Development of a High-Performance Building Material Using Wood-based Corrugated Panels Manufactured *via* Cold-Forming Technique

Suman Pradhan, Mostafa Mohammadabadi,* Edward Entsminger, Kevin Ragon, Laya Khademibami, and Jason Street

A wood-based sandwich panel with a corrugated core was developed as a building material. A matched-die mold manufactured from commercial plywood was used to fabricate the corrugated panels through a cold-forming process. A cold-setting resin was applied on southern yellow pine (*Pinus* spp.) veneers with an average thickness of 4 mm, and four plies of them were formed into a corrugated geometry using a wooden mold. When the resin was cured, the corrugated panel of veneers retained the corrugated shape after load removal. Facesheets of the sandwich structures were fabricated using three plies of the same veneers. To evaluate the effect of this corrugated geometry on the structural performance, the same veneers — regarding number, thickness, and orientation — used for the sandwich panel were adopted to fabricate laminated flat panels. Both sandwich and laminated flat panels were submitted to a four-point bending test. The results confirmed the sandwich effect, *i.e.* a 1741% increase in the bending stiffness of sandwich panels compared to that of laminated flat panels. Sandwich panels developed in this study were compared to Structural Insulated Panels (SIPs), wood-framed structures known as stud walls, and sandwich panels produced using a hot-pressing technique. The cold-formed sandwich panels had higher structural performance than commercial building materials.

DOI: 10.15376/biores.18.3.4666-4675

Keywords: Corrugated panel; Cold-forming process; Sandwich effect; Wood-based building materials; Structural performance; Southern yellow pine veneer

*Contact information: Department of Sustainable Bioproducts, Mississippi State University, Box 9820, Mississippi State, MS 39762; *Corresponding author: mm5132@msstate.edu*

INTRODUCTION

Wood is one of the oldest building materials, and still the construction industry, mainly building, is the main market for long-lived wood/ wood-based products. Wood and wood-based products can help us to reduce carbon emissions and tackle environmental concerns such as global warming, as they are carbon negative. Wood and wood-based products can also play an important role in sustainability, as they are derived from a natural and renewable resources. Considering these facts, wood and wood-based products have recently received increased attention and many studies have been carried out to develop new products or improve the performance of the current ones. In addition, it is important that the developed building materials fit the concept of prefabricated construction as costs can be cut by 20% (Bertram *et al.* 2019).

Cross laminated timber (CLT) is one of these recent achievements that has been used as a prefabricated product in high-rise construction and has been able to successfully compete with common traditional building materials including steel and concrete. Considering the concept of composite materials and the crosswise design, this wood-based product has high structural performance and dimensional stability. Bending strength of CLT is higher than that of individual boards (Bano *et al.* 2018).

To develop high-performance and lightweight products, wood-based sandwich structures have also been developed. Some researchers used wet-forming and hot-pressing techniques to form wood fiber and thin veneer into corrugated geometry using a matched-die mold (Hunt *et al.* 2004; Kavermann and Bhattacharyya 2019; Smardzewski 2019a). To avoid water waste, researchers have adopted a dry-forming process along with a matched die mold technique to develop wood-based sandwich panels (Pang *et al.* 2007; Way *et al*. 2016; Mohammadabadi *et al*. 2018, 2020a). Instead of using a matched-die mold, a roll-forming technique to form wood veneer into corrugated geometry (Srinivasan *et al.* 2007; Dykes *et al*. 2000) and 3D printing to develop lattice structure (Smardzewski and Wojciechowski 2019b) have also been developed. To a have better understating of performance of these wood-based sandwich structures, full-size sandwich panels (1.2-m by 2.4-m) with biaxial corrugated core geometry were designed, fabricated, and evaluated (Mohammadabadi and Yadama 2020b; Mohammadabadi *et al*. 2020c). It should be emphasized that heat was a required element in the fabrication process of these core structures with three-dimensional geometries in order to cure the thermoset resin or melt the thermoplastic one. Recently, researchers at Mississippi State University developed a cold-forming process to form wood veneer into corrugated geometry using a wooden matched-die mold with no heat (Mohammadabadi *et al*. 2023). Wood veneers with an average thickness of 0.68 mm were formed into a corrugated geometry with an average depth of 28.6 mm. Without using heat and wet-forming process to soften wood, the question arises as to whether this cold-forming technique can be used to form thick veneers with an average thickness of 3 to 4 mm into a corrugated geometry.

Structural insulated panel (SIP) is another building material with high energy performance that is used as a prefabricated product (Panjehpour *et al.* 2013; Amran *et al.* 2022; Khademibami *et al.* 2023). To fabricate SIPs, an insulating material mainly polystyrene- or polyurethane-based foam is sandwiched between two layers of a structural panel, mainly oriented strand board (OSB). While such structures are lightweight, energy efficient, and made from prefabricated material resulting in quick construction, SIPs suffer from low load-carrying capacity and structural performance. Currently, International Residential Code (IRC 2018) section R610 limits the wall height to 3048 mm (10 ft) and number of stories above the basement to two stories.

Buildings are responsible for 36% of global energy consumption and 40% of greenhouse gas emissions (Allende and Stephan 2022). Therefore, the development of energy-efficient and prefabricated building materials similar to SIPs but with high-structural performance is required. The goal of this study is to form thick wood veneers with an average thickness of 4 mm into a corrugated geometry using a cold-forming process. It was hypothesized that wood veneers, even thick ones, can be formed into a corrugated geometry through a cold forming process without using heat or steam. This corrugated panel along with insulating foam were used as a core to develop a sandwich structure as a new building material.

EXPERIMENTAL

Corrugated Panels

To fabricate a corrugated panel shown in Fig. 1a using a cold-forming process, a wooden matched die mold was designed and manufactured. Similar to the study carried out by Mohammadabadi *et al.* (2023), this wooden mold was manufactured using a table saw. To avoid defects and cracks introduced into the corrugated panels during the forming process, the wooden mold was designed with rounded corners rather than sharp ones. To develop smooth rounded corners using a table saw, the mold was designed from several layers that should be cut at different angles as shown in Fig. 1b. Commercial plywood with an average thickness of 5.84 mm (0.23 in) and 18 mm (0.71 in) was cut and screwed together (shown in Fig. 2a) to fabricate an 8-ft wooden mold as shown in Fig. 2b-c.

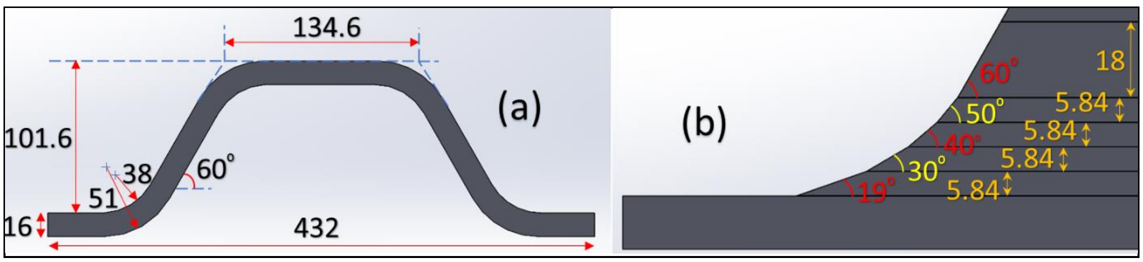

Fig. 1. Design process of the mold; (a) dimensions of the corrugated panel in mm, and (b) using different thicknesses and angles to develop a rounded corner

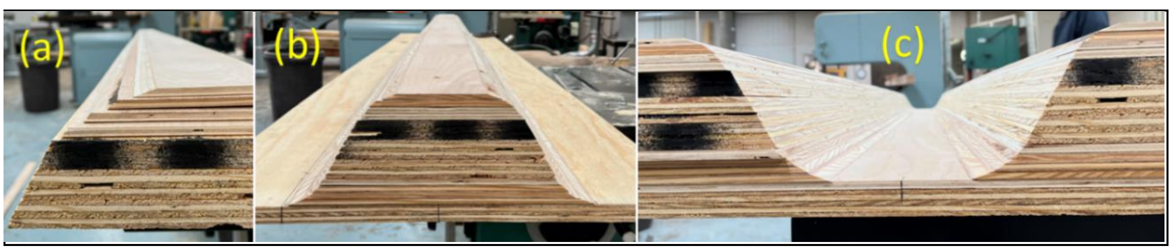

Fig. 2. (a) Cutting veneer in size and angle, (b) upper part (male) and (c) lower part (female) of the wooden mold with rounded corners

Fig. 3. Manufacturing process; (a) full-size, veneers with defects having an average thickness of 4 mm and (b) cold-pressing of four veneers to fabricate (c) Final corrugated panels with 432mm-wide and 2.6m-long dimensions

To fabricate the corrugated panels, veneers from southern yellow pine with an average thickness of 4 mm and average density of 535 kg/m^3, as shown in Fig. 3a, were used. To improve the utilization of veneers with defects and convert them into a high-performance product, veneers having pre-cracks and knots, as shown in Fig. 3a, were used in this study. For each corrugated panel, four layers with an average width of 0.57 m and length of 2.6-m were cut from full-size veneers. The average moisture content of wood veneers at the time of forming process was 8.25%, as they were kept at room temperature. A commercially available cold-setting wood glue, Titebond II premium, at a weight specification of 280 g/m^2, was applied to bond the veneers. Veneers brushed with resin were aligned in the same direction and placed between the top and bottom part of the mold and cold-pressed, as shown in Fig. 3b, to fabricate a veneer-based corrugated panel with an average thickness of 15.9 mm and depth of 116.5, as shown in Fig. 3c. The direction of wood fiber (*i.e.* the growth direction of the pine tree), which is parallel to the axial direction of the corrugated panel, is also shown in Fig. 3c.

Sandwich Panels

Facesheets, as a required component of sandwich panels, were fabricated from the same veneers having average thickness of 4 mm, average density of 535 kg/m3, and average MC of 8.25%. Three veneers with an average width of 0.48 m and length of 2.6 m were bonded together using the same resin, Titebond II premium, at the same target of 280 g/m^2 to make facesheets with an average thickness of 11.94 mm. Among the three layers of the facesheet, the ones attached to the top and bottom of the corrugated core were oriented perpendicularly, while the other two layers were in a parallel orientation with respect to the corrugated core. This orientation was made to increase the dimensional stability of the sandwich structure.

To develop an energy-efficient building material, the cavities between the corrugated core and the facesheets were filled with an insulating material. To this end, a commercially available extruded polystyrene (XPS) foam, FOAMULAR® 250 developed by Owens Corning, with the R-value of 34.7 mK/W per meter (5 h·ft2·°F/BTU per inch), was used. The same resin at the same target of 280 g/m^2 was used to bond the corrugated panel, facesheets, and XPS foam together to fabricate sandwich panels with an average thickness of 139 mm, as shown in Fig. 4a. Considering 101.6 mm-thick (4 in) foam, the R-value of 3.52 m^{2}K/W (20 h·ft2·°F/BTU) is expected for this sandwich structure.

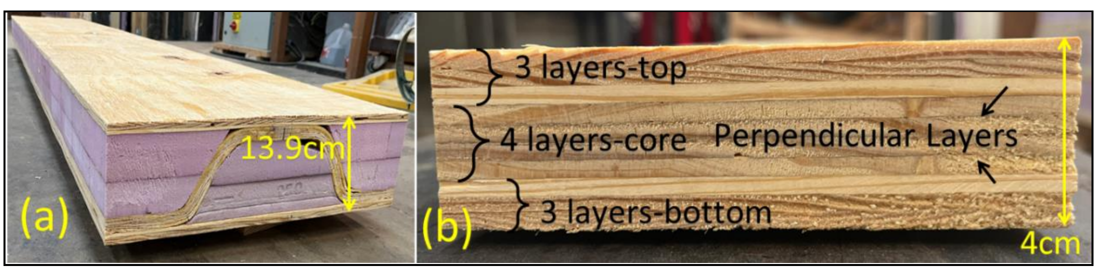

Fig. 4. (a) Sandwich and (b) laminated flat panel fabricated using the same number of veneers and same order

Sandwich panels developed in this study and shown in Fig. 4a were fabricated using 10 layers of veneer; three layers at the bottom (lower facesheet), four layers formed into corrugated panel (core) in the middle, and another three at the top (upper facesheet). As explained, all these 10 layers were aligned in the same direction except one layer of each facesheets that was aligned perpendicular and used to bond each facesheet to the corrugated panel. To examine the effect corrugated geometry on the structural performance of this sandwich structure, 10 layers of the same veneer were bonded in the same order to make laminated flat panels as shown in Fig. 4b.

Experimental Evaluation

Since the goal of this study was to introduce this sandwich structure as a new panel for building construction, ASTM E72 (ASTM 2022) was used to evaluate structural performance of this product. Both sandwich structures and laminated flat panels shown in Fig. 4 were submitted to a four-point bending test where the load span was half of the span length (*L*), known as quarter point loading. Bending stiffness (*EI*), bending strength known as modulus of rupture (MOR), maximum bending moment (M_{max}), and maximum shear stress (τ_{max}) that happens at nuteral axis were calculated using Eqs. (1-3), respectively,

$$EI = \frac{Pa}{48\Delta}(3L^2 - 4a^2) \tag{1}$$

$$\sigma = \frac{M_{max}C}{I} \tag{2}$$

$$M_{max} = \frac{Pa}{2} \tag{3}$$

$$\tau = \frac{VQ}{Ib} \tag{4}$$

where *P* is bending load, Δ is deflection at mid-span, *a* is the distance of loading point from the support which is one-fourth of the span length in this study, *L* is span length, *I* is moment of inertia, *C* is maximum distance from the neutral axis to the outermost fiber which is half of depth (*h/2*) for these specimens, *V* is shear force, Q is the first moment of area about the neutral axis for the area above or below the interest location, and *b* is specimen's width.

Because dead loads and live loads in the form of distributed loads are mainly used for the design of building materials, the bending load obtained from four-point bending test was converted into the distributed load. The equivalent distributed load is given in Eq. (5) was computed based on the maximum bending moment (M_{max}).

$$\left.\begin{aligned} Four-point\ load\colon\ M_{max} &= \frac{Pa}{2} \\ Distributed\ load\colon\ M_{max} &= \frac{wL^2}{8} \end{aligned}\right\} \rightarrow Equivalent\ Distributed\ Load = w = \frac{4Pa}{L^2} \tag{5}$$

RESULTS AND DISCUSSION

In this section, bending results of both sandwich structures and laminated flat panels developed in this study are reported. The bending results of the sandwich panel were compared with those of SIPs, stud wall used in traditional construction, and two-layered core sandwich panels fabricated using hot-pressing method. Details of all these specimens, dimensions and load, are given in Table 1.

Due to the increased height, sandwich structures have higher bending stiffness and lower normal stress at outer layers, which is known as the sandwich effect (Zenkert 1995). The effect of a corrugated panel on the structural performance of the sandwich structure, the sandwich effect, is shown in Fig. 5. To have an accurate comparison, bending stiffness and bending moment were normalized by width, as these specimens come with different widths. The normalized maximum bending moment and normalized bending stiffness of the sandwich structure, as shown in Fig. 5a, were 143% and 1741% higher than those of laminated flat panels made from the same number of veneers. The maximum normal stress of the sandwich panels, as shown in Fig. 5b, was 81% lower than that of laminated flat panels.

Table 1. Comparison between Dimensions and Maximum Bending Load of Specimens Developed in this Study with those of Reference Studies

	Specimens	#	Size: Length, Width, Depth (cm)	Span length, L, (cm)	$\frac{L}{h}$	Load Span	Max. Bend. Load, kN (Normalized*)
This study	Laminated Flat Panels	6	79×14×4	68.6	17	L/2	16(114)
	Sandwich Structures	4	253×42×13.9	239	17	L/2	33.6 (79.9)
Reference Studies	SIPs-Beam (Khademibami *et al*. 2023)	31	317×29.8×16.5	297	18	L/3	4.9 (16.4)
	SIPs-Panel (Abbasi 2014)	3	274×122×16.5	244	15	L/2	26.5 (21.7)
	Wood-Framed (Abbasi 2014)	3	274×244×16.5	244	15	L/2	68.8 (28.2)
	Hot-Press Sand. Panels (Mohammadabadi *et al.* 2021)	2	244×122×9.3	229	25	L/2	51.1(41.9)

* Numbers in the parenthesis show the maximum bending load normalized by specimens' width (kN/m).

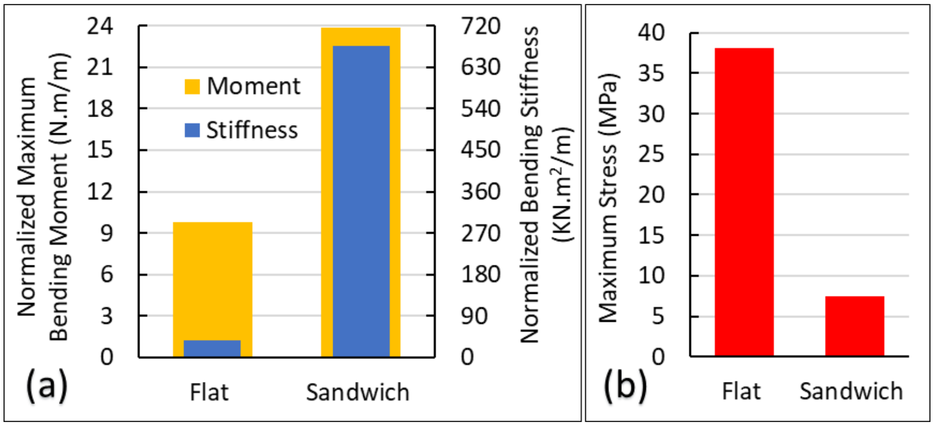

Fig. 5. Comparison between sandwich and laminated flat panels shown in Fig. 4, (a) maximum bending moment and bending stiffness normalized by width (per unit width) and (b) maximum normal stress (MOR)

Due to a decrease in maximum normal stress, sandwich panel failed in shear while laminated flat panel failed due to tensile stress at the bottom layer, as shown in Fig. 6. The maximum normal stress, as calculated using Eq. 2, and the maximum shear stress computed using Eq. 4 were 38 MPa and 2.2 MPa, respectively, for laminated flat panels, and 7.4 MPa and 4.9 MPa for sandwich panels. Since the shear modulus of the foam is smaller than that of veneer-based corrugated panel, most of the shear load is carried by the corrugated panel. Therefore, only the corrugated panel was used to calculate "*b*" in Eq. 4.

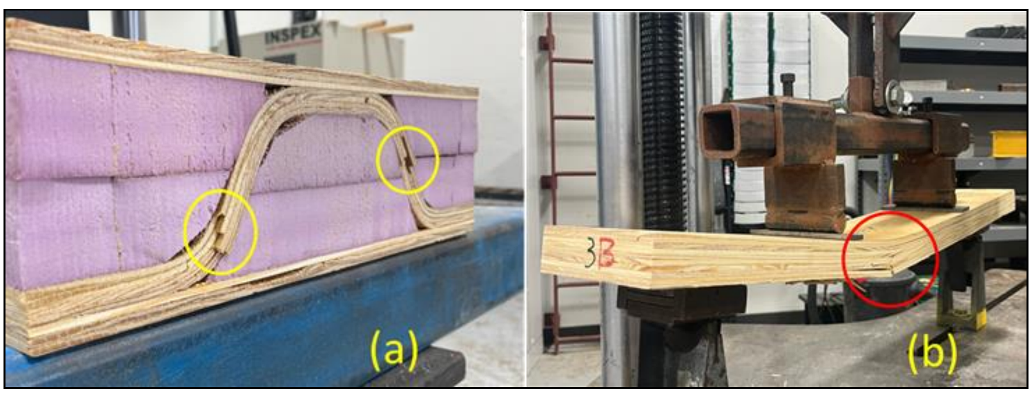

Fig. 6. Failure mode of (a) shear in sandwich panels and (b) tension in laminated flat panels

The bending results of the sandwich panel developed in this study using the cold forming process (Cold Forming Sand.) were compared with those of beam-like and panel-like SIPs (SIPs-Beam and SIPs-panel), traditional construction method of stud wall (Wood-Framed), and two-layered corrugated core sandwich panel manufactured using hot-pressing technique (Hot Pressing Sand.), as shown in Fig. 7. The maximum equivalent distributed load, which was calculated based on the maximum bending moment in Eq. 2, is reported in Fig. 7a. The maximum distributed load that can be applied on the sandwich panel developed in this study is higher than other building materials; 354% higher than beam-like SIPs, 276% higher than panel-like SIPs, 189% higher than stud wall, and 79% higher than hot-pressing sandwich panels. Even though beam- and panel-like SIPs have similar depths, their bending results are different, as they have been tested with different load span.

Because these specimens have different thicknesses, maximum stress (MOR) is compared in Fig. 7b to have an accurate comparison. Sandwich panels developed in this study exhibited a higher MOR than commercial building materials; 315%, 410%, and 73% higher than beam-like SIPs, panel-like SIPs, and stud wall, respectively. However, the MOR of cold-forming sandwich panel was 11% lower than that of hot-pressed sandwich panel. This can be explained because of the lower slenderness ratio of cold-forming sandwich panels, which is *L/h* and reported in Table 1, compared to that of hot-pressing sandwich panels. Due to the lower slenderness ratio, the effect of shear was significant; hence, cold-forming sandwich panels could not reach their true load-carrying capacity and failed due to high shear stress while tension was reported as the failure mode of hot-pressing sandwich panels. By increasing the slenderness ratio, the shear effect can be reduced, and high MOR and true load-carrying capacity for this sandwich panel can be obtained.

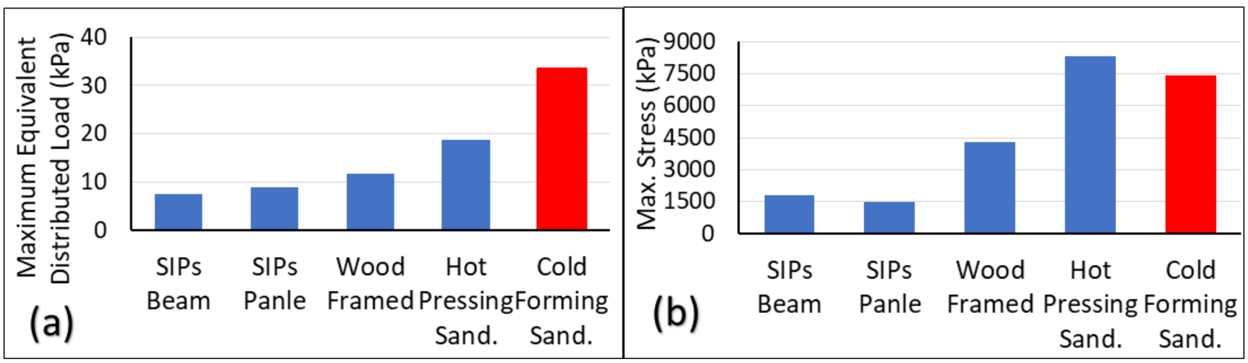

Fig. 7. Bending results of the cold forming sandwich panels developed in this study compared to commercial and similar building materials; (a) maximum equivalent distributed load and (b) maximum stress (MOR).

CONCLUSIONS

1. A cold-forming technique was developed to convert defective wood veneers into a high performance building material. Southern yellow pine veneers were formed into a corrugated geometry that was used as core of a sandwich structure. Insulating material was used to fill the cavities between the corrugated core and facesheets. Sandwich panels were submitted to four-point bending test and results were compared to those of commercial and similar building materials.
2. The effect of the corrugated veneer core on the structural performance of the sandwich panel was significant. The bending stiffness of the sandwich panels was 1741% higher than that of laminated flat panels made from the same number of veneers with the same orientation.
3. The equivalent distributed load that is an important factor to select and design building materials was computed for the sandwich panel developed in this study and was higher than those of commercial and similar building materials.
4. While the laminated flat panels failed due to tension, sandwich panels prepared with the corrugated veneer structures failed due to shear. By increasing the slenderness ratio of the sandwich panel, the effect of shear can be reduced, and their true load-carrying capacity can be obtained.

5. The cold-forming process was found to be an effective method to convert defective wood veneers to high-performance building materials. Since no heat was used during the manufacturing process, this cold-forming technique not only was successful to develop high-performance product but also can help to reduce carbon emissions.

ACKNOWLEDGEMENTS

The Authors would like to thank Winston Plywood and Veneer company for their support of this research. This material is based upon work supported by McIntire-Stennis project 7003668 and is a contribution of the Forest and Wildlife Research Center, Mississippi State University.

REFERENCES CITED

Abbasi, H. (2014). *Structural Behaviour of Insulated Foam-timber Panels under Gravity and Lateral Loading*, Ph.D. Dissertation, Ryerson University, Toronto.

Allende, A. L., and Stephan, A. (2022). "Life cycle embodied, operational and mobility-related energy and greenhouse gas emissions analysis of a green development in Melbourne, Australia," *Applied Energy* 305, article 117886. DOI: 10.1016/j.apenergy.2021.117886

Amran, Y. M., El-Zeadani, M., Lee, Y. H., Lee, Y. Y., Murali, G., and Feduik, R. (2020). "Design innovation, efficiency and applications of structural insulated panels: A review," *Structures* 27, 1358-1379. DOI: 10.1016/j.istruc.2020.07.044

ASTM E 72-22 (2022). "Standard test method for conducting strength tests of panels for building construction," ASTM International, West Conshohocken, PA, USA.

Baño, V., Godoy, D., Figueredo, D., and Vega, A. (2018). "Characterization and structural performance in bending of CLT panels made from small-diameter logs of loblolly/slash pine," *Materials* 11(12), article 2436. DOI: 10.3390/ma11122436

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., and Woetzel, J. (2019). "Modular construction: From projects to products," in: *Capital Projects and Infrastructure*, McKinsey and Company, pp. 1-34.

Dykes, R. J., Mander, S. J., and Bhattacharyya, D. (2000). "Roll forming continuous fibre-reinforced thermoplastic sheets: Experimental analysis," *Composites Part A: Applied Science and Manufacturing* 31(12), 1395-1407. DOI: 10.1016/S1359-835X(00)00076-2

Hunt, J. F., Harper, D. P., and Friedrich, K. A. (2004). "Three-dimensional engineered fiberboard: Opportunities for the use of low valued timber and recycled material," in: *Proceedings of the 38th International Wood Composites Symposium*, Pullman, WA, USA, pp. 207-216.

International Code Council. (2018). International Residential Code (IRC).

Kavermann, S. W., and Bhattacharyya, D. (2019). "Experimental investigation of the static behaviour of a corrugated plywood sandwich core," *Composite Structures* 207, 836-844. DOI: 10.1016/j.compstruct.2018.09.094

Khademibami, L., Shmulsky, R., Senalik, C. A., Seale, R. D., Ross, R. J., Mohammadabadi, M., Ward, K., and Williamson, T. (2023). "Flexural testing of structural insulated panels before and after creep testing," *BioResources* 18(2), 3319-3327. DOI: 10.15376/biores.18.2.3319-3327

Mohammadabadi, M., Yadama, V., and Geng, J. (2018). "Creep behavior of 3D core wood-strand sandwich panels," *Holzforschung* 72(6), 513-519. DOI: 10.1515/hf-2017-0088
Mohammadabadi, M., Jarvis, J., Yadama, V., and Cofer, W. (2020a). "Predictive models for elastic bending behavior of a wood composite sandwich panel," *Forests* 11(6), 624. DOI: 10.3390/f11060624
Mohammadabadi, M., and Yadama, V. (2020b). "Influence of a biaxially corrugated core geometry on flexural stiffness of wood-strand composite sandwich panels," *Materials Today Communications* 23, article 100931. DOI: 10.1016/j.mtcomm.2020.100931
Mohammadabadi, M., Yadama, V., and Smith, L. (2020c). "The effect of plate theories and boundary conditions on the bending behavior of a biaxial corrugated core sandwich panel," *Composite Structures* 241, article 112133. DOI: 10.1016/j.compstruct.2020.112133
Mohammadabadi, M., Yadama, V., and Dolan, J. D. (2021). "Evaluation of wood composite sandwich panels as a promising renewable building material," *Materials* 14(8), 2083. DOI: 10.3390/ma14082083
Mohammadabadi, M., Miller, J., Street, J., Kim, Y., and Ragon, K. (2023). "Wood-based corrugated core sandwich panels manufactured using a wooden mold," *BioResources* 18(2), 3033-3043. DOI: 10.15376/biores.18.2.3033-3043
Pang, W. C., Sandberg, L. B., Laks, P., and Forsman, J. W. (2007). "Corrugated strandboard structural panels," *Forest Products Journal* 57(3), 48.
Panjehpour, M., Abang Ali, A. A., and Voo, Y. L. (2013). "Structural insulated panels: Past, present, and future," *Journal of Engineering, Project and Production Management* 3(1), 2-8. DOI: 10.32738/JEPPM.201301.0002
Smardzewski, J. (2019a). "Wooden sandwich panels with prismatic core–Energy absorbing capabilities," *Composite Structures* 230, 111535. DOI: 10.1016/j.compstruct.2019.111535
Smardzewski, J., and Wojciechowski, K. W. (2019b). "Response of wood-based sandwich beams with three-dimensional lattice core," *Composite Structures* 216, 340-349. DOI: 10.1016/j.compstruct.2019.03.009
Srinivasan, N., Bhattacharyya, D., and Jayaraman, K. (2007). "Thermoforming of wood veneer composite sheets," *Holzforschung* 61(5), 558-562. DOI: 10.1515/HF.2007.105
Way, D., Sinha, A., Kamke, F. A., and Fujii, J. S. (2016). "Evaluation of a wood-strand molded core sandwich panel," *Journal of Materials in Civil Engineering* 28(9), article 04016074. DOI: 10.1061/(ASCE)MT.1943-5533.0001589
Zenkert, D. (1995). *An Introduction to Sandwich Construction*, Engineering Materials Advisory Services, Sheffield, UK.

Article submitted: April 6, 2023; Peer review completed: April 29, 2023; Revised version received: May 1, 2023; Accepted: May 14, 2023; Published: May 18, 2023.
DOI: 10.15376/biores.18.3.4666-4675