (WA) and thickness swelling (TS). Biblis *et al*. (1996) compared the flexural properties of wood veneer-overlaid OSB composite panels from southern pine. The E_{app} and MOR values in the parallel direction to the wood veneer grain were increased by 96% and 117% in comparison with those of OSB panels without wood veneer lamination. Results from other studies demonstrated that the mechanical properties of wood-based composites can be considerably improved if these are laminated with reinforced materials (Kawasaki *et al*. 1999; Ayrilmis *et al*. 2008; De Figueiredo *et al*. 2009; Büyüksari *et al*. 2012). Another mechanical property studied in wood-based composites and laminated panels is shear strength. Manalo *et al*. (2013) investigated the shear behaviour of a laminated panel comprised of glass fiber-reinforced polymer skins and modified phenolic core material. The results showed significant improvement of the shear strength of the laminated panels in the edgewise direction. The bonding strength of the face materials is important since the lamination materials are influenced by negative conditions such as high humidity, high temperature, and tensile and compression stresses (Kilic *et al.* 2009). The quality of adhesion depends on the anisotropic and heterogeneous character of wood or other materials, as well as the nature of adhesive. The adhesive must assure the transfer of the effort and compensate the differences of thermal expansion, moisture expansion, and elongation under constraints of different materials. Among the adhesives used, epoxy, polyester, and polyurethane stand out. The bonding strength in the laminated panels between material core and face-sheets has been extensively studied by Kilic *et al*. (2009). Li and Weitsman (2004) and Siriruk *et al*. (2008) used a laminated panel debonding fracture test to investigate toughness at the core/facing interfaces.

Objective

The objective of this study was to assess the performance of wood-based composites as a core layer of aluminum-laminated panels. This study evaluated physical properties, such as density, thickness swelling, water absorption, and linear expansion, as well as mechanical properties including bending properties, internal bond strength, edgewise shear, and tensile strength of the surface of wood-based composites with and without lamination of aluminum alloy sheets. The determination of physical and mechanical properties are critical to identify potential applications for the aluminum-laminated panels. Finally, this study determined an estimate of the manufacturing cost of aluminum-laminated panels. This estimate was determined considering all resources consumed in the manufacturing process, as well as variable costs and fixed costs.

EXPERIMENTAL

Materials

Four types of wood-based composite panels were used as cores: HDF, MDF, OSB, and aspen plywood (Table 1). These panels were obtained on the market as produced by the manufacturers, except the aspen plywood, which was manufactured in a laboratory with five 2-mm plies of aspen (*Populus tremuloides* Michx). Phenol-resorcinol-formaldehyde was used as an adhesive at a 260 g/m^2 spread rate. The plywood was manufactured under a pressure of 689 kPa at room temperature for 7 h.

Table 1. Physical Properties of Wood-based Composites

Wood-based Composites	Symbol	Moisture Content (%)[1]	Thickness (mm)	Density (kg/m^3)[1]
High-density fiberboard	HDF	6	9.74	817[2]
Medium-density fiberboard	MDF	7	9.99	798[2]
Oriented strand board	OSB	8	10.57	673
Aspen Plywood	PW	10	9.17	542

[1]Moisture content was determined using ASTM Standard D4442-07 (Method A-Oven-Drying), while the density of wood-based composites was determined according to ASTM Standard D2395-07 (Test Method A- volume by measurement).
[2]The acronyms HDF and MDF were used commercially by the fiberboard market.

The wood-based composites were trimmed to dimensions of 600 mm by 600 mm and conditioned at 20 °C and 50% RH until constant mass was achieved. These conditions reached an equilibrium moisture content (EMC) of between 6% and 10%, depending on their nature (Table 1). The laminating material consisted of aluminum alloy sheets 3003 with a thickness of 0.6 mm and a nominal density of 2740 kg/m^3. This aluminum alloy sheet was selected because of its water barrier properties, mechanical properties, and low cost, while the selection of the thickness was based on preliminary work. A liquid polyurethane adhesive (Macroplast UR-8346) provided by Henkel Canada Corporation was used to bond the aluminum to the core materials. The adhesive was selected after preliminary work, in which epoxy and polyurethane were considered. The aluminum honeycomb panel (EC-PI 626AS), provided by SCEI (Aéronautique Défense Spatial), was used for the purpose of comparison.

Methods

Panel lamination

To examine the effect of lamination with aluminum on wood-based composite performance, four panels out of seven were laminated for each type of wood-based composite. The three remaining panels were kept as control panels for comparison purposes. The wood-based composites were laminated on both faces with 0.6-mm-thick aluminum alloy sheets (Fig. 1).

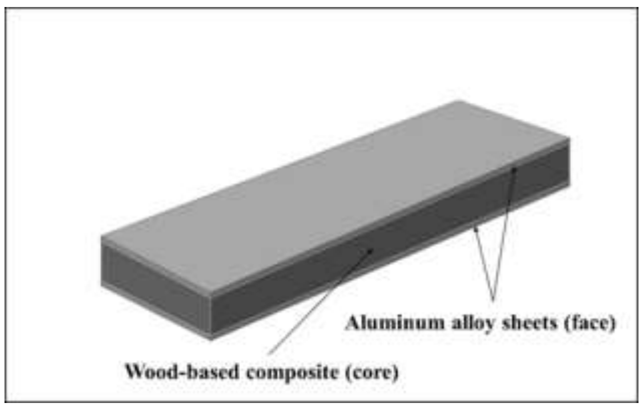

Fig. 1. Schematic illustration of aluminum-laminated panel

The polyurethane adhesive was applied at a spread rate of 130 g/m^2, according to manufacturer instructions. The aluminum alloy sheets were sanded with 150-grit sandpaper and cleaned with acetone. This pretreatment is common in the bonding of aluminum sheets. OSB and plywood panels were sanded with 120-grit sandpaper. The laminated panels with two aluminum alloy faces were pressed in the laboratory hot press at 689 kPa and 120 °C for 6 min using a Dieffenbacher press (Germany). After pressing, the laminated panels were stored in a conditioning chamber at 20 °C and 65% RH until a constant mass was reached.

Determination of physical and mechanical properties

Four laminated panels were used to prepare the test specimens by each type of wood-based composites. A total of ten 50 x 50 mm laminated specimens were prepared for each type of laminated panel for testing density and moisture content. A total of eight specimens of 150 x 150 mm were prepared for the TS and WA tests. Eight specimens of 76 x 300 mm were prepared for the linear expansion (LE) tests. Twelve laminated specimens were prepared for the mechanical tests. Non-laminated wood-based composite specimens were tested using the same procedures for comparison purposes.

The density (ρ*) of each laminated panel was calculated using Eq. 1,

$$\rho^* = (2h_f/h)^*\rho_f + (h_c/h)^*\rho_c \quad (1)$$

where "ρ_f" and "ρ_c" are the densities of the aluminum alloy sheets and wood-based composites, h is the total thickness of the laminated panel ($h = 2h_f+h_c$), "h_f" is the thickness of the aluminum alloy sheets, and h_c is the thickness of the wood-based composites (Carlsson and Kardomateas 2011).

Physical properties such as TS, WA, and LE were determined according to ASTM Standard D1037.06a (ASTM 2012). TS and WA were determined after 2-h and 24-h water immersions at room temperature (Method A-ASTM D 1037.06a).

The bending strength, internal bond strength (IB), and edgewise shear tests were conducted using ASTM Standard D1037.06a (ASTM 2012). A three-point static bending test was carried out. The rates of motion of the moving head were 5.19, 5.23, 5.51, and 4.87 mm/min, while lengths of span were 259.68, 261.36, 275.28, and 243.60 mm for R-HDF, R-MDF, R-OSB and R-PW, respectively (according to ASTM Standard D1037.06a). The mechanical properties as E_{app} and MOR were determined parallel to the face of grain for laminated OSB- and plywood-core panels. The E_{app} is defined in this article as the modulus of elasticity without considering the shear deformation (Bodig and Jayne 1993). The E_{app} and MOR values of aluminum-laminated panels were compared with aluminum honeycomb panel. The EC-PI 626AS panels were 10 ±0.3 mm in thickness with a face sheet of 0.6-mm thickness. Edgewise shear tests (shear normal to the plane of the panel) were carried out in axial compression on laminated specimens of 89 x 254 mm clamped between two pairs of steel loading rails according to ASTM Standard D1037.06a (ASTM International 2012).

The surface soundness of the laminated panels testing was conducted according to EN 311:2002 standard (European Standard 2002). A total of eight laminated specimens of 50 x 50 mm were prepared for each type of laminated panel for testing surface soundness. The variability between laminated panels with the same cores was not considered. A circular groove 35.7 +/− 0.2 mm in diameter was cut into the surface of the aluminum alloy sheets. The circular groove did not penetrate more than 0.3 +/− 0.1 mm into the core layer of the wood-based composite. A steel pad was bonded with epoxy to the area within the circular groove. The laminated specimens were installed in a test machine, and tensile force was applied at a constant speed so that failure occurred between 30 to 90 seconds after the beginning of loading. The surface soundness was calculated using Eq. 2,

$$SS = F/A, \quad (2)$$

where SS is surface soundness in megapascal (MPa); F is the maximum force in Newtons, and A is the surface area of the groove (1000 mm^2).

All data obtained were analyzed with an ANOVA ($\rho<0.05$) using Statistical Analysis System (SAS) software 9.3 (USA).

Determination of manufacturing costs

The manufacturing cost in the development of a material is a basic factor that informs decisions on its potential use in specific applications. This work attempted to estimate the manufacturing cost of aluminum-laminated panels. Cost analysis was carried out based on the technical cost modelling approach of Wakeman and Månson 2004 (Fig.

2), which considers all resources consumed in the manufacturing process of the panels (both variable and fixed costs).

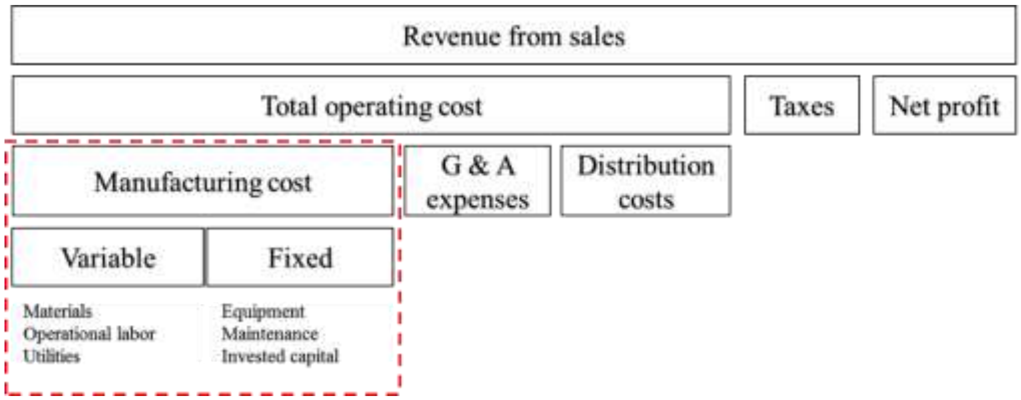

Fig. 2. Approach for estimation of manufacturing cost of aluminum-laminated panels

Variable costs are directly dependent on production and include the cost of materials (aluminum alloy sheet, wood-based composite, degreasers, and polyurethane adhesive) and utilities. Variable costs also include processing costs (operational labor) of each stage of the manufacturing process including sanding, cleaning, bonding, pressing, and trimming (Fig. 3). Fixed costs include mainly equipment, maintenance, and invested capital, which are not dependent on production.

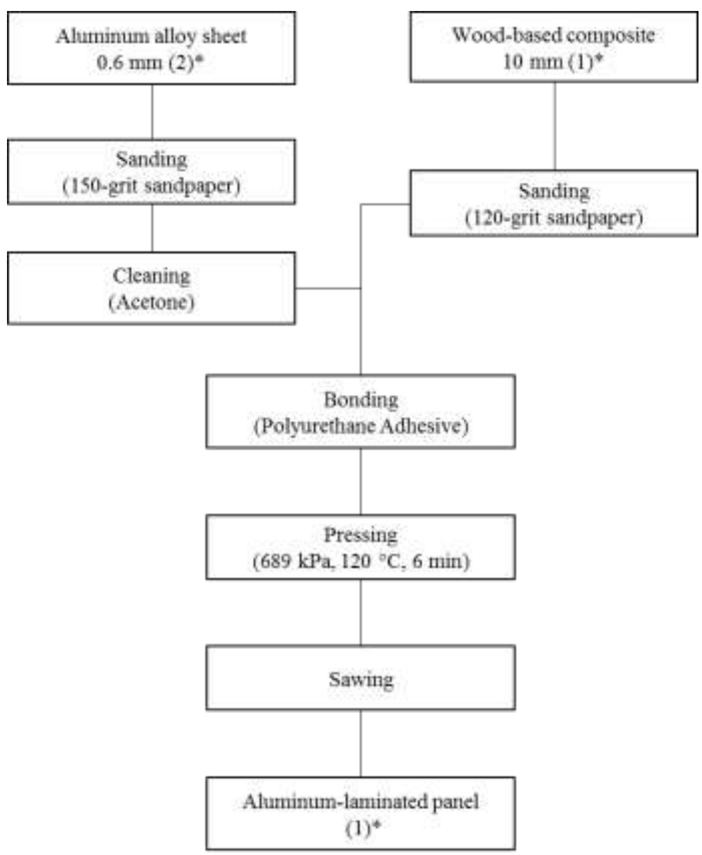

Fig. 3. Manufacturing process of aluminum-laminated panels. *Quantity of material

The manufacturing cost was estimated per square meter of aluminum-laminated panel considering a total production of 45,000 m^2/year. The variable costs were divided into material costs and processing costs for 2013. Wood-based composite cost was estimated based on a thickness of 3/8 inches (9.525 mm), using information published by Spelter *et al.* (2006) and RISI (2013). Aluminum alloy sheet cost was estimated at 70% of the retail price. The polyurethane adhesive cost was estimated in 6.5 CAD/Kg; this and the degreasing cost were estimated based on inquiries with a vendor.

A limitation to the accuracy of results from processing costs was the level of information available for each process of the bonding and pressing of aluminum-laminated panels. Although limited in accuracy, this evaluation provides an order of magnitude of the aluminum-laminated panel for the purpose of identifying potential applications.

RESULTS AND DISCUSSION

Physical Properties

Various physical properties of wood-based composites and aluminum-laminated panels such as TS, WA, and LE were studied in order to compare their technical performance when exposed to wet environmental conditions. The results are presented in Table 2.

Thickness swelling (TS) and water absorption (WA)

As expected for wood-based composites (without lamination), the dimensional stability after 24-h water soaking of plywood was higher compared with the other wood-based composites. The TS values of wood-based composites decreased with lamination with aluminum alloy sheets (Table 2), except for MDF. The TS value of R-HDF was 24 times lower than that of HDF, the TS value of R-OSB was six times lower than that of OSB, while the TS value of R-PW was 2.8 times lower than that of PW. This decrease in TS values was mainly caused by the reduced water penetration into the wood-based composite with aluminum lamination. The WA values of wood-based composites also decreased with aluminum alloy sheet lamination. These results are in concordance with previous studies (Cai 2006; Büyüksari *et al*. 2012). In the case of WA values, R-HDF presented the lowest WA value compared with the other wood-based composites with or without lamination (Table 2) for 24-h water soaking. The WA value of R-HDF was 8.5 times lower than that of HDF, the WA value of R-OSB was three times lower than that of OSB, while the WA value of R-PW was 2.9 times lower than that of PW. The WA values of MDF and R-MDF presented no significant difference. These results could be caused by fractures, which were observed in the MDF-core. These are thought to have occurred at the moment of laminating at 689 kPa the aluminum foils, although the pressure level used was lower than that for MDF lamination with polyvinyl chloride film used in Kilic *et al*. (2009). Additional laminated MDF-core panels were compressed in a hot press at 413 kPa and 138 kPa. These laminated panels did not show delamination on the wood-based composite. The TS and WA values of these laminated panels were lower than for MDF without lamination. No delamination between the aluminum alloy sheets and the wood-based composite was observed after 24-h water soaking, which suggests strong bonding.

Table 2. Physical Property Values of Wood-Based Composites with and without the Lamination of Aluminum Alloy Sheets

Wood Composites	Symbol	Thickness (mm)	Physical Properties							
			Density[1] (kg/m^3)	2-h Water Soak			24-h Water Soak			Linear Expansion Coefficient[1] (β) (%) 50% to 80% RH
				MC (%)	TS[1] (%)	WA weight[1] (%)	MC (%)	TS[1] (%)	WA weight[1] (%)	
High-density fiberboard	HDF	9.74	817 A	10.0	2.95	12.14 A	23.4	9.30 A	14.04 A	0.19 A
Laminated high-density fiberboard	R-HDF	10.82	1029 Ba	4.6	---	0.45 Ba	5.9	0.38 Ba	1.65 Ba	0.00 Ba
Medium-density fiberboard	MDF	9.99	798 A	14.5	3.17 A	4.59 A	33.7	14.25 A	22.05 A	0.16
Laminated medium-density fiberboard	R-MDF	10.89	1012 Ba	7.5	1.05 Aa	2.74 Ab	25.2	16.17 Ab	19.70 Ab	---
Oriented strand board	OSB	10.57	660 A	20.1	3.88 A	10.23 A	47.4	14.81 A	35.28 A	0.06
Laminated oriented strand board	R-OSB	11.47	886 Bb	7.0	0.81 Ba	2.77 Bb	15.9	2.46 Ba	11.37 Bc	---
Aspen plywood	PW	9.17	542 A	31.0	2.18 A	15.42 A	55.2	4.61 A	36.75 A	0.06 A
Laminated aspen plywood	R-PW	10.15	800 Bb	10.4	0.07 Ab	10.43 Bc	19.6	1.65 Ba	12.73 Bd	0.01 Ba

--- These data were not considered because of issues with the specimens.
[1]Means within a column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for comparison between each pairing of wood composites (non-laminated and laminated). Lowercase letters are for comparison between all aluminum-laminated panels.

Linear expansion

The linear expansion coefficients (β) of wood-based composites were improved by lamination with aluminum alloy sheets (Table 2). The laminated HDF- and plywood-core panels presented the lowest linear expansion coefficients (β) in relation to other non-laminated wood-based composites. The β values of R-HDF and R-PW were 19, 16, 6, and 6 times lower than those of HDF, MDF, OSB, and PW, respectively. The aluminum alloy sheets worked as a barrier to prevent the entry of water vapor into the core. In the case of the R-MDF- and R-OSB-laminated specimens, delamination was observed in the wood-based composites (core layer) during the change of relative humidity from 50% to 80%. Delamination of the OSB-core and MDF-core on the edge of the specimens caused a decrease in the measure of length specimens. Consequently, the linear expansion coefficients values for R-MDF and R-OSB were discarded.

Mechanical Properties

The results for static bending (E_{app}, MOR), IB strength, edgewise shear strength, and tensile strength of the surface tests are presented in Table 3.

Table 3. Mechanical Property Values of Wood-based Composites with and without Lamination with Aluminum Alloy Sheets

Wood Composites	Symbol	Thickness (mm)	Density[1] (kg/m^3)	**Mechanical Properties**				
				E_{app}[1] (MPa)	MOR[1] (MPa)	IB Strength[1] (MPa)	Edgewise Shear Strength[1] (MPa)	Surface soundness[1] (MPa)
High-density fiberboard	HDF	9.74	817 A	3664 A	28 A	1.08 A	12.20 A	---
Laminated high-density fiberboard	R-HDF	10.82	1029 Ba	20285 Ba	93 Ba	0.99 Aa	10.78 Aa	1.39 a
Medium-density fiberboard	MDF	9.99	798 A	3206 A	25 A	0.71 A	8.24 A	---
Laminated medium-density fiberboard	R-MDF	10.89	1012 Ba	18267 Bb	90 Ba	0.61 Aa	9.70 Aa	0.81 b
Oriented strand board	OSB	10.57	660 A	5497 A	27 A	0.43 A	7.96 A	---
Laminated oriented strand board	R-OSB	11.47	886 Bb	17354 Bb	61 Bb	0.37 Ab	11.51 Ba	0.96 b
Aspen plywood	PW	9.17	542 A	8977 A	68 A	2.26 A	7.48 A	---
Laminated aspen plywood	R-PW	10.15	800 Bb	19323 Ba	125 Bc	2.48 Ac	13.26 Bb	1.88 c

--- Tests not carried out on wood-based composites.
[1]Means within a column followed by the same letter are not significantly different at the 5% probability level. Uppercase letters are for comparison between each pairing of wood composites (non-laminated and laminated). Lowercase letters are for comparison between all aluminum-laminated panels.

Bending properties

Bending mechanical properties such as E_{app} and MOR were strongly influenced by lamination with aluminum alloy sheets. The E_{app} values significantly increased for all laminated panels in comparison with non-laminated wood-based composites (Fig. 4). The E_{app} values of R-HDF increased by 554% when compared with HDF, while E_{app} values of R-MDF, R-OSB, and R-PW increased by 570%, 316%, and 215%, respectively in comparison with non-laminated wood-based composites. This increase can be explained mainly by the high modulus of elasticity of the aluminum alloy sheets, by their thickness, and also by their location in the composite. When a laminated panel is under pure bending, the face sheets contribute more significantly to the bending properties. Stress in tension and compression is applied to the face sheets, consequently the face sheets need to be strong to be able to support the bending load. In that context, the core material contributes to the thickness of the laminates more than anything.

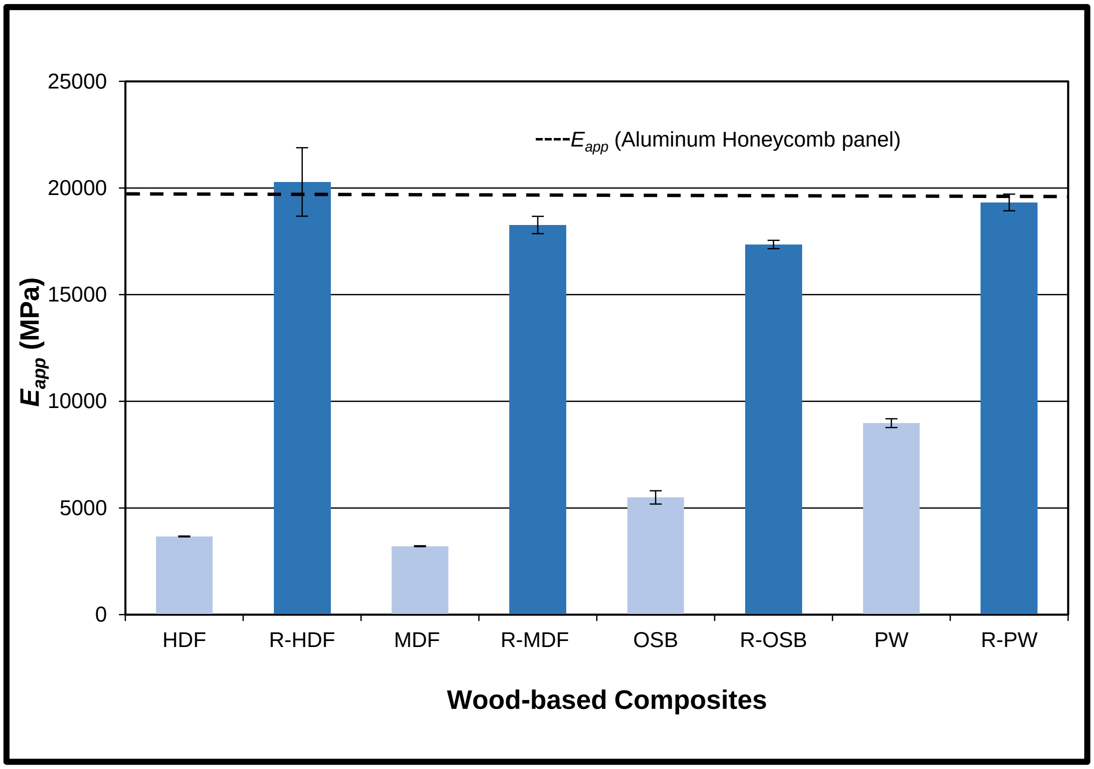

Fig. 4. Effects of aluminum alloy sheets on the E_{app} of wood-based composites. E_{app} values are the average of 12 replications for each laminated panel and of six replications for each non-laminated wood-based composite.

The MOR values showed a similar trend to those observed for E_{app}. MOR values significantly increased for all aluminum-laminated panels (Fig. 5). Laminated plywood-core panel presented an increase of 185% compared with plywood without lamination. The MOR values of laminated panels with HDF, MDF, and OSB core were increased by 335%, 366%, and 225%, respectively, as shown in Fig. 5. R-PW yielded the MOR with the highest value, while the R-MDF and R-HDF presented lower values. Finally, the R-OSB presented the weakest MOR values. The increase in average E_{app} and MOR values obtained with aluminum alloy laminates proved significantly higher than the gains reported in the literature with other types of laminates such as fiberglass, wood veneer sheets, or densified wood veneer sheets (Biblis *et al*. 1996; Biblis and Carino 2000; Cai 2006; Ayrilmis *et al*. 2008; Manalo *et al*. 2010). The increase in E_{app} and MOR values can be explained by the tension and compression strength and the thickness of the aluminum alloy sheets (0.6 mm). As in the previous tests, no delamination was observed between the aluminum alloy sheets and the wood-based cores.

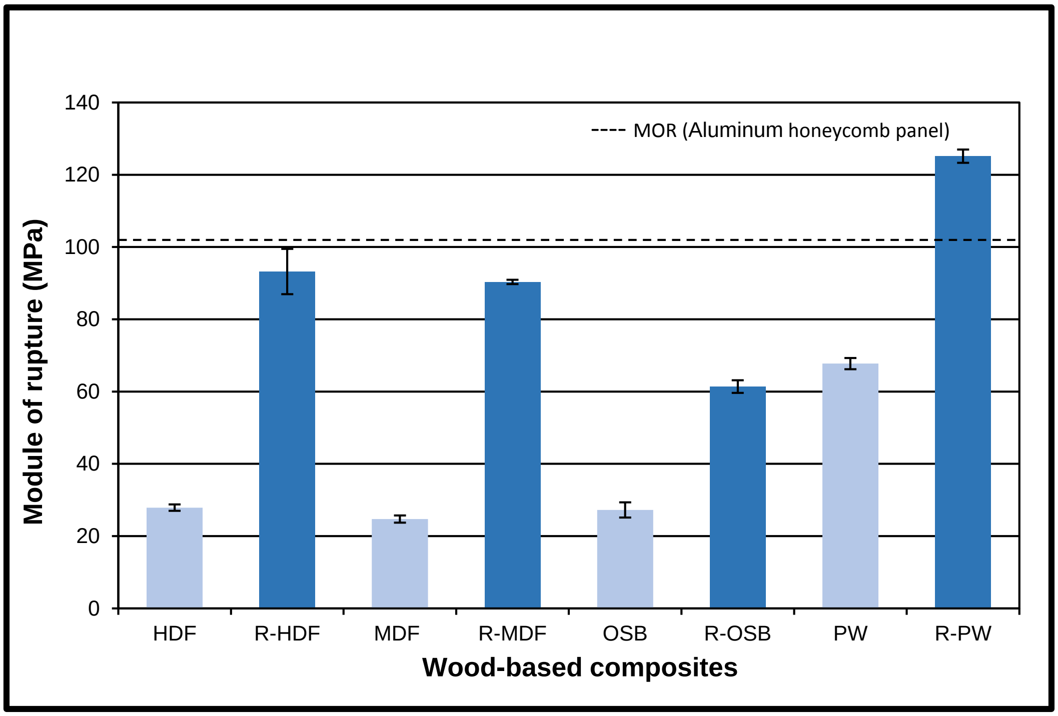

Fig. 5. Effects of aluminum alloy sheets on the MOR of wood-based composites. MOR values are an average of 12 replications for each aluminum-laminated panel and of six replications for each wood-based composite without lamination.

The E_{app} and MOR values of aluminum-laminated panels were compared with an aluminum honeycomb panel (EC-PI 626AS). The results for three-point static bending tests on the aluminum honeycomb panel (length direction) showed an E_{app} value of 19,570 MPa (±144) and an MOR value of 102 MPa (±2). These results are similar to those presented by the aluminum-laminated panels. The E_{app} values were not significantly different from R-HDF, R-MDF, and R-PW panels. The OSB-laminated panel (R-OSB) showed E_{app} values lower than the aluminum honeycomb panels. The MOR values of aluminum honeycomb panel were higher than MOR values of R-HDF, R-MDF, and R-OSB, while they were lower than those of R-PW. In general, tests confirmed the influence of the lamination with aluminum sheet alloy on the improvement of E_{app} and MOR values, and also the limited influence of the type of wood-based composite used as core.

Internal bond strength

Internal bond (IB) tests determined the weakest binding strength within a wood-based composite, normally in the lower-density core layer. According to the results obtained, the IB strength was not affected by the lamination of wood-based composites. There was no significant difference in IB strength between the wood-based composites and the aluminum-laminated panels (Fig. 6). During the IB tests, no failure in the interface between the aluminum alloy sheets and the wood-based composites was observed. For all specimens, the failure was in the wood-based composite (core layer). These results are in accordance with an earlier study (Cai 2006). The IB tests confirmed the choice of adhesive polyurethane, although the tensile strength of the surface tests were made to confirm this choice. To extend this work, it would have been interesting to conduct IB tests after 2-h and 24-h water soakings.

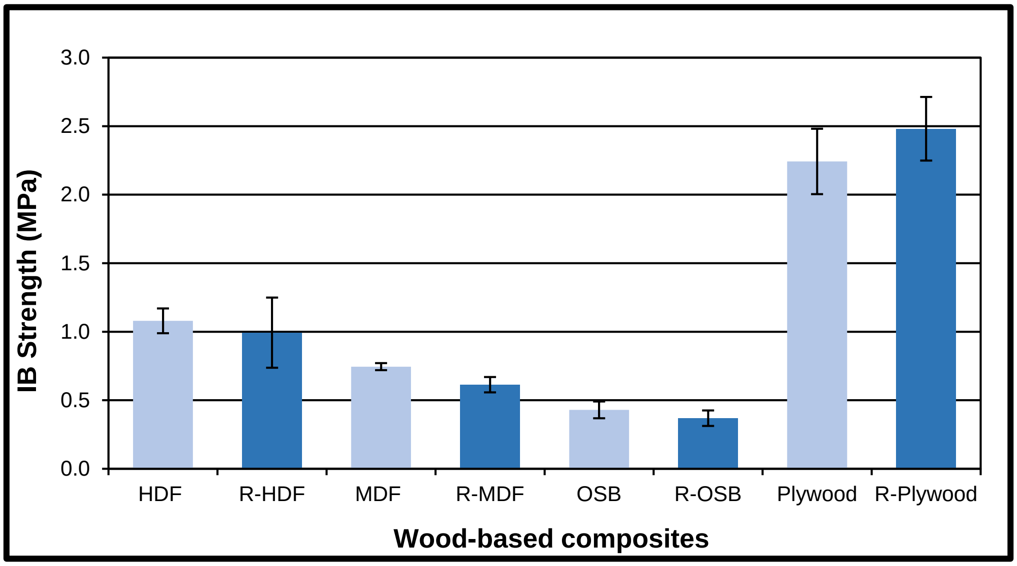

Fig. 6. IB strength values of laminated panels and wood-based composites without lamination. IB strength values are the average of 12 replications for each laminated panel and of nine replications for each wood-based composite without lamination.

Edgewise shear

The edgewise shear properties of wood-based composites with and without lamination were also studied. Table 3 shows the edgewise shear strength values for each type of wood-based composite. The results show that the edgewise shear strength of aluminum-laminated panels R-OSB and R-PW were higher by 44% and 77%, respectively, than non-laminated panels (Fig. 7). R-PW showed the highest edgewise shear strength at 13.262 MPa, while R-OSB, R-MDF, and R-HDF presented lower values.

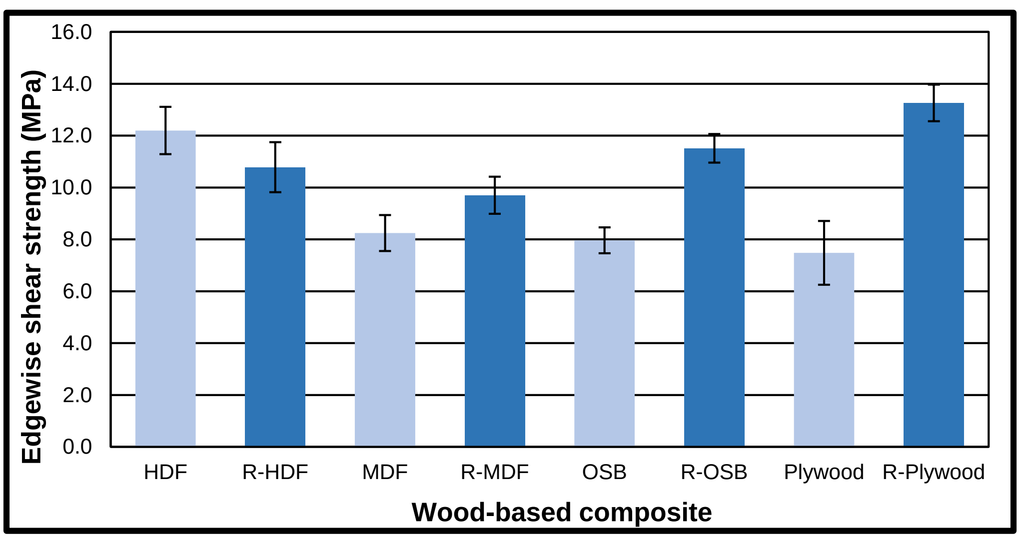

Fig. 7. Effect of aluminum alloy sheets on the edgewise shear strength of wood-based composites. Edgewise shear values are an average of eight replications for each laminated panel and wood-based composite without lamination.

Table 4. Estimated Manufacturing Cost of Aluminum-laminated Panels

Manufacturing Cost of Aluminum-laminated Panel (Canadian dollars/Square meter/10 mm)						
Variable Costs		**Quantity**	**R-HDF**	**R-MDF**	**R-OSB**	**R-PW**
	Materials					
	Aluminum alloy sheet (2 face sheets)	2 m^2	14.09	14.09	14.09	14.09
	Wood-based composite	1 m^2	2.94	2.87	1.76	3.20
	Polyurethane adhesive	130 g/m^2	1.69	1.69	1.69	1.69
	Subtotal		**18.72**	**18.65**	**17.54**	**18.98**
	Processing (operational labor)					
	Aluminum alloy sheet sanding-cleaning	1 m^2	2.50	2.50	2.50	2.50
	Wood-based composite sanding	1 m^2	2.26	2.26	2.26	2.26
	Aluminum-laminated composite bonding (2 face sheet)	2 m^2	1.60	1.60	1.60	1.60
	Aluminum-laminated wood composite pressing-trimming	1 m^2	3.77	3.77	3.77	3.77
	Subtotal		**10.13**	**10.13**	**10.13**	**10.13**
Fixed costs		1 m^2	**4.33**	**4.32**	**4.15**	**4.37**
Total cost (CAD)		1 m^2	**33.18**	**33.10**	**31.82**	**33.48**

The results shown in Fig. 7 show that the aluminum alloy sheets positively influenced the edgewise shear strength. This can be caused by the aluminum alloy sheets impeding the propagation and growth of the shear crack of the wood-based composites (Manalo *et al*. 2013). These results could not be compared with edgewise shear tests of aluminum honeycomb panel (EC-PI 626AS) because the shear test presented set-up problems; therefore these data were discarded.

The Surface Soundness

The IB test results confirmed that no failure existed at the interface between the aluminum alloy sheets and the wood-based composites. These tests were realized specifically from tensile strength between the wood-based composites and the aluminum alloy sheets. The average of surface soundness values also appear in Table 3. The laminated HDF-, MDF-, and OSB-core panels presented higher tensile strength values than IB strength values. The failure for tensile strength tests occurred at the surface of the wood-based composites, not in the polyurethane glue line. The R-PW presented the highest values of surface soundness (1.88±0.09 MPa) compared with other aluminum-laminated panels. The R-HDF showed lower values, while the R-OSB and R-MDF presented the weakest values. Face delamination occurred at the adhesive interface. A part of the adhesive remained on the surface of the plywood. The bonding strength between the aluminum alloy sheet and the plywood (as core material) could be improved. The core materials of this study were all sanded at 150-grit in the pretreatment for uniformity and comparison purposes. According to Kilic *et al*. (2009), a sanding treatment of plywood using 240-grit sandpaper is necessary to achieve higher bonding strength, although in his study, the tests specimens were MDF overlaid with polyvinyl chloride film.

Cost Assessment of Aluminum-laminated Panels

Table 4 shows the estimated manufacturing costs of aluminum-laminated wood-based panels. Aluminum alloy sheet represents approximately 44% of the total estimated cost, while wood-based composites represent between 6% and 9% of estimated costs varying with the wood-based composite used as core. Aluminum-laminated panels present a low estimated total cost compared with aluminum honeycomb sandwich panels (300 Canadian Dollars/m^2). The latter panel is used in aerospace applications; its overall density is low but its cost is much higher. The aluminum-laminated panel can also be compared with aluminum-plastic panel used in exterior walls and indoor decoration. These present similar costs (5 to 20 Canadian dollars/m^2), but their mechanical properties are inferior to aluminum-laminated panels. These comparable panels provide benchmarks to speculate against seeking proper applications for aluminum-laminated panels.

CONCLUSIONS

1. The aluminum-laminated panels showed excellent dimensional stability. The thickness swelling and water absorption values were clearly reduced as a result of the barrier to water penetration provided by the aluminum alloy sheets, except for laminated MDF-core panel, where the lamination process potentially induced fractures at the core where water could penetrate. The linear expansion coefficients (β) of laminated HDF- and plywood-core panels were also reduced as a result of lamination with aluminum alloy sheets.
2. The aluminum-laminated panels exhibited significantly greater E_{app} and MOR values in comparison with non-laminated wood-based composites. Bending properties were in the range of the performance of honeycomb aluminum sandwich panels. The E_{app} values were increased for laminated HDF-, MDF-, OSB-, and plywood-core panels by 554%, 570%, 316%, and 215%, respectively, and the MOR values were increased by 335%, 366%, 225%, and 185%, respectively.
3. The edgewise shear strength values of aluminum-laminated panels with a OSB, and Plywood core were increased by 44% and 77%, respectively, compared with non-laminated wood-based composites.
4. The absence of IB failure at the aluminum/wood interface demonstrated proper polyurethane adhesive bonding, a result that was confirmed by the tensile strength tests perpendicular to the surface. However, the laminated MDF-core panels presented a decrease in IB values because of fractures in the core layer during the lamination process; one possible solution would be to apply less pressure during lamination, but enough to ensure good bonding strength.

5. From the results of this study, it can be concluded that the physical and mechanical properties of wood-based composites were greatly improved by lamination with aluminum alloy sheet, opening the door to a new range of applications such as building interiors and exteriors, floor panels for buildings and transport vehicles, advertising panels, *etc*. The results confirm that aluminum-laminated panels have the potential to act as a structural material. Comparisons with an aluminum honeycomb panel showed similar mechanical performance.
6. Honeycomb panels are three times lighter, which is an advantage where weight is of importance. Nevertheless, aluminum-laminated wood-based panels show much lower manufacturing costs in comparison. Other desirable properties can be expected from these aluminum-wood panels, such as screw-ability, machinability, punching, and slotting, but these would have to be verified.

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