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# MECHANICAL PROPERTIES OF SANDWICH COMPOSITES USED FOR AEROFOIL SHELL STRUCTURES OF WIND TURBINE BLADE

**Fatih BALIKOĞLU[1], Tayfur Kerem DEMİRCİOĞLU[1*], Ali IŞIKTAŞ[2]**

[1]Engineering Faculty, Mechanical Engineering Department, Balıkesir University, Balıkesir, Turkey

[2]Vocational School, Tekirdağ Namık Kemal University, Hayrabolu, Tekirdağ, Turkey

## ABSTRACT

The grid-scored foams contribute significantly to the overall mechanical properties of the sandwich structures, such as aerofoil shell structure of wind turbine blades which are subjected to different loads under operating conditions. The goal of the present paper is to examine the four-point bending, flatwise and edgewise compression and in-plane shear behaviour of sandwich panels composed of composite face sheets of E-glass/ bisphenol-A epoxy resin and plain and grid-scored PVC foams. The four-point bending failure load of the grid-scored foamed sandwich beams increased by 28.1% compared to the plain foamed ones. The flatwise compression strength of samples with grid-scored foam increased by 546% compared to plain foamed samples. The resin grids contributed to an increase in the flat-wise compression stress inducing the core crushing. Under the edgewise compression load, using the grid-scored foam increased the maximum load values by only about 2.9% relative to the plain foam. The reason for this small difference can be addressed as the facings are more effective in carrying the edgewise loadings. With the use of the grid-scored foam, an increase of 38.2% was obtained in-plane shear strength compared to plain foamed sandwich beams. The resin grids improved bonding between the facings and PVC foam.

**Keywords:** Grid-scored foam, bending, shear, compression



## 1. INTRODUCTION

Wind energy is a clean and renewable source of energy that can help to minimize consumption of fossil fuels. Wind power is expected to play an enormously significant part in the future energy sector (Brøndsted, Lilholt, & Lystrup, 2005; Herbert, Iniyan, Sreevalsan, & Rajapandian, 2007; Sesto & Casale, 1998; Yang et al., 2013). The rotor blade is the most critical and the highest cost element of wind turbine systems (Kong, Bang, & Sugiyama, 2005; Mishnaevsky et al., 2017). The blade is a load-bearing aerodynamic structure comprising of suction and pressure aerodynamic shells and shear webs as seen in Fig. 1. Aerofoils and shear webs are fabricated individually and then assembled to the overall blade applying adhesive materials. In addition to the exterior geometry and the concept of aerodynamic efficiency, the aerofoils are also the load-bearing structure of the blade. The girder (spar cap) in the aerodynamic shells is the main load-bearing section that can be pre-fabricated as a component

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of the aerofoils. The role of shear webs is restricted to the support of aerofoils (aeroshells) and the transfer of shear forces (Yang et al., 2013) (see Fig. 1).

With a combination of laminated and sandwich composites, modern wind turbine blades are built using polymer matrix composites. The aerofoils and the internal shear webs are generally manufactured from lightweight sandwich composites, whereas the leading/trailing edges and girders on both the downwind and upwind sides are stiff and thick laminated composites. Polymer matrix composites are used due to their high specific strength and stiffness properties. The components for these materials can be categorized into three groups: resin, reinforcement material, and the core material for sandwich composites. Thermoset resins such as polyester and epoxy are often used as matrix for the blades. Glass fiber material is the main reinforcement material in the today's design, but carbon fiber materials are being used increasingly for large-scale turbine blades. A number of synthetic foams and balsa woods are used as core materials in sandwich concepts.

Currently, resin infusion technology (VARTM) is the most popular method for the production of turbine blades, particularly longer blades. This method is characterized by the fact that only one side of the mold is solid, while the other is flexible. In addition, the vacuum applied is used as the driving force for the transfer of the resin to the reinforcement. By using VARTM technique, the aerofoils and internal shear webs can be manufactured in single operation, respectively, that are then bonded together (Brøndsted et al., 2005; Laustsen, Lund, Kühlmeier, & Thomsen, 2014a; Mishnaevsky et al., 2017; Sørensen, Holmes, Brøndsted, & Branner, 2010; Yang et al., 2013).



Sandwich composites play a major role in advanced wind turbines, accounting for 10 to 15% of the total blade weight and about 20% of the blade cost. These structures are composed of thin, stiffer and stronger laminated composite face sheets, with a relatively thicker, softer and lighter core material. The facings and the core are adhered to ensure the force transfer between the components. Sandwich composites are built to carry transverse shear and bending loads, the basic design of which is that the facings bear mainly in-plane normal and also shear stresses while the core only carries shear stresses across the thickness (Thomsen, 2009).

Aerofoils are mainly constructed of sandwich composites due to their high specific flexural strength and stiffness properties. The production of aerofoils in wind turbine blades generally requires that composite sandwich panels should take a single or double curved geometric shape. This means that the face sheets and the core material in the manufacturing procedure of sandwich structures must be geometrically molded. For face sheets made from thin glass or carbon fiber fabrics, this does not cause problems, but the core materials (foam and balsa wood materials) are usually produced in thick sheets that cannot be directly attached to the blade geometry. The cores are cut into small blocks to make production easier, and tied to a thin carrier fabric, which can be draped. This core type is referred to as 'grid-scored'. The resin moves through these scores during the VARTM process, thereby forming a resin grid into the

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foam (see Fig. 2). This particular core configuration, including face sheets, is called a grid-scored sandwich composite (Laustsen et al., 2014a).

The scope of this paper is the grid-scored foamed sandwich composites, which are referred to as sub-structural element of the aerofoils of the wind turbine blade. To the best of the author's knowledge, very limited research has been conducted on the grid-scored foam cored sandwich panels (Fathi, Wolff-Fabris, Altstädt, & Gätzi, 2013; Laustsen et al., 2014a; Laustsen, Lund, Kühlmeier, & Thomsen, 2014b; Laustsen, Lund, Thomsen, & Kühlmeier, 2013; Laustsen, Thomsen, Lund, & Kühlmeier, 2012; Trofka, 2008). Trofka (Trofka, 2008) and Fathi et al. (Fathi et al., 2013) reported that the rigid resin grids had a significant influence on the shear properties of sandwich beams. The flexural and shear strength and the modulus increased while the shear strain at failure decreased. Laustsen, S. et al. (Laustsen et al., 2014b) conducted an elaborated research on a particular grid-scored foam cored sandwich panel subjected to multi-axial quasi-static loads. The experimental findings and numerical predictions indicated that maximum principal strain criterion applied for the onset of fracture in the resin grid within the foam core would be practical for engineering designs. The authors suggested that consideration should be given to compression-compression-bending loads when using grid-scored foamed panels in the aerofoils. For this loading case, progressive failure stages such as delamination and subsequent wrinkling in the face sheets were observed due to the initiation of cracks in the transverse resin slits of the grid-scored foam (Laustsen et al., 2014a).

The aim of this study is to obtain a detailed experimental characterization of the grid-scored foam cored sandwich composites tested under bending, compression, and shear loadings. Comparing their loads at failure and damage modes with those of plain foamed sandwich panels, the advantages of using grid-scored foam under different loadings are presented. Therefore, our experimental research is expected to contribute to the development of knowledge in the field of understanding the mechanical properties of aerofoil sandwich structures and the design of such components.



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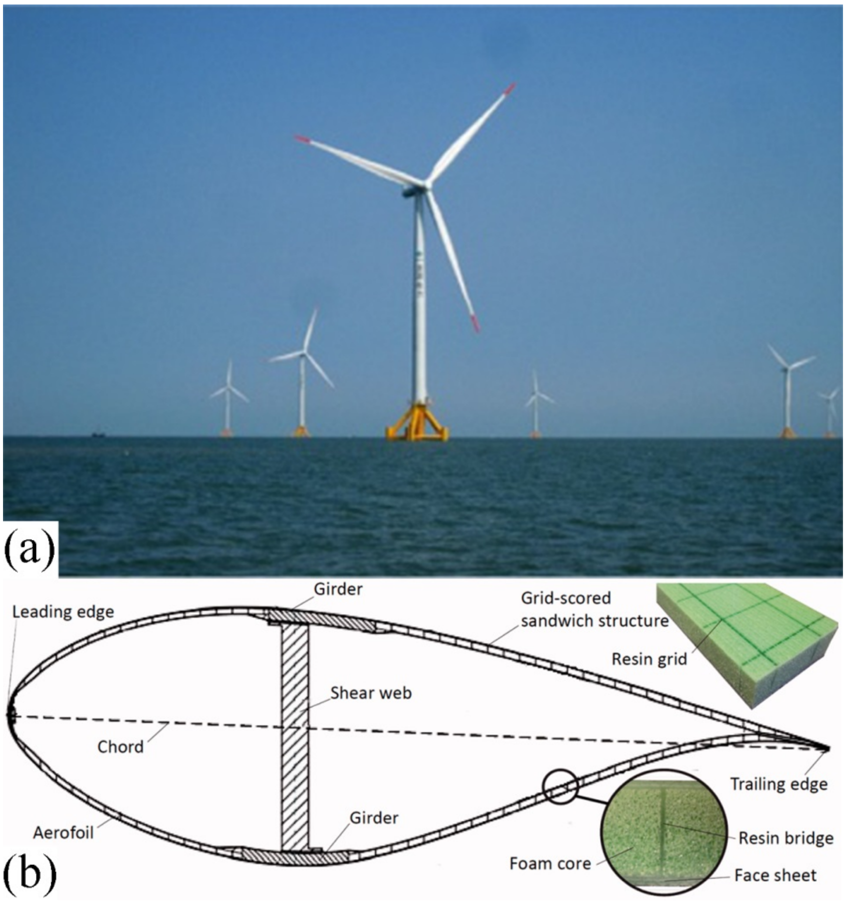




**Figure 1:** The cross-section of wind turbine blades (Laustsen et al., 2014b; Pemberton, Summerscales, & Graham-Jones, 2018).

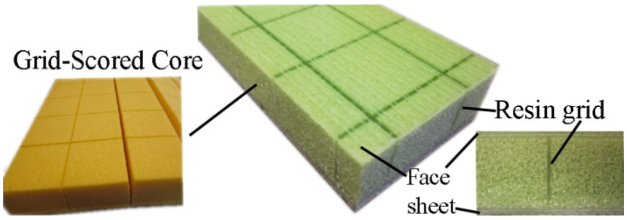


**Figure 2:** The grid-scored foam cored sandwich composite (Laustsen et al., 2014a).

## 2. MATERIAL AND METHODS

### 2.1. Materials

Sandwich panels consisted of E-glass fabric/bisphenol-A epoxy resin face sheets and PVC foam. Two types of PVC foam having a density of 80 kg/m$^3$ was used as core materials: plain and grid-scored foams with a thickness of 25 mm (*Datasheet for Airex C70 PVC Foam*, 2011). The grid-scored PVC foam core comprised of 30×30 mm$^2$ blocks with a 1.2 mm thickness slit in between and a scrim cloth on the bottom side. E-glass non-crimp biaxial $[0/90]_{2S}$ fabrics with an 850 gr/m$^2$ areal weight were used with bisphenol-A epoxy resin for upper and bottom face sheets (Metyx Composites Corporation, Istanbul/Turkey). The mechanical characteristics of face sheets of the sandwich panel were given in our previous study (F Balıkoğlu et al., 2020).

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## 2.2. Manufacturing of sandwich panels

Sandwich panels were produced with applying resin infusion method (VARTM) with bisphenol-A epoxy resin ("Data sheet for cured Polives 702 Bisphenol-A epoxy Vinylester Resin,") (Polives 702- Bisphenol-A epoxy) (Fig. 3). Sandwich panels were kept at room temperature for 2-3 weeks before being cut to sample sizes.

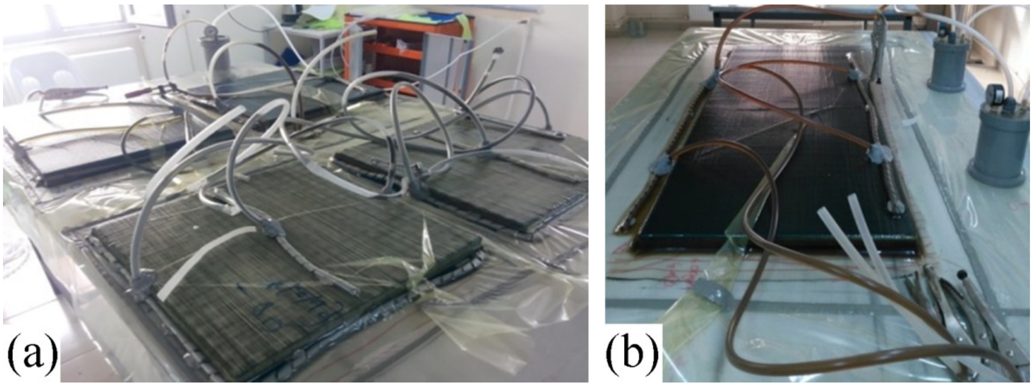


**Figure 3:** Vacuum assisted resin transfer method (a) Grid-scored foam (GSF), (b) Plain foam (PF) core sandwich panels.

## 2.3. Test set-up



Four-point bending tests of plain (PF) and grid-scored (GSF) foam cored samples were carried out according to the ASTM C393/C393M-16 standard (ASTM, 2016) (Fig. 4a). The support span was equal to 450 mm. The bending tests were performed with a constant crosshead speed of 6 mm/min. During the 4PB tests, two longitudinal strain gauges were attached to the upper and lower facings at the mid-span to determine the relation between applying loads and face sheet strain. Flatwise compression tests were carried out in accordance with the ASTM C365/C365M-05 with a crosshead speed of 0.5 mm/min (ASTM, 2005) (Fig. 4b). The sample dimensions are 80 (length) × 80 (width) × 30 mm (thickness) for the flatwise compression tests. Edgewise compression tests were carried out according to ASTM C364/C364M-7 with a crosshead speed of 0.5 mm/min (ASTM, 2012b) (Fig. 4c). The sample dimensions are 120 mm (length) × 80 mm (width) × 30 mm (thickness) for the edge-wise compression tests. Shear properties of sandwich composites were determined according to the ASTM C273/2733M-11 standard (ASTM, 2012a) (Fig. 4d). In-plane shear tests were conducted at a head displacement rate of 0.5 mm/min. The sample dimensions are 360 mm (length) × 60 mm (width) × 30 mm (thickness) for in-plane shear tests. The tests for each sample were performed at least three times. Samples containing plain foam are named "PF" and those containing grid-scored foam are named "GSF" in the text.

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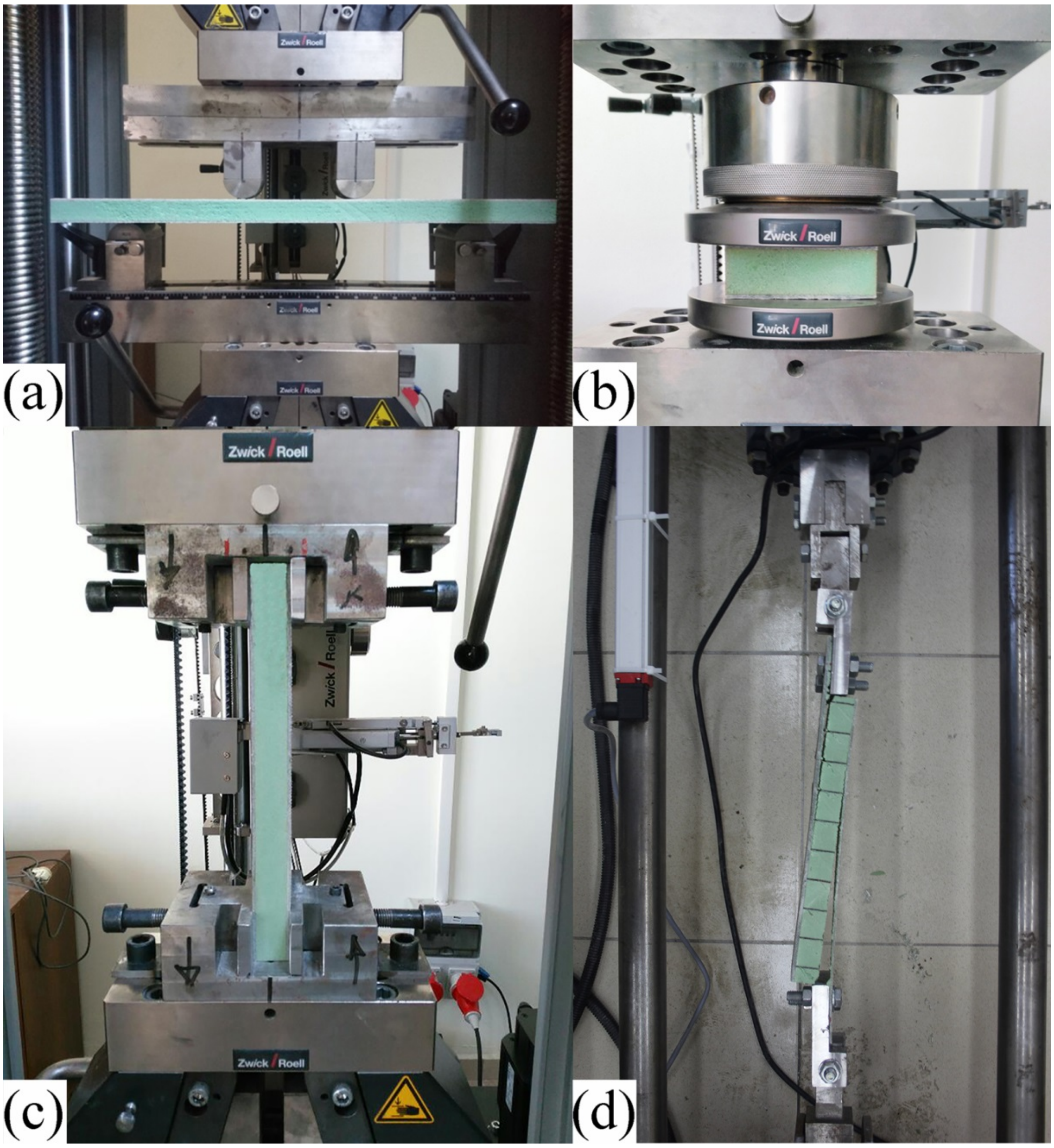


**Figure 4:** Test set-ups**: (**a) Four-point bending, (b) flatwise compression, (c) edge-wise compression, (d) in-plane shear test set-ups.

## 3. RESULTS AND DISCUSSION

### 3.1. Four-point bending test results

Figure 5 presents the load-displacement curves of the PF and GSF sandwich beams tested under four-point bending (4PB) loading. It can be observed from the curves that the GSF samples were stiffer than those of the PF samples; the rigid-resin cuts increased both the flexural and the shear stiffness of the sandwich composites. The bending failure load of the GSF sample was 28.1% higher than that of the PF sample. In contrast to the increase in strength, the deflection at failure load was decreased in all GSF sample compared to the PF sample. This can be due to the limited plastic deformation capability of the resin-filled cuts under shear stresses. The PF



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and GSF samples were collapsed due to core shear failure (see Fig. 6). However there was a clear difference in the failure development process for the PF samples; which was characterized by a sudden and catastrophic nature without providing initial warning, whereas irregular, weak sounds of shear cracks of transverse channels could be heard in the maximum shear region of the GSF samples (see Fig. 6). The load and mid-span longitudinal strain curves of the specimens are given in Figure 7. The experimental results revealed that tension and compression strains increased linearly at the initial loading points. In both PF and GSF specimens, however, a higher tensile strain was measured. This is due to the fact that tension modulus of face sheet material is lower than the compression. It was also observed that the tensile and compression strain values measured in the GSF samples were higher.

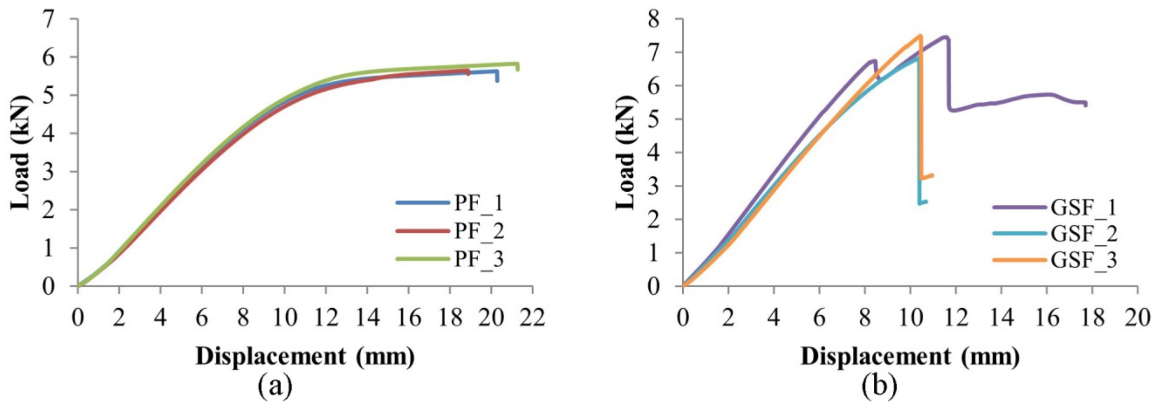




**Figure 5:** Load-displacement graphs of the PF and GSF samples tested under 4PB load, (a) PF samples, (b) GSF samples.

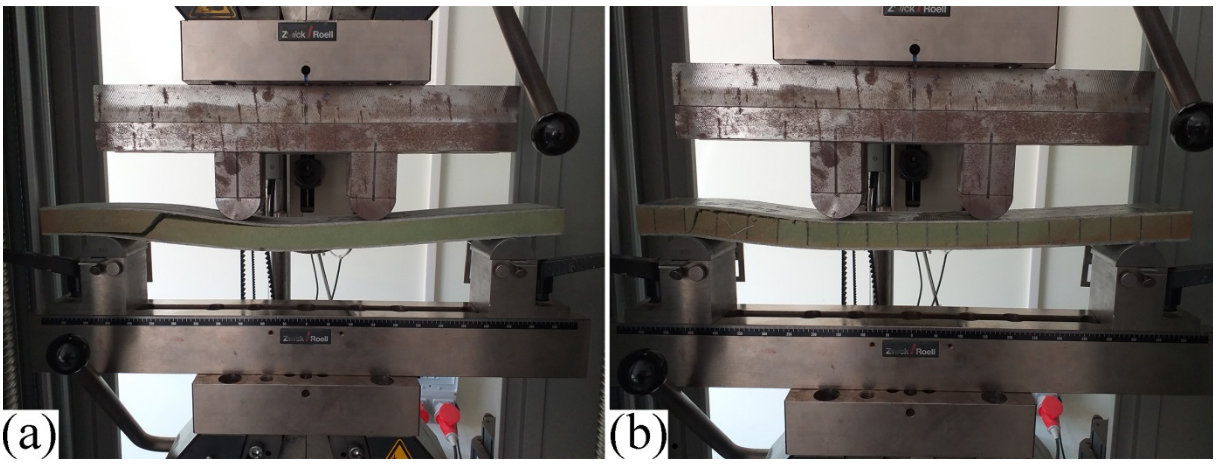


**Figure 6:** Damage photos of the PF (a) and GSF (b) samples tested under 4PB load.

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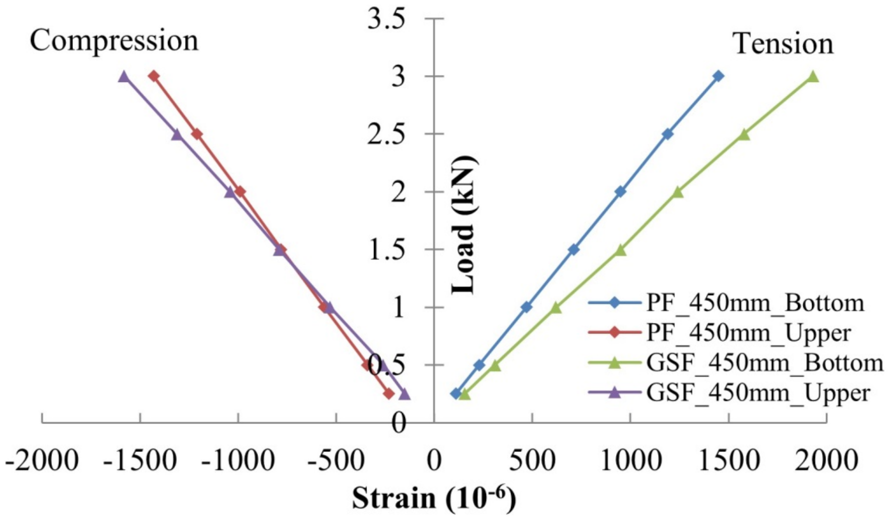


**Figure 7:** Load-strain responses of the PF and GSF sandwich samples tested under 4PB load.

### 3.2. Shear test results

Figure 8 shows the load-displacement graphs of the PF and GSF sandwich composites tested under in-plane shear load. The average shear load of the GSF sample was determined as 37304 N and for the PF sample as 28096 N. With the use of the grid-scored foam, an increase of 38.2% was obtained in-plane shear strength compared to PF sandwich beams. The deflection value of the PF sample corresponding to the maximum load was measured as 4.514 mm and 7.799 mm in the GSF sample. One can observed from damage photos that more foam remains in the separated skins in the GSF samples as seen in Fig. 9. This indicates that there is more bonding between grid-scored foam and the face sheets. These results showed that the rigid resin grids caused an increase in the shear strength values of the GSF sandwich panels.



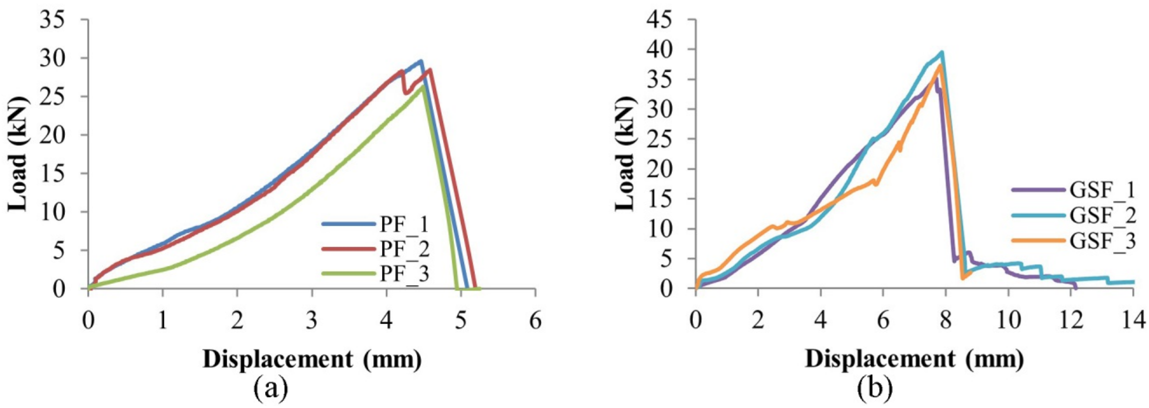


**Figure 8:** Load-displacement graphs of the PF and GSF sandwich samples tested under shear load, (a) PF samples, (b) GSF samples.

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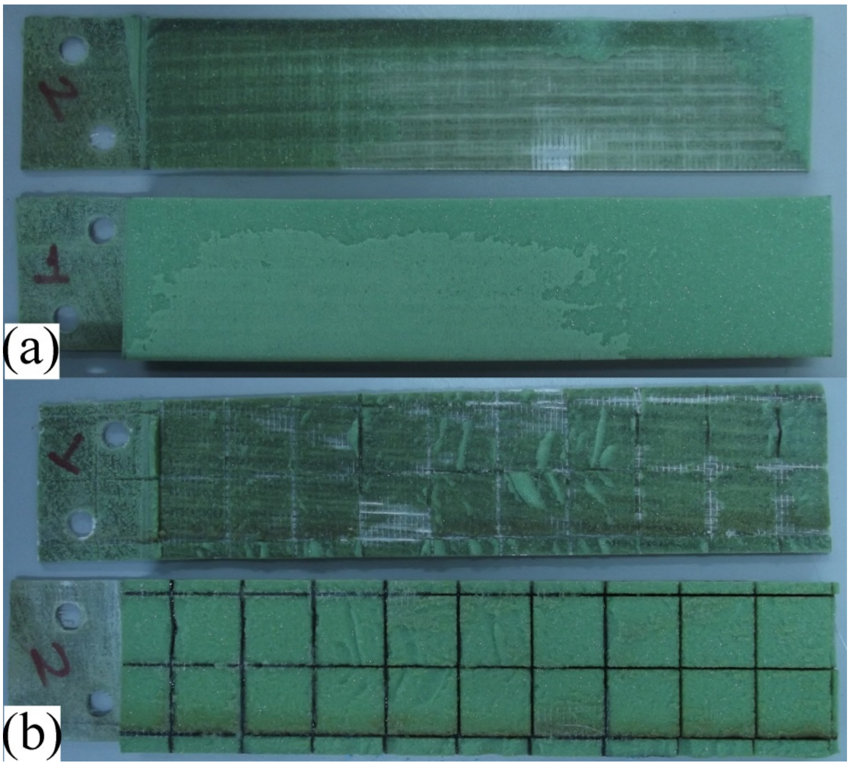


**Figure 9:** Damage photos of PF sample (a) and GSF samples (b) tested under shear test.



### 3.3. Edge-wise compression test results

Figure 10 shows the load-displacement graphs of the PF and GSF sandwich samples tested under edgewise compression loading. The PF samples were damaged with a load of 52584 N and a displacement of 2.909 mm, while the GSF sample was damaged at 60364 N and 3.098 mm. In this loading condition, the difference between the damage loads is not much, since the upper and bottom face sheets act. Face sheet compression failure was observed for the PF and GSF samples.

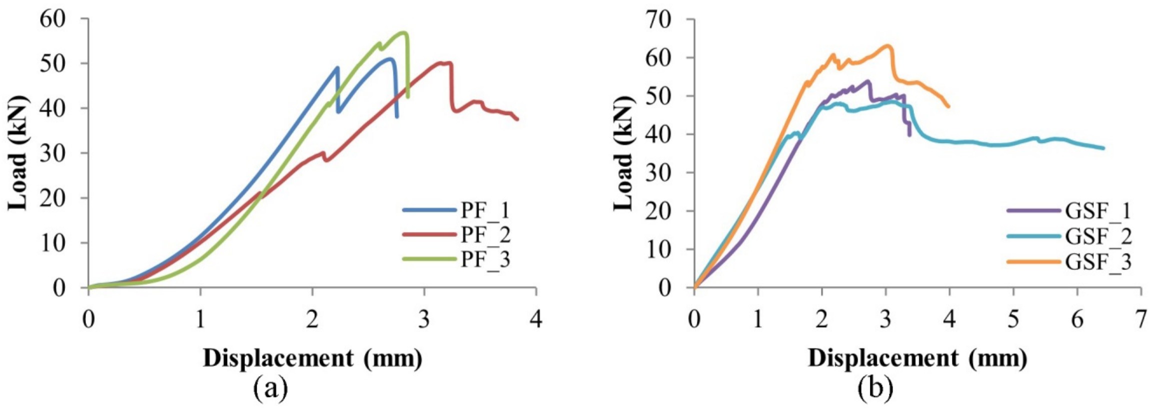


**Figure 10:** Load-displacement graphs of the PF and GSF samples tested under edge-wise compression test, (a) PF samples, (b) GSF samples.

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### 3.4. Flatwise compression test results

Figure 11 shows the load-displacement graphs of the PF and GSF sandwich composites tested under flatwise compression test. Load–displacement curves of the GSF samples showed non-linear manner up to the peak load. After that, load decreased smoothly with increasing displacement. The reason inducing this load drop is the crushing of the resin grids under the compression force. The rigid resin grids suffered from permanent buckling damage. (Fig.12). For the PF sample, the core carried the compression force alone and when the compression force reached its peak, the curve showed a large plateau region (Balıkoğlu, Demircioğlu, Yıldız, Arslan, & Ataş, 2020). However, the compression loads of the GSF samples are primarily carried by the resin grids. The PF samples were damaged with a load of 7191 N and a displacement of 0.615 mm, while the GSF sample was damaged at 47619 N and 3.189 mm. The flatwise compression strength of the GSF sample increased by 546% compared to those of the PF sample. It has been deduced from the flatwise compression results that the rigid resin grids significantly enhanced the foam crushing resistance against the compression load.

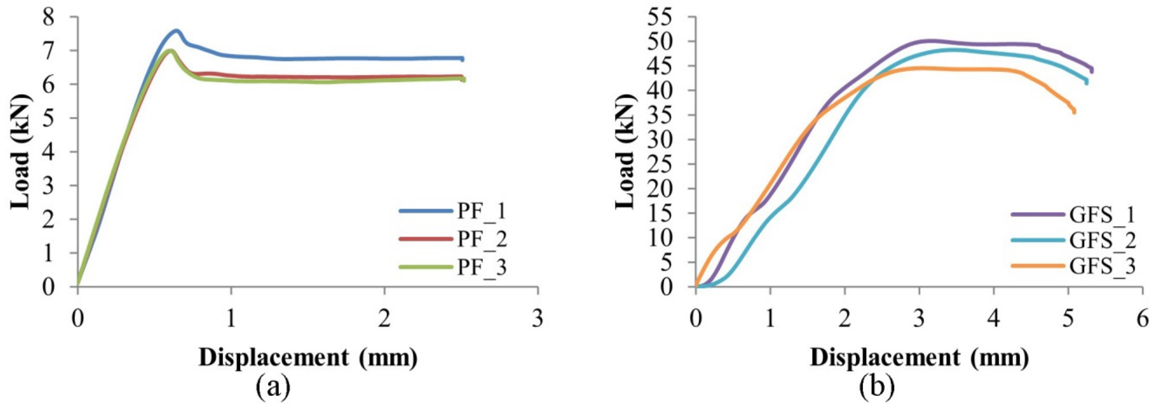


**Figure 11:** Load-displacement graphs of the PF and GSF samples tested under flatwise compression test, (a) PF samples, (b) GSF samples.

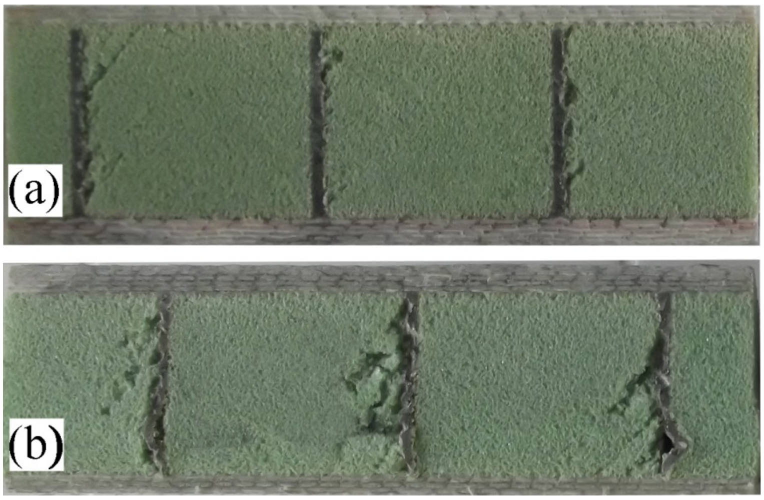


**Figure 12:** Damage photo of the GSF sandwich sample tested under flatwise compression test, a) before test, b) after test.



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## 4. CONCLUSIONS

In this study, the four-point bending, flatwise; edgewise compression and in-plane shear behavior of plain and grid-scored foam core sandwich composites were investigated. The failure load of the grid-scored foamed sandwich beams tested under 4PB test increased by 28.1% compared to the plain foam core ones. The flatwise compression strength of samples containing grid-scored foam increased by 546% compared to those containing rigid PVC foam. This result showed that the rigid resin grids significantly enhanced the foam crushing resistance against the compression load. Under the edgewise compression load, the grid-scored structure increased the maximum load values by only about 2.9% relative to the rigid foam structure. The difference is not as much as the flatwise compression test results. The reason for this small difference can be addressed as the face sheets are more effective in carrying the edgewise loadings. With the use of the grid-scored foam, an increase of 38.2% was obtained in-plane shear strength compared to plain foamed sandwich panels. It was concluded that the resin filled channels improved bonding between the face sheets and foam core.

## REFERENCES

ASTM. (2005). ASTM C365 / C365M-05, Standard Test Method for Flatwise Compressive Properties of Sandwich Cores. West Conshohocken, PA: ASTM International.

ASTM. (2012a). ASTM C273/C273M – 11, Standard Test Method for Shear Properties of Sandwich Core Materials. West Conshohocken, Pennsylvania 19428-2959, United States: ASTM International.

ASTM. (2012b). ASTM C364/C364M – 07, Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions. West Conshohocken, Pennsylvania 19428-2959, United States: ASTM International.

ASTM. (2016). ASTM C393 / C393M-16, Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure  West Conshohocken, PA: ASTM International.

Balıkoğlu, F., Arslan, N., Demircioğlu, T., İnal, O., İren, M., & Ataş, A. (2020). Improving four-point bending performance of marine composite sandwich beams by core modification. *Journal of Composite Materials, 54*(8), 1049-1066.

Balıkoğlu, F., Demircioğlu, T. K., Yıldız, M., Arslan, N., & Ataş, A. (2020). Mechanical performance of marine sandwich composites subjected to flatwise compression and flexural loading: Effect of resin pins. *Journal of Sandwich Structures & Materials, 22*(6), 2030-2048.

Brøndsted, P., Lilholt, H., & Lystrup, A. (2005). Composite materials for wind power turbine blades. *Annu. Rev. Mater. Res., 35*, 505-538.

Data sheet for cured Polives 702 Bisphenol-A epoxy Vinylester Resin. Retrieved 26.11.2018, 2018, from http://www.plasto.com.tr/files/upload/files/POLIVES%20702.pdf

*Datasheet for Airex C70 PVC Foam*. (2011).



Received 1 March 2021; Received in revised form 10 March 2021; Accepted 15 March 2021;
Available online 28 March 2021;
doi: 10.46291/ICONTECHvol5iss1pp26-37

Fathi, A., Wolff-Fabris, F., Altstädt, V., & Gätzi, R. (2013). An investigation on the flexural properties of balsa and polymer foam core sandwich structures: Influence of core type and contour finishing options. *Journal of Sandwich Structures & Materials, 15*(5), 487-508.

Herbert, G. J., Iniyan, S., Sreevalsan, E., & Rajapandian, S. (2007). A review of wind energy technologies. *Renewable and sustainable energy Reviews, 11*(6), 1117-1145.

Kong, C., Bang, J., & Sugiyama, Y. (2005). Structural investigation of composite wind turbine blade considering various load cases and fatigue life. *Energy, 30*(11-12), 2101-2114.

Laustsen, S., Lund, E., Kühlmeier, L., & Thomsen, O. T. (2014a). Development of a High-fidelity Experimental Substructure Test Rig for Grid-scored Sandwich Panels in Wind Turbine Blades. *Strain, 50*(2), 111-131.

Laustsen, S., Lund, E., Kühlmeier, L., & Thomsen, O. T. (2014b). Failure behaviour of grid-scored foam cored composite sandwich panels for wind turbine blades subjected to realistic multiaxial loading conditions. *Journal of Sandwich Structures & Materials, 16*(5), 481-510.

Laustsen, S., Lund, E., Thomsen, O. T., & Kühlmeier, L. (2013). *Experimental characterisation of the progresive failure of grid-scored sandwich structures in wind turbine blades.* Paper presented at the 19th International Conference on Composite Materials, ICCM 2013.

Laustsen, S., Thomsen, O. T., Lund, E., & Kühlmeier, L. (2012). *Analysis of Grid-Scored Sandwich Structures of Different Curvatures and Grid Sizes For Wind Turbine Blades.* Paper presented at the ECCM15-15Th European Conference On Composite Materials, Venice, Italy, 24-28 June 2012.



Mishnaevsky, L., Branner, K., Petersen, H. N., Beauson, J., McGugan, M., & Sørensen, B. F. (2017). Materials for wind turbine blades: an overview. *Materials, 10*(11), 1285.

Pemberton, R., Summerscales, J., & Graham-Jones, J. (2018). *Marine Composites: Design and Performance*: Woodhead Publishing.

Sesto, E., & Casale, C. (1998). Exploitation of wind as an energy source to meet the world's electricity demand. *Journal of Wind Engineering and Industrial Aerodynamics, 74*, 375-387.

Sørensen, B. F., Holmes, J. W., Brøndsted, P., & Branner, K. (2010). Blade materials, testing methods and structural design. *Wind power generation and wind turbine design*, 417-466.

Thomsen, O. T. (2009). Sandwich materials for wind turbine blades—present and future. *Journal of Sandwich Structures & Materials, 11*(1), 7-26.

Trofka, S. (2008). Effects of contour cuts on shear properties of ductile foam cores. *Compos Res J, 2*(1), 66-73.

Yang, J., Peng, C., Xiao, J., Zeng, J., Xing, S., Jin, J., & Deng, H. (2013). Structural investigation of composite wind turbine blade considering structural collapse in full-scale static tests. *Composite structures, 97*, 15-29.

Received 1 March 2021; Received in revised form 10 March 2021; Accepted 15 March 2021;
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doi: 10.46291/ICONTECHvol5iss1pp26-37