Journal of Techniques, ISSN: 2708-8383, Vol. 7, No. 2, 2025, Pages 36-45
DOI: https://doi.org/10.51173/jt.v7i2.2604

JOURNAL OF TECHNIQUES

Journal homepage: http://journal.mtu.edu.iq

RESEARCH ARTICLE - MECHANICAL ENGINEERING

Experimental Investigation of the Mechanical Properties of Sewing Cores in Composite Sandwich Panels

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Article Info.

Article history:

Received
30 July 2024

Accepted
29 May 2025

Publishing
30 June 2025

Abstract

In this paper, the effect of stitching the core to the skins of composite sandwich panels made of a foam core covered by two composite skins is studied. The main aim of the research is to investigate the effect of sewing the core of the sandwich panel using polyester yarn on the mechanical properties of the sandwich panel. Therefore, by connecting two layers of 5 mm polystyrene foam, a core with a thickness of 10 mm is constructed, and fiberglass fabric is used for the manufacturing of the skins. Four 150^mm×32^mm×12^mm samples of sandwich panels with different dimensions are sewn and tested under the three-point bending test. The arrangements of the sewing are named N, M, W, and V according to the form of binding. Based on the results, sewing of the core increases the shear stiffness of the core, but it can cause damage to the core and reduce the strength of the sandwich panel. Among different sewing arrangements, N sewing showed the highest strength and maximum core stiffness.

Publisher: Middle Technical University

Keywords: Sandwich Panel; Composite; Core Sewing; Foam; Stiffness.

1. Introduction

Sandwich panels are light structures that have a very high load tolerance to weight ratio, which are made by two rigid skins attached to a soft core on both sides and have vast applications in industry. For example, these structures are used as walls and ceilings of buildings, prefabricated walls, wooden doors of rooms and closets, hulls of boats and planes, or any structure that requires high bending stiffness relative to the weight. Sandwich panels are also used as thermal, moisture and sound insulators in buildings. Due to the variety of sandwich panels, different types of sandwich panels have also been designed and produced. By changing the type of core or skins, different types of sandwich panels can be obtained, which are chosen depending on the working conditions. For example, composite sandwich panels are commonly used in aerial structures such as aircraft wings. In composite sandwich panels, cores and shells are made of composite materials.

According to the amount of use, the cores can be divided into three categories: honeycomb, foam and engineered cores, each of which has its advantages and disadvantages [1]. The most important mechanical properties of the cores considered in the design of sandwich panels are the modulus and compressive, tensile and shear strength, as well as the stability of the cores against atmospheric conditions such as heat and humidity in the construction of solar panels, aerial structures and light structures which are evaluated [2].

One of the most widely used composite sandwich panels is the foam core sandwich panel in which its core is made of foam and its skins are made of a combination of polymeric resins and woven reinforcements (glass or carbon fibers). Important features of polymer foams are elasticity, lightness, hardness, high porosity, high impactability and high energy absorption capacity [2].

In sandwich panels, skins are responsible for tolerating intra-plate forces due to stretching and bending. In addition, a larger portion of external impacts must also be tolerated by skin. The basic features of the shells that are desired by engineers and designers are: High stiffness that causes high bending stiffness, high tensile and compressive strength, impact resistance, surface milling, environmental resistance (chemical, ultraviolet light, heat, etc.) and abrasion resistance. Perhaps the best materials for skins are composites that have significant positive effects on the design and manufacture of sandwich panels. This is due to the high strength while usually their rigidity and weight are much less than metals. For this reason, engineers mostly use composite shells to achieve high strength in a lightweight core sandwich panel [3].

The bonding between the core material, typically made of lightweight foam or honeycomb structures, and the outer skin layers plays a significant role in determining the overall strength, stiffness, and durability of the composite panel. The adhesive is a binding agent that spreads load between layers. By attaching the core to the skin, it gives considerable rigidity and strength to the overall structure. To successfully connect them, the adhesive must be compatible with the shell and core material. Shells are usually much stiffer than soft and light cores, so the connection of these two materials requires special arrangements [4]. The failure of the sandwich panel should not be due to the failure of sticky connections, so the separation of the core and shell is not allowed [5].

Nomenclature & Symbols			
b	Width of Sandwich Panels (mm)	D	Bending Stiffness (kN.mm^2)
c	Core Thickness (mm)	U	Transverse Shear Rigidity Modulus (N)
t	Facing Thickness (mm)	G	Core Shear Modulus (MPa)
d	Total thickness of Sandwich Panel (mm)	P	Load (N)
S	Support Span Length (mm)	Δ	Deflection (mm)
L	Load Span Length (mm)		

One of the weaknesses of composite sandwich panels with foam core is the separation of core and skins. The use of more resin to connect the core and shell can cause a sharp increase in the weight of the structure. Studying bonding mechanisms, such as adhesive bonding or mechanical interlocking, can provide insights into how to improve the load-bearing capacity and resilience of these panels under various stress conditions. Here, an overview of recent research on the binding of core and skins in composite sandwich panels, focusing on different bonding mechanisms, surface treatments, and their impact on mechanical properties is provided.

One study by Rodrigues et al. [6] investigated the influence of different surface treatments on the bond strength between the core and skins of composite sandwich panels. Their research focused on evaluating the adhesive bonding performance of various surface treatments, such as chemical etching and plasma treatment, to enhance the adhesion between the core material and skin layers. The results showed that specific surface treatments significantly improved the bond strength and durability of the composite panels, leading to enhanced mechanical properties and structural performance. Babu et al. [7] explored the use of nanomaterial-based adhesives for improving the bond strength and impact resistance of composite panels. Their study demonstrated that incorporating nanomaterials in the adhesive layer can lead to significant improvements in interfacial bonding, resulting in enhanced mechanical properties. Additionally, Zhang et al. [8] investigated the effects of surface roughness on the bonding performance of composite sandwich panels. Li et al. [9] focused on the influence of environmental factors, such as humidity and temperature, on the bonding behavior of composite sandwich panels. In similar research, Wang et al. [10] explored the use of novel surface treatments, including atmospheric plasma and corona discharge, to enhance the adhesion between the core material and outer skins. Their research demonstrated that these surface treatments can promote better bonding at the interface, leading to improved structural performance of composite sandwich panels. Moreover, studies by Kim et al. [11] and Wu et al. [12] investigated the mechanical properties and failure mechanisms of bonded core-skin interfaces in composite panels under different loading conditions.

Stitching techniques have been increasingly explored to enhance the bonding between the core and skins in composite sandwich panels. Gok and Eren [13] investigated the effects of stitching density on the mechanical properties of stitched composite panels. Their study demonstrated that increasing the stitching density can significantly improve the interlaminar shear strength and delamination resistance of the panels, leading to enhanced structural performance. Furthermore, research by Soutis et al. [14] explored the use of 3D stitching technologies to reinforce composite sandwich panels. Their study highlighted the advantages of 3D stitching in enhancing the overall mechanical properties and damage tolerance of the panels. Moreover, Feng et al. [15] studied the influence of stitching patterns on the bending and impact behavior of stitched composite sandwich panels. Their research demonstrated that optimizing the stitching patterns can effectively distribute the load and enhance the mechanical properties of the panels under different loading conditions. Additionally, studies by Akinc and Bakir [16] and Zhang et al. [17] focused on the development of advanced stitching materials and processes to improve the bond strength between the core and skins in composite sandwich panels. Their findings highlighted the importance of selecting appropriate stitching materials and techniques to achieve optimal bonding performance. Furthermore, research by Duan et al. [18] and Li et al. [19] investigated the fatigue behavior and failure mechanisms of stitched core-skin interfaces in composite panels. By conducting fatigue testing and failure analysis, these studies provided valuable insights into the durability and damage tolerance of stitched composite sandwich panels under cyclic loading conditions.

Overall, the research reviewed in this paper underscores the importance of enhancing the bond strength and durability of core-skin interfaces in composite sandwich panels and emphasizes the significant role of stitching techniques in improving the bonding of core and skins in composite sandwich panels. By exploring different stitching methods, patterns, materials, and their effects on mechanical properties, researchers and engineers can develop innovative solutions to enhance the structural performance and durability of composite materials for diverse applications in aerospace, automotive, marine, and other industries.

The purpose of this research is to stitch foam core to composite skins of sandwich panels with several different stitching patterns to improve the skin-core binding strength. Using bending tests, the strength shear modulus and flexural stiffness of the designed sandwich panels are determined and compared. In the next section, the method and procedures of sample manufacture and test performance will be explained and then, the results will be discussed and analyzed. The geometry of specimens for bending tests and fabrication techniques are explained in the next section. However, the stitching technique, which typically involves creating holes in the core, can weaken the overall properties of the structure. This drawback will be discussed in the results section, and some suggestions will be provided to overcome it.

2. Materials and methods

In this section, the materials used for the fabrication of beam sandwich panels and the method of fabrication will be presented. First, the ASTM standard test D7250 [20] is introduced for the 3-point bending test of the beam sandwich panel, in which the appropriate geometry of specimens is also determined.

2.1. ASTM standard test D7250

In order to calculate the shear and bending stiffness of the sandwich panel, the 3-point bending test based on the D7250 standard is performed. In this standard, two methods are presented to calculate flexural stiffness, transverse shear modulus and core shear modulus in a sandwich beam. the elastic modulus value of the skins (shells) is known, the first method is used in which each sample is tested more than once and in each loading the distance of the supports or bars (in 4-point loading) is different. If the elastic modulus of the skins is known, the second method is applied, and each sample is loaded only once. In our case, the elastic modulus of skins is known, so the second method of ASTM test D7250 which is a three-point bending test (Fig. 1) is introduced.

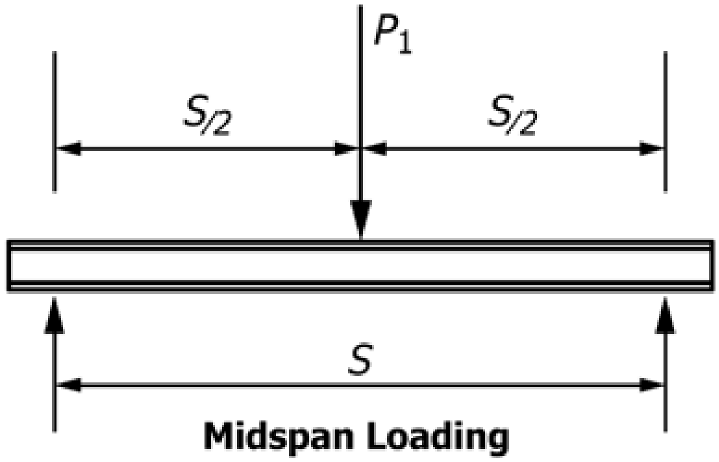


Fig. 1. Three-point loading [20]

In the second method of bending test, it is assumed that the elastic modulus value of the skins (shells) E is known and the shells on both sides are the same. In this case, the shear modulus of the core G and the transverse shear rigidity modulus of the sandwich panel U are obtained with only one bending test. First, flexural stiffness is calculated. Then, for each sample, shear rigidity and core shear modulus is calculated for a set of forces up to the maximum force. These values must be calculated for at least 10 force categories at equal intervals from zero to maximum force. The average value of shear rigidity and the core shear modulus is calculated using the obtained values. As a result, stiffness values are obtained as a function of the force value. If the sandwich panel behavior is linear, the mean value of bending stiffness, shear rigidity, and core shear modulus can be considered the same for all forces.

2.2. Design of sandwich panels

In this section, the design, method of construction, and preparation of sandwich panel samples will be explained. The size of sandwich panels is determined according to the D7250 standard. Then, the materials used and the fabrication method for the samples will be explained.

2.3. Dimensions of specimens

According to the D7250 standard, the samples must have a rectangular section. the depth of specimens should be uniform, and their width should not be less than twice the thickness of the whole should not be less than three times the size of a core cell and should not be greater than half the distance of the support. the length of the piece should be equal to the support distance plus 50 mm or half the thickness of the sandwich panel whichever is greater. According to these explanations, since foam core is used in this research, there is no limitation regarding the size of the sandwich panel width compared to the size of the core cells. Of course, the number of core sewings should be more than three along the width of sandwich panels. The proposed geometry of the sandwich panels is shown in Fig. 2.

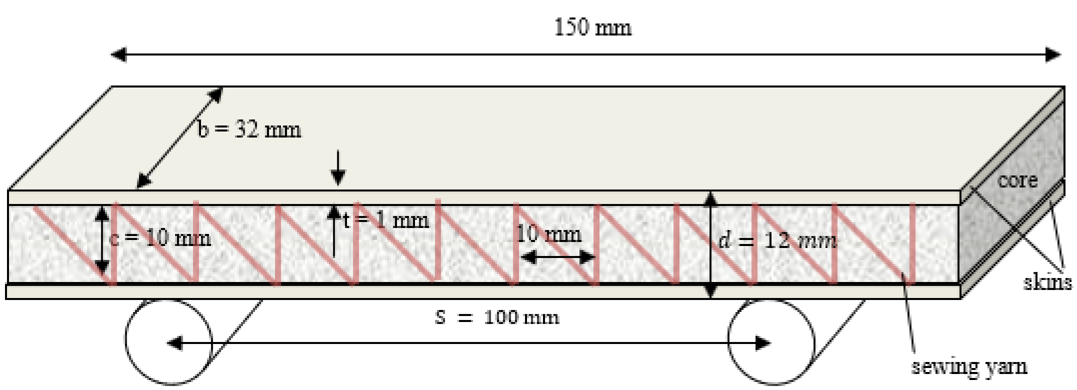


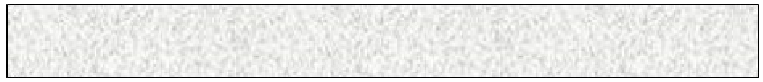
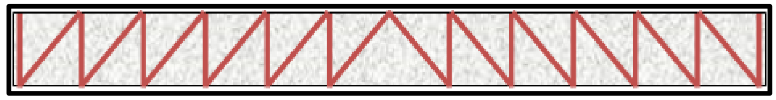
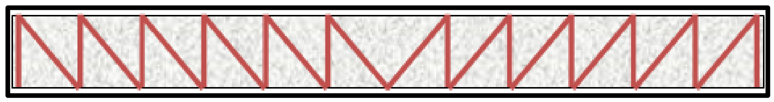
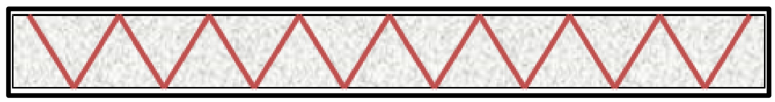
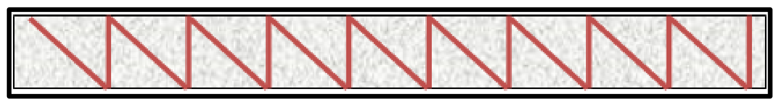
Fig. 2. The size of sandwich panels is determined according to the ASTM standard D7250

2.4. The patterns for the core-skins sewing

Polyester yarn is used to sew the skins to the core of the sandwich panel to avoid core-skin debonding and increase the flexural rigidity of the structure. The stitching patterns used in this study are shown in Table 1.

It is important to note that while the W and M stitching patterns are similar in structure, they differ in terms of loading directions and the consequent distribution of internal loads on the sewing yarns. In a three-point bending test, the top surface of the panel experiences compression, while the bottom surface experiences tension. By changing the direction of the stitched yarns from a W pattern to an M pattern, the influence of yarn direction on mechanical performance can be illustrated.

Table 1. Naming specimens based on the core-skin sewing pattern

Name of specimen		Sewing pattern
Foamy core	0	
Sandwich panel without sewing	1	
W shape sewing	2	
M shape sewing	3	
V shape sewing	5	
N shape sewing	6	

3. Fabrication of Specimens

To fabricate specimens, first the foam core was prepared in the required size. Then a layer of fiberglass fabric was wrapped around the core with millimetre checkered paper. It should be noted that the fiberglass fabric is aligned with the length of the beam. Then, according to the patterns introduced in Table 1, polyester yarn is used to sew the core to the fiberglass layer. To sew cores, first the polyester yarn passes through the sewing needle gap and is then impregnated with resin (Fig. 3.a). Additional resin should be removed, and the yarn should carefully follow the designed patterns. The main materials used for the manufacture of sandwich panels are plain textured fiberglass fabric (200), polyester yarn, epoxy resin, and expanded polystyrene foam (EPS). These sandwich panels are more suitable for applications where lightweight and thermal insulation properties are prioritized over structural strength, such as cold storage, lightweight transportation, marine applications, and packaging solutions.

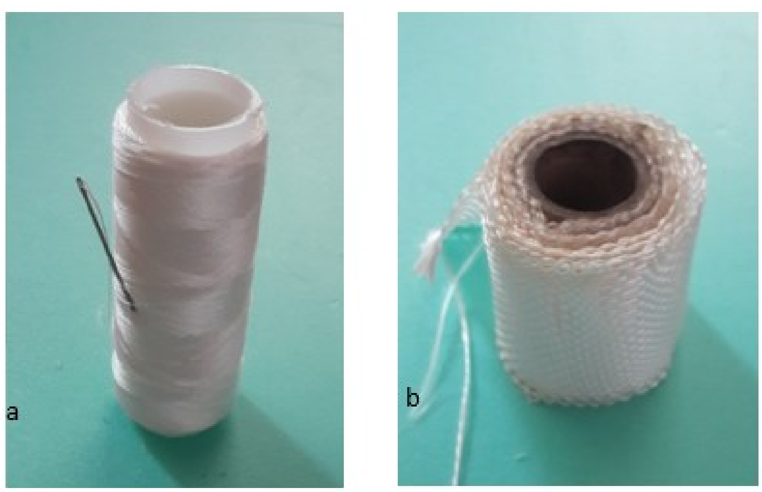


Fig. 3. a) Polyester yarn, and b) plain textured glass fiber fabric

It should be noted that polyester resins, although a good option for making fiberglass composites, are a strong solvent for polystyrene foam and this type of resin cannot be used alongside polystyrene foam. Therefore epoxy resin is used as a matrix of the composite skins of sandwich panels. The thickness of the foams is 5 mm. Therefore, in order to obtain a core with a thickness of 10 mm, two layers of foam core are glued to make a core with 10 mm thickness.

After drying the adhesive, the core is cut to the standard size by a sharp cutter, and then the strip of plain-woven glass fiber fabric is wrapped around the foamy core to create the first layer of the skins. On this strip of glass fibers, a checkered paper is pasted as a guide for stitching the core to the skins according to the patterns given in Table 1. Fig. 4 shown the EPS cores, cores with woven glass fiber and checkered paper are displayed.

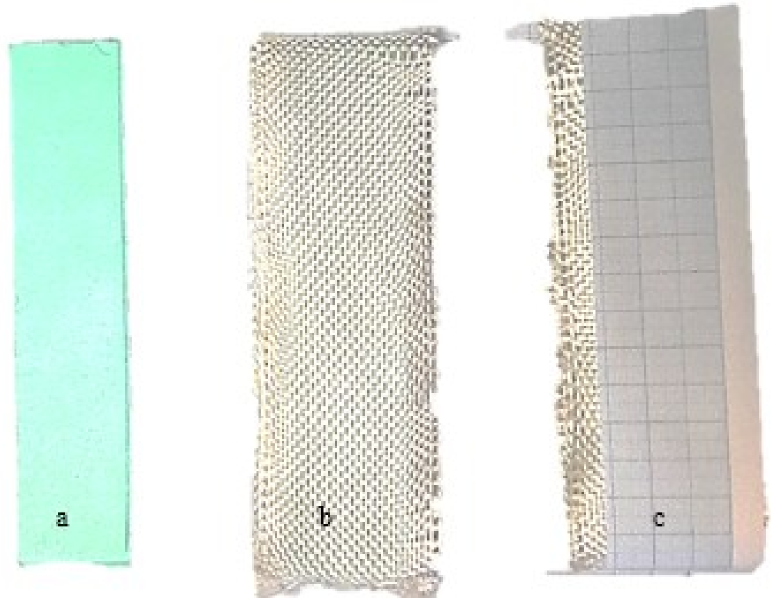


Fig. 4. Preparation and construction stages of foam core: a) foamy core, (150mm × 32mm), b) wrapping plain fiberglass tissue, c) wrapping crossword paper for stitching

Based on the patterns given in Table 1, the core is sewn without impregnating sewing yarn in resin. The sewing is performed carefully by hand without the use of any special devices. The resin-free sewing yarn acts as a truss structure that only tolerates tension. As shown in Table 1, the cores are sewn in N, M, W and V patterns. In Fig. 5, some samples of sewn cores are shown.

Finally, after completing the sewing of the skins to the core, two more layers of woven glass fibers are pasted to each side of the sandwich panels. Therefore, each skin of sandwich panels includes three layers of fiberglass fabric. Fig. 6 shows some of the stitched sandwich panels after adding two more fiberglass layers to each side.

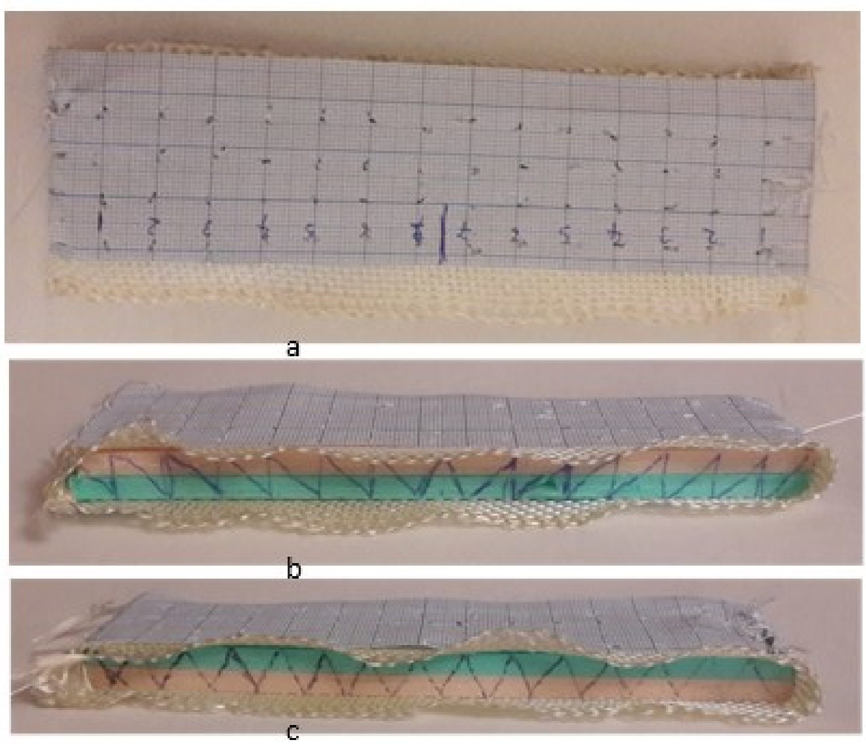


Fig. 5: a) Top view of the stitched sandwich panel before applying resin, b) side view of W pattern, and c) side view of V pattern

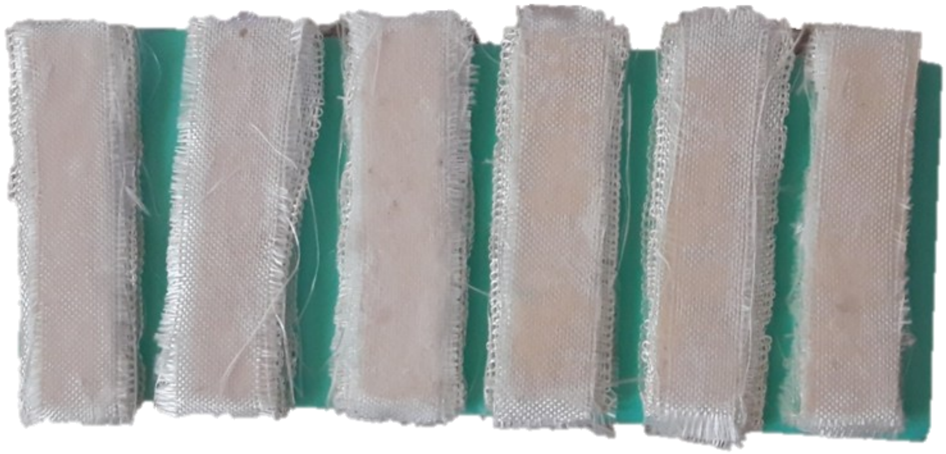


Fig. 6. Applying resin and adding two layers of fiberglass fabric to each side of stitched sandwich panels

Table 2. Geometric dimensions of samples

dimensions	unit	Explanation
b=32	mm	sandwich width,
c=10	mm	core thickness,
t=1	mm	Facing thickness
d=12	mm	Sandwich total thickness,
S=100	mm	support span length,
L=0	mm	load span length, mm [in.] (*L* = 0.0 for 3-point mid-span loading configuration)

4. Results and Discussion

In this section, the results of the three-point bending test on the fabricated sandwich panels are analysed. A tensile test machine is used to perform the three-point bending test, which produces a force-displacement diagram. Then, based on the relationships given by the ASTM standard test D7250, the shear modulus and transverse shear rigidity of the specimens are calculated. In order to minimize fabrication faults, a group of three specimens is used for each sewing pattern, and the average force-displacement curves of each group are determined for analysis.

4.1. Three-point bending test

As shown in Fig. 7, a two-ton SANTAM universal tensile testing machine is used to perform the bending tests. The Fig. 7 shows the tensile testing machine used for this test, and the geometric dimensions of samples and the three-point bending test parameters are given in Table 2.

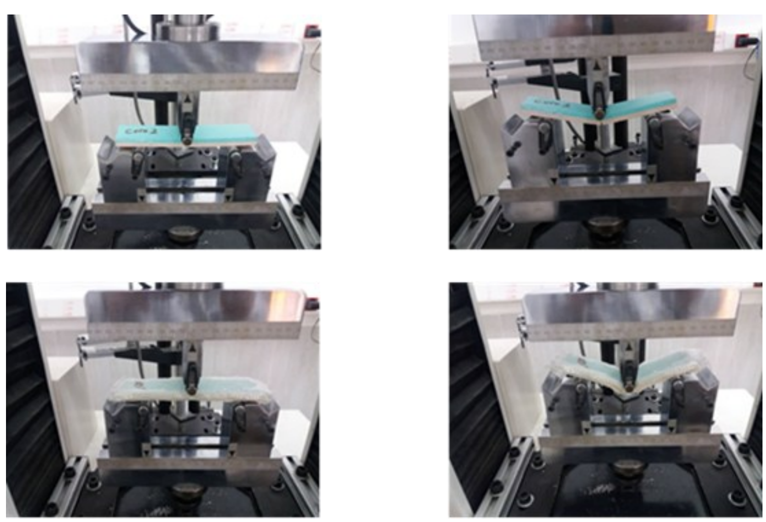


Fig. 7. A two-ton tensile test machine is used for the three-point bending tests of sandwich beams

4.1.1. Bending of foamy core

The results of the three-point bending test of a simple foamy beam (the core of sandwich panels) without skins are shown in Fig. 8. The load-deflection curve is almost linear until the compression load reaches a point, and then it reaches a maximum of 17 N of force with a deflection of approximately seven millimeters. The maximum deflection is 9 mm.

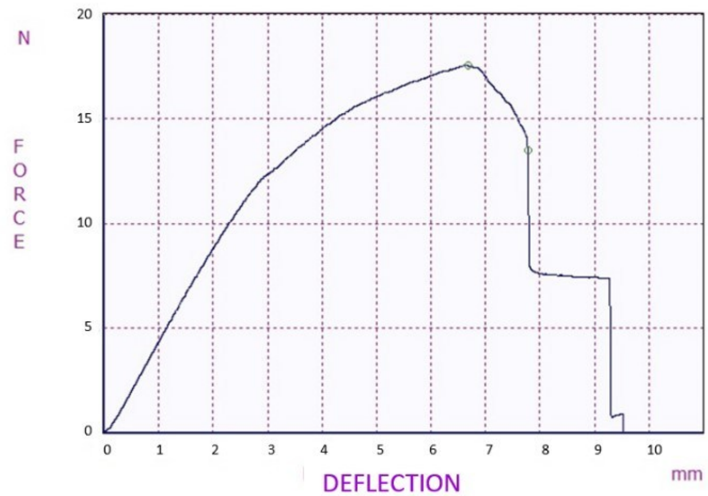


Fig. 8. Force-displacement diagram of a foamy core of sandwich panels

4.1.2. Sandwich panel without stitching

These samples have two composite shells, each consisting of three layers with a foam core, without sewing. The test result shows that the maximum tolerance force is 139.6 N, which occurs at 6 mm deflection. As the deflection of the beam increases, the necessary force drops, showing a 24 mm deflection before complete failure. For the sake of comparison, the average force-displacement diagram of each sample obtained from bending tests will be shown in Fig. 9.

4.1.3. Sandwich panel with N shape stitching

The samples with N shape stitching have a foam core with two composite skins, which have been sewn in the form of letter N. On average, this sample behaves linearly up to the maximum force point, which is 141.6 N. The composite beam deflection at the maximum point of force is 2.5 mm and has endured a maximum of 30 mm deflection. The remarkable point in this beam is the re-increase of maximum bearing load after the first failure point.

4.1.4. Sandwich panel with M shape stitching

The maximum tolerated force in this sample was about 106 N, which occurred at a 3 mm deflection. The maximum force is about 100 N at a 2.5 mm deflection. Like the N sample, this sandwich panel also shows an increase in force again after the reduction of strength, indicating the appearance of an internal resistance in the beam after the initial failure, which is due to the woven yarns.

4.1.5. Sandwich panel with W shape stitching

The W sample's mechanical response to the mid-span load is quite similar to the M samples. The ultimate load in W samples was approximately 103 N, which occurred at a 3 mm deflection. As shown in Fig. 9, after the initial failure, the W beam also shows hardening behaviour that is due to the generated tension in yarns.

4.1.6. Sandwich panel with V-shaped stitching

In these samples, the highest tolerant force was 100 N, which occurred at a 2.5 mm deflection. Unlike N, W, and M samples, this sample showed no secondary flexural stiffness. The maximum deflection of this beam is 26 mm.

4.2. Comparison

In Fig. 9, the average load-displacement curve of the three-point bending test is displayed for six different groups of specimens. According to these results, the foam core without skins (orange colour) has the lowest loading capacity compared to other specimens. The sandwich panel without sewing the core is shown in black, shows high loading capacity. However, the samples with a sewn core have a steeper diagram slope compared to the sandwich panel without sewing, which implies their higher flexural stiffness. Among these samples, the N sample has the highest slope of the diagram in the pre-failure region and also has higher yielding strength in comparison to the other specimens.

Another point to consider in these results is the gradual increase in the force required for deformation in the sewn beams after passing through the failure point. The initial yield point is due to the failure of composite shells, which causes the most changes in the behavior of the beam. In composite beams with sewn cores, the yarns used for sewing the core are gradually stretched, increasing the force needed for the deflection.

It is observed that the load-deflection diagram of the sewn samples shows significantly larger deflections compared to the simple panel after the initial failure. Interestingly, this large deflection is accompanied by a higher load. For example, in the N-shaped sewn panel, the maximum deflection exceeds 30 millimeters under a load of 110 N, whereas the simple panel fails at a deflection of 25 mm and a load of 70 N. The results also show that the sewn cores M, W, and V have less yield strength than the sample without sewing, since the yarn used for sewing the core is not impregnated with resin and only tolerates tension, it can be said that the sewing of the core causes cracks in the foam core, which reduces the strength of the core and consequently reduces the strength of the structure. Therefore, it is suggested that the core sewing method be modified in such a way that it does not cause damage to the core. Several approaches can be employed to minimize damage to the core during the sewing process, which can help mitigate the negative effects on overall strength. For instance, using high-speed drilling, hot needle, or laser drilling can significantly reduce the occurrence of microcracks in the core material. Additionally, exploring alternative fastening methods, such as adhesive bonding or composite materials for the core, may further enhance the design and performance of the sandwich panels.

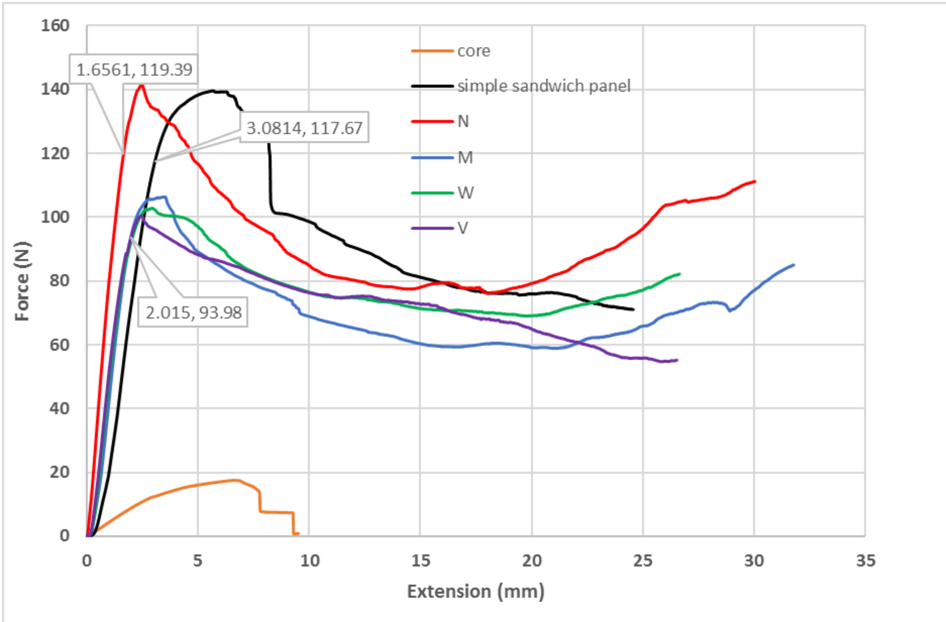


Fig. 9. Comparison of displacement-force diagrams of different samples

4.3. Calculation of core shear module, G

The ASTM test standard D7250 has introduced two methods to calculate the core shear module, G, and the cross-section rigidity modulus of the sandwich panel U. Here the second method is used to perform the calculations. In this method, it is assumed that the elastic moduli of the shells on two sides are the same. In this case, the modulus of the transverse shear rigidity of the beam U and the shear modulus of the core of the sandwich panel is obtained only by a single three-point bending test. Then for each sample, the shear rigidity and shear modulus of the core for a set of forces is calculated to the highest amount of force. These values must be calculated for at least 10 force categories at equal intervals from zero to the maximum force. The average value of shear rigidity and the core shear modulus are calculated using the obtained values. As a result, stiffness values are obtained as a function of the force values. If the sandwich panel behavior is linear, the mean value of bending stiffness D, shear rigidity U, and core shear modulus G can be considered the same for all forces.

$$D = \frac{E(d^3 - c^3)b}{12} \tag{1}$$

$$U = \frac{P(S_1 - L_1)}{4\left[\Delta - \frac{P(2S_1^3 - 3S_1L_1^2 + L_1^3)}{96D}\right]} \tag{2}$$

$$G = \frac{U(d - 2t)}{(d - t)^2 b} \tag{3}$$

Where E is the elastic modulus of the shell in terms of MPa and $c = d - 2t$ is the thickness of the core in mm. The elastic modulus of composite skins was obtained from a tensile test, equal to 14000 MPa. The dimensional differences in the beams are negligible, and the geometrical characteristics of the beams are considered identical. According to Eq. 1, bending stiffness is the same for all beams, $D = 27178.67\ kN.mm^2$.

For all samples, the force P and deflection Δ values are considered at the highest point of the force-displacement diagram, which has an insignificant deviation from linear behavior. The values of these parameters are shown in Fig. 9, where the three groups of specimens, M, W, and V are roughly the same.

The results of the calculation of the core shear modulus G and transverse shear rigidity modulus U are listed in Table 3 for different samples.

Table 3. Core shear modulus and transverse shear modulus values for different samples

Sandwich panel sample	load, P (N)	Deflectio ،Δ (mm)	Transverse shear rigidity modulus U (N)	Core shear modulus G (MPa)
(S) No sewing	117.7	3.08	984.2	2.54
N	119.4	1.66	1903.1	4.92
M	94	2.02	1206.4	3.12
W	94	2.02	1206.4	3.12
V	94	2.02	1206.4	3.12

As can be seen in Fig. 10, due to the uniformity of force and displacement in M, W, and V samples, the core shear modulus of these samples also shows the same values.

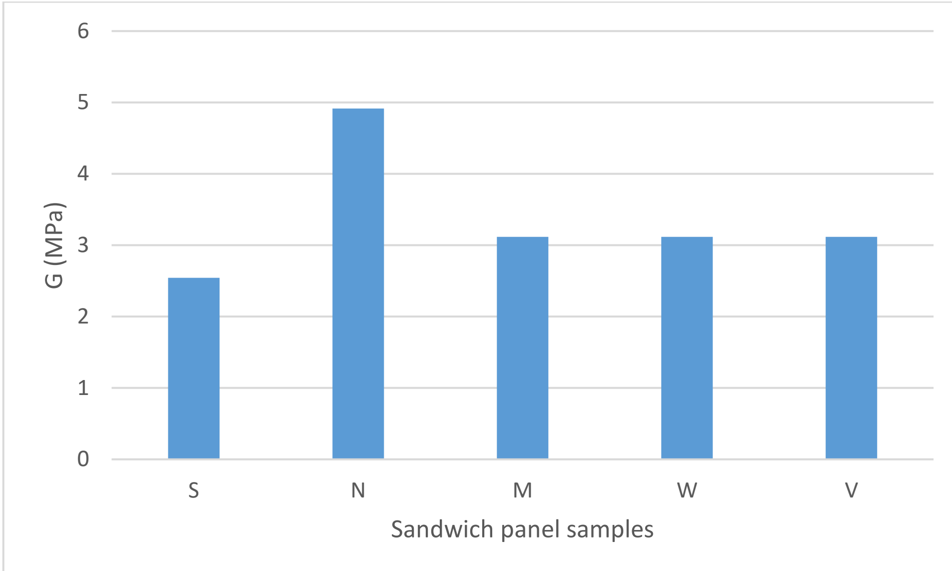


Fig. 10. Core shear modulus of sandwich panels

According to the above results, it can be concluded that sewing the core with fiber yarn can increase the shear stiffness of the sandwich panel core, but it may reduce its strength due to the damage caused by stitching.

5. Conclusion

In this paper, the stitching of the core skins of composite sandwich panels was studied. The purpose of this research is to sew the foam core to the skins and create tension members to improve the strength and stiffness of composite sandwich panels. For this purpose, using yarn-like reinforcement, the mechanical properties of the sandwich panel were enhanced, and the results were compared with simple sandwich panels. In this study, using a three-point bending test, the strength shear modulus and bending stiffness were determined and compared for six samples of sandwich panels. The geometry of the sandwich panels is determined by the ASTM standard D7250. The skins are made of fiberglass composite and EPS foam is used for the core. The specimens underwent three-point bending tests. Six groups of samples were tested, 5 of which were sandwich panels with composite shells and one sample was a foam core without skins. In four cases the core-skins are sewn in W, M, V and N patterns, and one of the samples left without stitching the core. The most important results obtained from these tests are:

- The core sewing samples demonstrate greater stiffness compared to the sandwich panel without stitching. Notably, the N sample exhibits the highest stiffness among the stitched samples, as indicated by its steep load-deflection curve, which suggests a more effective resistance to deformation under load.
- The force required for deformation in sewn beams, after passing through the yield point, is initially reduced and then increased. In composite beams with sewn cores, the yarns used in the core are gradually stretched, increasing the force needed to create a deflection in the beam.
- The results indicate that the sewn core samples (M, W, V) exhibit lower yield strength compared to the samples without sewing, which is attributed to the damage incurred during the sewing process.
- Sewing the core with yarn increases the shear stiffness of the sandwich panel.

Based on the observed results, some suggestions are presented to modify the core sewing method and to continue this research.

- It is suggested that the core sewing method be modified in such a way that it does not cause damage to the core.
- Using numerical modeling, the number of shell layers and pattern of sewing can be optimized.

Acknowledgment

The authors gratefully acknowledge the Kermanshah Campus of Islamic Azad University for its academic support and resources.

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