




## Research Article

# Determination of corrugated core sandwich panels elastic constant based on three different experimental methods and effect of structural integrity on flexural properties

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## Abstract

This study deals with the investigation of flexural stiffness and transverse shear rigidity in the direction of corrugation of the integrated and non-integrated corrugated core sandwich panels with the rectangular core. The non-integrated sandwich panels were reinforced with conventional 2-D fabrics in which resin provides the bond between core and skins. The integrated sandwich panels were reinforced with 3-D weft knitted fabrics in which bonding of the core wall to skins was carried out by combined efforts of knitted loop and resin. Using weft knitting technical capabilities, samples of the integrated and non-integrated structures were manufactured with the uppermost degree of resemblance in terms of geometry and mass. Flexural stiffness and transverse shear rigidity of the structures based on the known and unknown facing modulus of ASTM D7250 standard and Nordstrand–Carlsson methods were calculated. The estimated elastic constants based on unknown facing modulus and the Nordstrand–Carlsson methods were found to be highly compatible. However, the unknown facing modulus method is prone to disclose the statistical significant differences between the elastic constants of the structures with fewer tests. Regarding the unknown facing modulus method, it was found that the flexural stiffness and transverse shear rigidity of the non-integrated structure in the direction of corrugation were higher than those of the integrated structure. Results also indicated that the load-carrying capacity in the direction of corrugation was significantly higher in case of the non-integrated rectangular core structure compared with that of the integrated structure.

**Keywords** Corrugated core sandwich panel · 3-D weft knitted fabric · Integrated structure · Non-integrated structure · Flexural stiffness · Transverse shear rigidity

## 1 Introduction

Sandwich panels are composed of a thick and low-density core which is sandwiched by two thin and stiff skins or face sheets [1, 2]. High specific flexural stiffness and strength are among the main features of sandwich panels. The core can be composed of miscellaneous materials such as foam, honeycomb, and corrugated sheets. Corrugated cores in comparison with foam or honeycomb are superior as far as

factors such as shear strength in the transverse direction of corrugation, strength to weight ratio, structural integrity, and fluid storage capacity are concerned. The core geometry in the corrugated core sandwich panels is more than often trapezoidal (hat-type), rectangular, triangular, circular, and sinusoidal [3, 4]. An additional bonding operation using adhesive is used in the production of the laminated composite where core and skins have to be prepared separately. Poor mechanical performance of adhesive,

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complexity associated with predication, and determination of joints strength as well as small contact surface area between the core and the skins are among the disadvantages associated with the adhesively bonded corrugated core sandwich panels. The stated disadvantages may lead to the poor mechanical performance of the resultant composite structures or their delamination [5–10]. Taghizadeh et al. [11] experimental investigation revealed that the delamination of skin–core is the principle damage mechanism that can occur in corrugated core sandwich panel composites. Blingardi et al. [8] investigated the mechanical properties of the foam core sandwich panel composites using 4-point bending tests. It was found that skin–core delamination due to shear failure is the principle cause of structural failure of the sample. It was also established that the addition of a resin network perpendicular to the skins enhances flexural strength and impact resistance of the structure. Zhang et al. [7] investigated the effect of corrugation angle, core-sheet thickness, and core to skins bond length on the flexural strength of the corrugated core sandwich panel composites in the transverse direction of corrugation. It was found that not only failure occurs in the bond length but also specific flexural strength at a given corrugation angle and core-sheet thickness is reduced due to an increase in the bond length.

When 3-D fabrics are used as reinforcement in composites, the presence of Z-yarn along the thickness eliminates the poor bonding of the laminated layers [5, 12]. The integrated composites reinforced with 3-D fabrics have higher inter-laminar shear load-carrying capacity than the non-integrated version. The integrated composites possess higher delamination resistance. Additionally, strength along the thickness in the integrated structures is higher than those of the non-integrated version. The mechanical and thermal stability of the integrated structures along principle directions is unique [5, 13]. Karahan et al. [14] compared conventional foam core sandwich panel composites with 3-D integrated sandwich panel composites in which the connection of the skins to each other was made using pile yarns. It was concluded that the use of pile yarns significantly improves the compression behavior of the 3-D integrated sandwiched panel. Ivanov et al. [15] and Lomov et al. [16] compared conventional non-integrated 2-D woven laminated composite with integrated non-crimp 3-D orthogonal woven composite. It was found that as far as in-plane strength, failure strain, and damage initiation thresholds were concerned, the integrated composite was significantly superior in comparison with the non-integrated.

Numerous researchers have extensively investigated the elastic constants of the corrugated core sandwich panels using a variety of methods. Libove and Hubka [17] were the first in presenting an analytical method for the

determination of the elastic constants of the corrugated core sandwich panels based on homogenization theory. Boorle [3] using the same theory studied the effect of the corrugation angle on the elastic constants of corrugated core sandwich panels. Boorle, with aim of obtaining equal cross section area and equal weight and hence achieving better comparison, manipulated the core wall thickness in relation to changes in corrugation angle. Carlsson et al. [6] investigation was related to determination of the elastic constants of corrugated core sandwich panels. The investigation was based on the first-order shear deformation laminated plate theory and the experimental 3-point bending and block shear tests. It was found that in-plane extensional, shear, bending, and twisting stiffness are all dependent on the tensile and shear stiffness of the skins. Additionally, it was stated that the transverse shear rigidity is depended on both the integrity and geometry of the core together with the characteristics of the skins to core bonding. It was also concluded that the 3-point bending test in comparison with the block shear test is bound to yields more reliable results. Lu and Zhu [18] using 3-point bending, block shear and flat-wise compression tests, experimentally determined elastic constants of unequal weight corrugated cardboard panels with various core depth, pitches, skin, and core wall thickness. Carlsson et al. [6] and Lu and Zhu [18] using Timoshenko's deflection equation for the bent beams based on Nordstrand–Carlsson method [19] determined the flexural stiffness and transverse shear rigidity of the beam. An in-depth and precise review of the conducted studies vividly points to the inadequacy of the experimental studies in comparison with the elastic constants of weight-wise similar sandwich panels.

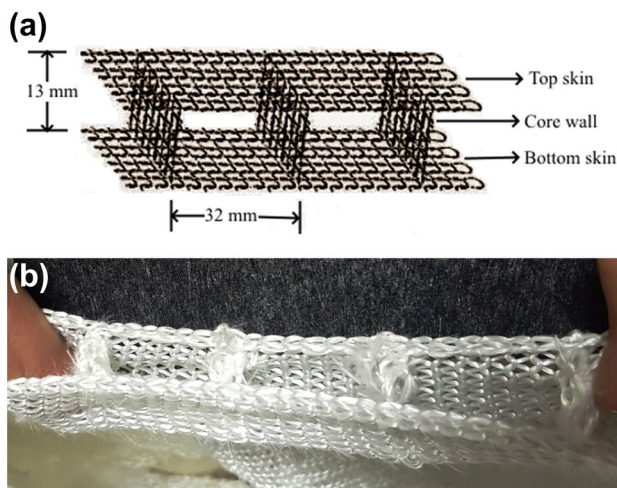
In this research, integrated and non-integrated corrugated core sandwich panels with uppermost weight and geometry resemblance were produced. The non-integrated sandwich panel sample was reinforced with conventional laminated 2-D weft knitted fabrics. The integrated sandwich panel was reinforced with a 3-D weft knitted fabric. Additionally, the bonding of the skins to core in the non-integrated sandwich panel was solely achieved using resin. The bonding of the core wall to the skins in the integrated sandwich panel was achieved by combined efforts of yarns and resin. These two types of composite structures were prepared using vacuum assisted resin transfer molding (VARTM) method. Experimental 3-point and 4-point bending tests were used to determine load-carrying capacity, flexural stiffness, and transverse shear rigidity of the integrated and non-integrated sandwich panels. In order to establish the effect of structural integrity on the flexural stiffness and transverse shear rigidity of the corrugated core sandwich panels, elastic constants of the integrated and non-integrated sandwich panels were

compared. Calculation of the elastic constants of the structures was carried out using three methods of known and unknown facing modulus based on ASTM D7250 standard and Nordstrand–Carlsson method. The tri-comparisons were used to vividly highlight the advantages and disadvantages associated with respected three investigation methods.

## 2 Materials and methods

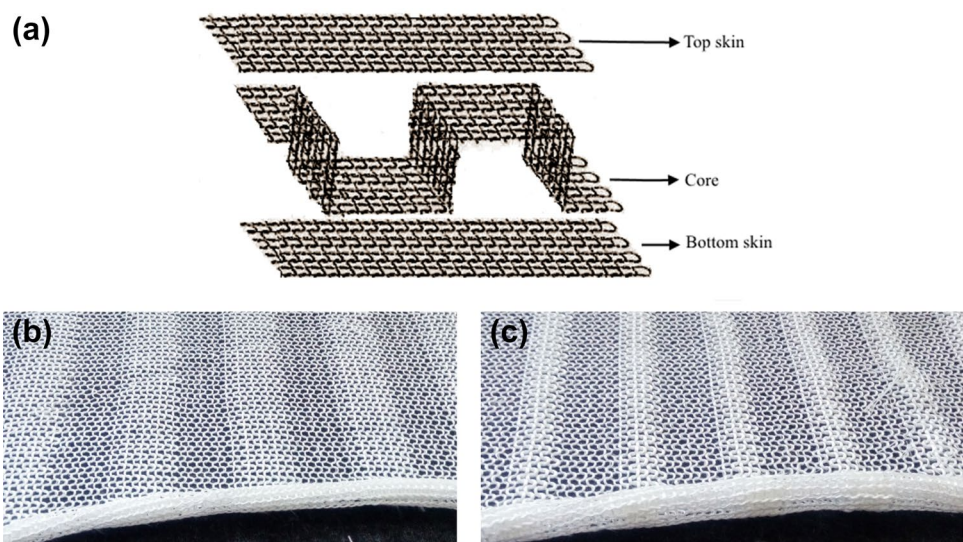
### 2.1 Material

Stoll CMS-400 (E5) flat weft knitting machine was used to knit the 3-D reinforcement fabric with rectangular cross section for use in integrated sandwich panel. The same



**Fig. 1** The 3-D weft knitted fabric (rectangular cross section); **a** schematic, **b** actual

**Fig. 2** **a** 2-D schematic weft knitted fabric lamination; **b** actual skin fabric, **c** actual core fabric



machine was also used to knit the conventional 2-D fabrics as the reinforcement of the non-integrated sandwich panel according to Abedzade et al. [20]. Figure 1 illustrates the schematic and the actual 3-D knitted fabric. Figure 2a shows the schematic illustration of the 2-D fabrics which was laminated to produce the non-integrated sandwich panel. Figure 2b and c shows the 2-D knitted fabric used in the production of the skins and core, respectively.

Comparison of Fig. 1a and Fig. 2a vividly shows that in case of the integrated sandwich panel, the 3-D reinforcement not only is produced by simultaneous knitting of the skins and the core wall, but the fabric loops also provide the connection of the core wall to the skins. This is in contrast to the case of the non-integrated sandwich panel in which the skins and core are knitted separately prior to lamination. The skins of the integrated structure were knitted using 400 Tex yarns. According to Fig. 2a, the skins of the non-integrated sandwich panel are partially in contact with the core. In order to achieve the equal weight structures aim, these parts of the skins and core of the non-integrated structure were knitted using 200 Tex yarn. The parts of the skins of the non-integrated structure that are not in contact with the core as well as the skins of the integrated structure were knitted using 400 Tex yarn.

Skins of 3-D fabric illustrated in Fig. 1 were knitted at an eight course repeat by the odd needles of the front and rear needle beds of the knitting machine using 400 Tex E-glass yarn. Connection of the core wall to the top skin was achieved at the 8th course by knitting action of even needles of the front needle bed. The core wall was knitted at four course repeat by the knitting action of even needles of the front needle bed using 600 Tex yarn. In order to connect the core wall to the bottom skin, the last knitted loops were transferred from the even needles of the front bed to the odd needles of the rear bed.

VARTM method was used to prepare the integrated sandwich panel composite. In order to prevent dimensional changes of the cells, waxed mandrels corresponding to the core geometry as shown in Fig. 1a were inserted in the reinforcement prior to application of vacuum and injection of the resin. The mandrels were withdrawn up on curing of the resin. The loop density in the top and bottom skin of the integrated structure was found to be 7.15 loop/cm<sup>2</sup>. Table 1 shows the characteristics of the epoxy resin EPL 1012 as supplied by the resin manufacturer.

Figure 2a vividly shows that the top and bottom skins of the non-integrated sandwich panel are in partial contact with the core. The skins of the non-integrated sandwich panel in the region in contact with the core and in the region not in contact with the core were knitted using 200 Tex and 400 Tex yarns, respectively. The 2-D core fabric in contact regions of core and skins was knitted at eight course repeats using 200 yarn. The regions of the core fabric that formed the core wall were knitted at four course repeats using 600 Tex yarn. This knitting sequence resulted in production of the non-integrated sandwich panel skins reinforced with two layers of fabrics knitted using 200 Tex yarn with uppermost weight-wise resemblance to the skin reinforced with the fabric knitted using 400 Tex yarn. The characteristics of base 100 Tex E-glass yarn as described by the manufacturer are shown in Table 1. This yarn was used as 2-ply, 4-ply, and 6-ply during knitting operation.

The effect of fabric curling in case of the non-integrated sandwich panel was eliminated by stretching and fixing the skin fabric on a flat table. This was carried out in such a manner that the course and wale per centimeter in the stretched state, exactly corresponded to the loop density of the integrated sandwich panel. For a given fiber volume fraction, the core and skin loop densities of both structures must be identical. The core fabric was then placed on the bottom skin reinforcement and the mandrels were inserted. The insertion of mandrels was done in such a manner that the regions of the core reinforcement knitted using 200 Tex yarn were superimposed on the region of the bottom skin reinforcement knitted using 200 Tex yarn and the region knitted using 600 Tex yarn formed the core wall. The top skin reinforcement was also stretched and was fixed on the core in such a manner that the region of the core reinforcement knitted using 200 Tex yarn was in contact with the region of the top skin reinforcement knitted using 200 Tex yarn. The non-integrated sandwich panel composite was also produced using VARTM method in which bonding of the core to skins in this type of the structure was achieved using resin. The bonding of the integrated sandwich panel was achieved due to the combined efforts of yarn and resin. Figure 3a and b shows the integrated and non-integrated sandwich panel samples, respectively. Comparison of these two structures vividly illustrates the effect of structural integrity on the elastic constants of sandwich panels.

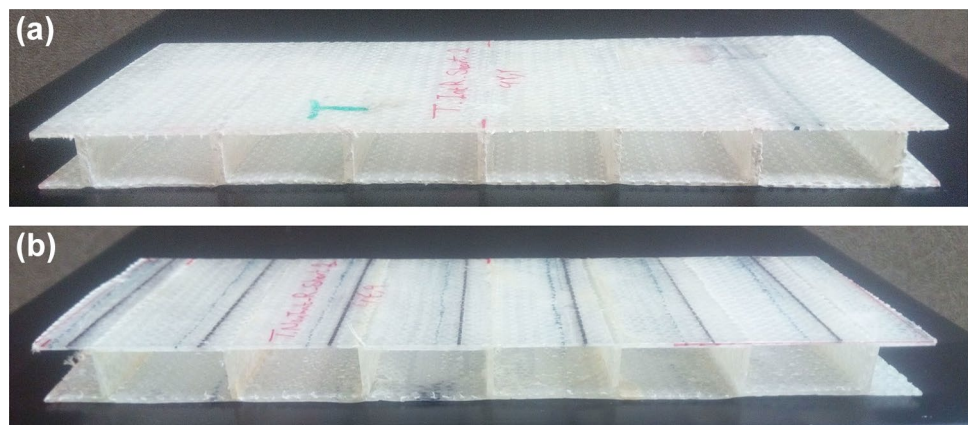
**Table 1** Resin and yarn characteristics (manufacturer supplied)

	Property	Value
EPL 1012 epoxy resin	Young's modulus (GPa)	2.789
	Compressive modulus (Gpa)	.937
	Flexural modulus (GPa)	3.645
100 Tex E-glass yarn	Young's modulus (GPa)	76
	Density (g/cm <sup>3</sup> )	2.56

### 2.2 Method

Flexural stiffness and transverse shear rigidity of the integrated corrugated core sandwich panel composite were determined using known and unknown facing modulus based on ASTM D7250 standard and the Nordstrand–Carlsson methods. These three methods are effectively versions of the Timoshenko beam theory that determine the flexural stiffness and transverse shear rigidity of the beam

**Fig. 3** a Integrated sample; b non-integrated sample



under various conditions. Timoshenko beam theory in comparison with Euler–Bernoulli beam theory which is affected solely by pure bending, deals with shear deformation and rotational bending effects. However, using a series of simplistic assumptions, the transverse shear strain can be assumed to be constant through the beam cross section. Equation (1) shows the deflection of the beam due to Timoshenko theory during the 3-point bending test.

$$\Delta = \frac{PS^3}{48bD_i} + \frac{PS}{4AG_{c,iz}} \tag{1}$$

where  $D_i$  is the flexural stiffness per unit width,  $AG_{c,iz}$  is the transverse shear rigidity of the sandwich beam, and  $A = bh^2/c$  is the effective shear area of the beam cross section, and  $h$  (mm) is the distance between the center lines of the skins [19].

The known facing modulus method which is based on ASTM D7250 standard cannot be used for determination of the elastic constants of the non-integrated sandwich panel. This is due to the fact that the skins of the non-integrated structure are alternately composed of a single-ply composite with the reinforcement which is knitted using 400 Tex yarn and a 2-ply composite with the reinforcement knitted using 200 Tex yarn. Therefore, in this type of structure, the modulus of the skins cannot be defined. Thus, flexural stiffness and transverse shear rigidity of the non-integrated sandwich panel were calculated using unknown facing Modulus based on ASTM D7250 standard and the Nordstrand-Carlsson methods.

### 2.2.1 Known facing modulus method

The elastic constants of the sandwich panel composed of two identical and homogeneous skins with known modulus placed on either side of a core can be determined using the known facing modulus method. Equation (2) [21] can be used to determine the flexural stiffness of the structure ( $D$ ) ( $N.mm^2$ ). Here,  $c$ ,  $b$ , and  $d$  (mm) are core thickness and sandwich width and thickness, respectively.  $E$  (MPa) is the known tensile modulus of the skins. Equation (2) and (3) assume linear force–deflection response of the

skin materials and structure. These assumptions are valid, provided no change occurs in beam thickness after deformation. Figure 4a shows the thickness dimensions of the sandwich panel.

$$D = \frac{E(d^3 - c^3)b}{12} \tag{2}$$

The transverse shear rigidity ( $U$ ) (N) can be calculated using Eq. (3) [21] with a 3-point bending test. Where  $S$  (mm) is the support span length,  $\Delta$ (mm) is the beam mid-span deflection and  $P$  (N) is the total applied load in the 3-point bending test.

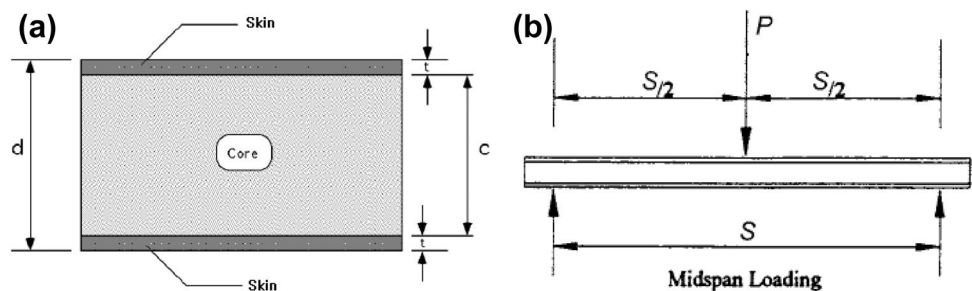
$$U = \frac{PS}{4 \left[ \Delta - \frac{PS^3}{48D} \right]} \tag{3}$$

The transverse shear rigidity is calculated by computing at least ten force points and the resultant deflections in the linear region of the load–deflection curve in Eq. (3). ASTM D7250 standard suggests that the 3-point bending test can be performed in accordance with ASTM C393 standard and support span length of 150 mm [21, 22]. Figure 4b shows the loading configuration of 3-point bending test.

### 2.2.2 Unknown facing modulus method

This method can be used to determine flexural stiffness and transverse shear rigidity of a variety of flat sandwich panels without the need for known value of the skin modulus. The unknown facing modulus method of ASTM D7250 standard suggests the 3-point and 4-point bending tests must be carried out on short and long beams in accordance with ASTM C393 and ASTM D7249 standards, respectively. Figure 5 shows the long beam bending configuration based on ASTM D7249 standard. According to ASTM D7250 standard, ratios of support span length to sandwich thickness and skin to core thickness must be greater than 20 and less than .1, respectively. Under such conditions, Eqs. (4) and (5) [21] can yield to the flexural stiffness and transverse shear rigidity, respectively.

**Fig. 4** **a** Sandwich panel thickness; **b** 3-point bending test configuration [22]



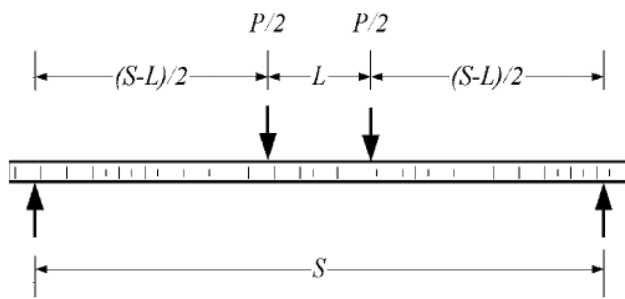


Fig. 5. 4-point bending test configuration [23]

$$D = \frac{3P_1 S_1^3 (141 - 121 S_2^2 / S_1^2)}{1936 \Delta_1 (11 - P_1 S_1 \Delta_2 / P_2 S_2 \Delta_1)} \tag{4}$$

$$U = \frac{9P_1 S_1 (141 S_1^2 / S_2^2 - 121)}{4 \Delta_1 ((1269 P_1 S_1^3 \Delta_2 / P_2 S_2^3 \Delta_1) - 1331)} \tag{5}$$

where the subscripts 1 and 2 show the support span length ( $S$ ), beam mid-span deflection ( $\Delta$ ), and total applied load ( $P$ ) for the 4-point bending and the 3-point bending tests, respectively [21]. The suggested support span length and load span length ( $L$ ) for 4-point bending test by ASTM D7249 standard are 550 mm and 100 mm, respectively [23]. According to ASTM D7250 standard Eqs. (4) and (5) are valid if  $L = 2S/11$  [21].

Contrary to the recommendation of the ASTM D7249 standard, due to the unavailability of suitable testing equipment, the transverse 4-point bending test of the long beam samples was carried out at the support span length of 500 mm. Since the skins of the structure were too thin, the load was exerted on the core wall of sandwich panels. This prevented local failure; thus, the load span length was set at 96 mm. Therefore, under these conditions,  $L = S/5.21$  replaces  $L = 2S/11$  as recommended by ASTM D7249 standard. Subsequently Eqs. (4) and (5) were replaced by Eqs. (6) and (7). In order to calculate the flexural stiffness and transverse shear rigidity of the sandwich panels, in accordance to ASTM D7250 standard, ten selected points of the load–deflection curve of the short and long beam at a given deflection were computed in Eqs. (6) and (7).

$$D = \frac{3P_1 S_1^3 (118.82 - 108.58 S_2^2 / S_1^2)}{1737.22 \Delta_1 (10.42 - P_1 S_1 \Delta_2 / P_2 S_2 \Delta_1)} \tag{6}$$

$$U = \frac{9P_1 S_1 (118.82 S_1^2 / S_2^2 - 108.58)}{4 \Delta_1 ((1069.36 P_1 S_1^3 \Delta_2 / P_2 S_2^3 \Delta_1) - 1131.37)} \tag{7}$$

The use of known and unknown facing modulus methods are confined to sandwich beams with the linear

load–deflection response. The use of these methods in structures with high core shear modulus is prohibited. This is due to the fact that in such structures the shear deflection is quite small. Thus smallest error in deflection measurement leads to considerable variations in the calculated shear modulus [21].

### 2.2.3 Nordstrand–Carlsson method

Nordstrand–Carlsson [19] with the aim of plotting  $\Delta / PS^3$  vs  $1/S^2$  divided Timoshenko’s beam deflection equation (Eq. (1)) by  $PS^3$  and carried out series of 3-point bending tests on sandwich panel samples at various support span lengths. The extrapolated vertical intercept of the fitted line through the  $\Delta / PS^3$  vs  $1/S^2$  points for different span lengths approximately expresses  $1/48bD_i$  and the slope of the line provides an acceptable estimate of  $1/4AG_{c,jz}$ . The value of  $\Delta/P$  is the slope of the linear region of the load–deflection curve of the sample during the bending tests. It should be noted that the initial behavior of the sample during the early stages of the test is rather nonlinear and must be discarded [19].

## 3 Bending test experiments

Using tensile test along the wale direction, the skin modulus of the integrated sandwich panel composite reinforced with fabric knitted using 400 Tex yarn was found to be 2.89 GPa. Despite the nonlinear behavior of materials and structures used in this research, in accordance with the stated aim of this research which is determination of the elastic constants, the behavior of the sample structures was studied in the linear region. Transverse shear rigidity of the integrated sandwich panel was determined using 3-point bending tests on short beam samples in accordance with the known facing modulus method. In case of unknown facing modulus method, in addition to the 3-point bending test on the short beam, 4-point bending test must also be conducted on the long beams. Additionally, based on two short and long beams 3-point bending test, the Nordstrand–Carlsson method was also used for determination of the elastic constants of the integrated and non-integrated sandwich panels. Thus, in order to conduct 3-point bending tests on the short beams, three  $75 \times 200$  mm samples of the integrated and non-integrated sandwich panel were prepared. Also, in order to conduct 3- and 4-point bending tests on the long beams, three  $75 \times 550$  mm samples of the two structures were prepared. Since the tests were performed in the elastic region, both 3- and 4-point bending tests were carried out on a single representative piece. Bending tests were performed using a Zwick Z250 testing machine equipped

with a 2.5 kN load cell at the rate of 3 mm/min. The cross-head motion was used to measure the mid-span deflection of the beams at the accuracy of  $\pm 2 \mu\text{m}$ . Table 2 represents the mean dimensions and weight of three samples of short and long beams. The use of modern weft knitting technology provided the production of the integrated and non-integrated samples resembling each other as far as weight and dimension are concerned. The joining of the core to the skins in integrated and non-integrated samples is the major difference between these two structures. Figure 6 shows examples of a 3-point bending test of the short beam and a 3- and 4-point bending test of the long beam.

## 4 Results and discussion

### 4.1 Comparison of the three methods of elastic constant determination

Figure 7a, b, and c shows the mean load–deflection behavior of three integrated and non-integrated sandwich panel samples due to 3-point bending test at the span length of 150 mm, 4-point bending test and 3-point bending test

at the span length of 500 mm, respectively. The distortion of the load–deflection curves of the long beams in Fig. 7b is due to the inappropriate fixtures that were used during the conduct of the 4-point bending test.

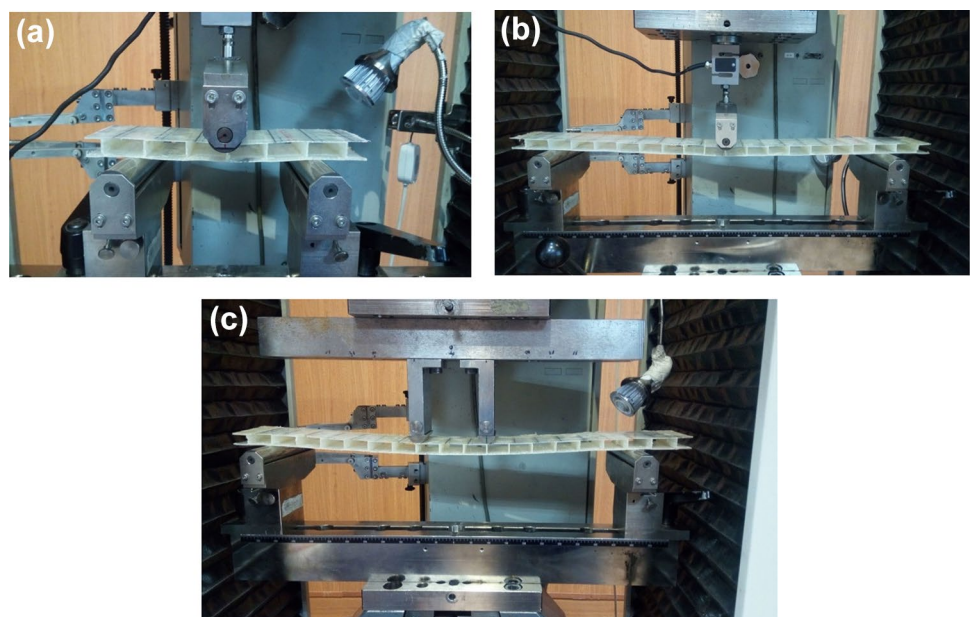
Since the modulus of the skin of the integrated sandwich panel which was reinforced with fabric knitted using 400 Tex yarn was known, the flexural stiffness in the direction of corrugation of this structure was calculated in accordance to ASTM D7250 standard using Eq. (2). Transverse shear rigidity was calculated using 3-point bending load–deflection curve. Figure 7a illustrates the mean load–deflection results due to 3-point bending of the integrated short beam in the direction of corrugation. Table 3 shows the calculated elastic constants of the integrated sandwich panel due to the known facing modulus method.

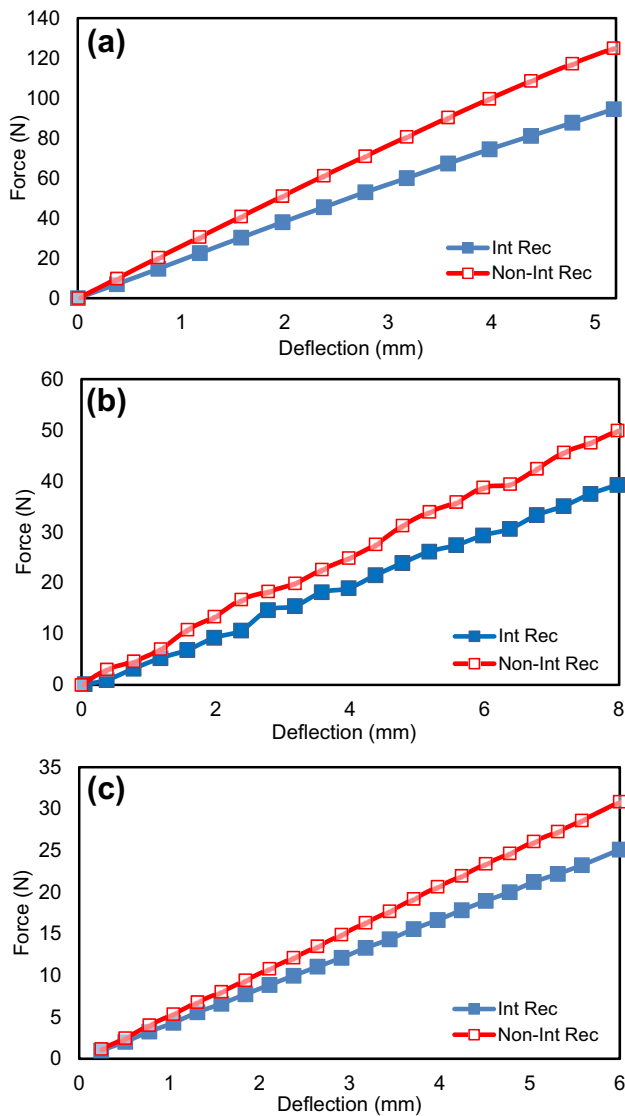
Based on the unknown facing modulus method, the flexural stiffness and transverse shear rigidity of the integrated samples were calculated using Eqs. (6) and (7). The calculations are the results of computation of ten force values and the corresponding deflection of 3-point bending of short beam (Fig. 7a) and 4-point bending of long beam (Fig. 7b). Table 3 shows the mean value of the flexural

**Table 2** Mean dimension and weight of sandwich panels

Structures type	Sample beam	Width (mm)	Sandwich thickness (mm)	Skin thickness (mm)	Core thickness (mm)	Weight (gr)
Integrated	Short	74.99	14.72	.97	12.78	61.50
	Long	75.56	14.97	1.06	12.85	180.33
Non-integrated	Short	75.42	15.47	1.05	13.37	63.65
	Long	75.38	15.58	1.01	13.55	185.30

**Fig. 6** Transverse bending test; **a** 3-point bending (short beam); **b** 3-point bending (long beam); **c** 4-point bending (long beam)





**Fig. 7** Load–deflection behavior of the sandwich panels; **a** 3-point bending (span length = 150 mm); **b** 4-point bending (span length = 500 mm) **c** 3-point bending (span length = 500 mm)

**Table 3** Elastic constants of the integrated sandwich panels due to the known and unknown facing modulus and Nordstrand–Carlsson methods

structure	Method	Flexural stiffness (N.m <sup>2</sup> )	Transverse shear rigidity (N)
Integrated	Known modulus	19.90	751.14
	Unknown modulus	33.50	746.65
	Nordstrand–Carlsson	34.35	714.20

stiffness and transverse shear rigidity of the three integrated samples. The transverse shear rigidity of the integrated sandwich panel due to the known and unknown

facing modulus is more or less equal. However, the difference in the value of flexural stiffness due to these two methods is considerably high. Thus in order to validate the results, it is advisable to calculate the elastic constants due to an alternative method.

The Nordstrand–Carlsson method was used based on 3-point bending test at a span length of 150 mm (Fig. 7a) and 500 mm (Fig. 7c). Table 3 shows the comparison between the flexural stiffness and transverse shear rigidity due to the Nordstrand–Carlsson method with those due to known and unknown facing modulus methods for the integrated sandwich panel. Table 3 is indicative of the fact that the known facing modulus method underestimates the amount of flexural stiffness in comparison with the other two methods. It must be emphasized that the difference in the flexural stiffness and transverse shear rigidity due to the unknown facing modulus and Nordstrand–Carlsson method is negligible.

Skin modulus of the non-integrated sandwich panel cannot be determined due to the fact that the skins of this structure are alternately composed of single-ply composite reinforced with fabric knitted using 400 Tex yarn and a 2-ply composite reinforced with fabric knitted using 200 Tex yarn. Therefore, the unknown facing modulus and Nordstrand–Carlsson method were used to determine the elastic constants of the non-integrated sandwich panel. Table 4 shows the comparison between the results of the Nordstrand–Carlsson and unknown facing method for the non-integrated sandwich panel. Table 4, in conjunction with Table 3, shows that the results of the two methods in case of the non-integrated structure are also highly compatible.

Elastic constants—flexural stiffness (*D*) and transverse shear rigidity (*U*)—and load-carrying capacity of the integrated and non-integrated structures are two independent sets of data. The statistical t test was used to investigate the significant differences between the mean value of the elastic constants of the integrated and non-integrated structures due to the unknown method. Table 5 shows the results of the conducted statistical t test. The level of significance in the fifth column points to existence significant difference in the elastic constants of the two types of structures. This is to state that the

**Table 4** Elastic constants of the non-integrated sandwich panels due to the unknown facing modulus and Nordstrand–Carlsson methods

structure	Method	Flexural stiffness (N.m <sup>2</sup> )	Transverse shear rigidity (N)
Non-integrated	Unknown modulus	40.63	1019.73
	Nordstrand–Carlsson	40.09	979.09



**Table 5** The independent sample t test, statistical significance difference in elastic constants of the integrated and non-integrated structures

Method	Elastic constants	T test for equality of means						
		t	df	Sig. (2-tailed)	Mean difference	Std. error difference	95% Confidence interval of the difference	
							Lower	Upper
Unknown	D	-2.607	28	.014	-7.13	2.74	-12.74	-1.53
	U	-19.874	28	.000	-273.08	13.74	-301.22	-244.93
Nordstrand–Carlsson	D	-1.701	3.617	.172	-5.74	3.37	-15.51	4.03
	U	-8.798	3.543	.002	-264.89	30.11	-352.91	-176.87

flexural stiffness and transverse shear rigidity in the direction of corrugation of the non-integrated rectangular core sandwich panel due to the unknown method as is shown in Table 4 is significantly higher than those of the integrated structure as is shown in Table 3.

The result of the t test between the elastic constants of the integrated and non-integrated sandwich panel due to the Nordstrand–Carlsson method is also shown in Table 5. Level of significance points to existence statistical significant difference in the transverse shear rigidity of the integrated and non-integrated structures due to the Nordstrand–Carlsson method. However, the difference in the flexural stiffness of the integrated and non-integrated sandwich panel due to the Nordstrand–Carlsson method is not significant. In the unknown facing modulus method, ten values of the load–deflection curve for each sandwich panel sample are used in determination of elastic constants. This is in contrast to the Nordstrand–Carlsson method in which one slope of the linear region of the load–deflection curve for each sample is used. This is statistically an advantage of unknown facing modulus method in the investigation of the difference in the elastic constants of the structures.

### 4.2 Effect of structural integrity

Table 6 shows the mean load (*P*) of three short beams of the integrated and non-integrated samples during the 3-point bending test at deflections ( $\Delta$ ) of 4 mm and 5.2 mm. Table 6 also shows the mean load (*P*) of three long beam samples during 4-point bending at deflections of 4 mm and 8 mm. The codes in the first column of Table 6 describe bending tests condition. For instance “B3P150 $\Delta$ 4 mm” denotes the result of the 3-point bending test at the support span length of 150 mm and at 4 mm deflection. The statistical t test points to general existence of significantly higher load-carrying capacity of the non-integrated sandwich panel in the direction of corrugation in comparison with the integrated sandwich panel except at 8 mm deflection. The higher load-carrying capacity of the non-integrated sandwich panel compared with the integrated sandwich panel is due to the higher flexural stiffness and transverse shear rigidity of the former panel. The higher flexural stiffness and transverse shear rigidity of the non-integrated sandwich panel in comparison with the integrated structure can be attributed to the fact that the non-integrated sandwich panel contains 2-ply laminated composite sections. The alternate sequence of 2-ply

**Table 6** Integrated and non-integrated sandwich panel transverse bending (mean load (*N*))

Group statistics		Core	N	Mean	Std. deviation	Std. error mean
B3P150 $\Delta$ 4 mm	Integrated		3	74.70	3.25	1.88
	Non-integrated		3	100.09	3.52	2.03
B3P150 $\Delta$ 5.2 mm	Integrated		3	94.71	4.53	2.61
	Non-integrated		3	125.28	5.81	3.36
B4P500 $\Delta$ 4 mm	Integrated		3	19.94	2.26	1.31
	Non-integrated		3	25.84	1.27	.73
B4P500 $\Delta$ 8 mm	Integrated		3	40.03	4.79	2.76
	Non-integrated		3	50.24	.00	.00
B3P500 $\Delta$ 4 mm	Integrated		3	16.75	1.44	.83
	Non-integrated		3	20.61	.40	.23
B3P500 $\Delta$ 6 mm	Integrated		3	25.14	2.09	1.21
	Non-integrated		3	30.84	.20	.12

laminates provide bending resistance in the direction of corrugation. The authors of this paper in their previous article have shown that in the transverse direction of corrugation integrated structure exhibits both higher natural frequency and higher flexural stiffness compared to the non-integrated structure [20]. Additionally, the thickness of the non-integrated samples is more than that of the integrated samples. The higher sandwich thickness of the non-integrated sandwich panel is due to inevitable inconsistencies during the preparation of the structures. It seems that the 8 mm deflection exception is due to the higher nonlinearity of the non-integrated sandwich panel in comparison with the integrated sandwich panel. This exception is also due to the reduction in load-carrying capacity of the non-integrated sandwich panel at the higher deflection. Table 6 also shows the mean load of three long beams of the integrated and non-integrated samples during the 3-point bending test at deflections of 4 mm and 6 mm. The conducted t test emphasizes the higher load-carrying capacity of the non-integrated sandwich panel in comparison with that of the integrated sandwich panel.

## 5 Conclusion

In this study, the effect of structural integrity on the flexural properties and elastic constants of corrugated core sandwich panel composites with the rectangular core in the direction of corrugation was investigated. Weft knitted 3-D and 2-D fabrics were used to produce integrated and non-integrated sandwich panels, respectively. Comparison of the weights and the dimensions of the structures revealed that weft knitting technology is a desirable method for production of weight-wise similar integrated and non-integrated corrugated core sandwich panel composites. The investigations were conducted based on the 3-point bending test of the short beam accompanied by the 3- and 4-point bending test of the long beam. Flexural stiffness and transverse shear rigidity of the structures in the direction of corrugation were evaluated using known and unknown facing modulus methods as recommended by ASTM D7250 standard and Nordstrand–Carlsson method. High compatibility was observed in the transverse shear rigidities due to the three methods used. However, the flexural stiffness due to the known facing modulus method was found to be considerably less than both the unknown facing modulus and Nordstrand–Carlsson methods. Considering the results of the unknown facing modulus method, it was concluded that the flexural stiffness and transverse shear rigidity in the direction of corrugation of the non-integrated structure were significantly higher than that of the integrated

structure. Additionally, it was established that the difference between transverse shear rigidities of the integrated and non-integrated structure due to the Nordstrand–Carlsson method is also significant. However, results pointed to the insignificant difference in flexural stiffness of the integrated and non-integrated structures due to the Nordstrand–Carlsson method. This was contributed to a lower number of data in the Nordstrand–Carlsson method than the unknown facing modulus method. It was established that the unknown facing modulus method is superior in expressing the statistical significant difference between the samples than the Nordstrand–Carlsson method. Finally, results demonstrated that the load-carrying capacity of the non-integrated rectangular core sandwich panel in the direction of corrugation is higher than that of the integrated sandwich panel. This was contributed to the existence of 2-ply region of the non-integrated sandwich panel in comparison with the integrated sandwich panel and greater sandwich thickness.

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## Compliance with ethical standards

**Conflict of interest** The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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