WOOD RESEARCH doi.org/10.37763/wr.1336-4561/66.5.875890
e-ISSN 2729-8906
66(5): 2021 875-890 pp.

WOOD-BASED SANDWICH PANELS: A REVIEW

PEIXING WEI[1], JINXIANG CHEN[1], YUE ZHANG[2], LIJUN PU[2]
[1]SOUTHEAST UNIVERSITY NANJING
CHINA
[2]JIANGSU VOCATIONAL COLLEGE OF AGRICULTURE AND FORESTRY
CHINA

(RECEIVED DECEMBER 2020)

ABSTRACT

A sandwich panel with a high ratio of strength to weight is commonly used in aerospace, construction, packaging and other fields. Using a renewable material such as wood to make sandwich panels can achieve a perfect unity of material and structure. In view of the lack of systematic analyses of wood-based sandwich panels, this work reviewed the development of wood-based sandwich panels. Based on the core structure, these panels can be divided into hollow-core structures and solid-core structures. With the emergence of new materials and new technologies, new wood-based sandwich products had been created. However, the current research only focused on the manufacturing, and the related novel design was still lacking. This work put forward a research idea of bionic design based on the integration of structure and function and pointed out the research direction for wood-based sandwich panels.

KEYWORDS: Wood-based sandwich panel, hollow-core structure, solid-core structure, property, application.

INTRODUCTION

Although the principle of a sandwich structure might have been applied much earlier, its concept was not clearly put forward until the middle of the 19th century (Fairbairn 1849). In general, sandwich panels were a kind of structural material composed of two high-strength stiff layers (facings) and one low-density layer (core) (Birman and Kardomateas 2018). The surface layer can bear the in-plane load and bending moment, which can be made from steel (Nilsson et al. 2017), wood (Kljak and Brezovic 2007), fibre reinforced concrete (O'Hegarty et al. 2019) or concrete (O'Hegarty and Kinnane 2020), and other materials (Boldis et al. 2016); the core layer mainly serves to transmit the load, and its function is to maintain the distance between the two layers and increase the inertia moment and bending stiffness of the panel (Noor et al. 1996, Zenkert 1995). The configurations of the core included corrugated core, plastically formed core, honeycomb cell core, and so on (Noor et al. 1996). Owing to low density of the core material, the sandwich panel can greatly reduce its dead weight under the same bearing capacity (Sandeep and Srinivasa 2020).

During World War II, the United Kingdom first used sandwich-structured plywood to manufacture mosquito bombers. At the same time, the United States (US) invented a sandwich structure with two reinforced plastic surface layers and one lower density core layer (Feichtinger 1989). Since the 1950s, the US Forest Products Laboratory studied on wood sandwich panels and had been in the leading position over the world for a long time (Vinson 2005). The surface materials of sandwich panels used in aircraft manufacturing were mainly plywood and pulp fibre in the early stage, and their cores were made of cork, balsa wood, and synthetic materials such as cellulose acetate. Later, aluminium alloy, titanium, and stainless steel were used for the surface layer and core layer of sandwich panels in aerospace (Noor et al. 1996). With the development of industrial synthetic materials, sandwich panels turned to using synthetic materials (Gibson and Ashby 1997).

In recent years, the ecological problems caused by petrochemical energy consumption and resource overexploitation have become serious, such as the frequent occurrence of extreme climates and the unprecedented challenges of human living environment. To reduce resources' consumption and environmental pollution, human beings urgently seek renewable and eco-friendly materials for daily life (Bekhta et al. 2013, Labans and Kalniņs 2014, Lakreb et al. 2015, Li et al. 2016, Asdrubali et al. 2017, Susainathan et al. 2017, Mirski et al. 2018, Mohammadabadi et al. 2018). As a renewable and degradable natural material, wood is a real low-carbon material (Robertson et al. 2012, Shao 2012, Vogtländer et al. 2014). Sandwich structures made of wood materials can give full play to the advantages of material and structure, and thus they are a kind of structural material with a great prospect (Negro et al. 2011, Monteiro et al. 2018).

Recent research in core materials of wood-based sandwich panels covered low-density wood fibre (Fernandez-Cabo et al. 2011, Zhang et al. 2012), plywood (Labans and Kalniņs 2014, Susainathan et al. 2017), wood strips (Li et al. 2016), cork (Lakreb et al. 2015), wooden dowel lattice (Jin et al. 2015), corrugated cardboard (Russ et al. 2013, McCracken and Sadeghian 2018), and 3D-shaped wood strand (Mohammadabadi et al. 2018). However, there is so far no systematic summary in this field. Therefore, this paper summarized the structure, properties, application and existing problems of wood-based sandwich panels, and proposed some research directions to better use sandwich structure and wood resource.

Structures and properties of wood-based panels

Structures of wood-based panels

Based on the different core configurations, wood-based sandwich panels can be classified into hollow-core structures and solid-core structures. There were six types of hollow-core structures: honeycomb core (Hao et al. 2020) (Fig.1a), I-shaped core (Labans and Kalniņs 2014) (Fig. 1b), interlocking lattice core (Chen and Tsai 1996, Han and Tsai 2003, Li et al. 2013, Klímek et al. 2016) (Fig. 1c), corrugated core (Srinivasan et al. 2008, Banerjee and

Bhattacharyya 2011) (Fig. 1d), moulded core (Way et al. 2016) (Fig. 1e), and pyramid lattice core (Yang et al. 2018) (Fig. 1f). The solid-core structures were relatively simple, namely, the core layer was composed of different light materials (Kawasaki and Kawai 2006, Hiziroglu 2012, Lakreb et al. 2015) (Fig. 1g,h,i).

Obviously, the hollow-core structures were undoubtedly more cost-effective than the solid-core structures. However, solid-core structures with a high porosity or a low density were also adopted in engineering application under the consideration of thermal and sound insulation.

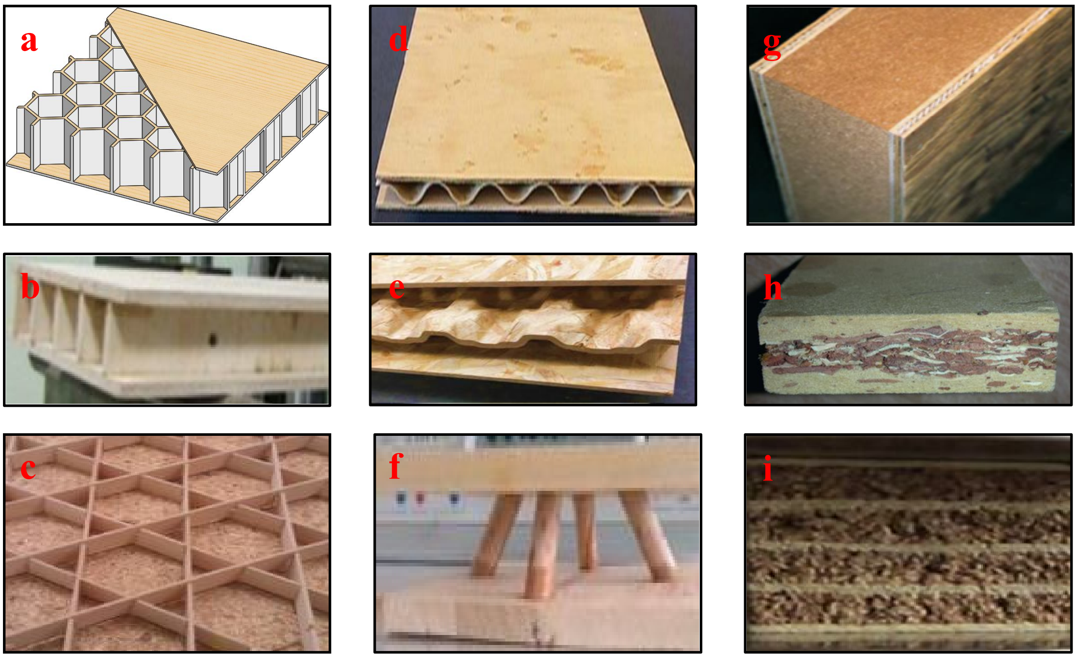

Fig. 1: Typical wood-based sandwich panels: a) honeycomb core; b) I-shaped core; c) interlocking lattice core; d) corrugated core; e) moulded core; f) pyramid lattice core; g) single-layer fiber core; h) single-layer strand core; i) multi-layer fiber core.

Structural properties of typical wood-based sandwich panels

Compressive properties of the wood honeycomb panel

Researchers have carried out many studies on honeycomb panels (Ramohalli 1983, Evans 1991, Chen 1994, Renji et al. 1996, Herup and Palazotto 1998, Horrigan et al. 2000, Okada and Kortschot 2002, Grove et al. 2006, Burlayenko and Sadowski 2010, Stocchi et al. 2014, Abbadi et al. 2015, Gunes and Arslan 2016, Balcı et al. 2017, Crupi et al. 2018, Ha et al. 2019, Gao et al. 2020), but it was limited in wood honeycomb panels. Xu (2007) prepared wood sandwich panels with different wood surface layers and paper honeycomb cores and carried out a comparative study (Fig. 2). It was found that there were five types of failure modes under lateral compression, namely, global instability, shear wrinkling, interfacial debonding, panel rupture, and panel buckling. The deformation mechanisms and lateral compressive strengths were different which depended on the surface materials.

Panel No.	Face sheet	Thickness of face sheet (mm)	Core	Thickness of core (mm)
A	Paper	0.31	Paper core	9.53
B	Sapele veneer	0.50	Paper core	9.53
C	Sapele veneer	0.50	Paperboard	10.52
D	Plywood	2.22	Paperboard	10.52
E	MDF	2.46	Paperboard	10.52

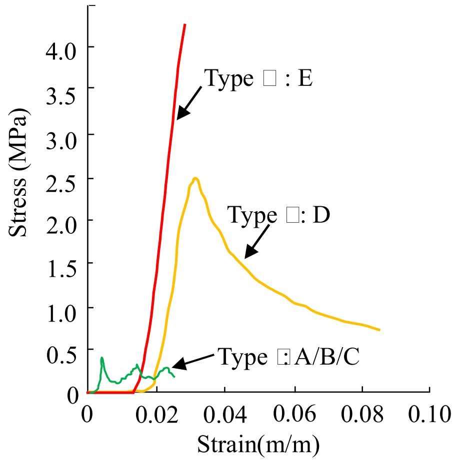

Fig. 2: Stress-strain relationship of wood honeycomb panels under lateral loading.

Creep behaviour of the wood honeycomb panel

There are few studies on the creep properties of paper-based honeycomb cores. Yan's research team from University of Toronto studied the creep properties of wood honeycomb panels with different material combinations. In their research, two kinds of honeycomb cores (Fig. 3a,b) and three kinds of surface layers (hardboard, medium density fibreboard (MDF), and plywood) were used to make wood honeycomb panels (Chen et al. 2011, Chen and Yan 2012). The results showed that the creep behaviour of the sandwich panel was closely related to the type of honeycomb core, the thickness of core and surface layer, and the surface material. To better combine the wood honeycomb panel with the hardware, Sambrew et al. (2010) proposed a concept of strengthening the edge of the wood honeycomb core and designed the edge reinforced wood honeycomb panel (Fig. 3c). This structure could effectively improve the compression and creep properties of wood honeycomb panels.

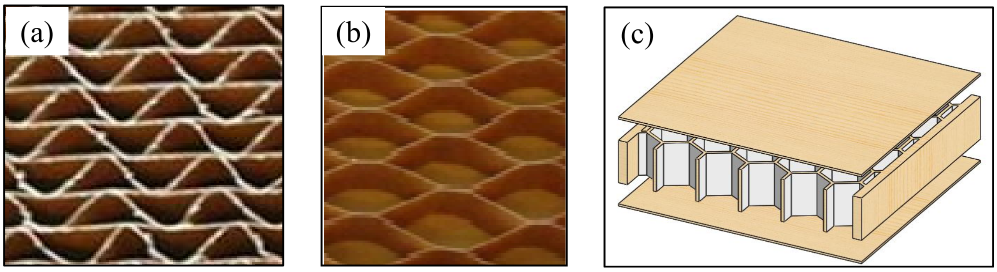

Fig. 3: Wood-based honeycomb panel: a) Corrugated honeycomb core; b) expanded honeycomb core; and c) wood-based honeycomb panel with edging reinforcement.

Applications of wood-based sandwich panels

Development and application of wood-based sandwich panels for furniture

With the continuous reduction of forest resource, to save resource and reduce dead weight has become an important issue in furniture industry (Labans and Kalniņs 2014). Using honeycomb structure in furniture can greatly save wood resource and also avoid the large deformation which often occurred for commercial wood composites. At present, honeycomb composite with a thickness of 20 mm above in furniture were widely used in Europe.

Traditionally, the honeycomb panel used in furniture was a frame honeycomb panel. Until 2005, lightweight frameless honeycomb panel manufacturing equipment and technology were created, which helped to realize industrialization and automation of wood honeycomb panels.

Jarusombuti et al. (2009) made a composite sandwich panel using local bamboo and straw resource in Thailand for the furniture industry. By testing the physical and mechanical properties of the samples, it was found that the composite sandwich panel can completely meet the requirements of indoor particleboard. Similarly, Hiziroglu (2012) developed a wood sandwich panel with eastern cedar (*Juniperus virginiana* L.) strands as the core layer and commercially produced Southern pine fibers as the surface layer. With the increase of density, the bending property increased, but the dimensional stability decreased.

MDF can easily deform while used for furniture components. To solve this problem, Büyüksari et al. (2012) proposed a wood-based sandwich panel, in which the MDF was the core layer and the hot-pressed wood veneer was the surface layer. Through tests on the physical and mechanical properties, it was found that the bending performance of the panel can be improved by increasing the temperature and pressure and the pressure had a great influence on the expansion rate of the water absorption thickness. Thus, to adjust the different combinations of temperature and pressure can make sandwich products meet the structural properties.

Development and application of wood-based sandwich panels for building

Compared with other commercial wood-based panels, wood-based sandwich panels had advantage in thermal insulation. Also, the sound absorption coefficient was almost zero, which was far lower than that of fibreboard. The research team from Kyoto University (Kawasaki et al. 1998, Kawasaki et al. 1999, Kawasaki and Kawai 2006) developed a sandwich panel with low-density fibreboard as the core layer for the thermal insulation wall or floor. Although Fernandez-Cabo et al. (2011) proposed a similar sandwich panel structure, their starting points for solving the problems were different. In Japan, Kawasaki et al. (2003) focused on the in-plane shear stiffness of sandwich panels. However, Fernandez-Cabo et al. (2011) examined the flexural response of sandwich panels subjected to wind loads. Labans and Kalni ņs (2014) developed a new type of I-shaped wood sandwich panel for construction. Under the condition of meeting the same stiffness as commercial plywood, the optimal design and experimental verification of this new type of wood sandwich panel were carried out. The results showed that, through reasonable design, a benefit building material with a low density and excellent mechanical properties can be obtained.

Development and application of wood-based sandwich panels for packaging

Paper-based honeycomb materials have been widely used in packaging industry owing to their advantages of high strength to weight ratio, good stiffness, good cushioning and vibration absorption performance, and environmental protection. According to the principle of a sandwich structure, the advantages of various materials can be fully utilized by using wood materials as the surface layer and paper honeycombs as the core layer. Through experimental verification, the physical and mechanical properties of these honeycomb sandwich materials are greatly improved (Xu 2007).

The creep of packaging materials often occurred during transportation which resulted in voids in container and led to an increase of the products' damage rate. For wood-based sandwich panels, creep originated from two reasons. One was the creep of the upper and lower surface layers, and the other was the shear deformation of the core layer. Xu (2007) studied the creep properties of sandwich materials with different combinations. However, the limitation was that the sandwich panels were regarded as homogeneous material, and in fact the wood honeycomb sandwich panel was an anisotropic material, which led to a large error. In addition, due to the problems associated with the test cycle, the short-term creep performance was used to predict the long-term creep properties of sandwich materials. Whether this prediction was correct needed to be examined.

Development trend of wood-based sandwich panels

Combined with other materials, wood with natural defects can be avoided. Thus, the study of wood composites has become a popular topic (Rao 2003, Yeniocak et al. 2016).

Wood-plastic composite (WPC) sandwich panels

WPCs have been widely utilized in construction, packaging, transportation and furniture products (Binhussain and El-Tonsy 2013). To improve the mechanical properties of WPCs, researchers have performed much research (Ou et al. 2010, Zolfaghari et al. 2013). Based on the sandwich structure, structure design of WPCs was carried out to improve mechanical properties (Vitale et al. 2016, Hao et al. 2018).

Tungjitpornkull and Sombatsompop (2009) studied the sandwich panel formed by the surface layer of wood/PVC composites and the core layer of glass fibre (GF)/PVC. It was found that the delamination of GF and PVC led to a decrease in the mechanical properties. To solve this problem, Mongkollapkit et al. (2010) studied the influence of the orientation angle of the GF and the viscosity index of the PVC and dicarboxylic acid on delamination. Hao et al. (2018) studied sandwich-structured WPCs composed of wood flour/high-density polyethylene and linear low-density polyethylene. The results showed that the bending strength and impact strength of the sandwich panel increased by 42% and 77%, respectively, while the water absorption rate was significantly reduced. However, the linear low-density PVC core layer did not cause a material change in the creep and relaxation characteristics of the panel, which led to an increase in the linear thermal expansion coefficient.

Edgars et al. (2017) designed two kinds of sandwich panels (Fig. 4). The bending tests showed that the flexural modulus of the sandwich panel with a corrugated GF reinforced resin core layer was 4180 MPa, the flexural strength was 22.6 MPa, and the density was 235 $kg \cdot m^{-3}$. The flexural modulus of the sandwich panel with plywood stiffeners and a foam core was 6200 MPa, the bending strength was 26.1 MPa, and the density was 325 $kg \cdot m^{-3}$. These two kinds of sandwich panels had the characteristics of light weight and high strength.

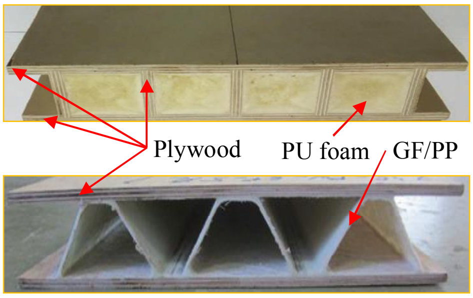

Fig. 4: Two types of lightweight and high-strength sandwich panels. Upper: sandwich panels with plywood stiffeners and a foam core; Bottom: sandwich panels with a corrugated GF/PP core.

Fibre reinforced wood-based sandwich panels

Yang et al. (2014) prepared a new type of composite wall panel using GF reinforced plastic (FRP) impregnated with vinyl resin and paulownia wood as the core material through vacuum induction moulding process. With the decrease in the height-thickness ratio, the ultimate bearing capacity of the specimens under axial compression increased. Fang et al. (2014) prepared a sandwich-structured bridge deck with glulam as the core material and GF reinforced composite (GFRP) as the surface layer (Fig. 5a) and carried out a bending performance test of a GFRP-glulam sandwich beam. Xiong et al. (2014) carried out a three-point bending test on a poplar sandwich composite panel (Fig. 5b) made by a pultrusion process. Wu et al. (2015) used GF reinforced composite as the surface layer and lattice web and paulownia wood as the core and chose the vacuum induction moulding process to prepare a paulownia wood sandwich beam with a lattice web panel interface (Fig. 5c). Wang et al. (2017) studied the bending properties of a paulownia wood sandwich panel (Fig. 5c) strengthened by a lattice web. Zou et al. (2017) proposed a new type of lattice web reinforced lightweight wood sandwich bridge deck (GFRP and balsa wood) (Fig. 5c).

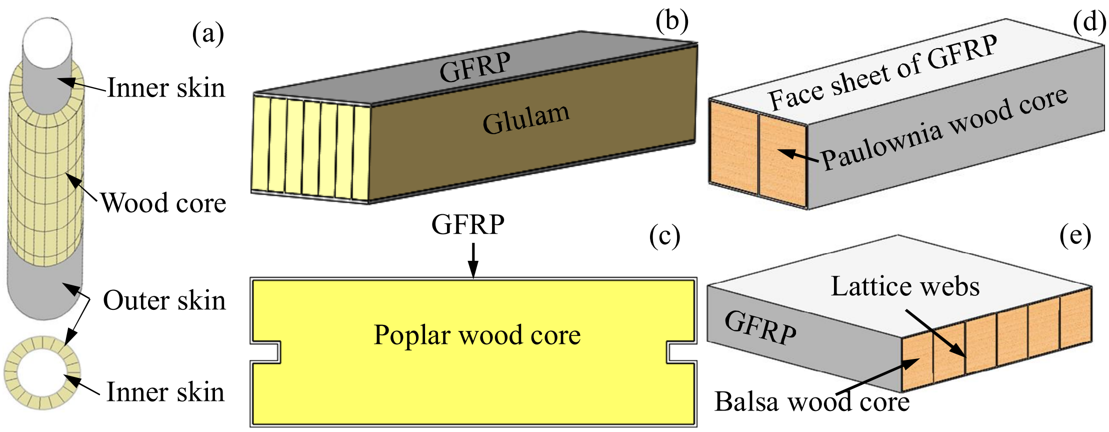

Fig. 5: Fibre reinforced wood-based sandwich panels.

Steel-wood composite sandwich panels

Due to its light-weight of wood, researchers have explored the feasibility of steel-wood composite for structural applications. For example, Teng et al. (2009) studied the flexural bearing capacity and ductility performance of cold-formed thin-walled steel and OSB composite floors; Han et al. (2010) and Li et al. (2008) studied the bending performance of profiled steel sheets and bamboo plywood composite floors, and found that they had a good combination effect. Poplar plywood had good bending performance and impact resistance as a structural cover panel (Zhao et al. 2010). Wood materials were generally used for the surface layers of sandwich panels, and steel was used for the core layer.

Wei et al. (2017) carried out finite element simulations and experimental research on the stress analysis of steel-wood sandwich panels. The core layer yielded first and then the panel yielded, and finally the debonding occurred. And bonding failure was the direct reason for the failure of this sandwich panel.

Bamboo-wood composite sandwich panels

Gao et al. (2010) designed three kinds of bamboo-wood composite sandwich walls (Fig. 6). The thermal insulation and sound insulation of three kinds of composite walls were tested. The results showed that the thermal insulation and sound insulation of the a-type wall was the worst, but it can be substantially improved by adding rock wool (type c); the thermal insulation and sound insulation of the wall exhibited no obvious changes after the interior wall panel was replaced by a gypsum board (type b).

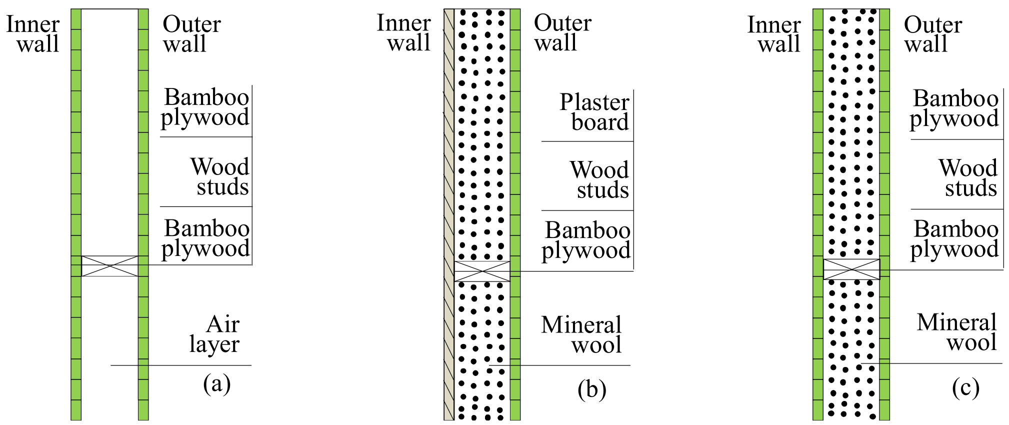

Fig. 6: Bamboo-wood sandwich wall: (a) bamboo plywood-overlaid hollow wall; (b) plaster board-overlaid sandwich wall; and (c) bamboo plywood-overlaid sandwich wall.

Zhou (2017) prepared a multifunctional composite wall (Fig. 7b) using a 33 mm-thick hollow-core particleboard (Fig. 7a). The core layer was an air layer separated by wood strips of different thicknesses (23 mm and 74 mm), and then a 9 mm gypsum board and plywood were applied on the surface of the particleboard (Fig. 7b). Jiang et al. (2017) improved the structure and proposed the use of small diameter bamboo as a reinforcement material to improve the main physical and mechanical properties of hollow-core particleboard (Fig. 7c). Then, resorcinol phenol formaldehyde adhesive was coated on the surface of the original bamboo-reinforced particleboard, and laminated veneer or plywood was installed on the surface of the particleboard to form a sandwich board structure. The results showed that bamboo had a substantial effect on the properties of hollow-core particleboard, and the mechanical properties and dimensional stability are greatly improved.

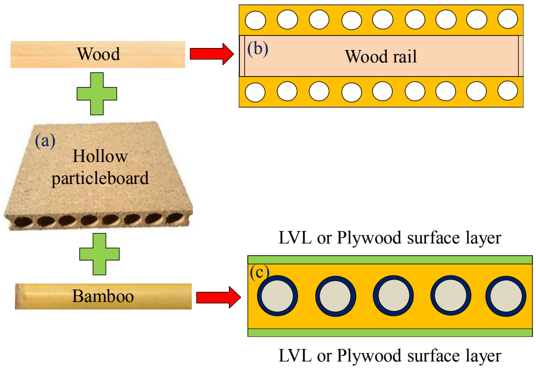

Fig. 7: Bamboo-wood sandwich panel.

Other wood-based sandwich panels

Renewable lightweight materials can be used to reduce carbon emissions and achieve sustainable development. Wood, an ancient material, can be compounded with other materials to form a lightweight and high-strength structure. Burnett and Kharazipour (2018) created a sandwich structure with a core layer made from popcorn particles and a surface layer of poplar plywood (Fig. 8). This sandwich panel can achieve the performance of traditional wood composites such as fibreboard and particleboard, and thus it may be used in the furniture industry. Susainathan et al. (2017) prepared wood composite sandwich panels using two kinds of plywood with different blank structures and four different surface materials (aluminium, GF reinforced resin, carbon fibre reinforced resin and flax reinforced resin) and studied the failure mechanism of quasi-static bending and low-speed impact performance (Susainathan et al. 2018). This kind of wood-based sandwich panel can not only give full play to the advantages of light wood, but also the strength of composite materials.

Fig. 8: Popcorn-wood sandwich panel.

CONCLUSIONS

Wood-based sandwich panels were a special kind of sandwich panels, which had an advantage of light weight and high strength. In addition, they also had the resource advantage that other materials such as metal and plastic did not have. Scientific planting and logging can realize a continuous supply of wood resource. Therefore, according to the literature search, it was evident that research on wood sandwich panels had obviously increased and accelerated. In this paper, the structural characteristics, applications, and development trends of wood sandwich panels were summarized: *(1)* Wood sandwich panels can be divided into hollow-core structures and solid-core structures. The hollow-core structures included corrugated structure, honeycomb structure, lattice structure, interlocking structure, and so on. The solid core structures mainly used wood, light fibreboard, particleboard, and crop straw fibres as the core material, and the structure was relatively simple. *(2)* According to the literature, researchers not only improved their structures of sandwich panels but also used new materials. The sandwich structure was formed by wood composite or mixed use of plywood, fibreboard, and particleboard. And even wood materials were combined with plastics, steel, bamboo, fibre reinforced materials, and so on. *(3)* Researchers focused on the development of new products. However, there was a lack of basic research on the design theory and failure mechanisms. Although there were many kinds of wood-based sandwich panels, most of them were still in the research stage of preparation, structural parameters, physical and mechanical properties, and engineering application and dynamics research have not been carried out. *(4)* Hollow-core wood sandwich panels had the advantage of light weight and high strength, but their insulation and sound insulation effects were not good due to poor sealing. And the poor compressive and shear properties of solid-core wood sandwich panels also limited their applications. Thus, the integration of structure and function is the basic principle for the development of new wood-based sandwich panels. *(5)* In future research, the bionic design concept should be applied to the structural design of wood-based sandwich panels to effectively improve the physical and mechanical properties. For example, according to the beetle coleoptera structure (honeycomb-column structure), the core layer structure of a wood-based sandwich panel can be first prepared, and then the straw fibre or wood fibre can be filled into the honeycomb, which can not only improve the mechanical properties of the wood sandwich panel, but also improve its physical properties such as thermal and sound insulation.

ACKNOWLEDGMENTS

This work is financially by Jiangsu Planned Projects for Postdoctoral Research Funds (2018K121C), and Qing Lan Project of Jiangsu Province (2019).

REFERENCES

1. Abbadi, A., Tixier, C., Gilgert, J., Azari, Z., 2015: Experimental study on the fatigue behaviour of honeycomb sandwich panels with artificial defects. Composite Structures 120: 394-405.
2. Asdrubali, F., Ferracuti, B., Lombardi, L., Guattari, C., Evangelisti, L., Grazieschi, G., 2017: A review of structural, thermo-physical, acoustical, and environmental properties of wooden materials for building applications. Building and Environment 114: 307-332.
3. Banerjee, S., Bhattacharyya, D., 2011: Optimal design of sandwich panels made of wood veneer hollow cores. Composites Science and Technology 71(4): 425-432.
4. Balcı, O., Çoban, O., Bora, M.Ö., Akagündüz, E., Yalçin, E.B., 2017: Experimental investigation of single and repeated impacts for repaired honeycomb sandwich structures. Materials Science and Engineering A 682: 23-30.

5. Bekhta, P., Korkut, S., Hiziroglu, S., 2013: Effect of pretreatment of raw material on properties of particleboard panels made from wheat straw. Bioresources 8(3): 4766-4774.
6. Binhussain, M.A., El-Tonsy, M.M., 2013: Palm leave and plastic waste wood composite for out-door structures. Construction and Building Materials 47: 1431-1435.
7. Birmana, V., Kardomateas, G.A., 2018: Review of current trends in research and applications of sandwich structures. Composites Part B 142: 221-240.
8. Boldis, M., Gasparik, M., Gaff, M., Ruman, D., 2016: Compression set of PU foam mattresses with self-clamping joints and sandwich structure. Wood Research 61(6): 1003-1016.
9. Burlayenko, V.N., Sadowski, T., 2010: Effective elastic properties of foam-filled honeycomb cores of sandwich panels. Composite Structures 92(12): 2890-2900.
10. Büyüksari, Ü., Hiziroglu, S., Akkılıç, H., Ayrılmış, N., 2012: Mechanical and physical properties of medium density fiberboard panels laminated with thermally compressed veneer. Composites Part B 43(2): 110-114.
11. Burnett, M., Kharazipour, A., 2018: Mechanical behaviour of a lightweight, three-layered sandwich panel based on the raw material maize. Holzforschung 72(1): 65-70.
12. Chen, R.S., 1994: Effect of curing process on mechanical properties of honeycomb-core sandwich plates. Composites Engineering 4(4): 445-458.
13. Chen, H.J., Tsai, S.W., 1996: Analysis and optimum design of composite grid structures. Journal of Composite Materials 30(4): 503-534.
14. Chen, Z., Yan, N., Deng, J., Smith, G., 2011: Flexural creep behavior of sandwich panels containing kraft paper honeycomb core and wood composite skins. Materials Science and Engineering A 528(16-17): 5621-5626.
15. Chen, Z., Yan, N., 2012: Investigation of elastic moduli of kraft paper honeycomb core sandwich panels. Composites Part B 43(5): 2107-2114.
16. Crupi, V., Kara, E., Epasto, G., Guglielmino, E., Aykul, H., 2018: Theoretical and experimental analysis for the impact response of glass fibre reinforced aluminium honeycomb sandwiches. Journal of Sandwich Structures and Materials 20(1): 42-69.
17. Evans, K.E., 1991: The design of doubly curved sandwich panels with honeycomb cores. Composite Structures 17(2): 95-111.
18. Edgars, L., Kaspars, Z., Kaspars, K., 2017: Structural performance of wood-based sandwich panels in four-point bending. Procedia Engineering 172: 628-633.
19. Fang, H., Han, J., Liu, W.Q., Zhu, L., 2014: Experiment on bending capacity and structural design of GFRP - *Pseudotsuga taxifolia* glulam bridge deck. Journal of Architecture and Civil Engineering 31(3): 58-63.
20. Fairbairn, W., 1849: An account of the construction of the Britannia and Conway tubular bridges. John Weale, London, UK.
21. Fernandez-Cabo, J.L., Majano-Majano, A., San-Salvador Ageo, L., Ávila-Nieto, M., 2011: Development of a novel façade sandwich panel with low-density wood fibres core and wood-based panels as faces. European Journal of Wood and Wood Products 69: 459-470.
22. Feichtinger, K.A., 1989: Test methods and performance of structural core materials-1. Static properties. Journal of Reinforced Plastics and Composites 8(4): 334-357.

23. Gao, X., Zhang, M.M., Huang, Y.D., Sang, L., Hou, W.B., 2020: Experimental and numerical investigation of thermoplastic honeycomb sandwich structures under bending loading. Thin-Walled Structures 155: 106961.
24. Gao, L., Wang, Z., Chang, L., 2010: Heat and sound insulation performance of prefabricated bamboo-wood wall. China Wood Industry 24(1): 26-28.
25. Gibson, L.J., Ashby, M.F., 1997: Chapter 9: the design of sandwich panels with foam cores. In book: Pp 345-386, Cellular solids. Cambridge University Press, UK.
26. Gunes, R., Arslan, K., 2016: Development of numerical realistic model for predicting low-velocity impact response of aluminium honeycomb sandwich structures. Journal of Sandwich Structures and Materials 18(1): 95-112.
27. Grove, S.M., Popham, E., Miles, M.E., 2006: An investigation of the skin/core bond in honeycomb sandwich structures using statistical experimentation techniques. Composites Part A 37(5): 804-812.
28. Ha, N.S., Lu, G.X, Xiang, X.M., 2019: Energy absorption of a bio-inspired honeycomb sandwich panel. Journal of Materials Science 54(8): 6286-6300.
29. Han, D.Y., Tsai, S.W., 2003: Interlocked composite grids design and manufacturing. Journal of Composite Materials 37(4): 287-316.
30. Han, T.S., Li, Y.S., Zhang, W.L., Shen, H.Y., 2010: Study on flexural performance of thin-walled steel-bamboo plywood composite slabs. Forest Engineering 26(3): 54-57.
31. Hao, X.L., Zhou, H.Y., Xie, Y.J., Mu, H.L., Wang, Q.W., 2018: Sandwich-structured wood flour/HDPE composite panels: Reinforcement using a linear low-density polyethylene core layer. Construction and Building Materials 164: 489-496.
32. Hao, J.X., Wu, X.F., Oporto, G., Liu, W.J., Wang, J.X., 2020: Structural analysis and strength-to-weight optimization of wood-based sandwich composite with honeycomb core under three-point flexural test. European Journal of Wood and Wood Products 78: 1195-1207.
33. Herup, E.J., Palazotto, A.N., 1998: Low-velocity impact damage initiation in graphite/epoxy/Nomex honeycomb-sandwich plates. Composites Science and Technology 57(12): 1581-1598.
34. Hiziroglu, S., 2012: Some properties of sandwich type composite panels manufactured from eastern redcedar. Composites Part B 43(8): 3288-3292.
35. Horrigan, D.P.W, Aitken, R.R., Moltschaniwskyj, G., 2000: Modelling of crushing due to impact in honeycomb sandwiches. Journal of Sandwich Structures and Materials 2(2): 131-151.
36. Jarusombuti, S., Hiziroglu, S., Bauchongkol, P., Fueangvivat, V., 2009: Properties of sandwich-type panels made from bamboo and rice straw. Forest Products Journal 59(10): 52-57.
37. Jin, M., Hu, Y., Wang, B., 2015: Compressive and bending behaviours of wood-based two-dimensional lattice truss core sandwich structures. Composite Structures 124: 337-344.

38. Jiang, J., Lu, X.N., Shen, H.Y., 2017: Characterization of original bamboo reinforced extruded particleboards (BRP) and stability design for its longitudinal compression. China Forest Products Industry 44(9): 28-32.
39. Kawasaki, T., Zhang, M., Kawai, S., 1998: Manufacture and properties of ultra-low-density fiberboard. Journal of Wood Science 44(5): 354-360.
40. Kawasaki, T., Zhang, M., Kawai, S., 1999: Sandwich panel of veneer-overlaid low-density fiberboard. Journal of Wood Science 45(4): 291-298.
41. Kawasaki, T., Hwang, K., Komatsu, K., Kawai, S., 2003: In-plane shear properties of the wood-based sandwich panel as a small shear wall evaluated by the shear test method using tie-rods. Journal of Wood Science 49(3): 199-209.
42. Kawasaki, T., Kawai, S., 2006: Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. Journal of Wood Science 52(1): 75-83.
43. Kljak, J., Brezovic, M., 2007: Influence of plywood structure on sandwich panel properties: Variability of veneer thickness ratio. Wood Research 52(2): 77-88.
44. Klímek, P., Wimmer, R., Brabec, M., Sebera, V., 2016: Novel sandwich panel with interlocking plywood kagome lattice core and grooved particleboard facings. BioResources 11(1): 195-208.
45. Labans, E., Kalniņs, K., 2014: Experimental validation of the stiffness optimization for plywood sandwich panels with rib-stiffened core. Wood Research 59(5): 793-802.
46. Lakreb, N., Bezzazi, B., Pereira, H., 2015: Mechanical behavior of multilayered sandwich panels of wood veneer and a core of cork agglomerates. Materials and Design 65: 627-636.
47. Li, J.H., Hunt, J.F., Cai, Z.Y., Zhou, X.Y., 2013: Bending analyses for 3D engineered structural panels made from laminated paper and carbon fabric. Composites Part B 53(5): 17-24.
48. Li, J.H., Hunt, J.F., Gong, S.Q., Cai, Z.Y., 2016: Simplified analytical model and balanced design approach for light-weight wood-based structural panel in bending. Composite Structures 136: 16-24.
49. Li, Y.S., Shan, W., Huang, Z.B., Ge, B.D., Wu, Y., 2008: Experimental study on mechanical behavior of profiled steel sheet-bamboo plywood composite slabs. Journal of Building Structures 29(1): 96-102.
50. McCracken, A., Sadeghian, P., 2018: Corrugated cardboard core sandwich beams with bio-based flax fiber composite skins. Journal of Building Engineering 20: 114-122.
51. Monteiro, S., Martins, J., Magalhães, F.D., Carvalho L., 2018: Lightweight wood composites: challenges, production and performance. In book: Lignocellulosic composite materials. Springer.
52. Mongkollapkit, N., Kositchaiyong, A., Rosarpitak, V., Sombatsompop, N., 2010: Mechanical and morphological properties for sandwich composites of wood/PVC and glass fiber/PVC layers. Journal of Applied Polymer Science116(6): 3427-3436.
53. Mohammadabadi, M., Yadama, V., Yao, L., Bhattacharyya, D., 2018: Low-velocity impact response of wood-strand sandwich panels and their components. Holzforschung 72(8): 681-689.

54. Mirski, R., Dziurka, D., Banaszak, A., 2018: Properties of particleboards produced from various lignocellulosic particles. BioResources 13(4): 7758-7765.
55. Negro, F., Cremonini, C., Zanuttini, R., Properzi, M., Pichelin, F., 2011: A new wood-based lightweight composite for boatbuilding. Wood Research 56(2): 257-266.
56. Noor, A.K., Burton, W.S., Bert, C.W., 1996: Computational models for sandwich panels and shells. Applied Mechanics Reviews 49(3): 155-200.
57. Nilsson, P., Al-Emrani, M., Atashipour S.R., 2017: Transverse shear stiffness of corrugated core steel sandwich panels with dual weld lines. Thin-Walled Structures 117: 98-112.
58. Ou, R.X., Zhao, H., Sui, S.J., Song, Y.M., Wang, Q.W., 2010: Reinforcing effects of Kevlar fiber on the mechanical properties of wood-flour/high-density-polyethylene composites, Composites Part A 41(9): 1272-1278.
59. Okada, R., Kortschot, M.T., 2002: The role of the resin fillet in the delamination of honeycomb sandwich structures. Composites science and technology 62(14): 1811-1819.
60. O'Hegarty, R., West, R., Reilly, A., Kinnane, O., 2019: Composite behaviour of fibre-reinforced concrete sandwich panels with FRP shear connectors. Engineering Structures 198: 1-15.
61. O'Hegarty, R., Kinnane, O., 2020: Review of precast concrete sandwich panels and their innovations. Construction and Building Materials 233: 117145.
62. Ramohalli, K., 1983: Thermochemical response of honeycomb sandwich panels. Journal of fire sciences 1(5): 379-395.
63. Rao, J.P., 2003: Developing situation and prospects on wood-based composites. Journal of Fujian College of Forestry 23(3): 284-287.
64. Renji, K., Nair, P.S., Narayanan, S., 1996: Modal density of composite honeycomb sandwich panels. Journal of Sound and Vibration 195(5): 687-699.
65. Robertson, A., Lam, F., Cole, R., 2012: A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: laminated timber or reinforced concrete. Buildings 2(3): 245-270.
66. Russ, A., Schwartz, J., Boháček, Š., Lübke, H., Ihnát, V., Pažitný, A., 2013: Reuse of old corrugated cardboard in constructional and thermal insulating boards. Wood Research 58(3): 505-510.
67. Sambrew, S., Semple, K., Smith, G., 2010: Edge reinforcement of honeycomb sandwich panels. Forest Products Journal 60(4): 382-389.
68. Shao, Z.P., 2012: Fracture mechanics of plant fibre (wood and bamboo). Science Press, China.
69. Srinivasan, N., Jayaraman, K., Bhattacharyya, D., 2008: Profile production in multi-veneer sheets by continuous roll forming. Holzforschung 62(4): 453-460.
70. Susainathan, J., Eyma, F., De Luycker, E., Cantarel, A., Castainie, B., 2017: Manufacturing and quasi-static bending behavior of wood-based sandwich structures. Composite Structures 182: 487-504.
71. Susainathan, J., Eyma, F., De Luycker, E., Cantarel, A., Castainie, B., 2018: Experimental investigation of impact behavior of wood-based sandwich structures. Composites Part A 109: 10-19.

72. Sandeep, S.H., Srinivasa, C.V., 2020: Hybrid sandwich panels: A review. International Journal of Applied Mechanics and Engineering 25(3): 64-85.
73. Stocchi, A., Colabella, L., Cisilino, A., Alvarez, V., 2014: Manufacturing and testing of a sandwich panel honeycomb core reinforced with natural-fiber fabrics. Materials and Design 55: 394-403.
74. Teng, X.F., Cao, B.Z., Xu, C., Lu, L.L., Sun, G.D., Cao, R., 2009: Experimental research on cold formed steel OSB floor. Journal of Jilin Institute of Architectural and Civil 26(2): 1-5.
75. Tungjitpornkull, S., Sombatsompop, N., 2009: Processing technique and fiber orientation angle affecting the mechanical properties of E-glass fiber reinforced wood/PVC composites. Journal of Materials Processing Technology 209(6): 3079-3088.
76. Vinson, J.R., 2005: Sandwich structures: past, present, and future. Springer.
77. Vogtländer, J.G., van der Velden, N.M., van der Lugt, P., 2014: Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle: cases on wood and on bamboo. The International Journal of Life Cycle Assessment 19(1): 13-23.
78. Vitale, J.P., Francucci, G., Xiong, J., Stocchi, A., 2017: Failure mode maps of natural and synthetic fiber reinforced composite sandwich panels. Composites Part A 94: 217-225.
79. Way, D., Sinha, A., Kamke, F.A., Fujii, J.S., 2016: Evaluation of a wood-strand molded core sandwich panel. Journal of Materials in Civil Engineering 28(9): 04016074.
80. Wang, Y., Fang, H., Liu, W.Q., Qi, Y.J., 2017: Experimental research on the flexural properties of paulownia wood core composite sandwich panel reinforced by lattice webs. Industrial Construction 47(8): 170-174.
81. Wei, B.N., Xu, H.M., Li, T., 2017: Experiment and finite element analysis on reliability of balsa sandwich panels. Journal of Guangxi University (Natural Science Edition) 42(1): 142-147.
82. Wu, Z.Y., Fang, H., Liu, W.Q., Zhu, L., Qi, Y.J., 2015: Experimental study on flexural behavior of paulownia wooden core sandwich composite beam reinforced with lattice web. Fiber Reinforced Plastics/Composites (10): 53-57.
83. Xu, Z.Y., 2007: Properties of the composite material of sandwich construction with wooden faceplate and a paper honeycomb core. Nanjing Forestry University, China.
84. Xiong, W., Qi, Y.J., Liu, W.Q., Shi, D., 2014: Experimental study on flexural performance of pultruded composite sandwich bridge decks. Fiber Reinforced Plastics/Composites 12: 97-100.
85. Yang, D.X., Hu, Y.C., Fan, C.S., 2018: Compression behaviors of wood-based lattice sandwich structures. BioResources 13(3): 6577-6590.
86. Yang, S.L., Liu, W.Q., Fang, H., Wang, L., 2014: Experiment study of composite wall boards with GFRP face sheets and a paulownia wood core. Industrial Construction 44(10): 30-35.
87. Yeniocak, M., Goktas, O., Ozen, E., Gecgel, A., 2016: Improving mechanical and physical properties of particleboard made from vine (*Vitis vinifera* L.) prunings by addition reinforcement materials. Wood Research 61(2): 265-274.

88. Zenkert, D., 1995: An introduction to sandwich construction. Chamelon Press, London, UK.
89. Zhao, L., Liu, L.Q., Zheng, X.Y., Sun, D.X., 2010: Performance study of Yiyang structure plywood under uniform load. Sichuan Building Science 36(1): 22-25.
90. Zhang, Y., Yu, Z.M., Shan, F.R., Shang, J.B., 2012: Characteristic and prediction model of vertical density profile of fiberboard with fiberboard with “pretreatment-hot pressing” united technology. Wood Research 57(4): 613-630.
91. Zolfaghari, A., Behravesh, A.H., Adli, A., 2013: Continuous glass fiber reinforced wood plastic composite in extrusion process: mechanical properties. Materials and Design 51: 701-708.
92. Zou, F., Fang, H., Qi, Y.J., Liu, W.Q., 2017: Preparation and flexural analysis of balsa wood core sandwich composite bridge deck reinforced by lattice webs. Fiber Reinforces Plastics/Composites (3): 44-48.
93. Zhou, T.J., 2017: Study on anti-corrosion performance of ginkgo branch and functional performance of wall materials. Nanjing Forestry University, China.

PEIXING WEI, JINXIANG CHEN*
SOUTHEAST UNIVERSITY
SCHOOL OF CIVIL ENGINEERING
NO.2 SOUTHEAST UNIVERSITY ROAD
NANJING
CHINA 210096
*Corresponding author: chenjpaper@yahoo.co.jp

YUE ZHANG, LIJUN PU
JIANGSU VOCATIONAL COLLEGE OF AGRICULTURE AND FORESTRY
SCHOOL OF LANDSCAPE ARCHITECTURE
NO 19 WENCHANG EAST ROAD
JURONG, JIANGSU
CHINA 212400