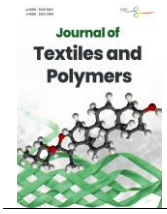

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The flexural behavior of Stitched Polyurethane Foam Composite Sandwich Structures

Shekoufeh Rasouli Rizi[1], Hooshang Nosraty*[1], Seyed Abolfazl Mirdehghan[1]

[1]Textile Engineering Department, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran.

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Abstract

One of the main advantages of sandwich composites is the high bending strength to their weight ratio. These structures have significant problems such as face sheet-core de-bonding, which could be prevented by a variety of techniques including z-pining and stitching through the thickness. In this study, the effect of stitching on the bending behavior of sandwich composites with E-glass composite face sheets and polyurethane foam core has been investigated. Specimens are stitched at three stitch spaces of 0.5, 1, and 2 cm with stitch pitch of 0.8 cm and stitch seam angles of 0, 90°, 0/90°, ±45°, 45°/90°, and ±60°. Face bending stress and core shear stress of stitched specimens have been studied by a three-point bending test and compared to the results of unstitched specimens. Results indicate that by decreasing the stitch spacing and therefore increasing the stitch density, bending strength improves, and the best bending behavior is observed in the ±45° stitch angle Sample.

1 INTRODUCTION

Sandwich structures are widely used for their low weight and ability to bear out-of-plane loads in aerospace, civil, marine, and high-speed train applications, as well as for acoustic and thermal insulation. In these structures, a thick core with low density is bonded between two face sheets[1-7].

To prevent de-bonding problems in sandwich structures, various chemical and mechanical solutions are employed, such as using solid adhesives or reinforcing through the thickness. For instance, in 1898, Sanders [8] first used copper wires for stitching layers of wood. Although stitching adds an extra step in the production process, it significantly helps in preventing crack propagation, de-bonding, and enhancing buckling behavior [9]. Additionally, inserting stitch threads through the structure's thickness reduces transverse displacements and shear stresses [10].

To use sandwich structures in high-technology industries, enhancing their flexural properties is essential. In the Advanced Subsonic Technology program (AST) [11], NASA investigated the effect of stitching on the mechanical behavior of through-thickness stitched structures. It was concluded that increasing stitch density improved flexural stiffness by approximately 174%. Aktas et al. [12] presented a method for joining carbon-fiber plies with a rigid foam core, with specimens stitched in both bias and orthogonal directions. Their study found that bias stitches provided higher stiffness in three-point bending tests. Kumar et al. [13] evaluated the effect of varying yarn twist per inch (TPI) on flexural behavior, showing that yarn with a 3 TPI value demonstrated the best performance and results.

Santhankrishnan et al. [14], explored stitched through-thickness (STT) bending properties with different stitching directions (90˚, 45˚, 90˚/45˚/90˚, and 90˚/45˚An impressive improvement was reported in the sample with a 90˚/45˚/90˚ stitch direction. Lascoup et al. [15] conducted a study discussing the influence of stitch pitch and the angle of stitch yarns on the mechanical properties of composites. Lee et al. [16] investigated the failure mechanisms of stitched sandwich panels, concluding that stitching through the thickness enhanced the flexural properties compared to unstitched specimens. Ai et al. [17] studied the influence of stitching parameters, such as stitching density and stitch yarn twist, on the mechanical behavior of stitched structures. They indicated that these parameters had a significant effect on sample strength and failure mechanisms. Ai et al. [18] also examined the effect of the number of stitch yarn strands on the mechanical performance of sandwich panels, showing that an increase in the number of yarn strands enhanced bending stiffness and strength. XiTao et al. [19] analyzed the effect of stitching on sandwich composites both analytically and experimentally. Specimens stitched at 90 degrees relative to the faces were subjected to flatwise tensile, bending, core shear, and compression tests, demonstrating that stitching

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* Corresponding author: hnosraty@aut.ac.ir

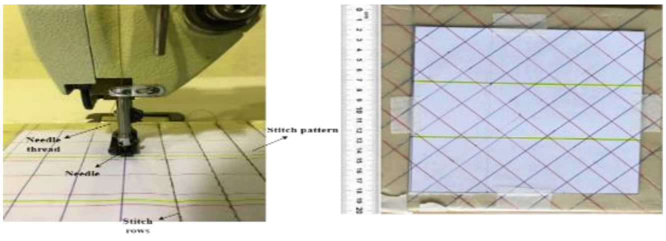
improved the maximum failure load in these tests. Henao et al. [20] evaluated the effect of tufting on sandwich structures by subjecting composites to edgewise three-point bending and compression tests. They compared tufted and non-tufted specimens, reporting significant improvements in bending strength for tufted specimens. Tufted specimens also showed better bending behavior compared to non-tufted ones, although tufting was more effective for bending behavior. Eyvazian et al. [21] studied the effect of resin pins through the thickness of sandwich composites subjected to quasi-static edgewise compression. The specimens, made with glass fabric, aluminium face sheets, and PVC foam core, were tested to establish the effects of face-sheet thicknesses, their sequence, boundary conditions, and resin pin diameter on crushing and buckling behavior. Their results clarified that resin pins increased buckling load and absorbed energy.

Regarding the effect of stitching on the mechanical properties of sandwich structures, this study discusses the effect of stitching angle and stitching density on the flexural behavior of through-thickness stitched foam sandwich panels. Previous research focused on stitching seam angles in two directions: zero and orthogonal degrees, with diagonal stitching angles (45 and 60 degrees) less investigated. This research examines a wider variety of angles, including combinations of stitching seam angles. With the X-axis defined as the length direction and the Y-axis as the width direction, the Z-axis is the through-thickness direction. Specimens were stitched at 0˚, 90˚, +45˚/-45˚, 0/90˚, 90˚/45˚, and ±60˚ to the X-axis. The stitch seam angle was considered along the specimen's length, with stitch spaces between lines set at 0.5, 1, and 2 centimeters.

2 MATERIAL AND METHODS

2-1 Material

In this study, the effect of stitching on the bending behavior of sandwich composites with glass face sheets and a foam core was investigated. Stitched sandwich structures were fabricated with polyurethane foam (density = 40 kg/m³, thickness = 1 cm) in the core section and plain-woven glass fabric (areal weight = 435 g/m²) in the face sheets. Different stitching patterns were utilized to investigate the effect of stitching angles, as shown in Table 1. Specimens were stitched with an industrial sewing machine (Figure 1(a)). The stitching thread used was 47-tex polyester filament yarn. The stitching patterns were drawn on paper and then placed on the specimens, as shown in Figure 1(b). A modified lock stitch (Figure 2) was used with an 8 mm stitch pitch and three different stitch spaces: 0.5, 1, and 2 centimeters. After sewing, the paper was removed. The glass face sheets of the specimens were impregnated with LR615 epoxy resin and H615 hardener in a 100:15 ratio.



(a) (b)

Fig. 1 a) Industrial sewing machine, b) Specimen with ±45° stitch pattern before stitching

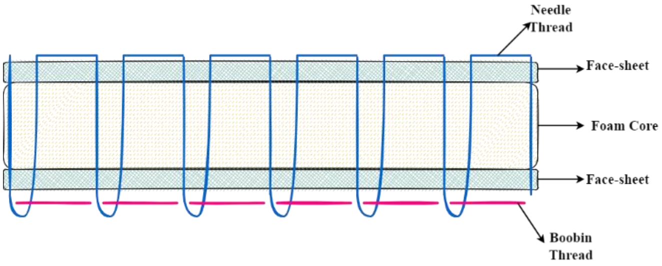
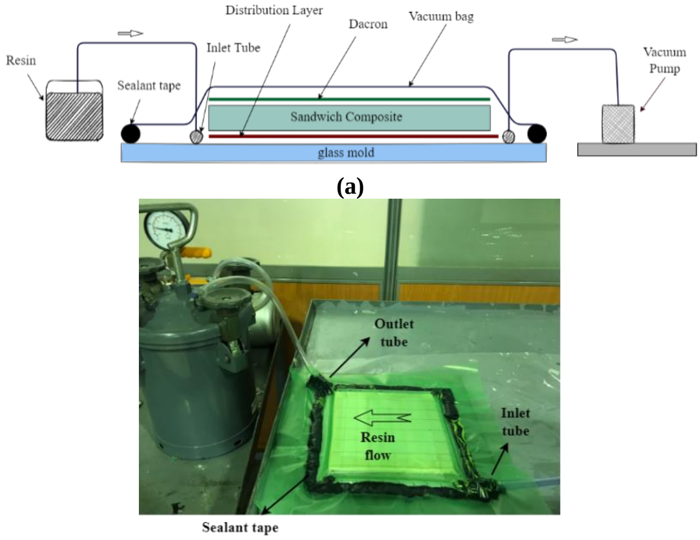


Fig. 2 The schematic of stitched sandwich composite with modified lock stitch

2-2 Vacuum infusion process

After preparing all specimens, the resin is transferred to the structure with the vacuum infusion process. This process could be divided into four steps: 1) Arrange the layers; in this step, the mold was coated with a release wax, then a layer of Dacron fabric and a distribution layer was placed on the mold surface and the stitched specimen laid into the mold. At the end, a vacuum bag sealed the layers. 2). Pre-transfer process accuracy test; possible leaks are checked with the vacuum pump. 3) Resin transfer; the resin is transferred through the intended input. The applied pressure was 0.8 bar. 4) After resin transferring; the extra resin was evacuated and the vacuum pump was disconnected. Then, specimens were cured for 72 hours at 25±1 °C, as recommended by the resin manufacturer. Figure 3 shows the vacuum infusion set up.



(a)

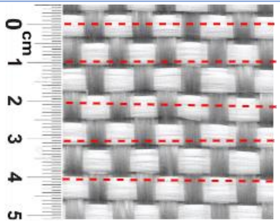
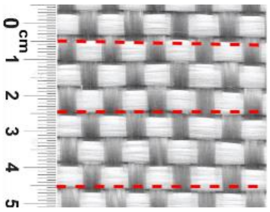
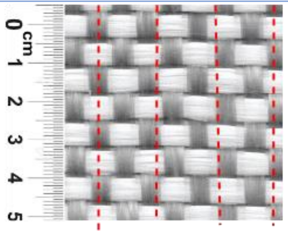
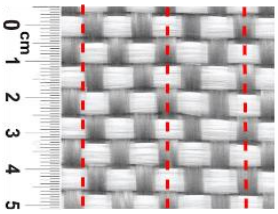
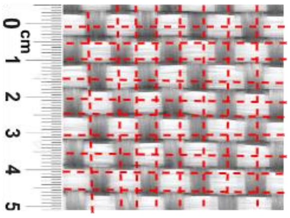
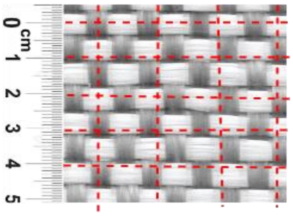
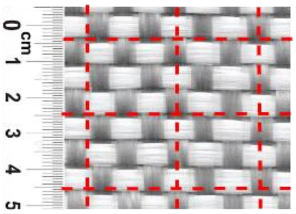
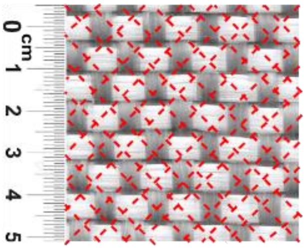
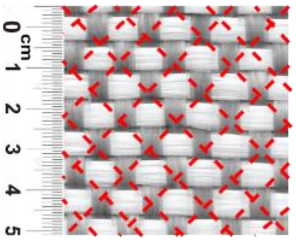
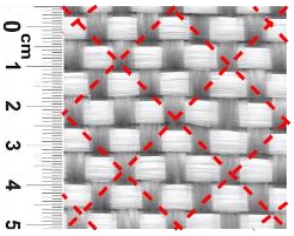
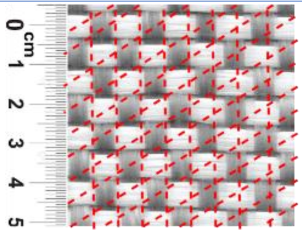
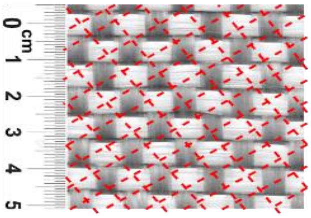
(b)

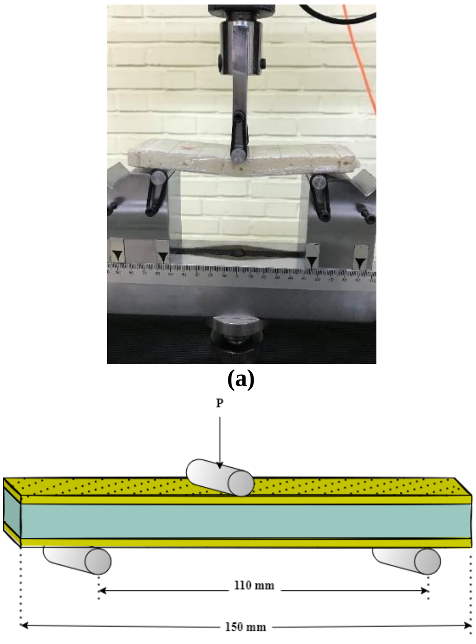
Fig. 3 a) Schematic of VIP method, b) VIP set-up in current study

2-3 Flexural testing

According to ASTM-C393 [22], a 3-point bending test on the sandwich composite panels was conducted on the universal testing machine (Santam, STM150) with a load cell of 2000 N capacity and a crosshead speed of 2 mm/min. The specimens were cut into 15 × 5 cm (length× width). The span length of the test was 11cm. Three samples were tested for each specimen .Using ANOVA analysis, significance is considered at a 95% confidence level. Figure 4 shows the bending test setup.

Table 1 Schematic of stitch patterns used in the current study

	Stitch spacing		
Stitch seam angles	**0.5 cm**	**1 cm**	**2 cm**
0°			
90°			
0°/90°			
±45°			
90°/45°			
±60°			



(a)

(b)

Fig. 4 a) 3-point bending test, b) geometry of 3-point bending test

3 RESULTS AND DISCUSSIONS

The effect of different stitch densities and angles has been investigated by a three-point bending test. In order to be concise and easy to express the results, specimens are coded as **Sx.Ay**, which **S** and **A** are symbols of stitch spacing and stitch angle, respectively and the **x** and **y** are the adopted values for stitch spacing (0.5, 1, and 2 cm) and stitch angles (0, 90°, 0/90°, ±45°, 45°/90° and ±60°). For example, S2.A0 means the specimen with 2 cm stitch spacing and stitch angle of zero degrees in X direction.

3-1 Experimental steps

According to flow diagram shown in Figure 5, in order to reduce the number of samples in the current study, in the first step, the specimens were stitched in 1 and 2 cm stitch spacing with angles of 0, 90°, 0/90° and ±45°.

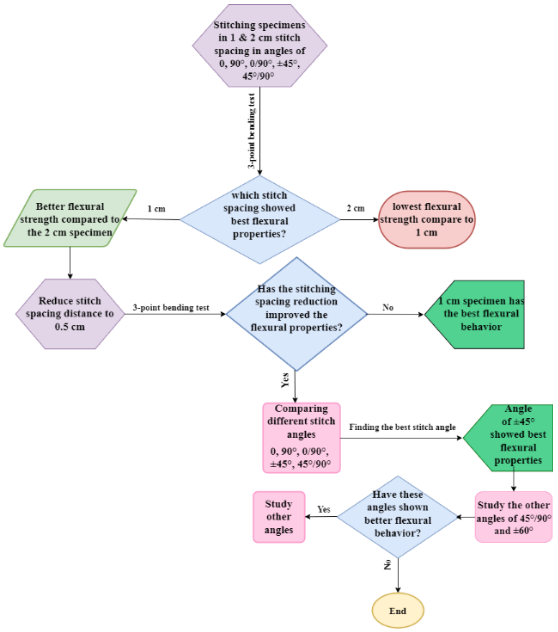
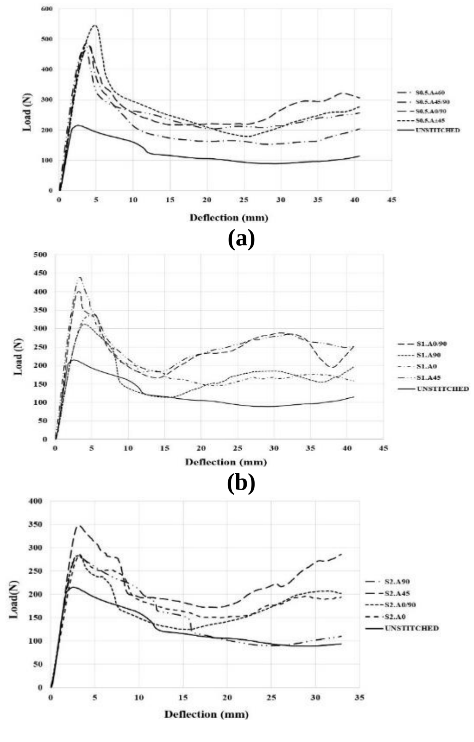


Fig. 5 Flowchart of the experimental steps

The results of three-point bending tests indicated that the specimens with 1cm stitch spacing have bending properties, so it was decided to reduce the stitch spacing to 0.5 cm. After the results of spacing reduction showed an increase in bending properties, the effect of other angles was investigated. The results indicated that the angle of ±45° showed better performance. So, for studying the effect of other angles, specimens with 0.5 cm stitch spacing were stitched in angles of 90°/45° and ±60°, but there wasn't a significant result. It was concluded that the ±45° has the best bending behavior.

3-2 Analysis of load-deflection curves

Figure 6 represents the load versus deflection plots obtained from the experimental test results. At the beginning of the curves, the structures are in the elastic stage, where the overall behavior of the sandwich composites is linear up to the maximum load. As shown in these figures, the maximum load of all stitched specimens is higher than that of the unstitched samples. After reaching the maximum load, the curve declines dramatically in the stitched sandwich panels, entering the plastic region. In the case of the unstitched specimen, the curve drops more gradually after the maximum load point. At this stage, core failure occurs due to crack formation in the foam, leading to a plateau behavior. As expected, the average force of stitched composites was consistently higher than that of unstitched samples during the plateau stage. Notably, the S0.5.A±45 specimen achieved the highest maximum load, which is 153.5% higher than that of the unstitched specimen. After core crushing, the densification stage is evident, with a rapid increase in load due to the compaction of the core section. The second drop in some curves indicates the failure of the bottom face-sheet.



(a)

(b)

(c)

Fig. 6 Load-deflection curves of stitched specimens: a) 0.5 cm stitch spacing, b) 1cm stitch spacing, c) 2cm stitch spacing, and comparison with unstitched specimen

In stitched specimens, after reaching the maximum load, a sharp drop in the curve has been observed. This drop increases with the increase of stitch density. Similar to the unstitched specimen, after the sharp drop, the curve progresses monotonically.

3-3 Faces bending stress and core shear stress

Faces bending stress and core shear stress were calculated by the equations (1) and (2) respectively [17], and the results are given in Table 2.

$$\sigma = \frac{PL}{2t(d+c)b} \quad (1)$$

$$\tau = \frac{P}{(d+c)b} \quad (2)$$

Where:

σ = face sheet bending stress (MPa);

τ = core shear stress (MPa);

P = load (N);

d = sandwich thickness (mm);

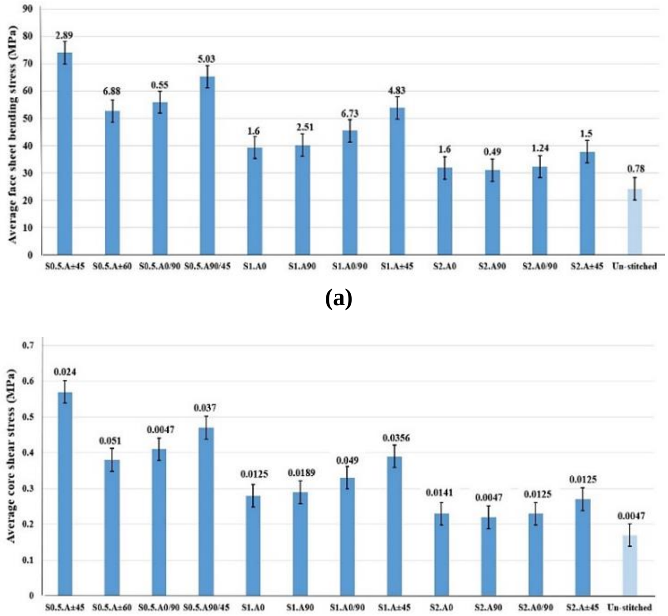
c = core thickness (mm);

b = sandwich width (mm);

t = facing thickness (mm);

L = span length (mm).

As previously stated, stitching results in an increase in maximum load. Specimens under bending load exhibit various stresses, with the upper face sheets experiencing compression and the bottom face sheets bearing tensile stress. The S0.5.A±45 specimen demonstrates the highest face-sheet bending stress and core shear stress, while the unstitched specimen shows the lowest values for both. Specifically, the face-sheet bending stress and core shear stress for S0.5.A±45 are 207% and 235% higher than those for the unstitched specimen, respectively. The comparison of face-sheet bending stress and core shear stress across different specimens is presented in Figures 7a and 7b. This is inferred that when the resin penetrates the stitch holes and makes resin columns, it causes an increment in stiffness and reduction of shear deformation in the core during bending loadings [23].



(a)

(b)

Fig. 7 Comparison of: a) Face-sheet bending stress, b) Core shear stress of specimens

Table 2 Results of three-point bending test of the sandwich composite specimens

Specimen	Thickness (mm)	Weight(g)	Max. Load (N)	CV%	Face-sheet bending stress (MPa)	CV%	Core shear stress (MPa)	CV%
S0.5.A±45	10.63	26.66	550	3.9	73.96	3.9	0.57	4.6
S0.5.A±60	11.81	24.53	436	13.1	52.56	13.1	0.38	13.42
S0.5.A0/90	12.31	27.35	484	0.98	55.83	0.98	0.41	1.14
S0.5.A90/45	10.64	24.15	485	7.7	65.13	7.71	0.47	7.87
S1.A0	11.64	21.76	321	4.06	39.23	4.07	0.28	4.3
S1.A90	11.62	20.63	327	6.28	40.073	6.26	0.29	6.5
S1.A0/90	12.35	23.39	394	14.84	45.37	14.8	0.33	14.84%
S1.A±45	12.15	22.63	459	8.9	53.77	8.9	0.39	9.12
S2.A0	13.48	21.03	302	5.24	31.78	5.03	0.23	6.13
S2.A90	13.02	20.17	285	1.57	30.98	1.5	0.22	2.04
S2.A0/90	12.61	22.98	286	3.84	32.2	3.84	0.23	5.43
S2.A±45	13.19	22.03	351	4.06	37.71	4	0.27	4.6
Un-stitched	12.77	19.70	217	3.24	24.08	3.2	0.17	2.8

3-4 Effect of stitch spacing and stitch angle

Obtained results from the 3-point bending test show that stitching improves the bending behavior of sandwich composites. In higher stitch densities, bending properties were enhanced.

Stitch spacing: In this study, three stitch spacing of 0.5, 1, and 2 cm were studied and compared to unstitched specimens. As was expected 0.5 cm spacing showed better flexural behavior. Dense stitching causes an effect named "bridge effect" in brittle cores, which results in the increment of flexural strength [16]. Figure 8 presents the comparison of different stitch spacing on maximum bending load. According to this figure, as the stitch spacing decreases, the ultimate bending load increases.

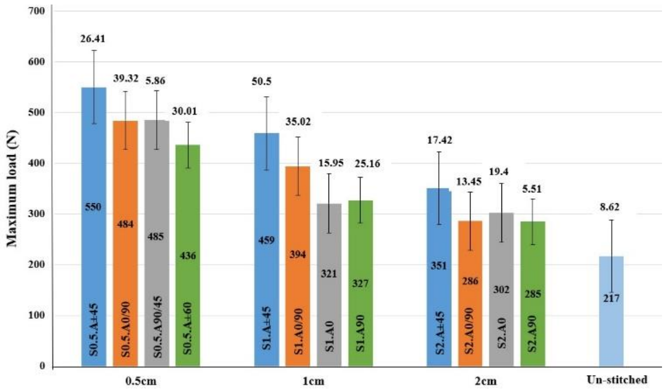


Fig. 8 Comparison of maximum load in different stitch spacing

Stitch seam angle: In all stitching angles, stitching has an impressive effect on the prevention of face-sheet and core de-bonding. In angles of 0˚ and 90˚ bending stress didn’t show any differences. According to Table 2, results showed that the face-sheet bending stress and core shear stress in specimens with stitch spacing of 1 and 2 cm and angles of 0° and 90° are very close. A combination of 0˚ and 90˚ gives better results. It can be concluded that specimen S0.5.A±45 had the highest improvement in bending rigidity compared to other specimens. In stitch angles of 0° and 90°, the stitch yarns are in alignment with the face-sheet fibers’ directions; therefore, the stitch yarns are unable to reinforce the sandwich composite in other directions. In specimen S0.5.A±45, because stitch yarns are reinforcing the composite at an additional angle, the specimen can control stress, especially shear stress, in the sandwich composite in additional directions. The comparison of load-deflection curves obtained from the 3-point bending test in ±45° in different stitch spacing is presented in Figure 9.

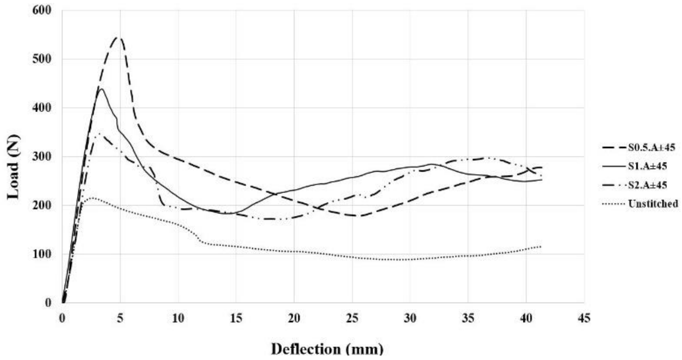


Fig. 9 Comparison of stitched specimens in ±45° and different stitch spacing with unstitched one

3-5 Absorbed energy

The absorbed energy could be obtained from the area under load versus displacement curves. In Figure 10, the absorbed energy for specimens with the angle of ±45˚ (the best stitch angle in the current study) and stitch spacing of 0.5, 1, and 2-centimeter are compared with unstitched specimens. The area under curves of stitched samples is more than the unstitched ones, which means that these specimens have absorbed much more energy. In other words, the energy required for the failure of stitched specimens is more than unstitched ones. The maximum amount of absorbed energy is 12.04 J for S0.5.A±45, which is 74.61% higher than the minimum value which is 6.89 J for the unstitched specimen.

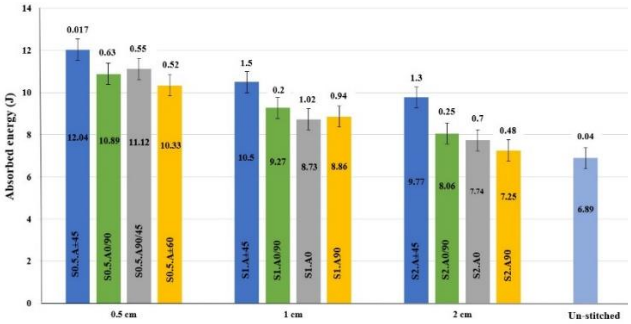
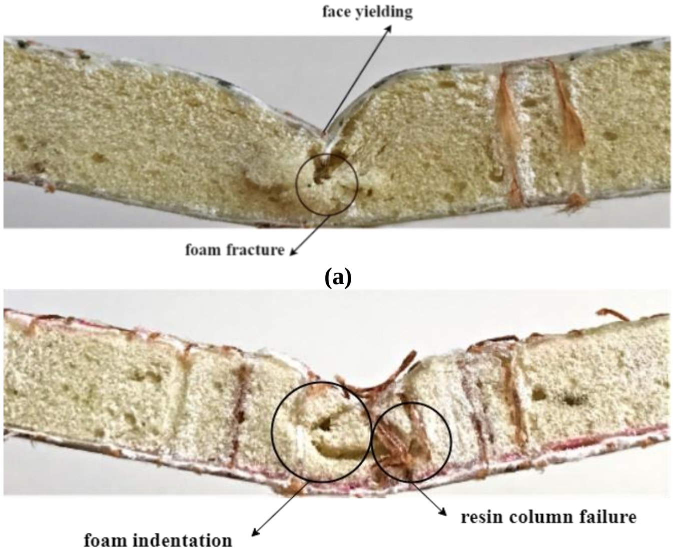


Fig. 10 Comparison of absorbed energy between stitched specimens in ±45° in different stitch spacing with unstitched specimen

3-6 Failure mode

In this section, the failure mode of sandwich composites was studied. In unstitched specimens, the structure is not brittle because of the homogenous structure of the core. According to Figure 11, the stitched specimens have higher flexural strength, and this makes the composite more brittle due to the presence of resin columns in the core section. In Figures 11(a) and 11(b), foam core fracture, indentation, and resin column fracture are shown. In applied load, indentation failure occurs in the core section of the sandwich structure; in other words, indentation happens in three point bending test when the foam core sandwich structure is under concentrated load. Stitching could prevent big indentations.



(a)

(b)

Fig. 11 Different failure modes; a) Face sheet yielding and foam core fracture, b) Foam indentation and resin column failure

4 CONCLUSIONS

Foam core sandwich composites are used more than other sandwich structures due to their stability, lightweight, and cost efficiency. Despite these advantages, there are some possibilities for failures of sandwich panels such as core yielding and face and core de-bonding. For the prevention of de-bonding problems in sandwich structures, there are chemical and mechanical solutions such as using solid adhesives or reinforcing through the thickness. In this study, the effect of stitching on the bending behavior of sandwich composites with E-glass composite face sheets and polyurethane foam core has been investigated. Specimens are stitched in stitch spacing of 0.5, 1 and 2 cm in different angles of 0, 90°, 0/90°, ±45°, 90°/45° and ±60°.

Results show that face-sheet bending stress, core shear stress, and the maximum load of all stitched specimens are higher than that of unstitched samples.

It has been observed that decreasing the stitch spacing improves flexural behavior, and 0.5 cm spacing samples showed better flexural behavior. Also, in terms of stitched angle, the best results are obtained for ±45°. Due to the highest stitch density and, therefore the higher volume of resin columns, the specimens with stitch spacing of 0.5 cm and stitch seam angle of ±45° (S0.5.A±45) have a 207% increase in face-sheet flexural stress and a 235% increase in core shear stress compared to the unstitched sample.

The area under curves of stitched samples, which indicates the absorbed energy, is more than the unstitched one, which means that these specimens have absorbed much more energy. In other words, the energy required for the failure of stitched specimens is more than unstitched ones. Also, the absorbed energy of stitched specimens increases with the increase in stitch density. The S0.5.A±45 sample had the highest amount of absorbed energy which was 74.61% more than the unstitched one.

In unstitched specimens, the structure is not brittle because of the homogenous structure of the core and stitching could prevent big indentations.

REFERENCES

[1] Dawood M, Taylor E, Rizkalla S. Two-way bending behavior of 3-D GFRP sandwich panels with through-thickness fiber insertions. Composite structures:2010;92:950-963.

[2] Midrehghan A, Nosraty H, Shokrieh MM, Akhbari M. Experimental Study on the Bending Behavior of 3D Woven Glass Fiber Sandwich Composite Panels. Journal of Textiles and Polymers: 2021; 9(2):3-14.

[3] Hasanalizadeh F, Dabiryan H. New Approach to characterize low-velocity impact behavior of sandwich-structured composite reinforced with weft-knitted spacer fabric. Journal of Textiles and Polymers: 2022; 10(3):35-41.

[4] Salimian A, Hadizadeh M, Zeini M. Investigations on the Reinforcement of Mechanical Properties of Gypsum Composites Containing E-glass Woven Fabrics. Journal of textiles and polymers: 2015; 4(1): 20-26.

[5] Tehrani Dehkordi M. Meso-scale Modeling of Tension Analysis of Pure and Intra-ply Hybrid Woven Composites Using Finite Element Method. Journal of Textiles and Polymers: 2015; 3(2):76-85.

[6] Nasr-Esfahani M, Latifi M, Amani-Tehrani M, Warnet L, Halvaei M. Enhancement of composite performance by hollow polyester fibers. Journal of Textiles and Polymers: 2014; 2(2): 5-10.

[7] Ahmadi-Vamakani S, Nosraty H, Tehrani-Dehkordi M. Study on Bending Damage of Intra-Ply Basalt/Nylon Hybrid Composites. Journal of Textiles and Polymers: 2018; 6(2): 59-66.

[8] Dow M B. Development of stitched, braided and woven composite structures in the ACT program and at Langley Research Center. National Aeronautics and Space Administration, Langley Research Center: 1997;206234.

[9] Sharma S, Krishna M, Murthy HN. Buckling response of stitched polyurethane foam composite sandwich structures. Journal of reinforced Plastics and Composites.2004; 23(2): 1267-1277.

[10] Potluri P, Kusak E, Reddy T. Novel stitch-bonded sandwich composite structures. Composite structures:2003;59(2):251-9.

[11] Stanley Larry E, Adams Daniel O. Development and evaluation of stitched sandwich panels. NASA/CR-2001-211025.

[12] Aktas A, Potluri P, Porat I. Multi-needle stitched composites for improved damage tolerance. in ICCM 17 International Conference on Composite Materials: 2009;17.

[13] Vả AK, Aả B, Aamanchi K. Mechanical Characterization of Stitched Foam Sandwich Panel by Varying Thread TPI. International Journal of Current Engineering and Technology 2014:62-66.

[14] Santhanakrishnan R, Dash P, Stanley AJ, Sabarish M. Flexural property evaluation of GFRP-foam sandwich composite–an experimental approach. ARPN J Eng Appl Sci:2012;7:1300-6.

[15] Lascoup B, Aboura Z, Khellil K, Benzeggagh M. On the mechanical effect of stitch addition in sandwich panel. Composites Science and Technology:2006;66(10):1385-1398.

[16] Lee GW, Choi JS, Lee SS, Park M, KIM, J, Choe CR, Lim S. Mechanical properties and failure mechanism of the polymer composite with 3-dimensionally stitched woven fabric. Macromolecular research:2003;11(2):98-103.

[17] Ai S, Mao Y, Pei Y, Fang D, Tang L. Effect of stitch on thermodynamic properties of sandwiched thermal protection structures. Composite Structures:2013;99:41-47.

[18] Ai S, Chen Y, He R. Effects of stitching parameters on the mechanical properties of stitched sandwich panel structures. Ceramics International:2021;47(4):5249-5255.

[19] Zheng XT, Zhang JF, Yang F, Chai YN, Li Y. Experimental and analytical study on the mechanical behavior of stitched sandwich composite panel with a foam core. *Advanced Materials Research. Trans Tech Publ*. 2008; 33:477-482.

[20] Henao A, Carrera A, Miravete A, Castejón L. Mechanical performance of through-thickness tufted sandwich structures. *Composite structures*. 2010; 92(9): 2052-2059.

[21] Eyvazian A, Taghizadeh SA, Hamouda AM, Tarlochan F, Moeinifard M, Gobbi M. Buckling and crushing behavior of foam-core hybrid composite sandwich columns under quasi-static edgewise compression. *Journal of Sandwich Structures & Materials*. 2021; 23(7): 2643-2670.

[22] ASTM C393-00, Standard Test Method for Flexural Properties of Sandwich Constructions. 2000.

[23] Yalkin HE, Icten BM, Alpyildiz T. Enhanced mechanical performance of foam core sandwich composites with through the thickness reinforced core. Composites Part B: Engineering. 2015; 79: 383-391.