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Authors: Çağrı UZAY

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Enhancing The Out-Of-Plane Compressive Performance of Lightweight Polymer Foam Core Sandwiches

Çağrı UZAY*[1]

Abstract

This study investigates the flatwise compressive performance of the developed sandwiches with core stitching modification. Polyvinyl chloride (PVC) foam cores with a density of 0.048 g/cm^3 were stitched with 600-tex glass fiber yarns. Then the core materials were sandwiched with carbon/epoxy and glass/epoxy face sheets, respectively. The composite sandwich structures were produced by applying the vacuum bag method, and the composite layers were co-cured. The non-stitched foam core sandwiches were also manufactured as the benchmark. The developed sandwich panels were subjected to flatwise compression tests per the ASTM C365 Standard to obtain compressive properties. The mechanical testing showed that the stitched foam core sandwiches carried dramatically higher compressive loads and presented additional load peaks. Almost 80% and 90% enhancement were achieved in resistance to compressive forces for the sandwiches made of carbon/epoxy and glass/epoxy face sheets, respectively. Also, the increments in the compressive strength of the developed sandwich panels were found above 80% with a minimum weight penalty. Core stitching, providing the sandwich panels to have better out-of-plane strength, is a simple and less time-consuming through-thickness reinforcement process among the other core modification methods.

Keywords: core stitching, flatwise compression, sandwich composite, strength, modulus

1. INTRODUCTION

Sandwich structures, a kind of hybrid laminated composites, are constructed with two thin and stiff face sheets, which are bonded to relatively thicker and low-density core material by a polymer matrix. While the core materials can be made of honeycomb, corrugated plates, balsa wood, polymer, and aluminum foams, the face sheets are commonly made of very thin metal alloy sheets or fiber-reinforced polymer composites. The core material mainly resists shearing, provides stability of two separated face sheets and load transfer between the face sheets, whereas the face sheets carry the compressive and tensile loads. The sandwich composites have emerged with superior specific strength and the stiffness-to-weight ratio [1-4]. Depending upon the sandwich constituents, they can also resist higher impact loads [5, 6], provide acoustic and vibration damping [7], and have better out-of-plane strength [8]. Therefore, the sandwiches have found widespread application areas in such industries as aerospace, automotive, marine, and

* Corresponding author: cagriuzay@ksu.edu.tr
[1] Kahramanmaraş Sütçü İmam University, Faculty of Engineering and Architecture, Department of Mechanical Engineering
ORCID: https://orcid.org/0000-0002-7713-8951

civil infrastructures where lightweight and higher stiffness are the primary design considerations [9-12]. To characterize the mechanical behaviors of the sandwich composites, they are subjected to several testing methods under various loadings, e.g., low-velocity impact [13], flexural [14, 15], edgewise and flatwise compression [9], and tensile [16] loads. The extensively obtained knowledge about the failure modes helps the designers and researchers to reveal optimal sandwich systems satisfying the desired requirements.

The typical failure modes encountered for sandwich structures are core shear, face sheet yielding, indentation, delamination, debonding, and face sheet wrinkling. The initiation and propagation of the failures depend upon the sandwich materials, type of loading, and design geometry [17, 18]. For instance, assuming the sandwiches are irrespective of the manufacturing defects, the core shear and indentation failure modes are commonly encountered under bending loadings, whereas delamination and debonding can be seen under impact loads [19] or flatwise compression [8]. One of the most common failure modes encountered in practice is the debonding or delamination of the core and the face sheets materials [9]. The compressive behavior of the sandwiches has been investigated to analyze these failure modes. Many researchers used high-density core materials to increase shear load carrying capacity, preventing the debonding of the laminates [1, 2, 8, 12, 20]. Some practical approaches for the developments of compressive performance of the sandwich composites are the insertion of shear key elements into the structure [20], z-pinning [16], tufting [21], and through-thickness stitching [16] of the core materials together with or without the face sheets [1]. Abdi et al. [1] obtained a dramatic increase in flatwise compression performance of the sandwiches by inserting polymer pins into the foam core.

Stitching, providing through-thickness reinforcement, can be applied to whole sandwiches, including face sheets and core [22], or applied only to the core material [23]. However, it was stated in the literature that only the core stitching rather than stitching the core with face sheets provided a sandwich panel to had better flatwise compression properties [16]. This might be due to the fiber damages during the stitching process [7]. The stitched core sandwich contributes to the interfacial strength of face sheets to the core leading to obtaining higher out-of-plane properties. The stitching with fiber bundles increases the energy requirement for delamination of the sandwich laminates and prevents face sheet-core debonding. Yalkin et al. [16] reported that core stitching is a simple and less time-consuming process than other through-thickness reinforcement methods such as inserting shear key elements, composite rods, and polymer pins. Malcom et al. [22] stitched the glass/epoxy face sheets and PVC foam core with aramid fiber to increase the shear and compressive properties. Han et al. [4] used 167-tex glass fiber yarns and stitched carbon/epoxy face sheets and polyurethane (PU) foam core with different stitching densities. Drop weight impact test results showed that stitching increased the energy absorption capacity, and also, the delamination area was smaller as the stitched density was increased. Yalkin et al. [23] the PVC foam core glass/epoxy face sheets sandwiches at various tex numbers of glass fiber yarns from 600-tex to 2400-tex. The researchers obtained enhanced compressive, shear, bending, and impact properties. However, they indicated that increasing tex number caused individual fiber damages during the stitching, which made the process more difficult.

In this study, the effects of stitched core on the flatwise compression properties of the low-density polymer foam core sandwich panels were investigated. 15 mm thick, closed-cell, and rigid polyvinyl chloride (PVC) foam cores with a density of 0.048 g/cm^3 were sandwiched with carbon/epoxy and glass/epoxy face sheets. The stitching was applied to the pre-drilled foam core and carried out with glass fiber yarns (600-tex). The vacuum bagging method was applied to manufacture the sandwich panels, in which the laminates were co-cured under a vacuum atmosphere at room temperature. According to ASTM C 365 Standard [24], the flatwise compression tests were performed to discover the developed sandwiches' compressive properties.

2. MATERIALS AND METHOD

2.1. Materials

Low-density foam core fiber reinforced sandwich panels were fabricated with polyvinyl chloride (PVC) foam core, woven plain glass and carbon fiber fabrics, and polymer epoxy resin set. PVC foam is a linear cross-linked, rigid, closed-cell core material and has widespread application in industrial practice due to its low cost and better environmental resistance like moisture absorption, flammability [25, 26]. Woven plain fiber fabrics were preferred since they provide better fiber yarn stability in both fill and warp directions, which leads to ease of fabrication. They also provide almost equal in-plane elastic properties and high out-of-plane strength compared to unidirectional fibers [27, 28]. In order to obtain the same thickness for the face sheets, 5-ply glass fiber fabrics was used, whereas 4-ply carbon fiber fabrics were used. Although it seems that the use of such ply numbers is not matching the same thickness value, approximately the same face sheet thickness values were obtained as the resin impregnation behaviors are different. The decision made for face sheets' layers was due to the laboratory experiences. The fiber face sheets and the core material were processed with a polymer epoxy resin set. The material properties of the sandwich constituents are given in Table 1.

2.2. Core Stitching and Sandwich Panel Manufacturing

PVC foam core materials were firstly drilled with a CNC milling machine to obtain stitching holes. The diameter of the holes is 2.5 mm. Figure 1 shows the schematic view of the drilled PVC foam core and drilling orientations. The stitching was made manually with a hole density of 0.36 hole/cm^2, which determines the number of stitching holes in a unit cm^2. The core stitching was made on the perforated foam core by using E-glass fiber yarns with 600-tex.

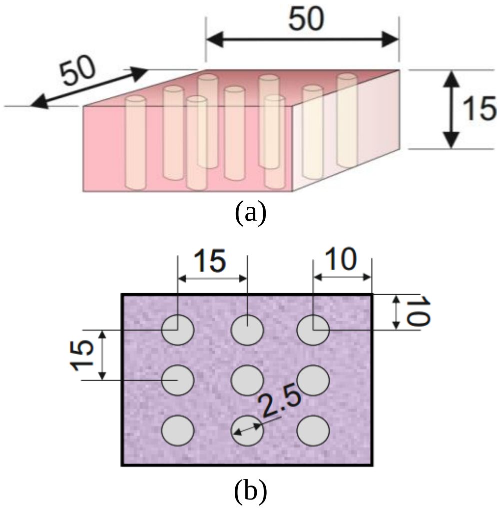


Figure 1 a) Schematic view of a drilled PVC core, b) drilling orientation

Table 1 Material properties of the sandwich constituents [29-31]

Material Property	Value
Carbon fiber	
Fabric Description	Woven, 3K plain, continuous
Areal Mass	200 g/m^2
Thickness	0.20 mm
Density	1790 kg/m^3
Tensile Strength	3800 MPa
Tensile Modulus	240 GPa
Tensile Strain	1.6 %
Glass fiber	
Fabric Description	E-glass, woven, continuous
Areal Mass	200 g/m^2
Thickness	0.18 mm
Density	2560 kg/m^3
Tensile Strength	2400 MPa
Tensile Modulus	76 GPa
Tensile Strain	4.8 %
PVC foam core materials	
Description	Rigid, linear, closed-cell
Density	48 kg/m^3
Thickness	14 mm
Compressive strength	0.60 MPa
Compressive modulus	48 MPa
Tensile strength	0.95 MPa
Tensile modulus	35 MPa
Shear strength	0.55 MPa
Shear modulus	16 MPa
Epoxy matrix	
Density	1180-1200 kg/m^3
Resin to hardener ratio	100:25 in weight
Tensile strength	70-80 MPa
Tensile modulus	3.2-3.5 GPa
Tensile strain	5-6.5 %
Compressive strength	80-100 MPa
Impact strength	40-50 kJ/m^2

Sandwich panels' manufacturing was carried out by applying the vacuum bagging method. The face sheet fabrics were co-cured with the foam cores. Once all the composite layers, including fiber fabrics and core material, were stacked in a specified order, a perforated release film was placed over the resin-impregnated composite sandwich structure to allow the removal of excessive resin and air bubbles. Then, a vacuum breather was placed to collect the excessive resin. Lastly, the composite system was enclosed entirely by a vacuum bag. The non-stitched foam core sandwich panels were also fabricated as the benchmarks. The curing was performed at room temperature under a vacuum pressure of 0.005 mbar. The illustration of the manufacturing method I schematically demonstrated in Figure 2. The total sandwich thickness was obtained at 15.80 mm with a face sheet thickness of 0.9 mm.

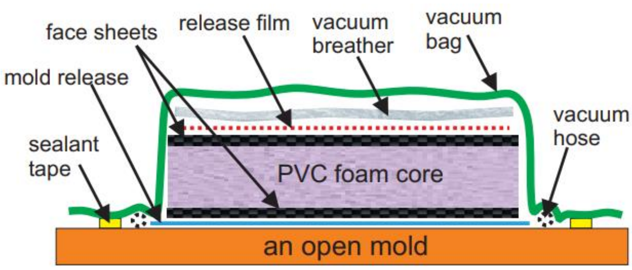
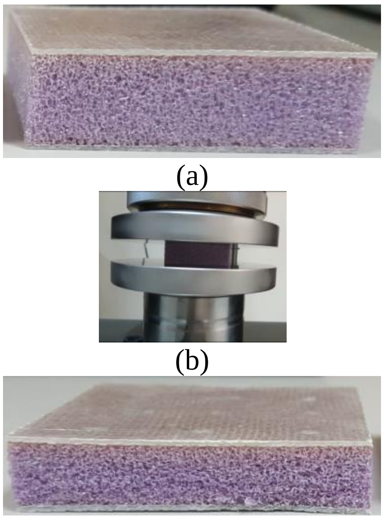


Figure 2 Schematic illustration of the vacuum bag method

2.3. Flatwise Compression Test

The flatwise compression tests were applied since the typical use of sandwich panels are generally under the compressive loads such as bridge decks, floors, roofs, etc. [9]. Therefore, the sandwich panels in the present study were subjected to flatwise compression tests according to ASTM C365 Standard. Dimensions of the testing specimens are 50 mm x 50 mm x 15.80 mm. A universal testing machine named ZwickRoell Z100 was used to perform the compression tests. The cross-head speed was set to 0.5 mm/min. A test specimen under compressive loading was presented in Figure 3. Compressive load and deflection values were recorded by the universal testing machine, and compressive strength and compressive modulus of the sandwich panels were determined based on Equations 1 and 2.



(a)

(b)

(c)

Figure 3 Flatwise compression test of a sandwich specimen; a) before test, b) compression, c) after test

$$\sigma_z = \frac{P}{a.b} \quad (1)$$

$$\varepsilon_z = \frac{\Delta t}{t_c} \quad (2)$$

Where σ_z and ε_z are the thorugh-thickness stress and the strain; a and b are the specimen's surface dimensions; t_c is the core thickness, and Δ_t is the deflection value of the specimen.

3. RESULTS AND DISCUSSION

Sandwich panels were tested under flatwise-compressive loading with five repetitions. The closest curves to each other were used to present load-deflection (Figure 4 and 5) and stress-strain (Figure 6 and 7) curves. While four specimens are introduced for non-stitched foam core sandwiches, three specimens are introduced for stitched foam core sandwiches. Table 2 presents the average values of compressive load capacity, stress, and modulus data together with their standard deviations. The compressive modulus was calculated by dividing the stress to the corresponding strain value in the linear elastic region. The table also includes the sandwich weights.

As seen in Figure 4a, non-stitched foam core sandwiches with glass/epoxy face sheets exhibited a linear initial elastic zone, followed by a plastic region (a larger plateau), and finally, a densification stage. After the linear elastic zone, the gaps in PVC foam core cells start to close, which carry out in a wide deflection value, and then, densification occurs at last, which the foam core behaves like a solid structure. Similar findings were also obtained by Mostafa [2]. The non-stitched sandwich behaviors under flatwise-compressive loads were found irrespective of the face sheet materials. Because the sandwich with glass/epoxy face sheets carried a compressive load of 1330 N, whereas the sandwich with carbon/epoxy face sheets carried 1270 N. The results are very close to each other. The deflection values where the plastic region initiated were also closer to each other. Garay et al. [9] also obtained similar behaviors even in using both different types of core and face sheet materials. Consequently, the type of fiber reinforcement in face sheets does not significantly affect the failure behavior of the structures when designing a sandwich working under compressive loading.

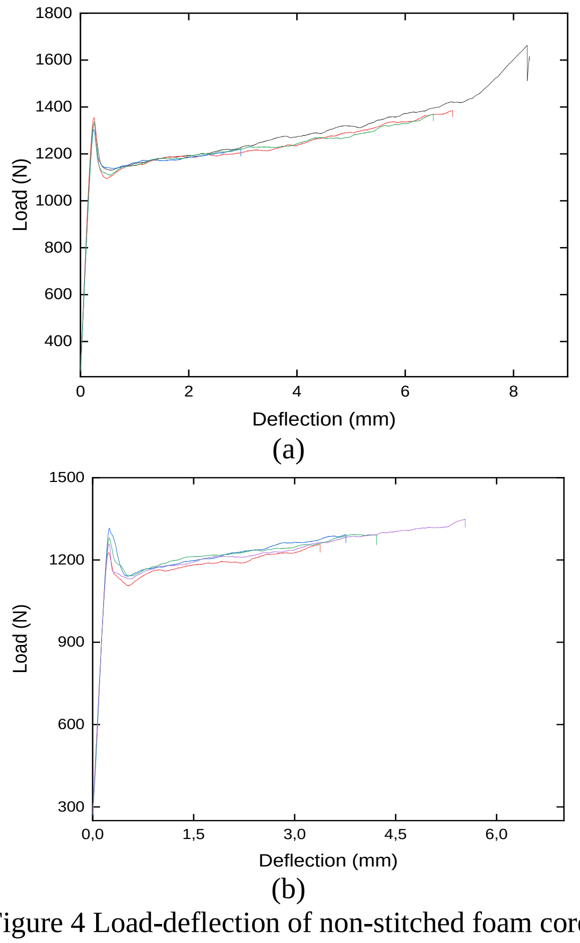


Figure 4 Load-deflection of non-stitched foam core sandwiches with; a) glass/epoxy face sheet, b) carbon/epoxy face sheet

Using stitched core provided the sandwich panels to resist higher compressive forces. In the linear elastic region, the increment in compressive load carrying capacity was obtained by 56.02% for the sandwich with glass/epoxy face sheets, whereas it was 77.95% for the sandwich with carbon/epoxy face sheets compared to the non-stitched foam core sandwiches. Contrary to non-stitched foam core sandwiches, the load capacity and compressive behavior were varied for the stitched sandwiches depending upon the face sheets. Moreover, additional force peaks were observed, as seen in Figure 5. The stitched core sandwich with glass/epoxy face sheets carried 2075 N average compressive load, and then after a yielding, it resisted to a force of 2514 N, which is 21.16% higher than the initial peak. On the other hand, in the case of using carbon/epoxy face sheets, the sandwich carried a compressive load of 2260 N, then after a decrease in the force for particular deflection values, the sandwich showed a second peak force of 2256 N, which is almost the same as the first peak force value. This might be due to the better integration of the sandwich layers thanks to the glass/epoxy columns in stitching holes, leading to improved interfacial strength, and the stitching restricted the core movement between the face sheets [23].

Table 2 Compressive properties and weights of the sandwich panels (SC: Stitched core, NSC: Non-stitched core, G/E: glass/epoxy, C/E: carbon/epoxy, FS: Face sheets)

Sandwich configuration	Load capacity (N)	Strength (MPa)	Modulus (MPa)	Weight (N)
NSC, G/E FS	1330.25 (18.45)	0.533 (0.007)	47.38 (1.82)	0.0838 (0.0006)
NSC, C/E FS	1269.75 (32.87)	0.508 (0.018)	43.5 (1.12)	0.0767 (0.0014)
SC, G/E FS	1st peak: 2074.33 (23.83) 2nd peak: 2514.33 (173.63)	1st peak: 0.830 (0.009) 2nd peak: 1.006 (0.069)	57.83 (3.79)	0.0905 (0.0008)
SC, C/E FS	1st peak: 2272.00 (21.27) 2nd peak: 2256.67 (123.51)	1st peak: 0.911 (0.008) 2nd peak: 0.918 (0.038)	46.33 (7.77)	0.0839 (0.0020)

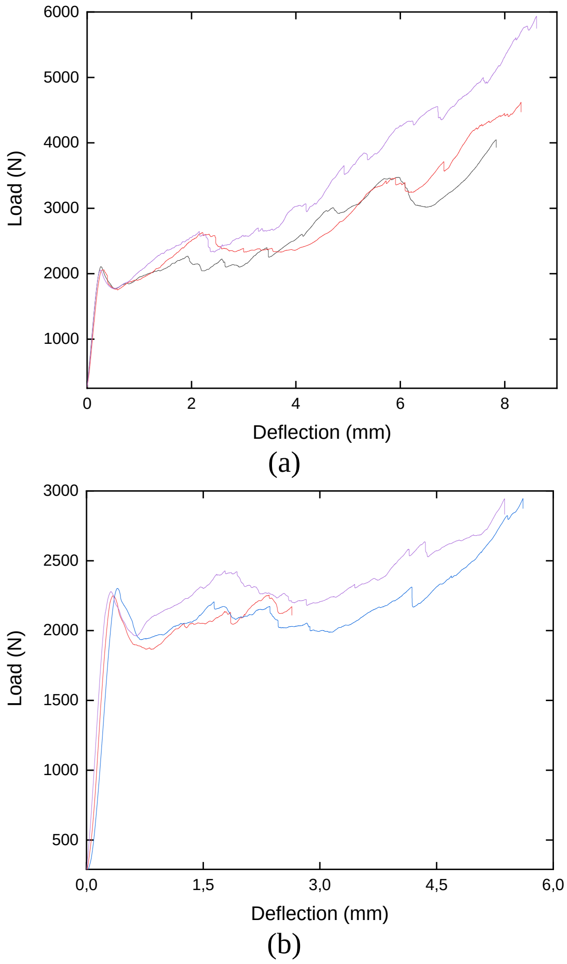
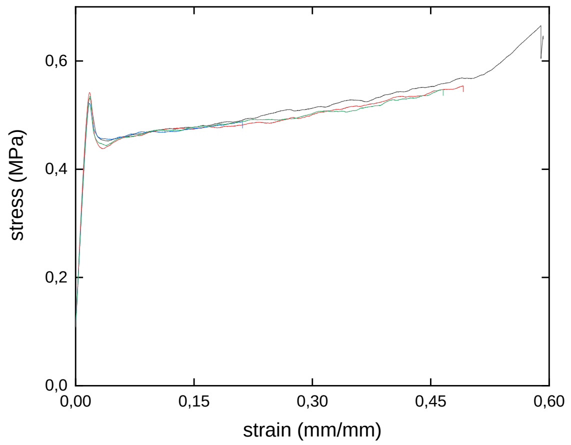


Figure 5 Load-deflection of stitched foam core sandwiches with; a) glass/epoxy face sheet, b) carbon/epoxy face sheet

The stress-strain curves of the non-stitched foam core sandwich panels with fiber face sheets (Figure 6) are found similar to the behavior of only the core material. The compressive strength of the sandwiches was obtained closer to that of core material as provided by the manufacturer. Also, in the literature, Mostafa [2] and Yalkin et al. [16] also demonstrated that the compression strength of only the foam core is very close to that of composite sandwich with fiber face sheets. The sandwiches showed a linear elastic phase until the yield stress. Then, the stress value decreased with the increase of strain since the closed cells were exposed to buckling in the core. After certain strain values, no significant change was observed in the compressive stress with increased strain value. Lastly, the sandwiches underwent densification at the end of that stress region since the closed cells were in self-contact in the core. The occurrence of the densification led to an increase in the stress value. The densification strains are about 0.52 mm/mm for the sandwiches. In recent literature, Akar [12] found a strain of 0.60 mm/mm for a 10 mm thick, 0.060 g/cm^3 PVC foam core sandwich with glass/epoxy face sheets. However, the researcher obtained approximately 0.40 MPa compressive strength, whereas it was 0.533 MPa in the present study. In fact, the higher the core density, the higher the compressive strength can be obtained. Compared to ref [12], a relatively thicker core was used in this work and provided the closed cell to resist more buckling loads.

The average values of the compressive strength and compressive modulus are given in Table 2. The standard deviations are given in parenthesis.



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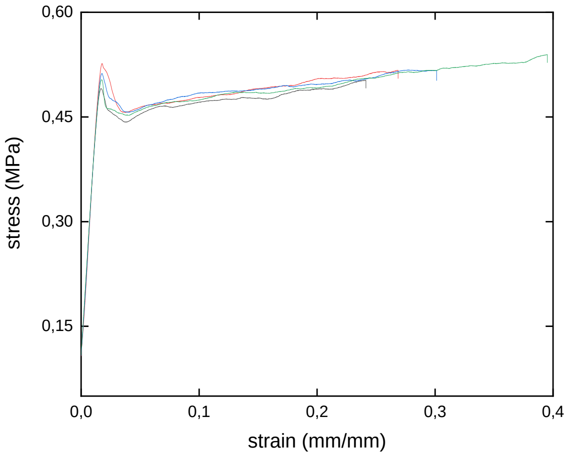
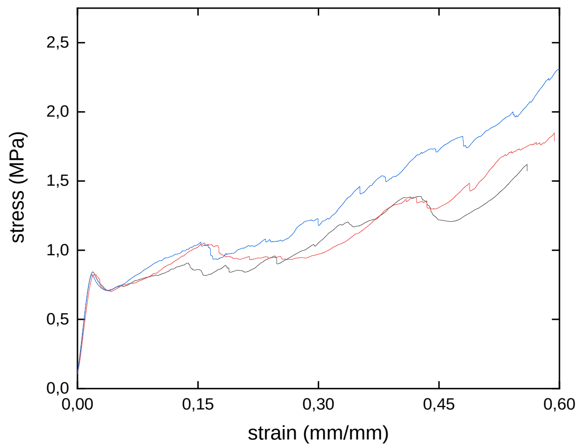
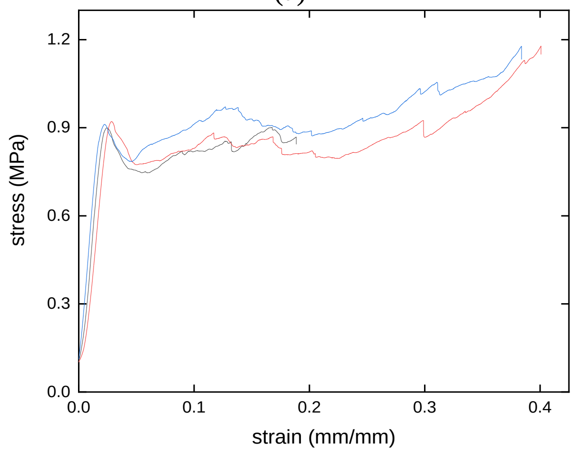


(b)

Figure 6 Stress-strain curves of non-stitched foam core sandwiches with; a) glass/epoxy face sheet, b) carbon/epoxy face sheet



(a)



(b)

Figure 7 Stress-strain curves of stitched foam core sandwiches with; a) glass/epoxy face sheet, b) carbon/epoxy face sheet

The stress-strain curves of the stitched core sandwiches are obtained quite differently in the present study, although the shape of the curves of both stitched and non-stitched foam core sandwiches was presented similar to each other in the literature [16, 23, 25]. After the yield stress was reached, the stress value decreased for a particular strain, and then the stress value increased again, reaching the second peak in the stress. The second peak in the stress value was obtained thanks to the glass/epoxy columns in the stitching holes of the core. These through-thickness reinforcements provided to carry most of the compressive loads acting on the sandwich panels. While the failure of the non-stitched core sandwiches was due to only the buckling of the closed cells, the stitched core sandwiches failed due to the damage of both glass/epoxy fiber columns in the stitching holes and the closed cells in the core.

When the sandwich weights are considered, it is seen in Table 2 that the core modifications did not make a notable effect on the structural weight. Because core stitching with 600-tex E-glass fiber yarns increased the weight of the sandwich panels by 7.98% and 9.42% for glass/epoxy and carbon/epoxy face sheets sandwiches, respectively. On the other hand, thanks to the stitching process, the compressive strength of the sandwiches was enhanced by 80.71% and 88.74% for carbon/epoxy and glass/epoxy face sheets, respectively.

4. CONCLUSION

In the present study, PVC foam cores were stitched with 600-tex E-glass fiber yarns; then, sandwich composites were manufactured with both carbon/epoxy and glass/epoxy face sheets. The flatwise compression test results showed that using stitched core in a sandwich structure significantly improved the compressive load capacity, strength, and modulus with a minimum weight increase. Because the resin impregnated fiber yarns within the stitching holes acted as the primary load-carrying members. These reinforcements also provided better interfacial bond strength between the core and the face sheets materials leading to high delamination resistance and structural integrity of the sandwiches. Unlike the previous studies, the core stitching provided the sandwich composites to resists additional load peaks, which are higher than the first peaks.

Core stitching is a simple and less time-consuming through-thickness reinforcement process among the other core modifications methods; thus, the stitched core materials with different hole densities can be supplied from the manufacturer or prepared in a laboratory before using them in composite sandwich manufacturing. Therefore, the effects of counts of fiber bundles to make stitching and hole density are potential subjects for future investigations.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declare that he comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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