Comparison of Wood Composite Properties Using Cantilever-Beam Bending

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Wood-based composite panels generally are first tested out-of-plane in the primary panel direction followed by the cross panel direction, but rarely edgewise. While most applications use wood-based composites in the flat-wise orientation and only need the out-of-plane properties, there are construction configurations where edgewise properties are needed for improved design configurations. A square cantilever beam was used to determine the apparent stiffness (*EI*) and modulus of elasticity (*E*) differences for 3 wood-based composite panel materials. Specimens were cut along the primary panel direction or machine direction (MD) and perpendicular to the primary direction or cross-machine direction (CD). The square specimens were first non-destructively tested oriented in the normal or out-of-plane position, then rotated 90 degrees to measure edgewise properties. The results for a 20 mm thick medium density fiberboard (MDF) showed that the MD properties were 56% higher than the CD properties. The other two composite materials, 12 mm thick particleboard (PB) and 12 mm thick MDF, were essentially the same in the MD or CD directions. For all the materials, the differences between the out-of-plane and the edgewise loading directions showed higher *EI* and *E* between 17 to 61%, respectively. The largest difference was found in the PB composite material properties that were between 42 to 61% higher for the out-of-plane properties. For the 12 and 20 mm thick MDF material, in-plane properties were 27 to 33% and 17 to 23% higher, respectively. The cantilever bending method was able to quickly assess the difference using the same specimen.

Keywords: Wood-based composites; Cantilever-beam bending; Mechanical properties; MD and CD orientation; Out-of-plane properties; Edgewise properties; Stiffness; Modulus of elasticity

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INTRODUCTION

The bending properties for wood-composite panels are generally obtained using standard test methods in which a supported beam with a standard width is centrally loaded while measuring out-of-plane displacement and load (ANSI A208.1 1999; ANSI A208.2 1999; ASTM D1037 2006; GB/T 17657 1999, BS EN 310:1993). These standards specify reporting bending properties obtained from the primary panel direction or machine direction (MD) and perpendicular to the primary direction or cross-machine direction (CD) panel properties. In the literature, CD properties were typically lower than the MD values (Groom *et al.* 1999). These differences are a result of non-uniform fiber alignment characteristics, primarily on the faces. For most applications, panels are generally subjected to out-of-plane bending forces, such that knowing the apparent modulus of elasticity property in either MD or CD directions are necessary for basic design purposes. However, wood-composites are increasingly being used for applications where not only out-of-plane loading may occur but also where edgewise loading conditions may be present and edgewise properties are necessary to characterize the performance (Fridley and French 2000). The European standard EN 13879 (BS EN 13879: 2002) describes a method that requires the specimen be made by laminating face-to-face sections and recut into a beam for testing following standard bending test methods to determine edgewise bending properties. Depending on the laminating procedure the adhesive has the potential to slightly modify the performance characteristics.

It is known that most wood-composites panels have a non-uniform density or vertical density profile and/or a change of material type through the thickness, such that there may be finer particles as compared with the core. These have an effect on the out-of-plane properties (Cai 2004; Ganev *et al.* 2005; Sackey *et al.* 2008; Migneault *et al.* 2010). The standards do not address specific non-uniform effects on properties through the panel thickness, but only report the results as an overall apparent properties in either MD or CD directions. The non-uniform density profile causes the board to behave differently when loads are applied edgewise and cannot be assumed to be homogeneous. In some furniture applications, wood-composite pieces are rotated and loads are applied edgewise rather than just in bending, *e.g.*, a spacer between two legs that also supports the desktop. In general, these pieces act as spacers and edgewise support members. It is important when designing these sections to know the load carrying potential of piece based on its properties in that orientation.

This manuscript seeks to explore the potential of using a square beam to test wood-based composite panel materials. By testing square specimens, either the out-of-plane or edgewise could be achieved without changing the specimen length requirement. While the small width of the beam may introduce some edge affects that would influence the properties of a wider beam, the relative differences between properties should be similar and thus important to determine. This study is part of a larger program to investigate the use of the cantilever beam test method for determining various material properties for wood-based composite materials (Turk *et al.* 2008; Zhang *et al.* 2010; 2014; Hunt *et al.* 2013; Zhang *et al.* 2014; Hunt *et al.* 2015). Further research will compare results from standard bending tests, and correlate those with the square beam.

Cantilever Beam Equations for Stiffness and MOE

Calculation of stiffness (*EI*) and modulus of elasticity (*E*) for a homogeneous cantilever beam can be obtained by using Eq. 1. The equation assumes that the material properties are uniform through the material thickness. For wood-composites, this is not the case, and most wood-composite panels have higher-density surface layers compared to the lower-density cores. However, it is easier to just measure the outside specimen dimensions in order to determine the global density and then assume uniform properties. From the dimensions, the loads *vs.* displacement data are used to determine an apparent panel *EI* and *E*. If the density profile is relatively flat or uniform, then when the specimen is rotated the bending properties would be similar. However, if the profile or properties through the thickness are dissimilar, then the rotated beam test should be different.

For a cantilever beam, beam deflection (*y*) at the end of the beam (Fig. 1) can be used to determine the stiffness (*EI*), and modulus of elasticity (*E*) using Eq. 1,

$$y = \frac{PL^3}{3EI} \Rightarrow \text{ rearranged } \Rightarrow EI = \frac{P_{\max} L^3}{3y} \Rightarrow \text{ rearranged } \Rightarrow E = \frac{4P_{\max} L^3}{ybh^3} \qquad (1)$$

where y is the end deflection (m), E is the bending modulus of elasticity (N/m^2), P is the end-point load (N), L is the cantilever beam length (m), I is the area moment of inertia (m^4), b is the base width of the specimen (m), and h is the thickness of the specimen (m).

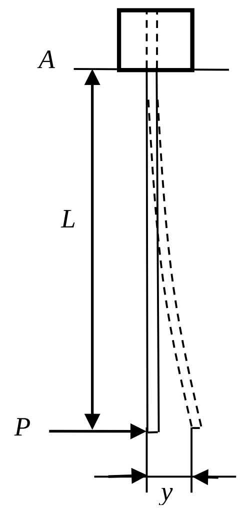


Fig. 1. Cantilever beam bending displacement, and resulting load for wood-composite materials

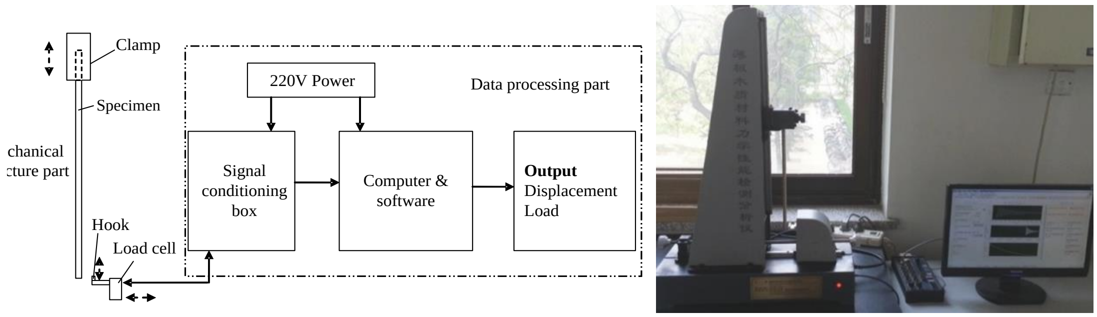
By using a square beam it was possible to determine bending properties for both out-of-plane (normal test orientation), as well as the properties edgewise to the surface direction. While the beam is assumed to be square, care must be taken to account for slight variations in width, depth, or height of the sample. These variations may influence the calculations when the sample is rotated 90° since the beam height (h) is cubed in order to determine the modulus of elasticity (E) (Eq. 1).

EXPERIMENTAL

Apparatus and Materials

A vertical cantilever beam apparatus (Zhang *et al.* 2010) was used to apply a known displacement while measuring the load. The components of the apparatus are shown in Fig. 2a, and the apparatus photo is shown in Fig. 2b. The specimen was clamped in a hanging position, and a static displacement was created by displacing the end of the specimen to a specific distance using an end hook. A load cell attached to the hook measured the applied load at the end of the beam. A laser displacement gauge was used to determine initial and final displacement of the beam's end.

Three wood-composite panels were used for testing: 20 mm thick medium density fiberboard (MDF), 12 mm thick particleboard (PB), and 12 mm thick MDF (Fig. 3). The specimens were cut into square beams. Half of the samples were cut parallel in the panel's MD direction, and the other half were cut in the CD direction of the panel. The beam dimensions were measured to an accuracy of ± 0.01 mm using a hand held digital caliper (Guanglu 111-102-20G, Guilin Guanglu Measuring Instrument Ltd., Guizhou, China).



(a) Components diagram (b) Vertical cantilever beam

Fig. 2. Cantilever beam test apparatus

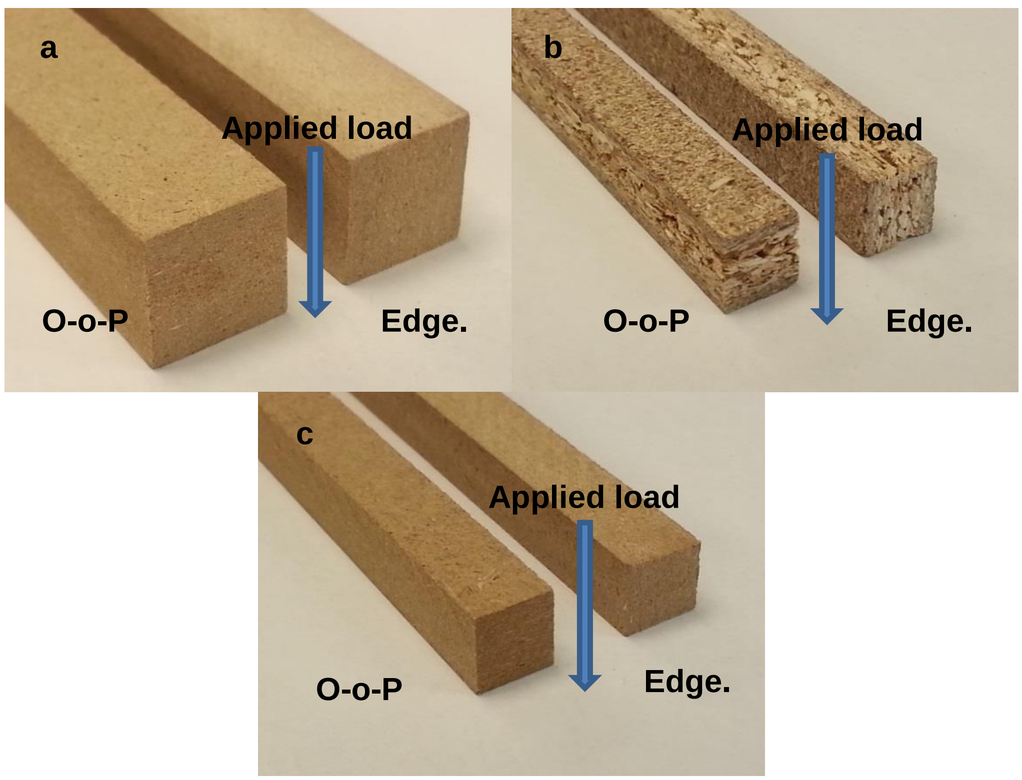


Fig. 3. Square beams tested: (a) 20 mm thick MDF; (b) 12 mm thick PB; and (c) 12 mm thick MDF. The top surfaces as seen in the beam on the left in each group had similar surfaces as those of the larger panel. The applied loading was out-of-plane (O-o-P) to the panel surfaces. The top panel surfaces were rotated 90° for beams on the right in each group. The applied loading was edgewise (Edge.) to the panel surfaces. Note: It is easier to see orientation differences for the beams in (b).

Test Methods

The specimens were clamped in the apparatus with a length (292 mm) of the beam extending from the end of the clamp. The end displacement of the beam ranged between 3.0 to 5.0 mm. The maximum bending strength was not determined as part of this study. If the standard span-to-depth ratio of 24 was used for a simply supported beam test, then test span-to-depth ratio for the cantilever beam would be a length of 12 times the depth or equivalent to the simply supported beam. The calculated ratio for the 20 mm MDF was

292:20 or 14.6 times. For the 12 mm thick PB and MDF beams the span-to-depth ratios were 292:12 or 24.3 times. All specimen beam lengths were greater than the required test length. The beam span-to-depth ratios are important to help reduce the influence of shear on the elastic properties determined from Eq. 1.

The square beams were clamped into the cantilever-beam apparatus with their panel surface perpendicular to the bending direction (normal or out-of-plane testing orientation). After applying a known deflection (3 to 5 mm) in one direction, the load was recorded. For the next test, the beam was rotated by 90° in order to align the panel faces parallel to the loading direction, re-inserted into the apparatus, then deflected the same distance, and the load was recorded. The beam deflection for each specimen and direction were recorded (Table 1). The stiffness (*EI*) and modulus (*E*) were determined using Eq. 1.

Table 1. Type, Size, Symbol, and Number of the Specimens

Set	Type	Specimen Orientation	Cantilever beam ($h \times b \times l$, mm)	Number of specimens
1	Medium-density fiberboard	MD CD	20 × 20 × 292 20 × 20 × 292	12 12
2	Particleboard	MD CD	12 × 12 × 292 12 × 12 × 292	12 12
3	Medium-density fiberboard	MD CD	12 × 12 × 292 12 × 12 × 292	12 12

RESULTS AND DISCUSSION

Figure 4 shows the beam's stiffness (*EI*) plotted against the apparent density. The thicker MDF panels (20 mm) were stiffer than the thinner (12 mm) beams, as might be expected with the combined modulus and extra thickness that increased the calculated area moment of inertia (*I*). Figure 5 shows the beam's modulus (*E*) plotted against apparent density. Modulus is a basic material property independent of the calculation for *I* which is purely geometry and when it is removed from the stiffness calculation (Fig. 4), the properties for the thicker beam are shown to be slightly less or weaker than the modulus for the two thinner beams. For all the materials, the data shows that higher *EI* and *E* values for the MD *vs.* the CD oriented beams. Generally, panels are manufactured with their fibers or particles aligned in the MD which results in higher values. The PB and thinner MDF beams had similar MD and CD values, which suggests that the panel manufacturing process produces a panel with more uniform or random fiber alignment.

The beam stiffness and moduli for all the wood-composite materials had data pairs with similar densities. The beams' highest values occurred with a perpendicular surface orientation with respect to the loading direction, out-of-plane bending, while the same beam that was rotated 90°, loaded parallel, or edgewise had lower values. It was expected that the tests in the out-of-plane or perpendicular to the loading direction had higher-density material and total amount of material located furthest from the neutral axis. The denser surface material functions as flanges of an I-beam and increases the stiffness and apparent modulus of the small beams or specimens when perpendicular to the loading direction. The PB beams had the largest difference between out-of-plane and the edgewise properties of between 42 to 61% for CD and MD, respectively. Table 2 lists the average *EI* and *E* of the beams and the percent difference for all the beams when rotated 90°.

Some of the differences between groups of specimens need to be taken into consideration when cutting products from either MD or CD directions. Additionally, loading in the out-of-plane or edgewise direction should be considered. The PB properties, when rotated, were quite low and were not expected. If, for a specific application, only the manufacturer's MD bending modulus were available, the low apparent *E* for the edgewise direction may not provide sufficient stiffness for that application. It is visually evident from Fig. 3, especially for the PB material, that there was a non-uniform material distribution and that the higher-density material was present on the top and bottom surfaces. Such higher density material tends to have higher strength and stiffness than the core. The thicker 20 mm MDF had less of a difference between the out-of-plane and edgewise properties, but had higher MD *vs.* CD property differences than either the 12 mm PB or MDF.

The authors realize that the beams being tested were not the standard width; however, the long beam to depth ratio aided in eliminating any shear effects. The beams were sufficiently loaded to calculate the modulus, but were not overloaded to failure; thus size effects should be minimal. Further research will be conducted to develop comparisons between full width beams and square beams and comparisons with standard test methods and the cantilever beam method. Additionally, future studies will include comparison of cantilever beam *EI* and *E* data with standard supported mid-point testing data. The cantilever beam apparatus test is part of a larger program to obtain multiple property data types from one specimen without having to modify the specimen conditions or use other equipment. Other tests being explored include dynamic vibration (Zhang *et al.* 2010; Hunt *et al.* 2013), stress relaxation (Zhang *et al.* 2014; Hunt *et al.* 2015), and in-plane and out-of-plane bending properties as discussed in this manuscript.

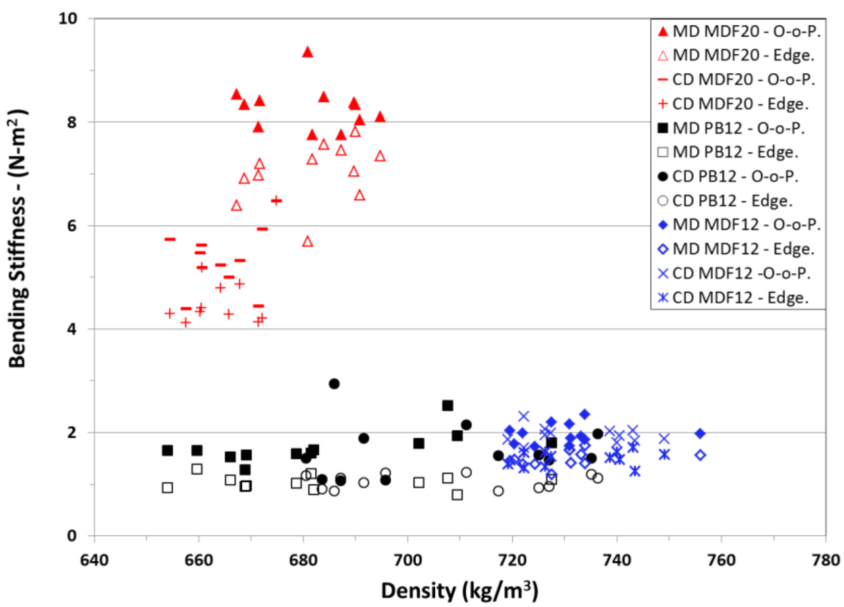


Fig. 4. Bending stiffness for the square cut beams from large sheets of material along the longitudinal (MD) direction and cross-wise (CD) direction of the panel. The panels include 20 mm thick MDF, 12 mm thick PB, and 12 mm thick MDF. Each beam was oriented with the surfaces of the beam out-of-plane and edgewise with the loading direction.

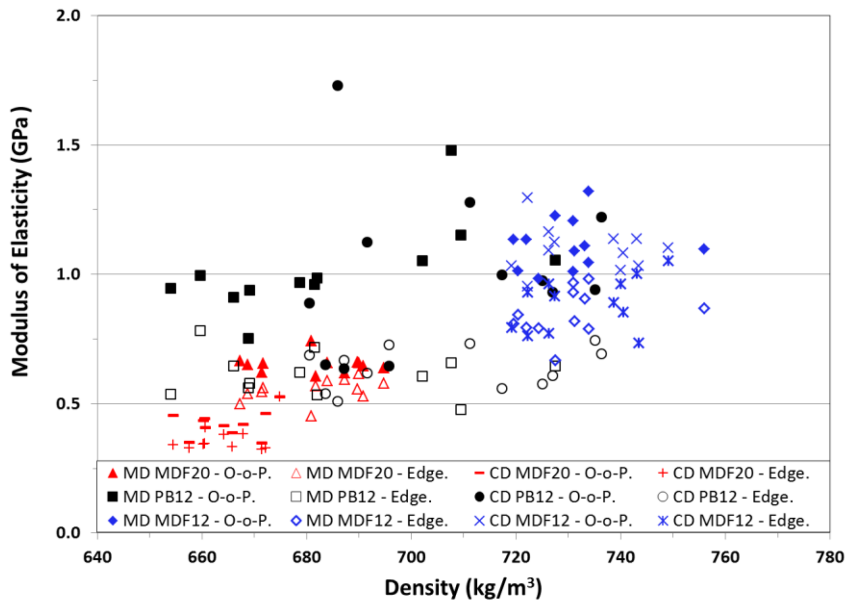


Fig. 5. Modulus of elasticity for the square beams cut from large sheet of material along the longitudinal (MD) direction and cross-wise (CD) direction of the panel. The panels include 20 mm thick MDF, 12 mm thick PB, and 12 mm thick MDF. Each beam was oriented with the surfaces of the beam out-of-plane and edgewise with the loading direction.

Table 2. Stiffness and Moduli for the Three Composite Panels Along the MD and CD Directions, Loading Orientation Out-of-plane (O-o-P.) and Edgewise (Edge.)

Beam Type and Size (mm)	Beam Orient. w/panel	Load Dir.	Density (kg/m^3)	*EI* ($N\text{-}m^2$)	*EI* O./E. Diff. (%)	*EI* MD/CD Diff. (%)	*E* (GPa)	*E* O./E. Diff. (%)	*E* MD/CD Diff. (%)
MDF **20**	MD	O-o-P.	682	8.34	17.1	56.6	0.65	16.8	55.5
		Edge.		7.12		64.5	0.56		62.4
	CD	O-o-P.	664	5.28	23.0		0.42	22.0	
		Edge.		4.37			0.35		
PB **12**	MD	O-o-P.	684	1.65	60.8	7.5	0.98	59.3	1.9
		Edge.		1.03		-5.1	0.61		-4.6
	CD	O-o-P.	706	1.53	41.9		0.96	49.1	
		Edge.		1.08			0.64		
MDF **12**	MD	O-o-P.	730	1.95	32.7	0.2	1.10	32.7	0.7
		Edge.		1.47		-3.8	0.83		-7.8
	CD	O-o-P.	733	1.95	27.3		1.10	21.5	
		Edge.		1.53			0.90		

CONCLUSIONS

1. The major differences for the *EI* and *E* occurred between the MD to CD, where the CD properties decreased by 57 to 65% for the 20 mm MDF panel. In contrast, the MD to

CD ratios for the 12 mm PB and MDF were minimally different or exhibited near uniform properties.

2. For all the panels, comparisons between the out-of-plane and edgewise bending showed that for both *EI* and *E*, there were decreases (17 to 61%) for the edgewise properties compared with the out-of-plane properties.
3. Testing a square cantilever beam could be used to provide insight for optimum utilization of composite wood panels whether along MD or CD directions as well as out-of-plane or edgewise orientation. The test results from these randomly selected wood-based composites should show that there are big differences in material properties out-of-plane and edgewise and thus one should not assume that composite wood panels have uniform properties in all directions. It may be necessary to test composite materials in multiple test orientations to gain a better understanding of the performance of the composite panel.
4. It is possible that a cantilever bending test could be used to quickly determine material properties in two orientations with the same sample that is at the same environmental conditions and material make-up just only rotated.

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