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Effect of Fiber Orientation on the Mechanical Properties of Glass Fiber Reinforced Polymer (GFRP)/PVC Sandwich Composites

Elyaf Yöneliminin Cam Elyaf Takviyeli Polimer (CETP)/PVC Sandviç Kompozitlerin Mekanik Özellikleri Üzerine Etkisi

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Abstract

In this study, laminated sandwich composites consist of glass fiber reinforced polymer (GFRP) face-sheets (skins) and polyvinyl chloride (PVC) foam were bonded together via conventional hand lay-up method. The effect of fiber orientation (0/90 or +45/-45) was examined in terms of compression and flexural properties. Flatwise (FW) compressive test provided the core dominated properties and only 0/90 fiber-oriented samples were tested. When the average edgewise (EW) compressive strength of (0/90)GFRP/PVC and (+45/-45)GFRP/PVC sandwich composites were compared, both of them showed similar results. Core crushing, local bending, debonding and core shear were observed as the common failure modes in the sandwich structures under bending. In terms flexural response, the 0/90 fiber oriented GFRP skin slightly showed better strength values as compared with +45/-45 fiber-oriented structures. By considering the all-quasi-static tests, it can be concluded that 0/90 and +45/-45 fiber oriented GFRP skins exhibited similar performance and there was no significant superiority for any of them.

Keywords: Sandwich composite, Flatwise test, Edgewise test, Flexural test, Failure modes

Öz

Bu çalışmada, cam elyaf takviyeli polimer (CETP) yüzey tabakaları ve polivinil klorür (PVC) köpükten oluşan lamine sandviç kompozitler, geleneksel el yatırma yöntemi ile üretilmiştir. Fiber oryantasyonunun (0/90 veya +45/-45) etkisi, basma ve eğme özellikleri açısından incelenmiştir. Düzlemsel (yüzey-FW) basma testi, çekirdek (ara tabaka) özelliklerini domine ettiği için sadece 0/90 fiber yönelimli numuneler test edilmiştir. (0/90)CETP/PVC ve (+45/-45)CETP/PVC sandviç kompozitlerin ortalama yanal (EW) basma dayanımları karşılaştırıldığında, her ikisi de çok benzer sonuçlar göstermiştir. Sandviç yapılarda eğme yükü altında ortak çökme/kırılma tipleri olarak köpük ezilmesi, lokal eğilme, sandviç bileşenlerinin ayrışması ve çekirdek yapının kaymaya uğraması gözlenmiştir. Eğme davranışı açısından, 0/90 fiber yönelimli GFRP yüzey plaka, +45/-45 fiber yönelimli yapılara kıyasla az da olsa daha iyi mukavemet göstermiştir. Tüm statik testler göz önüne alındığında, 0/90 ve +45/-45 fiber yönelimli CETP yüzey plakalarının benzer performans sergiledikleri ve hiçbirinde belirgin bir üstünlük olmadığı sonucuna varılabilir.

Anahtar Kelimeler: Sandviç kompozit, Düzlemsel (Yüzey) basma testi, Yanal basma testi, Eğme testi, Kırılma tipleri

1. Introduction

Application of composite materials in many fields is becoming so popular due to their specific strength and stiffness values as well as light weightness. As a specific group of composites, sandwich structures are mainly used in maritime, aerospace, aviation and automobile industries (Oterkus et al. 2016). Laminated sandwich composites are utilized in high performance lightweight structures and comprised of a low-density porous core material locates in between top and bottom face-sheets (or skins). Those thin face-sheets show strong and stiff characteristics under in-plane loading (Pareta et al. 2020). Additionally, in sandwich composites, core component enhances both flexural rigidity and energy absorption capacity, which exhibit vital importance. The cores used in sandwich composites can be produced from various polymeric or metallic materials such as PU, honeycomb, PVC, aluminum and nickel (Girish and Mohandas

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2020, Uzay and Geren 2020). In general, fiber reinforced polymer (FRP) composites are the most popular type of face-sheet constituents. As it is well known that, polymeric resin is the matrix phase and the fiber is considered as the reinforcement component in FRP systems. The presence of fibers provides stiffness and strength due to its high aspect ratio and those fibers are embedded into a low density but tough polymer matrix. (Kosedag et al. 2021). To enhance the fatigue and corrosion resistance as well as other mechanical properties, some metals such as aluminum, titanium and magnesium have been integrated with FRP and led to significant improvements paricularly in military and defence applications (Kosedag et al. 2022, Kosedag and Ekici 2021). In literature, performance of glass, carbon, aramid, flax and jute fiber reinforced composite skins with various foams have been investigated by many researchers (Samlal, et al. 2020, Balıkoglu et al. 2022). For instance, in case of marine applications, it is primarily aimed to enhance the resistance to seawater, which causes degradation of materials. Furthermore, weight reduction and improved mechanical properties are the other major concerns in naval structures. With the introduction of sandwich composites into ship hulls, decks and bulkheads, remarkable improvements in terms of those aspects have been observed (Palomba et al. 2021, Calabrese et al. 2016). Crupi et al. (2013) investigated the aluminium sandwiches used in ship buildings and they compared the impact characteristics of cellular foam and honeycomb-based sandwiches via experimental tests. According to that study, the collapse of the honeycomb panel emerges due to progressive crumpling of cell walls while the cellular foam samples fail because of crushing of core. Balıkoglu et al. (2020) focused on the flatwise compression and flexural loading performances of pin-reinforced foam core sandwich (PRFCS) panels. E-glass non-crimp biaxial fiber/vinyl ester skin material was integrated with perforated PVC foam to understand the effects of hole diameters. This study showed that the foam cores with denser area fraction of the holes can be utilized in sandwich composites with enhanced load-carrying capacity. Shen et al. (2017) examined the ultimate strength and fatigue properties of L-joints used in ship structures. That research revealed that both fatigue life and stiffness of sandwich L-joints are declined with the increase of loading and the significant failure types are sandwich debonding, sandwich face/core delamination, and gelcoat damage.

As briefly expresses above, a great portion of studies explore the performance of foams and composite stacking sequences. Core type and thickness, skin material, the number of layers in the face-sheet (if it is fiber reinforced polymer-FRP composite) or the test parameter variation (such as span length in flexural test or the strain rates in edgewise test) in various tests have been investigated thoroughly. However, there have been limited studies concentrated on the fiber orientation effects on the quasi-static mechanical behavior, which can exhibit some alterations in terms of mechanical response of sandwich composites. Present paper examined the mechanical properties sandwich composites consisted of glass fiber reinforced (GFRP) face-sheet and polyvinyl chloride (PVC) foam core. The 0/90 (cross-ply) and +45/-45 oriented fiber clothes were integrated with epoxy matrix and consolidated with core material via traditional hand lay-up technique. Flatwise (FW) compression, edgewise (EW) compression and flexural responses of prepared samples were determined to compare their mechanical performances.

2. Materials and Method

The E-glass fabrics with 600 g/m^2 (Metyx^{TM}) areal density was selected as the reinforcement phase and integrated with epoxy resin (Duratek^{TM} DTE 1200 resin and DTS 2110 hardener for a resin-hardener ratio of a 100:20 by weight) for composing skin (face-sheet) component of sandwich structures. Two different fiber orientation (0/90 and +45/-45) from the same fabric system were used for comparison and 10 mm thick PVC foam (MaricellÔ-M080 foam with 80 kg/m^3 density) was chosen as the core material. Three layers of glass fabric were stacked as the skin and consolidated with core component by conventional hand lay-up technique. The manufactured sandwich panel containing 2x3 layers of composite face-sheets with approaximately 4 mm total thickness cured at room temperature for 48 hours. Ater post-curing process (80°C for 8 hours), whole structure were cut into required dimensions regarding to ASTM standards for mechanical characterization (see Figure 1). In this study, the samples containing glass fibre reinforced polymer (GFRP) composite with 0/90 fibre orientation and PVC foam core are abbreviated as (0/90) GFRP/PVC. Similarly, the sandwich composites consisting of +45/-45 fibre-oriented face-sheet is symbolized as (+45/-45) GFRP/PVC.

In the present work, flatwise (FW) compression test was only applied to (0/90) GFRP/PVC specimens. ASTM C-365M is a core dominated standard therefore it is concluded that the characteristic behaviour of one sandwich sample group was sufficient for this test (Ferreira et al. 2016). The average length, width and thickness values of three FW test samples were calculated as 50.3±0.08, 50.03±0.07 and 14.2±0.33 mm, respectively. To precisely determine the effect of fibre orientation in terms of mechanical performance, both edgewise (EW) compression and flexural tests were carried out by considering ASTM C-364 and ASTM C-393 standards, respectively. Three specimens were used for each test and the crosshead speed value was determined as 1 mm/min for EW and FW tests while 1.5 mm/min was applied during flexural test. It should be noted here that three-point bending apparatus was utilized for flexural characterization. The average dimensions of sandwich samples are given in Figure 2 with their standart deviations.

Representative test samples are displayed in Figure 3 and the necessary equations to calculate the mechanical parameters related with those tests are given in Table 1. The σ^{ult}_{FW} , E_{FW} , σ_f , σ_{cs} and σ^{ult}_{EW} correspond to the flatwise ultimate strength, flatwise compression modulus, face-sheet bending strength, core shear strength and edgewise ultimate strength, respectively. Additionally, *c*, *t* and *d* represent the core, face-sheet, and total sandwich thickness values, respec-

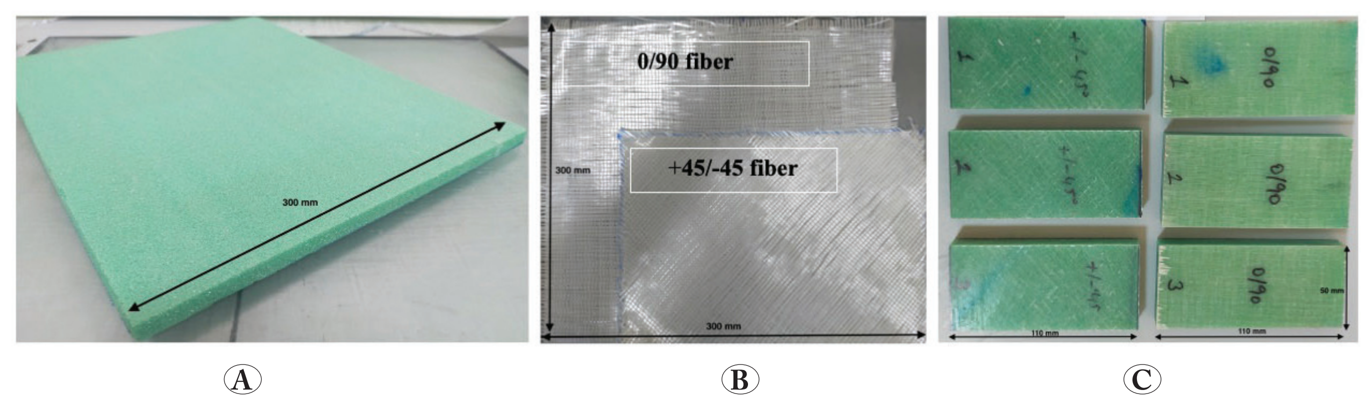

Figure 1. A) PVC foam core, **B)** 0/90 and +45/-45 fibre clothes, **C)** sandwich composite samples with 0/90 and +45/-45 fibre orientations.

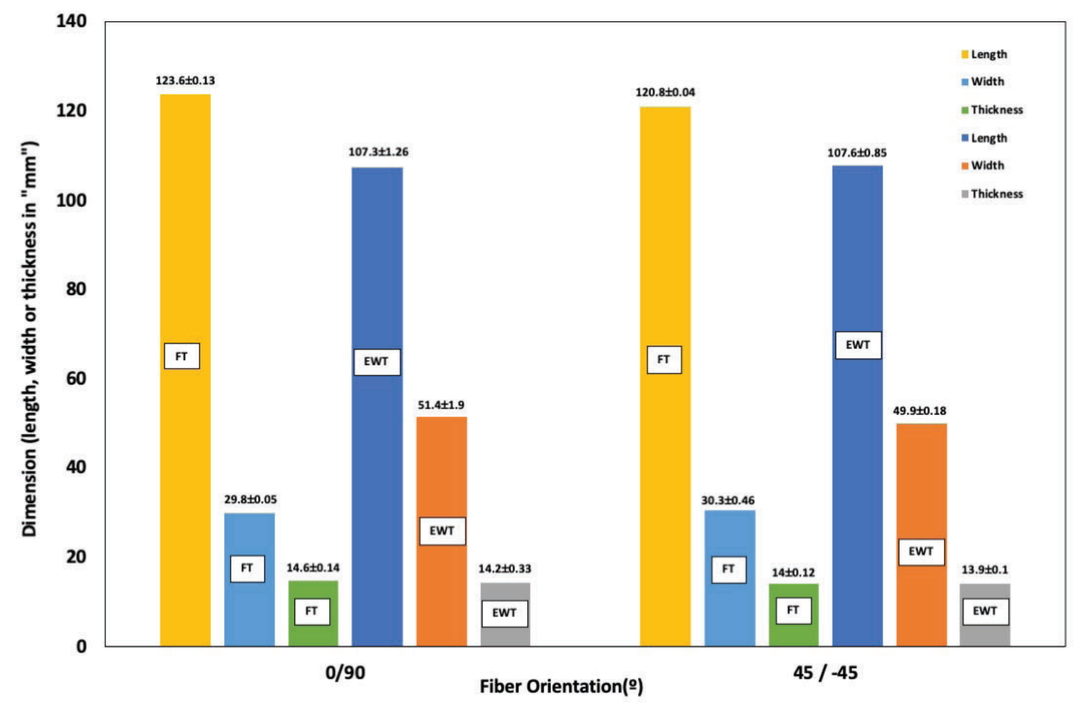

Figure 2. Average dimensions of sandwich composite samples' (length, width and thickness) in "mm" scale in conjunction with ±standard deviations (**FT**: flexural test and **EWT**: edgewise test).

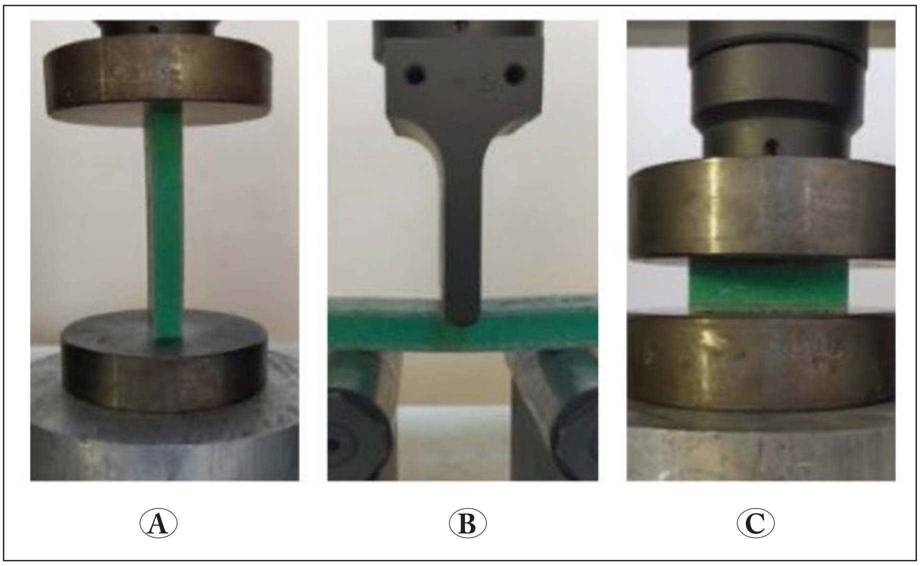

Figure 3. A) Edgewise compression test, **B)** flexural test with three-point bending (3PB) apparatus, **C)** flatwise compression test.

Table 1. Applied test types and characteristic equations used for parameter calculations

Test Type	ASTM Standard	Characteristic Equation(s)
Flatwise compression	ASTM C-365	$\sigma_{FW}^{ult} = \frac{F_{\max}}{A}$ $E_{FW} = \frac{\left(F_{\max}/\delta\right)\times t}{A}$
Flexural	ASTM C-364	$\sigma_f = \frac{F_{\max}\times L}{2t(d+c)b}$ $\sigma_{cs} = \frac{F_{\max}}{(d+c)b}$
Edgewise compression	ASTM C-393	$\sigma_{EW}^{ult} = \frac{F_{\max}}{w(2t)}$

tively while L is the span length in flexural test, and specified as 70 mm with regard to related ASTM standard. The b and w sequentially symbolize the width in flexural and EW compression tests. Additionally, F_{max} and δ in FW test were determined as the maximum force matching to the maximum strain (ε) in compression of 0.002 and corresponding displacement (Ferreira et al. 2016).

3. Results and Discussions

The flatwise compressive properties of PVC foam-based sandwich structures were performed to determine the modulus and strength values under that loading direction. As expressed in the previous section, FW test is a core dominated test, therefore both of those parameters referred above basically reflect the core characteristics. The force-displacement (F-δ) graphs of (0/90) GFRP/PVC sandwich composites are shown in Figure 4 and the resultant properties such as FW strength (σ_{FW}^{ult}) and modulus (E_{FW}) are given in Table 2. As it is known that the foams and foam based sandwiches exhibit three different zones and the typical curves are seen in Figure 4. In the first zone (elastic region), the force increases linearly in a short period of time while it almost shows no variation in the second zone (plateau region). In the final stage (densification regime), force dramatically increases with a sharp slope due to the ending of foam cell collapsing, which results in the formation of foam densification (Mane, et al. 2017). Based on Table 2, average strength and stifness values were calculated as 0.39±0.047 MPa and 19.66±2.35 MPa, respectively by considering 0.002 strain. Additionally, it can be clearly concluded that there is no significant variation in terms of those parameters among the samples, which indicates relatively homogeneous flatwise characteristics.

Table 2. Calculated FW and EW compression test parameters

Sample ID	σ_{FW}^{ult} **(MPa)**	E_{FW} **(MPa)**	σ_{EW}^{ult} **(MPa)**	**SAE (kj/kg)**
(0/90) GFRP/PVC_1	0.35	17.47	73.77	0.47
(0/90) GFRP/PVC_2	0.44	22.16	72.64	0.28
(0/90) GFRP/PVC_3	0.38	19.36	56.94	0.21
(+45/-45) GFRP/PVC_1	-	-	68.97	0.43
(+45/-45) GFRP/PVC_2	-	-	67.93	0.32
(+45/-45) GFRP/PVC_3	-	-	65.78	0.42

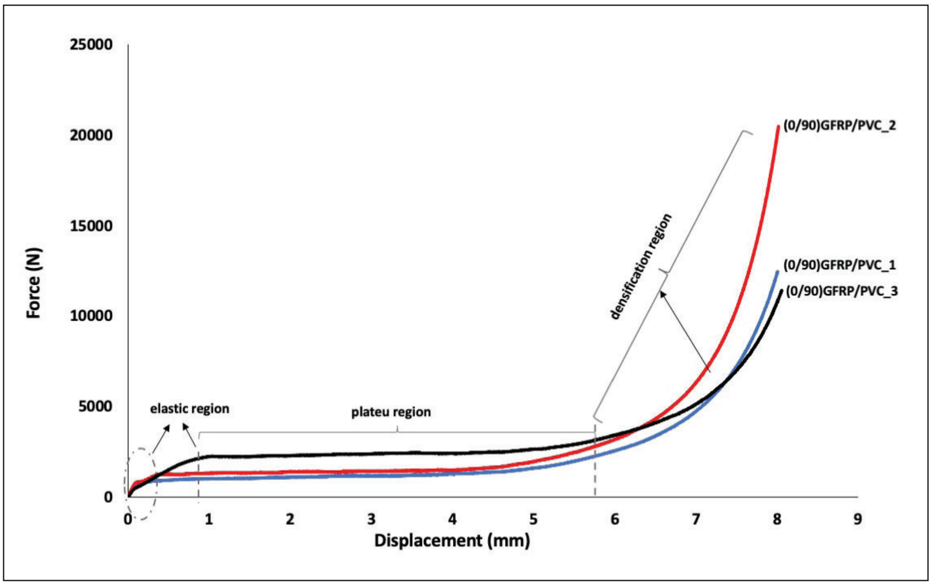

Figure 4. Force-displacement graphs of (0/90)GFRP/PVC sandwich composites.

EW compression properties were determined regarding to the test graphs plotted in Figure 5. To explicitly specify the main differences between 0/90 and +45/-45 oriented composite face-sheets, force-displacement curves are seperately shown in the same figure as 5 (a) and (b). As it is seen, all samples initially exhibit a linear curve up to the maximum value and a dramatic force decrease is observed after the top point. Face-sheet dominates the EW test (Lei, et al. 2016), therefore the deformation patterns of sandwiches containing those materials are shown in Figure 6(a) and (b), respectively. Due to the local bending of face-sheets, buckling phenomena occured and debonding between GFRP and PVC through the edges of the panels touching to the crossheads was monitored. This situation is corresponding to the ending of linear zones in Figure 5(a) and (b). On the compressive side of the specimens, failure took place between core and skin, which can be attributed to the shear force acting at the interfacial region (see Figure 6). It is also noteworthy that none of the GFRP materials delaminated during the test. According to Table 2, average EW compression strength values of (0/90)GFRP/PVC and (+45/-45)GFRP/PVC sandwich composites were calculated as 67.79±9.40 MPa and 67.56±1.62 MPa, respectively. Although the forces carried by the samples with different GFRP skins showed a bit of variations, it can be concluded that (0/90) and (+45/-45) oriented glass fabrics displayed quite similar performance under EW compression direction. With regard to specific absorbed energy (SAE) parameter calculated under EW loading, the +45/-45 fiber orientation exhibited nearly 21% higher average value (0.39±0.061 kj/kg) as compared with cross-ply fiber sequence (0.32±0.14 kj/kg). Although,it is quite difficult to find and compare the parameter evaluation for the similar and/or same cases in literature, some studies related with this work have been analysed. For instance, Mamalis et al. (2005) investigated the buckling response of polymer foam core/GFRP face-sheet

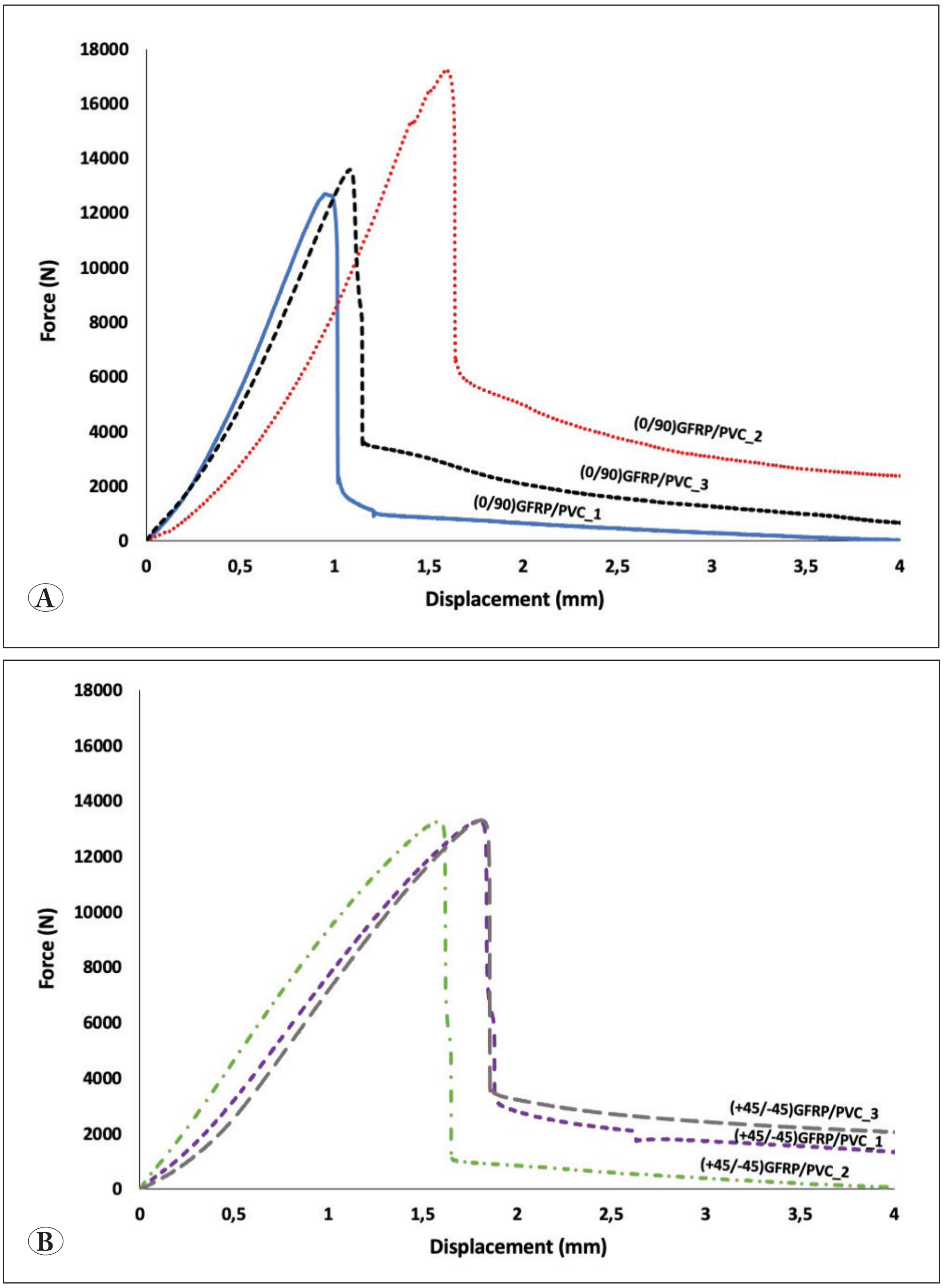

Figure 5. Edgewise force-displacement graphs of **(A)** (0/90)GFRP/PVC and **(B)** (+45/-45)GFRP/PVC sandwich composites.

sandwich structures under edgewise loading. They concluded that three main collapsing mechanisms were present in sandwich panels: unstable sandwich column buckling with foam core shear failure (mode I), unstable sandwich disintegration with buckling of faceplates to opposite directions (mode II) and progressive end-crushing of the sandwich panels (mode III). Ding et al. (2018) examined the hygroscopic ageing behaviors of PVC foam core (with 80 kg/m^3 density and 10 mm thickness) bonded glass fibre reinforced vinylester composite skin sandwich samples. Based on their EW test results, they observed not only local wrinkling but also global buckling, which is also seen in this study. Garay et al. (2016) compared the effects of 0/90 bidirectional plain weave E-glass cloth and E-glass fiber mat reinforced PVC or PET foam sandwich composites. Since the buckling is highly dependent on the face-sheet properties, PVC/E-glass cloth attained the highest strength and exhibited mode I and mode II with respect to layer thickness.

Flexural tests were performed to determine the critical failure forces and deformation mechanisms under out of plane loading. Three or four point bending configurations are generally utilized to generate flexural loading. It is known that core material resist shear forces while the top and bottom face-sheets restrict the effect of forces under tensile and compression directions. Specific failure modes are observed during this test such as face yielding, core shear, face wrinkling and core indentation (Jaliu et al. 2022, Balcıoglu, 2018; Kaboglu, et al. 2018). The load-displacement graphs of 0/90 and +45/-45 GFRP oriented PVC foam sandwich samples are given in Figure 7 (a) and (b), respectively. Independent of fiber oriantation, a linear-elastic regime is followed by an elasto-plastic path until the maximum value of force. After that, an abrupt decrease of loading is observed due to the major failure(s) occuring in the samples. This type of behavior is consistent with the results present in the literature (Xia et al. 2018, Pareta et al. 2020). For 0/90 oriented GFRP structures, core crushing of foam and local bending of the compressive skin beneath the roller were observed as the common damage modes. Additionally, core shear and debonding of core-GFRP component were seen as the other failure mechanisms. In general, indentation of the top skin causes to the core crushing with the progress of flexural loading and a similar situation is present in those samples as well (see Figure 8-a). As observed in Figure 8 (a), sample 1 initially failed due to core shear, which led to the sudden drop of applied force, and core crushing took place as the secondary damage type. In sample 2, an extensive debonding between GFRP and PVC core is seen as well as face-sheet bending. The core crushing was the third failure appeared in the same sandwich specimen.The specimens contained +45/-45 oriented GFRP face-sheet usually exhibited local debonding beneath the upper roller followed by bending (see Figure 8-b). It is interestingly seen that only one sample (#3) showed core crushing and no shear cracking was observed.

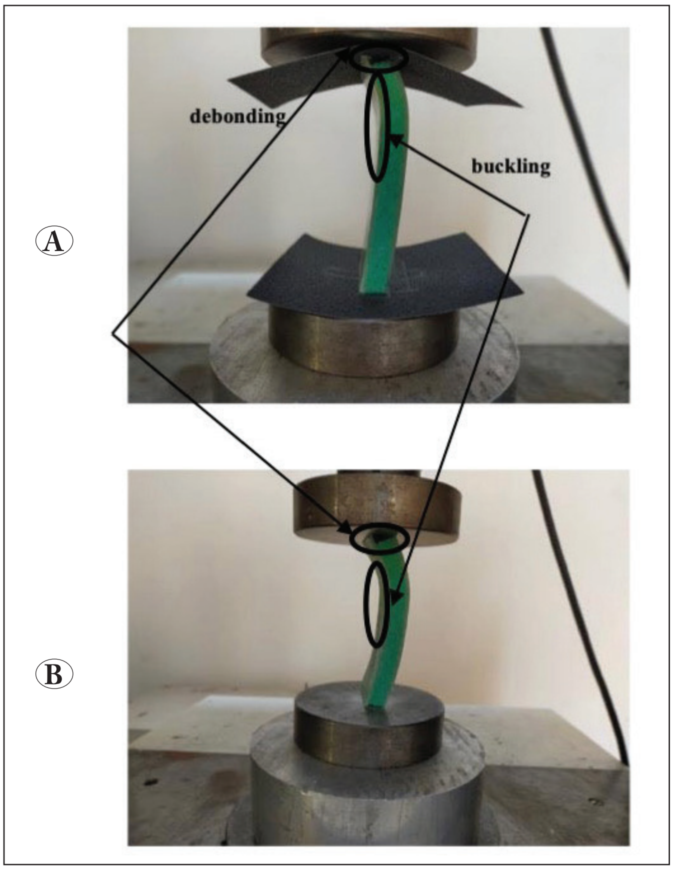

Figure 6. Deformation images of samples under EW compression loading at 2 mm displacement for **(A)** (0/90)GFRP/PVC and **(B)** (+45/-45)GFRP/PVC sandwich composites.

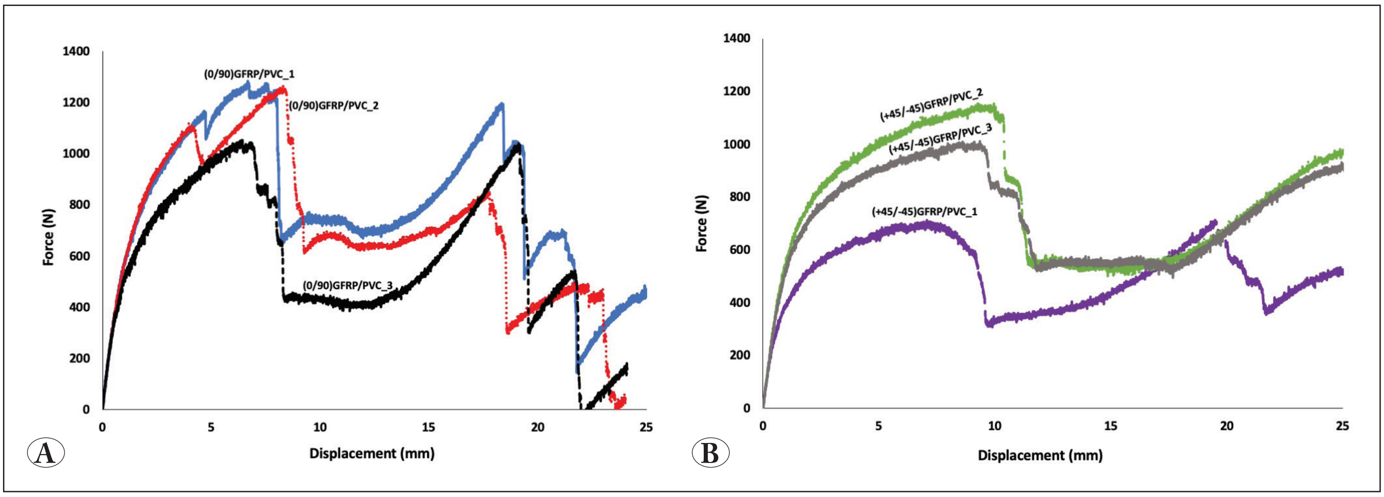

Figure 7. Flexural force-displacement graphs of **(A)** (0/90)GFRP/PVC and **(B)** (+45/-45)GFRP/PVC sandwich composites.

Table 3. Calculated flexural test parameters of sandwich composites

Sample ID	Failure load (N)	Peak displacement @failure load (mm)	σ_f (MPa)	σ_{cs} (MPa)	Failure load/ weight (N/g)
(0/90) GFRP/PVC_1	1284.37	6.68	-	1.74	43.66
(0/90) GFRP/PVC_2	1265.62	8.30	25.96	-	43.45
(0/90) GFRP/PVC_3	1053.12	6.39	22.49	-	38.60
(+45/-45) GFRP/PVC_1	712.50	7.06	18.15	-	26.12
(+45/-45) GFRP/PVC_2	1153.12	9.29	27.86	-	41.25
(+45/-45) GFRP/PVC_3	1012.50	9.34	23.49	-	35.70

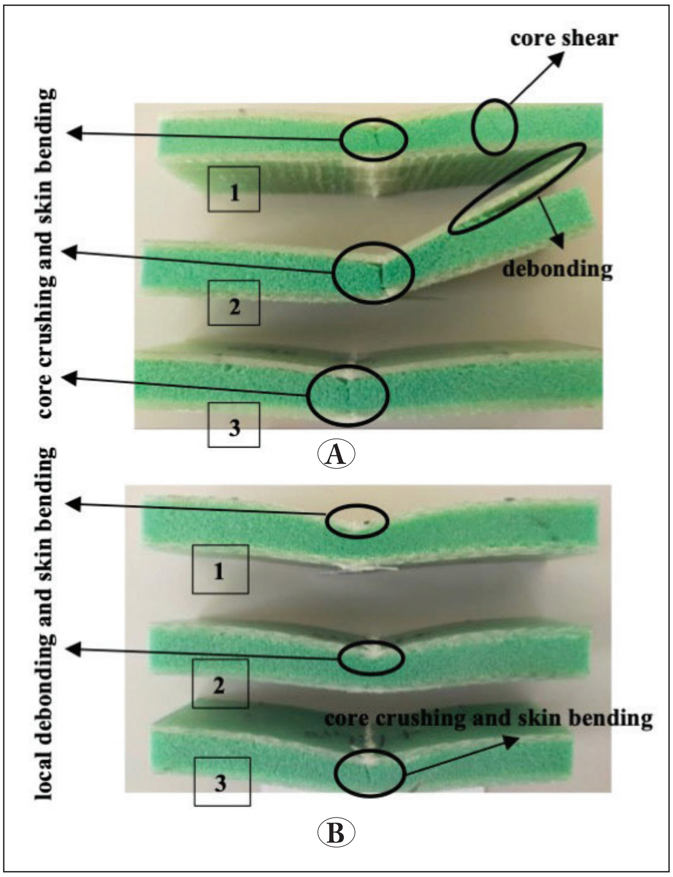

Figure 8. Failure modes of samples under flexural test for **(A)** (0/90)GFRP/PVC and **(B)** (+45/-45)GFRP/PVC sandwich composites.

Depending on the damage modes, face-sheet strength (σ_f) and core shear strength (σ_{cs}) parameters with maximum load and their corresponding displacement values are reported in Table 3. Except one specimen, all specimens showed skin bending as the main failure mechanism. The average σ_f values of (0/90)GFRP/PVC and (+45/-45)GFRP/PVC sandwich composites were calculated as 24.23±2.45 MPa and 23.17±4.86 MPa, respectively. It can be concluded that the 0/90 fiber oriented GFRP skin slightly showed better strength values as compared with +45/-45 fiber oriented structures. By considering average peak displacements, it is observed that cross-ply introduced sandwich samples acquired to their maximum values (7.12±1.03 mm) before +45/-45 fiber oriented speimens (8.56±1.3 mm). The ratio of failure load to weight of the sandwich structures are also compared in the same table. The average values of that parameter for (0/90)GFRP/PVC and (+45/-45)GFRP/PVC samples were calculated as 41.90±2.86 N/g and 34.35±7.77 N/g, respectively. Based on that data, it is comprehended that cross-ply orientation provided improved results (approximately 22%↑) in terms of failure load/weight. Radhakrishnan and Mathialagan (2022) compared the flexural behavior of 0/+90/PET foam/-90/0, 0/ +45/PET foam/-45/0 and 0/+30 /PET foam/-30/0 sandwich structures. Based on their studies, it is concluded that the flexural strength values of whole samples exhibited close values with each other. However, of 0/+30 /PET foam/-30/0 composite system achieved highest strength magnitude while 0/+90/PET foam/-90/0 panel exhibited the lowest strength. Dhaliwal (2021) concentrated on the flexural responses of carbon fiber reinforced polymer/polyurethane foam (CFRP/PU) and glass fiber reinforced polymer/polyurethane foam (GFRP/PU) sandwich beams. In that study, slightly higher stiffness and peak load level were observed for the sandwich specimens having woven CFRP facesheets as compared to the sandwich beam having cross ply GFRP skins. According to their test results it was interestingly revealed that, the variation of fiber type did not show a significant effect in terms of flexural characteristics.

4. Conclusions

The GFRP/PVC foam sandwich composites were manufactured with hand lay-up method. Both cross-ply (0/90) and (+45/-45) fiber orientation inside of GFRP face-sheets were compared in terms of compression and flexural characteristics. The main conclusions are listed below:

i. According to FW compression test, average elastic modulus and strength parameters of specimens were only calculated for (0/90)GFRP/PVC structures by considering 0.002 starin, to obtain foam core characteristics.

ii. There was almost no variation for the EW compressive strength values of (0/90)GFRP/PVC and (+45/-45) GFRP/PVC sandwich composites. In terms of specific absorbed energy (SAE) parameter, the +45/-45 fiber orientation exhibited 21% higher average value than 0/90 fibre sequence, which provides higher toughness under edgewise loading.

iii. For 0/90 oriented GFRP structures, core crushing of foam and local bending of the compressive skin beneath the roller were observed as the main failure modes under flexural loading. The specimens contained +45/-45 oriented GFRP face-sheet generally showed local debonding beneath the upper roller followed by bending. The average σ_f values of (0/90)GFRP/PVC and (+45/-45) GFRP/PVC sandwich composites were so close to each other while the average failure load/weight parameter of the latter sandwich group exhibited nearly 22% lower value than the cross-ply introduced specimen.

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