Engineering Structures and Technologies
ISSN 2029-882X / eISSN 2029-8838
2020 Volume 12 Issue 1: 25–31
https://doi.org/10.3846/est.2020.14046

BEHAVIOUR OF MINERAL WOOL SANDWICH PANELS UNDER BENDING LOAD AT ROOM AND ELEVATED TEMPERATURES

Ashkan SHOUSHTARIAN MOFRAD*, Hartmut PASTERNAK

Chair of Steel and Timber Structures, Brandenburg University of Technology, Cottbus, Germany

Received 31 August 2020; accepted 20 November 2020

Abstract. This paper presents a parametric study for the bending stiffness of mineral wool (MW) sandwich panels subjected to a bending load. The MW panels are commonly used as wall panels for industrial buildings. They provide excellent insulation in the case of fire. In this research, the performance of sandwich panels is investigated at both ambient and elevated temperatures. To reach that goal, a finite element (FE) model is developed to verify simulations with experimental results in normal conditions and fire case. The experimental investigation in the current paper is a part of STABFI project financed by Research Fund for Coal and Steel (RFCS). The numerical study is conducted using ABAQUS software. Employing simulations for analysis and design is an alternative to costly tests. However, in order to rely on numerical results, simulations must be verified with the experimental results. In this paper, after the verification of FE results, a parametric study is conducted to observe the effects of the panel thickness, length and width, as well as the facing thickness on the bending stiffness of MW sandwich panels at normal conditions. The results indicate that the panel thickness has the most significant effect on the bending stiffness of sandwich panels.

Keywords: composite sandwich panels, bending stiffness, load-bearing capacity, finite element models, elevated temperatures, mineral wool foams.

Introduction

Sandwich panels are typically composites of two thin steel sheets and a core of higher thickness and lower density. They are valued for their good thermal properties. Sandwich panels provide higher bending stiffness than steel sheets for smaller area densities (Naik et al., 2020; Hassinen et al., 2011). Since composite sandwich panels have shown excellent mechanical properties, their fabrication method and mechanical behaviours were extensively investigated by researchers (Wu et al., 2016; Liu et al., 2018; Moongkhamklang et al., 2010; Sun & Li, 2017; Wang et al., 2010; Yin et al., 2011; Zhang et al., 2012). Steel sheets of sandwich panels are usually designed to carry normal and flexural loads, while the core material is aimed to resist shear loads (Noor et al., 1996). They are commonly applied in industrial and commercial buildings to stabilize the entire structure. It is shown that by applying panels as stabilizing elements at normal conditions, substantial savings can be achieved compared to bracings (European Convention for Constructional Steelwork [ECCS], 2013). The main question that comes into the mind here is how they can perform at elevated temperatures. Therefore, in this paper, the performance of sandwich panels at room and elevated temperatures is investigated. There are different core materials for sandwich panels, such as mineral wool (MW) and polyisocyanurate (PIR) cores. The bending stiffness and resistance of PIR sandwich panels at room and elevated temperatures were discussed in (Mofrad et al., 2019). In this study, the sandwich panels consist of trapezoidal sheetings along with a PIR core. However, the experimental conditions were similar to the current research. It was observed that at room temperature, PIR cores had shown greater load-bearing capacity than MW cores. Stainless steel trapezoidal sheeting is used for applications with higher requirements regarding appearance or corrosion resistance, and they provide higher bending resistance than flat sheetings (Misiek et al., 2010). Vignesh Iyer et al. (Iyer et al., 2018) carried out a comparative study between the three-point and four-point bending of rigid glass epoxy sandwich composites. The effects of temperature on the mechanical properties and failure mechanisms of composite sandwich panel with Y-shaped cores under out-of-plane compression were studied by Junmeng Zhou et al. (Zhou et al., 2018). Srivaro et al. (Srivaro et al., 2015) studied the bending stiffness and strength of oil palm-

*Corresponding author. E-mail: *ashkan.shoushtarianmofrad@b-tu.de*

wood (OPW) core sandwich panels under bending loads. They used linear elastic beam theory to predict the bending performance of the panels. Results showed that the applied linear elastic beam theory adequately predicted the stiffness and bending strength of the sandwich beams. Joseph et al. (Joseph et al., 2018) carried out experimental and analytical research to find out and compare the flexural behaviour of concrete sandwich panels under two different loading conditions, including punching and four-point bending. The experimental study proved that type of loading conditions influence the flexural behaviour of the concrete sandwich panels.

In this study, the initial objective is to verify the numerical results with experimental results at ambient and elevated temperatures. For that reason, the load-displacement curves obtained from experiments and simulations are compared. Two main parameters, including bending stiffness and load-bearing capacity, are the criterion of verifications. The second aim of the research is to conduct a parametric study at room temperature. In this part, the influence of each parameter, for example, thickness, width and length of the panel on the bending stiffness of the whole specimen is studied. Consequently, it is found out from this study that which parameters have the most significant effect on the bending stiffness of sandwich panels.

1. Test program

During the experiments, the MW panels with thicknesses of 100 mm and 230 mm are selected. In the first step, the displacement is monotonically increased so that the parts of specimens come into contact, and then the temperature is increased using ceramic heating pads to the predefined temperatures, such as 200, 300, 450 and 600 °C. As shown in Figure 1, the vertical load is applied to the panel through four beams HEA120 (steel grade S355) from the upper side of the panel. The sandwich panel has an inner sheet thickness of 0.5 mm and an outer sheet thickness of 0.6 mm, and its width is 1200 mm (Cábová et al., 2019).

The steel sheet is heated using ceramic heating pads uniformly distributed on the inner sheet of the panel. The temperature of the inner panel face was controlled by coated thermocouples. Besides, the heating pads are covered by insulation materials to prevent wasting the heat. The average temperature of thermocouples is considered as the pre-defined temperature. After reaching that temperature, the machine maintained a constant temperature until the end of the test. When the temperature of the inner sheet reaches the pre-defined values, the mechanical loading of the panel starts. The panel was fixed to both plates of size 150×1200 mm by the aid of threaded rods. A circular rod of diameter 50 mm was welded to the lower plate. The rod was placed on a steel plate of size 300×1200 mm. This plate was equipped with an equal leg angle which did not allow any movement of the panel end during loading. Deflections of the panel, the applied force and the temperature of the inner sheet are recorded by transducers and thermocouples during the tests. Figure 2 indicates one specimen before and after the test. The main damage during the tests is due to the shear failure and cracking of core material (Cábová et al., 2019).

Figure 2. Bending tests of the sandwich panel:
a) before the test; b) after the collapse

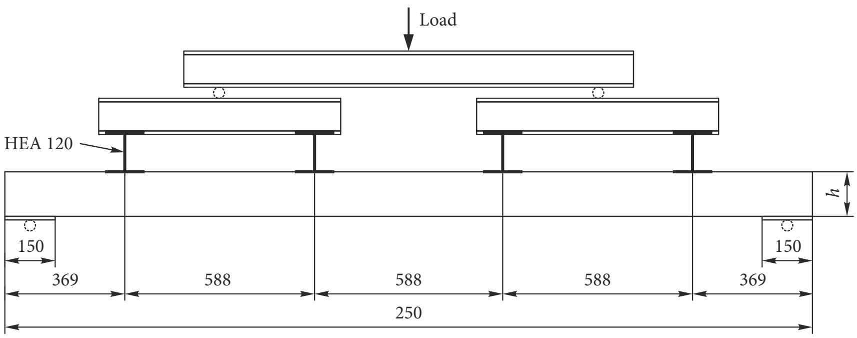


Figure 1. Test arrangement of MW core, dimensions in mm

2. FE modelling

To simulate tests, the ABAQUS program (Dassault Systemes, 2017) is employed. For this reason, first, "heat transfer" analysis to obtain the temperature distribution and then the "static general" analysis to generate load-displacement curvatures are conducted. The model considers the material nonlinearity and geometric nonlinearity. Furthermore, the contact behaviour is "Tie" between core and steel facings, as already shown in (Ozyurt, 2020). The core is modelled by solid elements, while shell elements are applied for the steel sheeting. The dimensions of the created models are according to the real dimensions of the specimens.

2.1. Material properties

Steel S280GD+Z, with a density of 7850 kg/m^3, is used as the material properties for facings, and thermal properties of steel are defined according to EN 1993-1-2 (European Committee for Standardisation, 2005). Moreover, the mechanical properties of steel facing at elevated temperatures are decreased based on EN 1993-1-2.

The mechanical properties of the MW core are received from the testing. Figure 3 illustrates the strain-stress curvatures for the MW core. All thermal properties for core materials such as thermal conductivity and specific heat are taken from the literature (Liu et al., 2017).

2.2. Boundary condition and loading

To simulate the boundary conditions precisely such as experiments, both ends of the internal face of the sandwich in a surface of 150×1200 mm is fixed in X, Y and Z directions. Mechanical loading is applied directly to the top sheet at four bands with an area of 120×1200 mm equal to the bottom surface of HEA 120 beams (Figure 4).

3. Verification of models

Nine models of MW sandwich panels for the finite element models are verified by the experimental results. The load-displacement curvatures from the experimental results and simulations are used for comparison in Figure 5 and Figure 6. To simplify simulations, damage criteria parameters and delamination effects are not applied in the models. Thus, the numerical simulation of this paper focuses mostly on the initial linear behaviour of the sandwich panel.

Although at 600 °C, the displacement in the tests is higher than the FE results, the experimental and numerical results show a good agreement in terms of the bending stiffness and load-bearing capacity, which are the two parameters studied in this research (Figure 5 and Figure 6). The difference can be due to the movement of boundary conditions caused by incomplete installation and the expansion at elevated temperatures. In order to control the experimental conditions, the tests were stopped at some intervals.

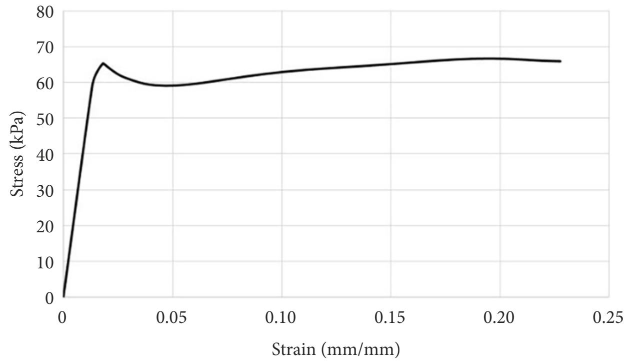
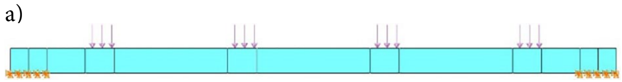


Figure 3. Stress-strain curvature for MW core

a)



b)

Figure 4. Finite element models of the sandwich panel: a) boundary conditions; b) failure mode

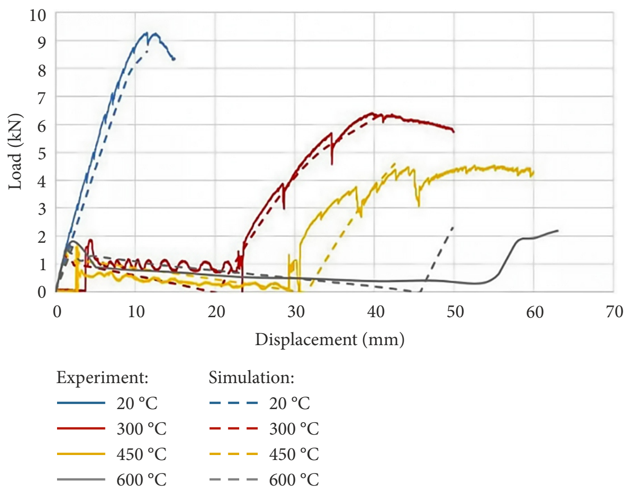


Figure 5. Load-displacement curves for MW panels 100 mm

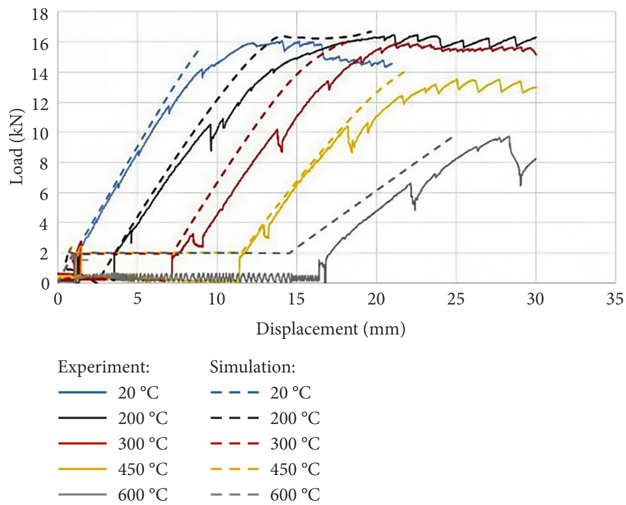


Figure 6. Load-displacement curves for MW panels 230 mm

These pauses during the tests are the cause of some jumping (sharp movement) in the experimental curvatures. When the thickness of the panel changes from 100 mm to 230 mm, the load-bearing capacity increases up to 78%; furthermore, the bending stiffness of the panel rises around 129%.

4. Parametric study

After numerical simulations are verified with the experimental results, the finite element model is applied for a parametric study focusing on the bending stiffness of sandwich panels at room temperature. The range of changing parameters is based on the sandwich panels dimensions produced in the industry.

In Table 1, the bending stiffness of MW sandwich panels achieved from FE models at normal condition is presented.

Where, D, B and L are the thickness, width and length of the sandwich panel, respectively. t_{F1} and t_{F2} are the nominal thickness of external and internal faces, and k_{FEM} and F_{max} show the bending stiffness and maximum load of sandwich panels, respectively.

In Figure 7, the load-displacement curves for MW sandwich panels with different length are compared. As expected, with the increase of the panel length, the bending stiffness is decreased. The effect of the panel width on the stiffness is demonstrated in Figure 8. There is a direct relation between stiffness and panel width, which changes in a range between 600 mm to 2500 mm.

One of the most crucial factors in the bending stiffness of sandwich panels is the panel height. Greater panel heights lead to a higher moment inertia for the panel section. According to the Eurocodes EN 14509:2013 (European Committee for Standardization, 2013), the moment inertia for the panel section has a significant influence on increasing the bending stiffness of sandwich panels (Figure 9). On the other hand, it has been observed that changing the face thickness in the ranges, as mentioned earlier, does not play a substantial role in the load-bearing capacity and bending stiffness of sandwich panels. Figure 10 indicates the load-displacement curves for panels with a different internal thickness of steel sheets.

4.1. Results and discussion

The thicker steel sheets have a higher bending stiffness than thinner ones; nevertheless, in comparison to other parameters, such growth is not significant. This fact can be interpreted through the dependence of the bending stiffness on cross-section geometry of sandwich panels. Indeed, the effect of facings thickness is slight compared to the whole sandwich panel section. Consequently, changing in facings thickness does not play any crucial role in the moment inertia of the entire panel. For instance, when the thickness of the internal sheet becomes 2.5 times thicker, the bending stiffness of the sandwich panel increases only 10%. Such changes for the load-bearing capacity is even less, around 4.6%.

Table 1. Bending stiffness of MW sandwich panels at room temperature

Case	D	B	L	t_{F1}	t_{F2}	k_{FEM}	F_{max}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN/mm)	(kN)
MW-tF2-0.4	100	1200	2500	0.6	0.4	0.81	8.11
MW-tF2-0.7	100	1200	2500	0.6	0.7	0.85	8.49
MW-tF2-1	100	1200	2500	0.6	1	0.87	8.49
MW-tF1-0.4	100	1200	2500	0.4	0.5	0.79	8.19
MW-tF1-0.7	100	1200	2500	0.7	0.5	0.84	8.19
MW-tF1-1	100	1200	2500	1	0.5	0.86	8.20
MW-D-90	90	1200	2500	0.6	0.5	0.74	7.73
MW-D-100	100	1200	2500	0.6	0.5	0.83	8.19
MW-D-160	160	1200	2500	0.6	0.5	1.31	13.49
MW-D-230	230	1200	2500	0.6	0.5	1.73	18.71
MW-D-300	300	1200	2500	0.6	0.5	2.06	23.51
MW-L-1875	100	1200	1875	0.6	0.5	1.3	8.49
MW-L-2500	100	1200	2500	0.6	0.5	0.83	8.19
MW-L-3125	100	1200	3125	0.6	0.5	0.64	8.48
MW-L-4500	100	1200	4500	0.6	0.5	0.34	7.34
MW-L-6000	100	1200	6000	0.6	0.5	0.2	7.12
MW-B-600	100	600	2500	0.6	0.5	0.41	4.06
MW-B-900	100	900	2500	0.6	0.5	0.62	6.13
MW-B-1200	100	1200	2500	0.6	0.5	0.83	8.19
MW-B-1500	100	1500	2500	0.6	0.5	1.04	10.54
MW-B-2500	100	2500	2500	0.6	0.5	1.5	15.2

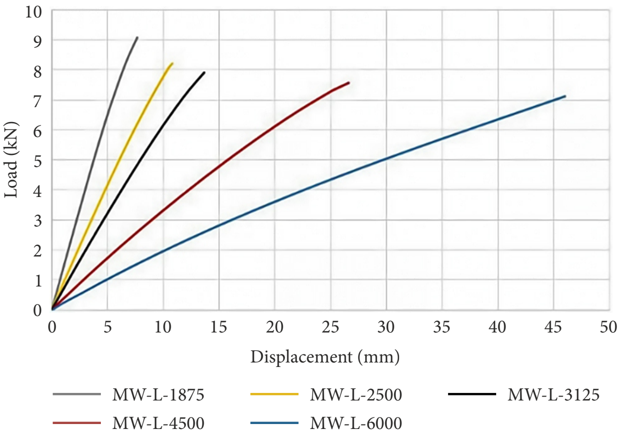


Figure 7. Load-displacement curves for MW panels with different lengths

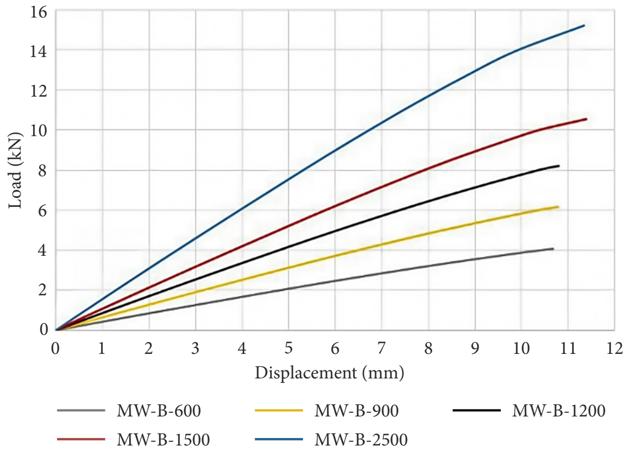


Figure 8. Load-displacement curves for MW panels with different widths

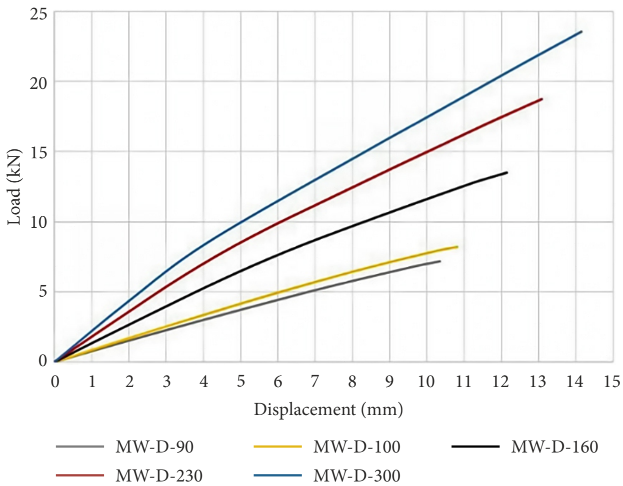


Figure 9. Load-displacement curves for MW panels with different heights

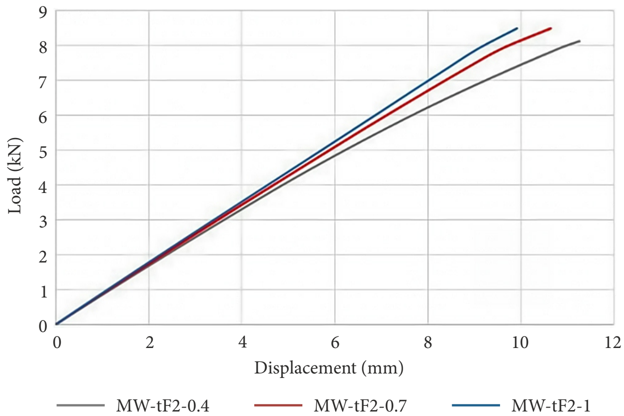


Figure 10. Load-displacement curves for MW panels with different thickness of internal faces

When it comes to the panel thickness, the direct effect of panel height on the resistance of specimens is noticeable. As an example, once the height of panel changes from 90 mm to 300 mm, the load-bearing capacity and stiffness of the panel increase from 7.73 kN to 23.51 kN and 0.74 kN/mm to 2.06 kN/mm.

On the contrary, the enlargement of the panel span reduces the load-bearing capacity and bending stiffness of sandwich panels. Nonetheless, the decrease in stiffness is higher than the load-bearing capacity. A larger panel span postpones the shear failure in the panels and increases the maximum deformation of panels.

Another investigated parameter in this research is the width of panels. According to the results, when the width rises from 600 mm to 2500 mm, both the stiffness and the maximum load increase approximately by 51%.

Conclusions

The focus of this paper has been first on the verification of simulation with experimental results for normal and fire cases and then the presentation of a parametric study at ambient temperatures. It has been observed that, at elevated temperatures, the performance of both bending stiffness and load-bearing capacity of sandwich panels deteriorate. The fundamental reason for such deterioration is the degradation of material properties at high temperatures. Moreover, other factors such as initial deformation, cracks and delamination caused by fire can worsen the performance of sandwich panels at elevated temperatures. The numerical results show that in the case of MW sandwich panel with a thickness of 100 mm, the bending stiffness and load-bearing capacity reduce around 69% and 73% respectively as soon as the temperature rises to 600 °C. When the thickness of the panel is 230 mm, these decreases for 600 °C are 36% and 43% respectively. It can be explained by the fact that for the thicker panel, at the same time and temperature condition, the heat penetrates in a smaller volume of the core material.

The parametric study has proved that changing the panel width, length and height, as well as the thickness of steel sheets, affects the value of the bending stiffness and maximum load-bearing capacity. However, these effects can be different. For example, it was revealed that changing in the thickness of the internal and external facings have the least effect on the panel behaviour. On the contrary, other parameters such as the thickness, span and width of the panel have a more significant impact on the bending stiffness. At elevated temperatures, the panels with a thickness of 230 mm showed higher fire resistance than the panels with a thickness of 100 mm. Consequently, in the conditions that there is a possibility for longer fire duration, the thicker panels are recommended. As future work, a parametric study at elevated temperatures will be conducted.

Acknowledgements

The authors would like to express great thanks to the colleagues from the Department of Steel and Timber Structures, Czech Technical University in Prague who carried out the bendings tests in the laboratory of Faculty of Civil Engineering. We would also appreciate the efforts of other partners of "Steel cladding systems for stabilization of steel buildings in fire" (STABFI) project who contributed to the testing phase of the research.

Funding

The research is conducted by the financial support of the German Academic Exchange Service (DAAD). The experimental tests have received funding from the Research Fund for Coal and Steel under grant agreement No 751583.

Author contributions

Ashkan Shoushtarian Mofrad performed writing – original draft, methodology, validation, formal analysis, visualization and conceptualization.

Hartmut Pasternak performed revision and supervision.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Cábová, K., Arha, T., Lišková, N., & Wald, F. (2019). Experimental investigation of stiffness in bending of sandwich panels at elevated temperatures. In *6th International Conference "Applications of Structural Fire Engineering"* (*ASFE'19*) (pp. 1–6). Nanyang Technological University.

Dassault Systemes. (2017). *ABAQUS*. https://www.3ds.com/support/hardware-and-software/simulia-system-information/abaqus-2017/abaqus-2017-graphics-devices/

European Committee for Standardisation. (2005). *Eurocode 3: Design of steel structures – Part 1–2: General rules – Structural fire design* (EN 1993-1-2).

European Committee for Standardization. (2013). *Self-supporting double skin metal faced insulating panels – Factory made products – Specifications* (EN 14509:2013). https://standards.iteh.ai/catalog/standards/cen/b1a522e8-6be2-4edb-97ea-64ea66c5134f/en-14509-2013

European Convention for Constructional Steelwork. (2013). *European recommendations on the stabilization of steel structures by sandwich panels* (CIB Publication 379). http://site.cibworld.nl/dl/publications/pub_379.pdf

Hassinen, P., Misiek, T., & Naujoks, B. (2011). Cladding systems for sandwich panels. Refurbishment of walls and roofs. In *Conference: Eurosteel 2011* (pp. 2199–2204). Budapest.

Iyer, S. V., Chatterjee, R., Ramya, M., Suresh, E., & Padmanabhan, K. (2018). A comparative study of the three point and four point bending behaviour of rigid foam core glass/epoxy face sheet sandwich composites. *Materials Today: Proceedings*, *5*(5), 12083–12090. https://doi.org/10.1016/j.matpr.2018.02.184

Joseph, J. D. R., Prabakar, J., & Alagusundaramoorthy, P. (2018). Flexural behavior of precast concrete sandwich panels under different loading conditions such as punching and bending. *Alexandria Engineering Journal*, *57*(1), 309–320. https://doi.org/10.1016/j.aej.2016.11.016

Liu, F., Fu, F., Wang, Y., & Liu, Q. (2017). Fire performance of non-load-bearing light-gauge slotted steel stud walls. *Journal of Constructional Steel Research*, *137*, 228–241. https://doi.org/10.1016/j.jcsr.2017.06.034

Liu, J., Liu, J., Mei, J., & Huang, W. (2018). Investigation on manufacturing and mechanical behavior of all-composite sandwich structure with Y-shaped cores. *Composites Science and Technology*, *159*, 87–102. https://doi.org/10.1016/j.compscitech.2018.01.026

Misiek, T., Krüger, H., Ummenhofer, T., & Kathage, K. (2010). Buckling of stiffeners for stainless steel trapezoidal sheeting. *Steel Construction*, *3*(4), 225–230. https://doi.org/10.1002/stco.201010029

Mofrad, A. S., Shlychkova, D., Ciupack, Y., & Pasternak, H. (2019). Evaluating bending stiffness and resistance of sandwich panels at elevated temperatures. In *The Proceedings of the 13th International Conference "Modern Building Materials, Structures and Techniques"* (*MBMST 2019*) (pp. 463–469). Vilnius Gediminas Technical University. https://doi.org/10.3846/mbmst.2019.032

Moongkhamklang, P., Deshpande, V. S., & Wadley, H. N. G. (2010). The compressive and shear response of titanium matrix composite lattice structures. *Acta Materialia*, *58*(8), 2822–2835. https://doi.org/10.1016/j.actamat.2010.01.004

Naik, R. K., Panda, S. K., & Racherla, V. (2020). A new method for joining metal and polymer sheets in sandwich panels for highly improved interface strength. *Composite Structures*, *251*, 112661. https://doi.org/10.1016/j.compstruct.2020.112661

Noor, A. K., Burton, W. S., & Bert, C. W. (1996). Computational models for sandwich panels and shells. *Applied Mechanics Reviews*, *49*(3), 155–199. https://doi.org/10.1115/1.3101923

Ozyurt, E. (2020). Finite element study on axially loaded reinforced Square Hollow Section T-joints at elevated temperatures. *Thin-Walled Structures*, *148*, 106582. https://doi.org/10.1016/j.tws.2019.106582

Srivaro, S., Matan, N., & Lam, F. (2015). Stiffness and strength of oil palm wood core sandwich panel under center point bending. *Materials & Design*, *84*, 154–162. https://doi.org/10.1016/j.matdes.2015.06.097

Sun, Y., & Li, Y. (2017). Prediction and experiment on the compressive property of the sandwich structure with a chevron carbon-fibre-reinforced composite folded core. *Composites Science and Technology*, *150*, 95–101. https://doi.org/10.1016/j.compscitech.2017.06.029

Wang, B., Wu, L., Ma, L., Sun, Y., & Du, S. (2010). Mechanical behavior of the sandwich structures with carbon fiber-reinforced pyramidal lattice truss core. *Materials* & *Design* (*1980–2015*), *31*(5), 2659–2663. https://doi.org/10.1016/j.matdes.2009.11.061

Wu, Q., Ma, L., Wu, L., & Xiong, J. (2016). A novel strengthening method for carbon fiber composite lattice truss structures. *Composite Structures*, *153*, 585–592. https://doi.org/10.1016/j.compstruct.2016.06.060

Yin, S., Wu, L., Ma, L., & Nutt, S. (2011). Pyramidal lattice sandwich structures with hollow composite trusses. *Composite Structures*, *93*(12), 3104–3111. https://doi.org/10.1016/j.compstruct.2011.06.025

Zhang, G., Ma, L., Wang, B., & Wu, L. (2012). Mechanical behaviour of CFRP sandwich structures with tetrahedral lattice truss cores. *Composites Part B: Engineering*, *43*(2), 471–476. https://doi.org/10.1016/j.compositesb.2011.11.017

Zhou, J., Wang, Y., Liu, J., Liu, J., Mei, J., Huang, W., & Tang, Y. (2018). Temperature effects on the compressive properties and failure mechanisms of composite sandwich panel with Y-shaped cores. *Composites Part A: Applied Science and Manufacturing*, *114*, 72–85. https://doi.org/10.1016/j.compositesa.2018.08.003