Wood-based Corrugated Core Sandwich Panels Manufactured Using a Wooden Mold

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A wooden matched-die mold was manufactured to develop wood-based corrugated panels. Wood veneers brushed with resin were cold pressed between the mold halves and formed into a corrugated geometry. The corrugated panels were used as a core and bonded to flat veneer-based facesheets to develop sandwich panels. The whole manufacturing process involved a cold-forming technique that allowed panels to be produced with no heat. Specimens cut from both corrugated and sandwich panels were submitted to a four-point bending test to evaluate their structural performance. Adopting the same number of layers used to make the sandwich panels, flat panels were fabricated and tested to find the effect of this corrugated geometry and cold-forming process on the load-carrying capacity of the sandwich structures. A comparison with flat panels made with the same stacking of veneers showed an increase of 272% of the bending stiffness of the sandwich panels, which is known as the sandwich effect. Comparison between the bending results of the panels developed in this study with those manufactured using thermoset resin and hot-pressing technique indicated that the cold-forming process using the wooden mold is an effective and inexpensive method to develop wood-based corrugated sandwich panels.

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INTRODUCTION

Lightweight materials with a high structural performance are key features sought by different industries. Because sandwich structures with a low-density core or profiled geometries, such as corrugated and honeycomb shapes, have been able to satisfy these two important factors, they have found extensive applications in the aerospace, automotive, and marine industries (Castanié *et al*. 2020; Chen and Das 2022; Palomba *et al*. 2022). Considering the environmental concerns and crucial benefits, such as sustainability, renewability, and recyclability, researchers have tried to develop natural fiber-based sandwich structures by forming wood and other natural fibers into profiled geometries.

Researchers at the USDA Forest Product Laboratory adopted this concept to develop value-added products from small-diameter trees to create a high-value market for these underutilized materials (Hunt and Winandy 2002; Hunt *et al*. 2004). Using a wet-forming process, they formed wood fibers into three-dimensional geometries used as a core to make sandwich panels. The use of water for the wet forming of the profiled geometry that resulted in wastewater was one of the disadvantages of this process (Voth 2009). To tackle this problem, a dry forming process has been developed and used by researchers. Neucor, Inc. (Fuji 2014) patented such a dry forming process and used this technique to form wood fibers (Fuji 2013) and wood strands (Way *et al*. 2016) into a profiled geometry, as shown in Fig. 1a. Using the same dry forming process, researchers at Washington State University (WSU) fabricated a biaxial corrugated panel shown in Fig. 1b from wood strands (Voth *et al*. 2015; Mohammadabadi *et al*. 2018a, 2018b). In addition to wood fibers and wood strands, researchers have also tried to form wood veneers into corrugated geometries (McGraw *et al.* 2010; Labans and Kalniņs 2011). Researchers at the University of Auckland formed thin wood veneers, 0.6 mm thick, into profiled geometries as shown in Fig. 1c after soaking them in hot water, 70 ± 5 °C, for 90 to 180 s (Srinivasan *et al*. 2008; Kavermann and Bhattacharyya 2019). Smardzewski (2019a,b) soaked 1.4-mm-thick wood veneers in water for 72 h and plasticized this material in a microwave chamber to form them into a uniaxial corrugated geometry. Dry forming process has been also used to develop bamboo-based sandwich panels (Yang *et al.* 2014). All these studies have used a matched-die process to form wood materials into profiled geometries. However, researchers at the University of Auckland developed a roll-forming technique that is a continuous process and mainly used to form metal sheets to produce profiled wood-based panels (Dykes *et al*. 2000; Srinivasan *et al*. 2008). A thermomechanical process was also developed to improve the forming process of wood by densification and then a water-shock process for rapid opening of the closed cell walls (Xiao *et al.* 2021).

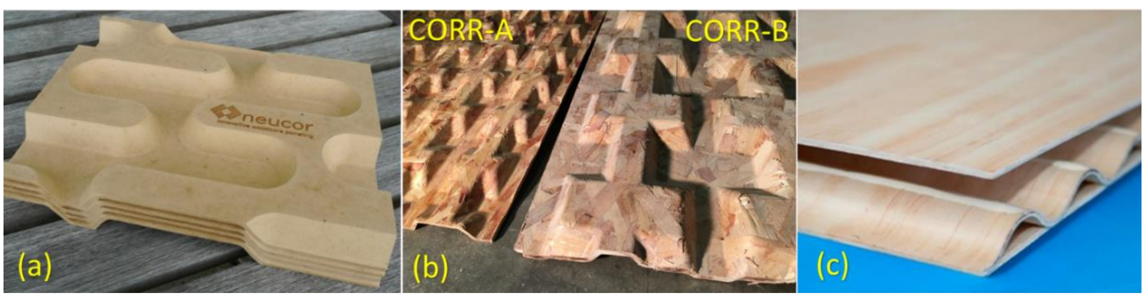


Fig. 1. Wood-based profiled geometries; (a) 3D wood fiber panel (Fuji 2013; Way *et al*. 2016), (b) biaxial corrugated panels from wood strands (Mohammadabadi *et al*. 2019), and (c) uniaxial corrugated panel from wood veneer (Kavermann and Bhattacharyya 2019)

Regardless of the material types (fiber, strand, or veneer), wet or dry forming process, and a batch processing or continuous production methodology, heat is an essential element to form wood materials into profiled geometries in the discussed methods and studies. To transfer the heat to the wood materials and apply the required pressure, matched-die molds in the batch processing or rollers in the continuous methods are made of metal. Considering the expenses associated with metal and their machining process to fabricate either mold or rollers, the initial cost to start mass production of such natural fiber-based geometries is high. Other manufacturing methods, such as injection molding, resin transfer molding, and die casting, require metal with specific geometries and also suffer from costly matched tooling (Verma *et al*. 2016). Tooling accounts for over 25% of the total cost of the products manufactured using such methods (Nagahanumaiah *et al.* 2005). Therefore, tooling cost acts as a hinderance for these lightweight, high-performance, and natural fiber-based products to reach the commercial market. All the discussed panels have been fabricated in an academic laboratory with the exception of the 3D panel developed by Neucor, Inc. shown in Fig. 1a. Therefore, it is essential to tackle this problem and develop a cost-effective method to form wood materials into lightweight and high-performance profiled products.

This study considers a manufacturing strategy that avoids a costly process involving a metal machining process. A wooden matched-die mold was fabricated on a table saw. Using this mold and a cold setting resin, wood veneers were formed into a corrugated geometry with no heat and no required softening process. Using the corrugated panel as core, sandwich structures were developed and evaluated.

MATERIALS AND METHODS

Wooden matched-die mold

The corrugated geometry and associated matched-die mold were designed using SolidWorks® software. The dimensions of the corrugated geometry are given in Fig. 2a. Considering the sketch, the mold parts shown in Fig. 2b were cut from commercially available medium-density overlay (MDO) plywood on a table saw and were screwed together to develop the matched-die mold (Fig. 2c). Because this mold was designed to produce corrugated panels with 6.35 mm (0.25 in)-thick wall, wooden stoppers on both sides of the mold shown in Fig. 1b were installed to block further movement of the upper half and prevent any extra compression resulting in varying wall thickness. In the case of metal molds, release agent is usually sprayed on both halves to avoid sticking of the profiled panels into the mold. Therefore, both halves of the wooden mold were covered with aluminum foil to mimic this concept.

Fig. 2. (a) Dimensions of the corrugated geometry in mm, (b) mold's parts during assembly, and (c) final wooden mold with stoppers on both sides

Corrugated Panels

Thin red-oak veneers with an average thickness of 0.68 mm (Fig. 3a) and stored at room temperature with an average moisture content of 9% were used to fabricate corrugated panels. Since these thin veneers were pliable and easy to form around the sharp corners of the mold, corrugated panels with no defects and cracks were developed. A commercially available cold-setting wood glue, one-component poly(vinyl acetate) Titebond II premium (Franklin International Inc, Columbus, Ohio, USA), was brushed on the veneers at a weight specification of 205 g/m^2 (Entsminger 2022). All wood veneers were coated with the resin and oriented in the same direction, parallel to the flute direction, and cold-pressed using the wooden mold as shown in Fig. 3b. Ten veneer plies were used to fabricate a corrugated panel with wall thickness of 6.35 mm (0.25 in) as shown in Fig. 3c. Density of corrugated panel was 770 kg/m^3 by measuring the density of small pieces cut from this panel.

Facesheets

Thick southern yellow pine veneers with an average thickness of 4 mm were used to fabricate facesheets of the sandwich panel. Unlike the corrugated panel fabricated by orienting all veneers in the same direction, facesheets were developed by bonding veneers at right angles to improve the dimensional stability of the sandwich panels. Three layers of veneer were bonded using the same cold-setting wood glue, Titebond II premium, to develop facesheets with an average thickness of 11.3 mm. Density of 582 kg/m^3 was measured for these flat panels.

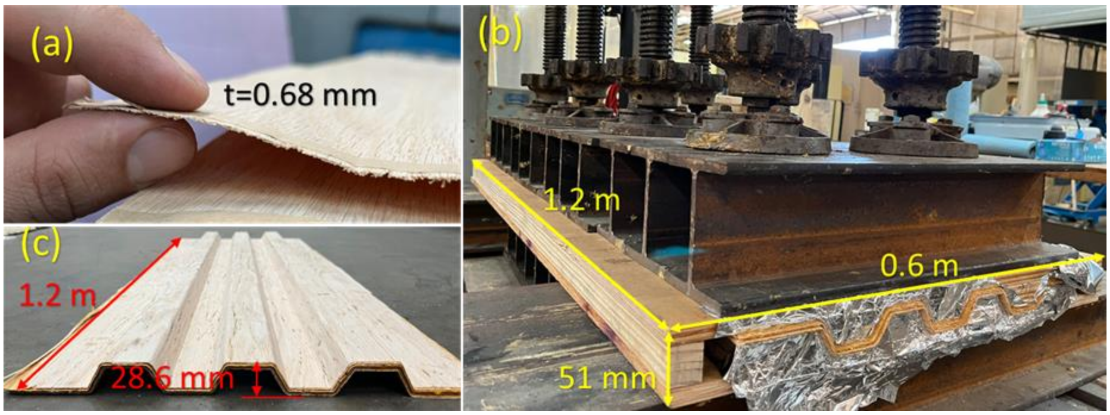


Fig. 3. (a) Red-oak veneers, (b) cold-pressing of resinated veneers using the wooden mold, and (c) final wood-based corrugated panel

Sandwich Panels

To make sandwich panels, a commercially available polyurethane resin, original Gorilla Glue, was used to bond facesheets to the corrugated panel. Considering the cold-setting behavior of this resin, this bonding process was also accomplished using a cold-press, no heat.

As discussed, sandwich panels (Fig. 4a) were fabricated of three thick veneers at the bottom (lower facesheet), ten thin veneers formed into corrugated panel in the middle (core), and another three thick veneers at the top (upper facesheet). To examine the effect corrugated geometry on the structural performance of the sandwich panel, the same type of veneers regarding both thickness and quantity were used in the same order to make flat panels as shown in Fig. 4b.

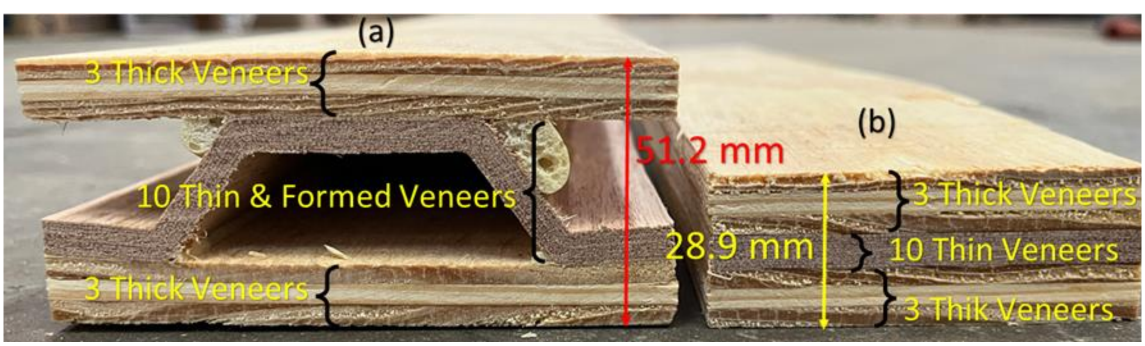


Fig. 4. Corrugated core sandwich panels manufactured with no heat, and (b) flat panel made with the same recipe used to fabricate sandwich panels regarding quantity, quality, and orientation of veneers

Experimental Evaluation

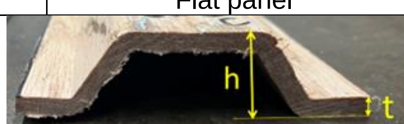
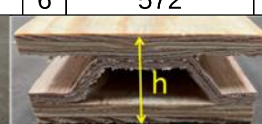
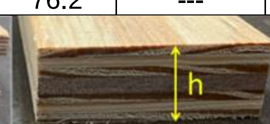
Specimens cut from corrugated, sandwich, and flat panels were submitted to four-point bending test where the load span was one-third of the span length (L). To have consistent results and better comparison, ASTM D7249 (2012) was followed for all specimens. Dimensions of these flexural test specimens are given in Table 1. To ensure that the relationship of simple beam theory used to calculate the structural performance is valid, specimens were selected with a slenderness ratio, span length divided by specimens' depth, of greater than 20 (ASTM 2016). Considering the results of the bending test, the structural performance of these specimens was computed. Since the relationship between bending load (P) *versus* deflection at mid-span (Δ) for four-point bending test is given in Eq. 1a, the simplified relation of bending stiffness (EI) for third point loading is given in Eq. 1b. Bending strength known as modulus of rupture (MOR) is dependent on maximum bending moment (M) as it is computed using MC/I. Therefore, maximum bending moment for any specific bending load which occurs between the point loads can be computed using Eq. 1c,

$$\Delta = \frac{Pa}{48EI}(3L^2 - 4a^2) \quad \text{(a)} \qquad \xrightarrow{a=\frac{L}{3}} \qquad EI = \frac{23PL^3}{1296\Delta} \quad \text{(b)} \qquad (1)$$

$$M = \frac{Pa}{2} = \frac{PL}{6} \quad \text{(c)}$$

where a is the distance of loading point from the support, which is one-third of the span length, L, in this study.

Table 1. Dimensions of Specimens Tested in Current Study and Reference Studies

	Specimen	#	Span Length L (mm)	Width b (mm)	Thickness t (mm)	Depth h (mm)
This Study	Corrugated panel	6	686	112	6.31	28.6
	Sandwich panel	6	1143	112	---	51.2
	Flat panel	6	572	76.2	---	28.9
						
Reference Studies	CORR-A (Mohammadabadi and Yadama 2020a; Mohammadabadi *et al.* 2020b)	5	572	108	6.4	25
	CORR-B (Mohammadabadi and Yadama 2020a)	- -	559	203	7.6	35
	Sandwich A (Mohammadabadi *et al.* 2020b)	5	559	108	---	38
	Sandwich B (Mohammadabadi *et al.* 2021)	4	1219	203	---	48

Bending results of both corrugated and sandwich specimens developed in this study were compared against those of wood-based corrugated panels (Fig. 1b) and associated sandwich panels developed using hot-pressing method. Both corrugated panel A, labeled CORR-A, and Corrugated panel B, labelled CORR-B, shown in Fig. 1b have biaxial corrugated geometry. However, CORR-A has been redesigned to develop CORR-B with higher structural performance (Mohammadabadi and Yadama 2020a). The dimensions of these corrugated panels, CORR-A and CORR-B, and their associated sandwich panels, Sandwich A and Sandwich B, used for comparison are also given in Table 1 as "Reference Studies".

RESULTS AND DISCUSSION

To avoid any confusion, this section will be divided into two subsections to separately present the bending results of the corrugated panels from those of the sandwich structures.

Corrugated Panels

A chart of the bending load *versus* deflection for the corrugated specimens is given in Fig. 5a. The failure of these specimens involved a large deformation resulting in the opening and flattening of the corrugated geometry under the loading points, as shown in Fig. 5b. Because of this deformation, the load dropped, and the test was stopped. Through removing the load, the large portion of the deformation was recovered, and specimens came back to the original configuration. Only one specimen (out of 6) totally failed. Because the geometrical dimensions of CORR-A given in Table 1 are similar to those of the corrugated panel developed in this study, its load-deflection curve is compared in Fig. 5a. For CORR-A, both experimental (Exp) and finite element (FE) results have been reported (Mohammadabadi *et al*. 2020b). This comparison shows that the corrugated panels developed in this study using the wooden mold and no heat were stiffer than CORR-A manufactured with thermoset resin and hot-pressing process. Using the linear portion of these curves and Eq. 1b, bending stiffness of these corrugated panels was computed as 299 $N.m^2$ for CORR-A and 812 $N.m^2$ for the corrugated panel of this study, a 170% increase in the bending stiffness.

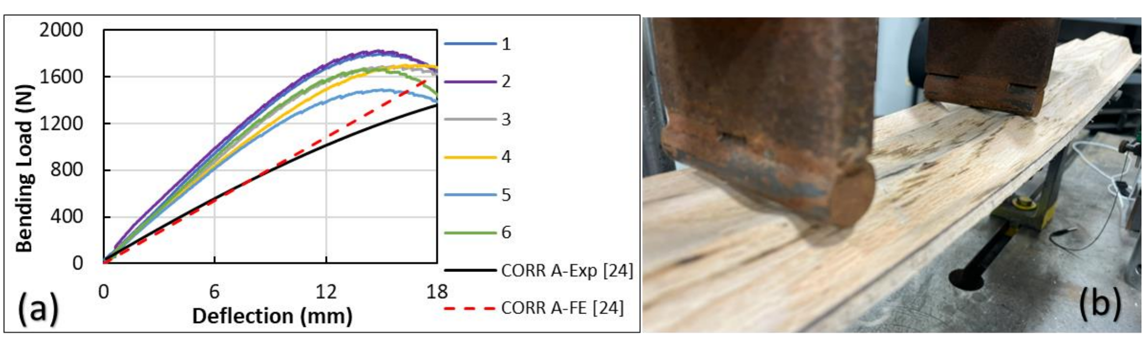


Fig. 5. (a) Comparison between the load-deflection curve of the corrugated panel of this study with that of the reference study (Mohammadabadi *et al*. 2020), and (b) failure mode of the corrugated panel under bending load

Because the corrugated panels developed in this study had a different width from those of the reference studies, their normalized bending stiffness values, *i.e.* bending stiffness divided by the width of the specimen, are computed and compared in Fig. 6. It has been reported that the normalized bending stiffness of the CORR-B is 59% higher than that of CORR-A (Mohammadabadi and Yadama 2020a). The normalized bending stiffness of the corrugated panel of this study was 162% and 65% higher than those of CORR-A and -B, respectively. Configuration of the corrugated panel is one reason for this difference, as both CORR-A and -B had biaxial corrugated geometries, as shown in Fig. 1b, while this study developed a uniaxial corrugated panel. It has been found that having extra corrugation in the direction normal to the main (flute) direction (longitudinal) increases the bending stiffness in that direction while reduces the bending stiffness in the main direction (Mohammadabadi and Yadama 2020a). Feedstock and fiber length could be another reason for this difference. Both CORR-A and -B were manufactured from wood strands, while wood veneers were used to develop the corrugated panels in this study.

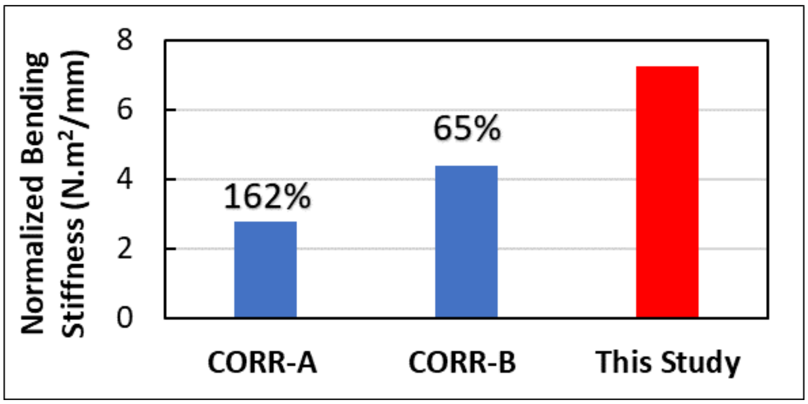


Fig. 6. Comparison between the normalized bending stiffness of the corrugated panel with those of CORR-A (Mohammadabadi *et al.* 2020b) and CORR-B (Mohammadabadi and Yadama 2020a)

Sandwich Panels

Separating flat panels by a core to make a sandwich structure results in an increased bending stiffness and load-carrying capacity. This concept is known as the "*sandwich effect*," and research has been conducted to specify the relation between the mechanical properties and dimensions of the core and facesheets with the structural performance of the sandwich panel (Zenkert 1995; Carlsson and Kardomateas 2011). To show the *sandwich effect*, the bending results of the sandwich specimens shown in Fig. 4a were compared to those of flat panels (Fig. 4b) made of the same veneers — regarding quantity, quality, thickness, order, and orientation — that were used to fabricate the sandwich panels. A similar slenderness ratio was used for these bending specimens; approximately 20 for flat specimens and 22 for the sandwich ones. Comparison of the normalized bending stiffness in Fig. 7a indicates that the sandwich panel was 272% stiffer than the flat panel. Comparison of normalized maximum bending moments, which is the maximum bending moment (Eq. 1c) divided by the width, shows that the normalized maximum bending moment of the sandwich structure was 107% higher than that of the flat panels as shown in Fig. 7a.

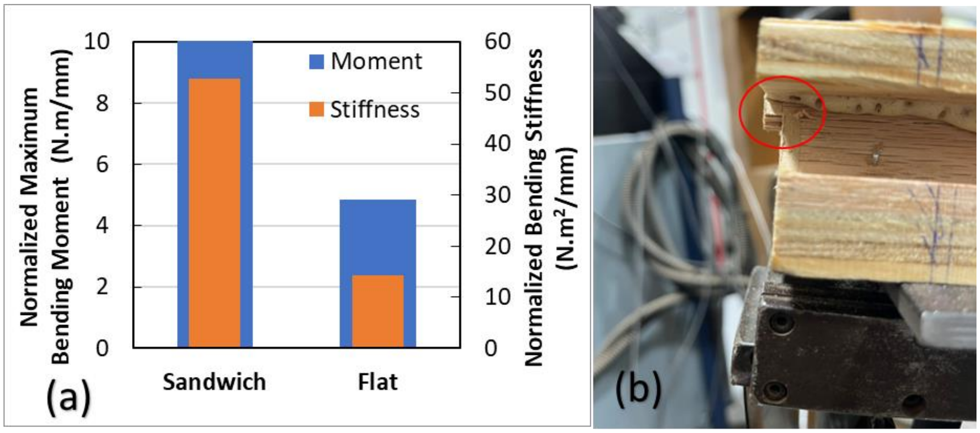


Fig. 7. (a) Comparison between bending results of sandwich panels and flat panels made from the same veneers, and (b) failure of sandwich specimens under a bending load

All flat panels failed in tension, while the most common failure for the sandwich specimens was due to shear in the corrugated panel, as shown in Fig. 7b. Out of six sandwich specimens, five of them failed in shear and one failed in tension. To avoid such an early failure due to shear, it is recommended to orient some of the veneers of the corrugated panel in the direction normal to the main direction.

The bending results of the sandwich panels were compared with Sandwich A and B, which had been developed using CORR-A and -B as a core, respectively. The dimensions of these sandwich specimens are given in Table 1. A comparison of the normalized bending stiffness in Fig. 8a shows that the sandwich panels developed in this study using a cold-forming method were approximately 101% and 6% stiffer, respectively. The sandwich panels A and B were fabricated using a hot-pressing technique. The normalized maximum bending moment of the sandwich panel developed in this study was 66% higher than that of sandwich panel B as shown in Fig. 8b. The bending moment for sandwich A was not reported, so no comparison was possible. The comparisons presented in Fig. 8 showed that the sandwich panels developed in this study using a wooden mold and a cold-forming process had higher structural performance compared to those fabricated using a thermoset resin and a hot-pressing technique.

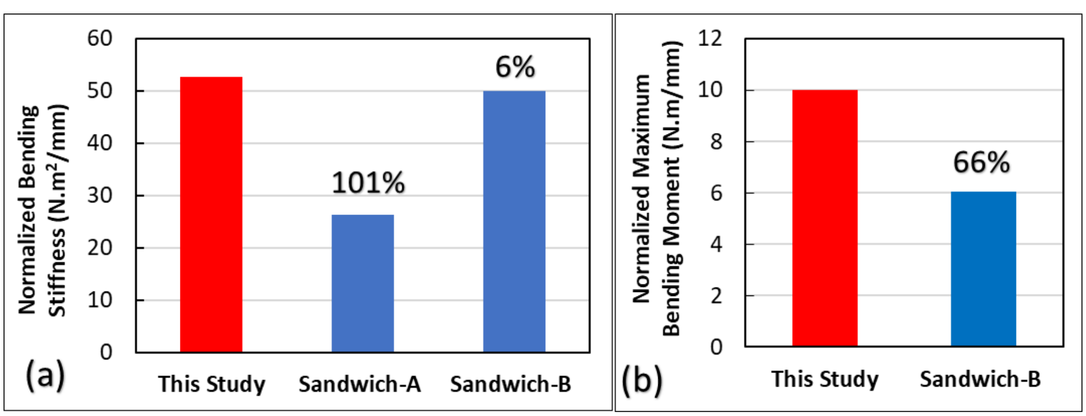


Fig. 8. Comparison between (a) normalized bending stiffness and (b) normalized maximum bending moment of the sandwich panel developed in this study with Sandwich A (Mohammadabadi *et al.* 2020b) and Sandwich B (Mohammadabadi *et al.* 2021) developed using hot-pressing process

CONCLUSIONS

Sandwich panels with a corrugated core were developed from wood veneers through a cold-forming process using a wooden matched-die mold and cold-setting resin. Specimens from both a corrugated panel and sandwich structure were cut and submitted to a bending test to evaluate their structural performance. Some of these findings are summarized as follows:

1. The bending stiffness of the corrugated panel was higher than those fabricated using hot-pressing techniques and thermoset resins.
2. The concept of *sandwich effect* showed that the normalized bending stiffness and normalized maximum bending moment of the sandwich panel were 272% and 107% higher than those of flat panel, respectively.
3. Compared to wood-based sandwich panels developed using the hot-pressing process, the sandwich panel developed in this study showed higher bending stiffness and bending moment.

These findings emphasize that the cost-effective, cold-forming process using a wooden matched-die mold that does not need heat is an effective method to fabricate profiled geometries to develop lightweight and high-performance sandwich structures. This cold-forming process is also an eco-friendly method, which not only does not use heat but also employs a carbon-sink material to develop the mold rather than those with large carbon footprint such steel and aluminum.

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