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Static behavior of three-dimensional integrated core sandwich composites subjected to three-point bending

Mehmet Karahan¹, Hakan Gul¹, Nevin Karahan¹ and Jan Ivens^{2,3}

Abstract

In the current study, the effect of the thickness and the foam density in three-dimensional integrated woven sandwich composites on quasi-static mechanical properties under three-point bending was investigated. Bending modulus and core shear modulus were determined by subjecting the samples, which were cut with varying span lengths according to their core thicknesses, to three-point bending test. Obtained results were optimized by taking core thickness, foam density and panel weights into consideration. Damages that occurred on the tested samples were reported. When compared to conventional foam core sandwich composites, it was found that three-dimensional integrated sandwich composites have superior mechanical properties and due to the fact that the pile yarns in the core and the foam support each other, contrary to conventional sandwich composites no catastrophic core breakage occurs under load, thus the load bearing capacity of the structure is sustained.

Keywords

Three-dimensional integrated sandwich composites, three-point bending, damage tolerance

Introduction

Sandwich composites are used in different areas such as automotive, aerospace, marine and construction industry, and with a wide variety since they combine light weight with high flexural properties.

Three-dimensional (3D) textile production methods have led to interesting developments in the composites industry.^{1–3} The use of 3D integrated fabrics in the production of sandwich composites has presented a new concept on this topic.^{4–7} 3D integrated sandwich fabrics are made by the velvet carpet weaving technique, where two parallel skins (top and bottom skins) are woven together using pile yarns,⁶ keeping a defined distance between the skins to form a core. This integrated connection provides a through-the-thickness reinforcement, in which the pile yarn architecture increases the shear rigidity, which is the most significant disadvantage of many core materials.^{8,9} The warp and weft yarns constitute the skins while the pile yarns create a hollow core section, the pile yarn free length determining the core thickness. This sandwich fabric structure has the following advantages: (1) sandwich panels can

be produced in a single step, production costs are reduced in line with the shortened production time, (2) top and bottom skins are integrally woven together with the core section and this ensures a stronger binding between the layers: skin-core delamination is virtually impossible and (3) the hollow core section can be filled by several means, thus different functional capabilities can be given to the structure.

There are several studies available on 3D woven sandwich production processes and properties.^{10,11} Some researchers examined the mechanical properties

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of 3D sandwich composites.^{12–15} They found that 3D sandwich composites have a high skin-core delamination resistance and the pile yarns have a significant influence on flatwise compression and shear properties. Shiah et al.¹⁶ examined the elastic modulus and impact properties of 3D integrated sandwich composites. Wang et al.¹⁷ focused on the three-point bending and flatwise compression properties of multi-face sheet 3D integrated sandwich composites and reported that such structures have superior mechanical properties than mono-spacer 3D sandwich composites. In another study, Wang et al.¹⁸ determined the bending, compression and shear properties of 3D sandwich composites for different foam densities. Brandt et al.¹⁹ examined the planar properties (strength and modulus), damage properties, energy absorption capacities and mechanical breakage properties of different 3D woven composites. Van Vuure et al.^{8,20} focused on strength and modulus properties on an empirical and simulative way. 3D sandwich fabrics constitute a good potential for the production of multi-functional composites.²⁰ Researchers^{21–24} also studied other properties of woven textile sandwich composites such as fatigue, damage and low-velocity impact properties: in a study,²⁵ woven textile sandwich composites were compared with honeycomb sandwiches. The results showed that the properties of 3D woven sandwich composites are better in the weft direction compared to the warp direction.

Compression, bending and impact properties of 3D woven sandwich composites are quite low without any extra skin reinforcement. Also, core shearing resistance decreases as the pile height increases. Due to this, core sections of these materials are generally filled with foam, although it causes a weight increase.^{8–12} Change of core thickness and use of foam filling in the core significantly affects the mechanical properties.^{7,26,27} Furthermore, core thickness and the use of

foam filling require the simultaneous optimization of mechanical properties and weight.

In the present study, 3D sandwich composites with varying core thicknesses were filled with foam of varying densities and the effects of the changes in thickness and foam density on quasi-static mechanical properties were examined. For this purpose, produced samples were subjected to three-point bending tests. Bending modulus and core shear modulus were determined by subjecting the samples, which were cut with varying span lengths according to their core thicknesses, to three-point bending test. The damages in the tested samples are reported.

Materials and experimental methods

3D integrated fabrics

The 3D sandwich fabrics have been supplied by Parabeam BV (NL). The 3D integrated fabrics used in the research had a core thickness of 10, 15, 18 and 22 mm. All four fabrics are identical in terms of their top and bottom skin layers, the yarns used and the weaving architecture. The only difference is their free pile yarn length and thus the core thickness. Figure 1 illustrates the layout of the yarns in the structure and a typical weaving architecture of a 3D integrated sandwich fabric. It shows that binding yarns connect the top and bottom skins of the structure in thickness direction and consequently the core of the fabric becomes hollow. The parameters of the fabrics used in the study are given in Table 1. All yarns consist of type E-glass fibres. The linear density of the warp, weft and pile yarns is 300 tex.

The structure of 3D integrated sandwich fabrics is different from conventional woven fabrics.²⁸ Therefore, the fabric geometry was established based on the yarn intersections within the fabrics, to understand the fabric

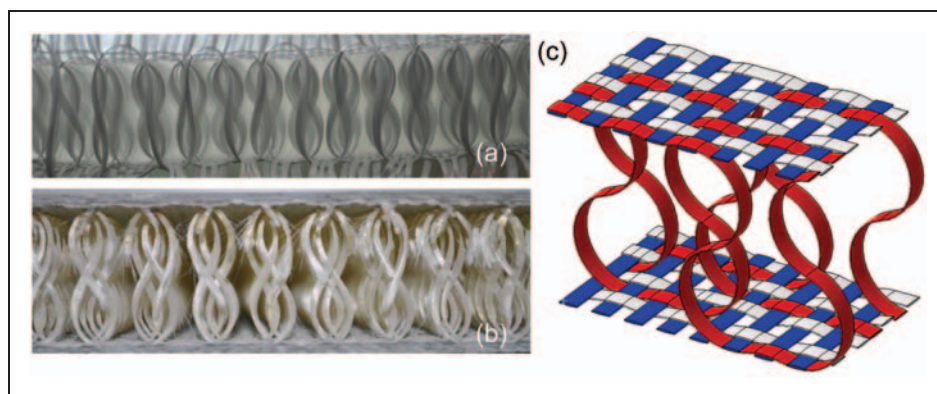
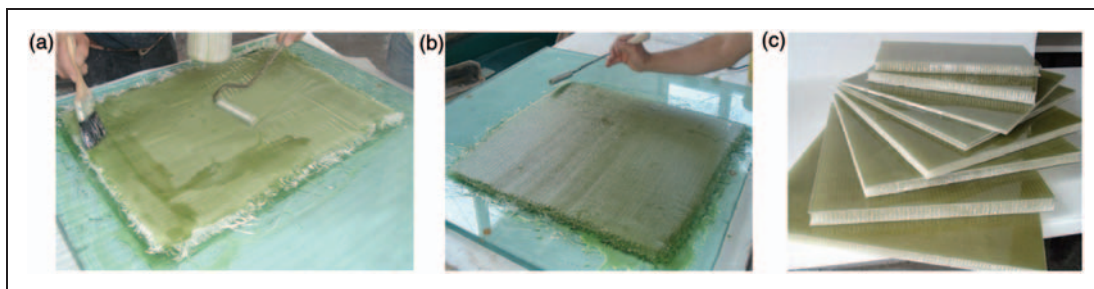


Figure 1. Cross-sectional view of 3D dry fabric (a) and resin impregnated plate (b); the schematic display of the 3D fabric structure. 3D: three-dimensional.

Table 1. Main properties of the three-dimensional (3D) fabrics and composite plates.

Core thickness (mm)	3D dry fabric (g m^{-2})	Total dry fabric (g m^{-2})	Fibre volume fraction (%)	3D composite core thickness (mm)	3D composite plate thickness with additional face sheets (mm)
22	1680	4680	36	22.1	24
18	1720	4720	36	18	19.5
15	1600	4600	36	14.9	16.3
10	1430	4430	35	10.1	12

**Figure 2.** Fabrication of 3D integrated panels (a and b) and view of finished plates (c). 3D: three-dimensional.

structure and geometry, and from basic parameters such as yarn width, yarn thickness, weave densities and yarn spacing. The drawings have been carried out with the Katia CAD program. The schematic display of the 3D fabric structure is presented in Figure 1(c).

The top and bottom skins of sandwich panels have been reinforced with an additional plain weave E-glass fabric. Three additional plain woven fabric layers of 500 g m^{-2} were used in both the top and bottom skins during composite production.

Fabrication of 3D integrated core sandwich panels

3D integrated sandwich composites were produced from 3D integrated sandwich fabrics. An Atlac 580 AC 300 type vinylester urethane resin was used. A 6% cobalt naphthalate accelerator was added in a ratio of 0.25 phr. A 50% active methyl ethyl kethone peroxide catalyst was used with a mixing ratio of 2 phr. The vinylester resin has a Young's modulus of 3 GPa and 3.4% strain to failure.

All test panels were manufactured using the hand lay-up technique. Production of the panels has been carried out on a glass plate, treated with a release agent. Special care was taken to control the fibre volume fraction during the production of each panel. The top and bottom skins of the panel have been reinforced with an additional three plies plain weave glass fabric. After applying the resin to the skins from both sides, it has been ensured that the resin thoroughly penetrated the entire fabric and that all entrapped air

was removed using aluminum impregnation rollers (Figure 2(a) and (b)).

After the application of the resin, the fabrics were kept for 4 h at room temperature for curing. During this time, the impregnated fabric opens up due to the way the pile yarns are woven into the skins. The additional plain weave fabrics have been bonded to the top and bottom skins after the 3D panels have cured with same resin by using hand lay-up. The additional skins cannot be co-laminated as their weight would affect the core thickness. Therefore, the additional fabric layers are laminated onto the sandwich panel after the curing of the 3D sandwich panels. Subsequently, the panels were kept for 1 day for complete curing. The appearances of the plates are shown in Figure 2(c).

The weights of the plates and the weight ratio of fiber and resin of each plate were determined. Since the core sections are hollow, the fiber weight ratios have been determined rather than fiber volume fraction. Table 2 shows the resin and fabric ratios separately for plates of different thicknesses.

Foam filling of 3D integrated core sandwich composites

Some of the panel core sections were filled with rigid polyurethane (PUR) foam, consisting of a mix of 1.08 g cm^{-3} polyol and 1.23 g cm^{-3} isocyanate (MDI), in a 107/100 isocyanate-polyol mixing ratio (by weight). The foaming process was performed in a mould. During the foam expansion, a pressure of approximately 0.5 bar was built up. A constant temperature

Table 2. Finished properties of sandwich samples and their sample codes.

Core thickness (mm)	Sample code	Foam filling	Density of foam filling (kg m^{-3})	Weight ratio of fabric/resin/foam (%)	Unit weight of finished plates (g m^{-3})	Weight ratio difference due to foam filling (%)
10	A1	No	–	64/36/0	6710	–
	A2	Yes	100	57/32/11	7550	12.5
	A3	Yes	120	59/27/14	7762	15.7
	A4	Yes	130	58/27/15	7810	16.4
15	B1	No	–	65/35/0	6981	–
	B2	Yes	100	56/29/15	8262	18.3
	B3	Yes	120	54/28/18	8532	22.2
	B4	Yes	130	53/27/20	8647	23.9
18	C1	No	–	65/35/0	7173	–
	C2	Yes	100	51/27/22	8760	22.1
	C3	Yes	120	52/28/20	9076	26.5
	C4	Yes	130	50/28/22	9218	28.5
22	D1	No	–	64/36/0	7088	–
	D2	Yes	100	51/24/25	9283	31
	D3	Yes	120	49/27/24	9695	36.8
	D4	Yes	130	49/24/27	9839	38.8

**Figure 3.** Fabrication steps of foam filling process (a and b) and view of foamed and unfoamed panels (c).

of 50°C is maintained throughout the process to enhance the foam penetration between the pile yarns and the homogeneity of the foam. The process of injecting foam into the composite plates in the mold is shown in Figure 3. The appearance of the obtained plates with and without foam filling are shown in Figure 3(c). In the end, samples of four different thicknesses (foamed and unfoamed) are obtained. The names of the produced 3D sandwich samples are given in Table 2.

Experimental studies

Three-point bending tests. Three-point bending tests were carried out in accordance with the ASTM C393-62 (standard bending test for flat sandwich constructions) (Figure 4). Three different span lengths were used during the tests. Span lengths were determined

separately for each sample according to their core thickness. In the determination of span lengths, the length/core thickness (L/c) ratio was set as 5, 10 and 20 for each sample (Table 3). Bending tests conducted at different span lengths are an alternative method for determining core shear strength and modulus, and it was shown that this method provides results similar to the block shear test.²⁰ The tests were carried out on samples cut in both weft (0°) and warp (90°) directions. By conducting four tests for each span length, a total of 12 tests were carried out.

The advantages of flexural bending tests are that they are easy to conduct and they allow the determination of the core shear properties of sandwich composites, as well as the in-plane properties of the skin. Three-point bending test geometry provides a combination of bending and shear deformations.

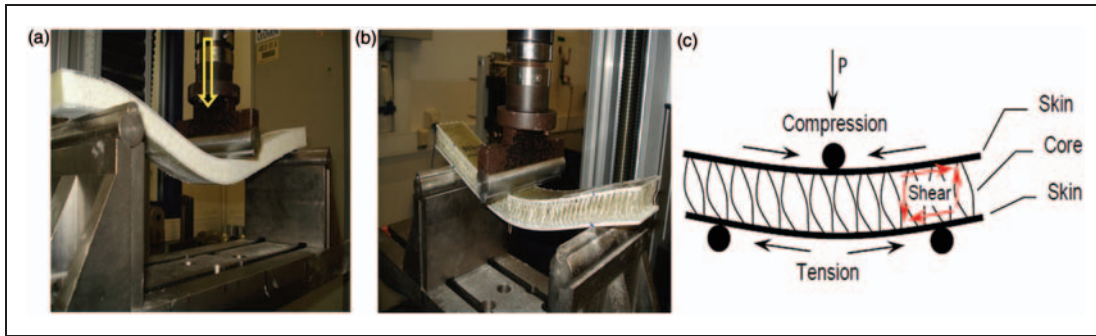


Figure 4. View of three-point bending test fixtures (a and b) and schematic display of the stresses that occur on sample core and skins under bending load (c).

Table 3. Span lengths of samples used in three-point bending tests.

Core thickness (mm)	Span lengths for different L/c ratios (mm)		
	L/c = 5	L/c = 10	L/c = 20
10	50	100	200
15	75	150	300
18	90	180	360
22	110	220	440

L/c: length/core thickness.

Elastic analysis of the tests is based on the assumption that shearing completely concentrates on the core material. In this case, vertical deflection w takes place under the P central load and:

$$w = \frac{PL^3}{48D} + \frac{PL}{4N} \quad (1)$$

Here L is the span length while P is the applied load. The bending rigidity D for a symmetrical sandwich structure is given in equation (4). Here, the contribution of core material to the modulus can be ignored. The sandwich shear rigidity N is obtained from equation (5).

$$D = \frac{E_s(h^3 - c^3)b}{12(1 - \nu^2)} \quad (2)$$

$$N = \frac{G_c(h + c)^2b}{4c} \quad (3)$$

Here, E_s is the mean skin modulus, G_c is the effective core shear modulus, h is sandwich thickness, c is core thickness, b is sample width and ν is the poisson ratio of the skin material.

In order to determine the skin modulus E_s and effective core shear modulus G_c , test results obtained from three different span lengths were used. The total

deflection of the sample decreases with increasing span length. Samples are loaded in the elastic region only. Care has to be taken for local deformations at the load introduction and support regions as it may add to the apparent beam compliance.²⁰ This is particularly true for the cases where shorter spans and a thin skin or weak cores are used.

Results and discussion

Load-displacement curves and damage evaluation

The span length significantly affects curve characteristics. Load-displacement curves obtained for different span lengths are shown as example in Figure 5 for the samples A1 and A2. A shorter span length results in a higher peak load. The peak load and rigidity are strongly increased by the addition of foam. Sandwich composites behavior under bending depends on the tension/compression resistance of the skins and the shear resistance of the core.

According to the curves shown in Figure 5, in the curve obtained for the lowest span length ($L/c=5$), there is a linear elastic part from the start, followed by a non-linear region, and after the peak load, load decreases sharply. This sharp decrease in load corresponds to shear cracks and later the load start to increase again. The next decrease in the peak load at the second peak was caused by skin failure or core-extra skin delamination.

The above-mentioned load-displacement characteristic changes as the span length increases. In the curves obtained for the $L/c=10$ ratio, a linear elastic behavior is observed from start until the peak load, followed by a plateau where the load remained nearly constant. This part corresponds to a gradual development of shear damage in the core. At the end of this, part load decreases rapidly. A similar case is also observed for the curves with $L/c=20$ ratio, the length of the plateau increases with increasing span-to-thickness ratio.

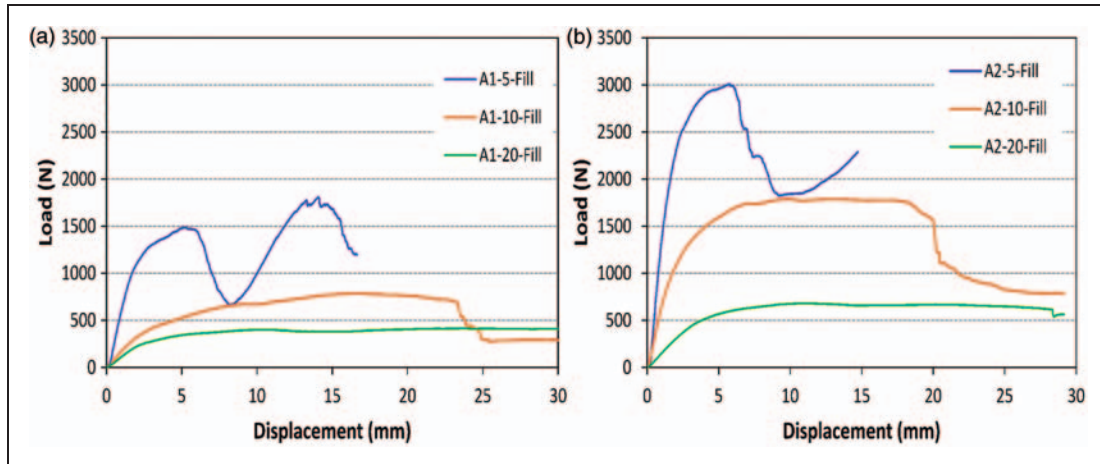


Figure 5. Load-displacement curves obtained from three-point bending tests for unfoamed (a) and foamed samples (b) for different span lengths. (A1 and A2 indicate the sample codes; 5, 10 and 20 indicate the L/c ratios for span length; and fill indicate the fill direction tests.) L/c : length/core thickness.

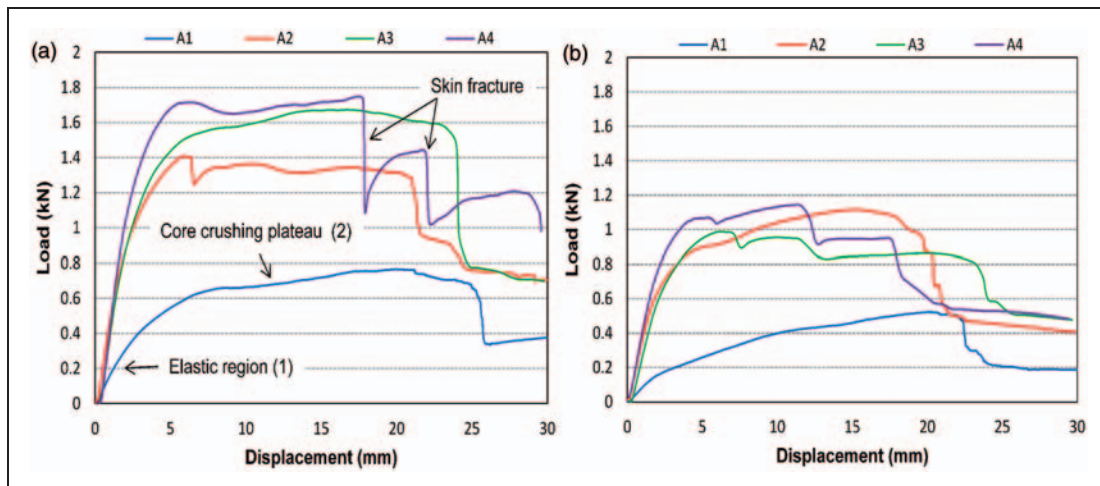


Figure 6. Load-displacement curves obtained for $L/c = 10$ weft (a) and warp (b) directions, based on change of foam density. L/c : length/core thickness.

Figure 6 shows the load-displacement curves for warp and waft directions of sandwich composites under three-point bending load, depending on the foam density. Exemplary load-displacement curves were given only for sample A and $L/c = 10$. Since the peak load decreases linearly in line with the increase in core thickness, load-displacement curves for other samples are not presented. As it is seen from Figure 6, load-displacement behavior of 3D sandwich composites under bending loading can be generalized as follows: (1) Linear-elastic region, (2) Pile buckling and core shear deformation area and (3) Plastic deformation and extra skin deformation area. In the first region, a linear increase of load was observed. No damage occurs in this part. As for the second area, the decrease of the load indicates the development of damage. The damage

is specified as pile buckling and core shear deformation. However, this situation varies according to the core properties of the samples. While the curves of the unfoamed samples, where shear deformation is more dominant, exhibited a long plateau, a shorter plateau is observed for foam filled samples. The third area is where the samples get seriously damaged; core and extra skin rupture or extra skin-core delamination occurred. With shorter span length and increased foam density, skin failure and extra skin-core delamination take place right after the peak load in the upper skin. Furthermore, core and pile yarns subjected to compressive stress showed pile yarn rupture. This was also reported by other researchers.^{29,30}

Due to the low shear resistance of unfoamed samples, the load bearing capacity of the skins cannot be

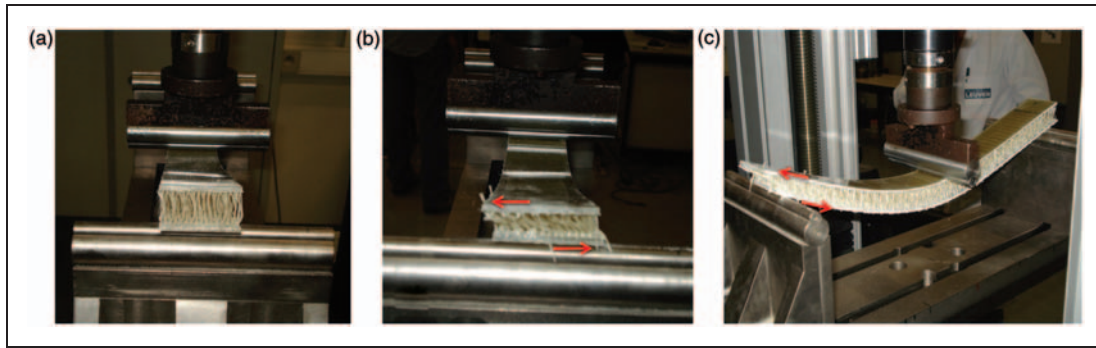


Figure 7. Shear deformation taking place in samples without foam filling under bending loading: (a) original state, (b) transversal skin-core shear and (c) longitudinal skin-core shear.

utilized. Shear deformation of unfoamed sandwich material under bending load is given in Figure 7 as an example. This effect increases in line with the increases in span length and core thickness. With the tilting of pile yarns under load, a shear based on core thickness occurs between the upper and lower skins. This part that corresponds to the shearing deformation in the load-displacement curve of unfoamed samples is the plateau where the load remained constant. As the core gets more compressed, both pile yarns and the skins take damage under the bending load and at the end of the plateau the load falls sharply. Comparing the warp and weft directions, it can be seen that the load-displacement curve is nearly the same, yet the peak load in the weft direction is higher. This is due to the fact that the pile yarns in the warp direction exhibit lower bending resistance due to their 8 shape. After the bending loading is removed from the unfoamed samples, the structure has a tendency to turn back to its original form and due to the 8 shape of the pile yarns it exhibits perfect elastic-plastic properties.

From the load-displacement curves of the foam-filled samples, it can be seen that bending stiffness increased considerably. In foam-filled samples, the core shear resistance increases resulting in the dominance of the skin bending rigidity. As foam density increases, higher peak loads are reached. Since the additional skin layers used in all samples were primarily the same, also skin bending rigidity are also expected to be the same. However, due to the fact that the foam contributes to bending resistance, the bending resistance increases with increasing foam density. Bending rigidity in foam-filled samples depends on the foam density and core thickness. As core thickness decreases and foam density increases bending rigidity increases.

The plateau region in the load-displacement curve of foam-filled samples is shorter. This can be attributed to the deformation of the foam. As the foam density increases or as shear resistance rises, the deformation of foam core causes a gradual decrease in the load and

no apparent plateau area could be observed. This indicates the advantage of 3D sandwiches over the conventional foam core sandwich composites. In conventional foam core sandwiches, a cracking deformation on the foam core causes a rapid decrease of the load.³¹ Whereas, even if a foam core deformation takes place in 3D sandwiches, no rapid decrease in the load occurs because the pile yarns support the foam core and in this way the load-bearing capacity of the structure is sustained.

In a three-point bending test, three different stresses are applied on the sandwich samples. With the loading made from the upper skin of the sample compression stress on pile yarns and torsion and tensile stress on lower sample skins occur.^{32–34} (Figure 4(c)). Compression on the piles occurs at load introduction points.³⁵ The shear stress is maximum in the middle and drops to 0 at the surfaces. Therefore, the shear stress in the skin is neglected. The tensile and compressive stresses are low in the core, because of its low modulus compared to the skin. Shear deformation causes relative displacement of the skins with respect to each other. Therefore the pile yarns are loaded in tension. Deformations on the core and the skins occur with the effect of these three stresses. As the loading continues, a breakage occurs on the interface of extra skins and the core due to the shear stresses. The point of which of these stresses is more effective depends on core thickness, foam density and span length.

Damage that occurs during three-point bending test varies according to span length and the foam filling. Due to this reason, it is necessary to evaluate damage properties separately for samples with and without foam filling. Since shear deformation on the core starts to become dominant as the core thickness increases in unfoamed samples, the damage consists of shear deformation of the pile yarns upper skin breakage. Figure 8 shows the upper skin and side views of the samples without foam filling after bending for $L/c = 10$. No additional skin delamination occurred on the

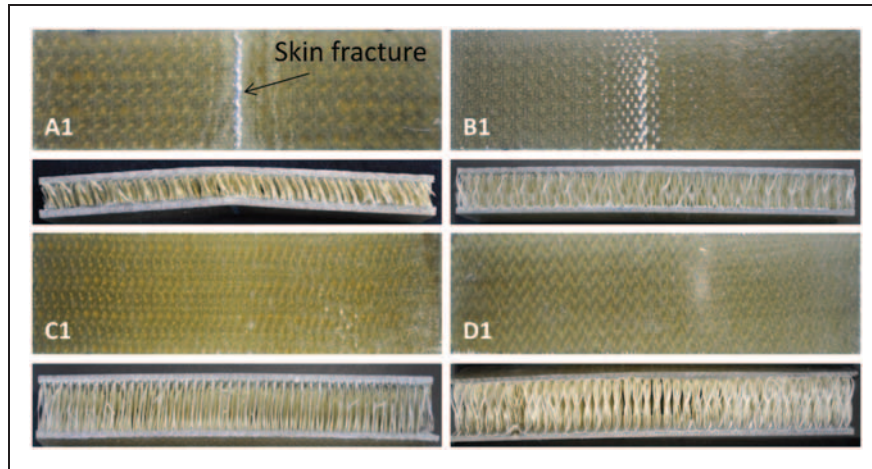


Figure 8. Display of the upper skin and side sectional damages for $L/c = 10$ samples without foam filling. L/c : length/core thickness.

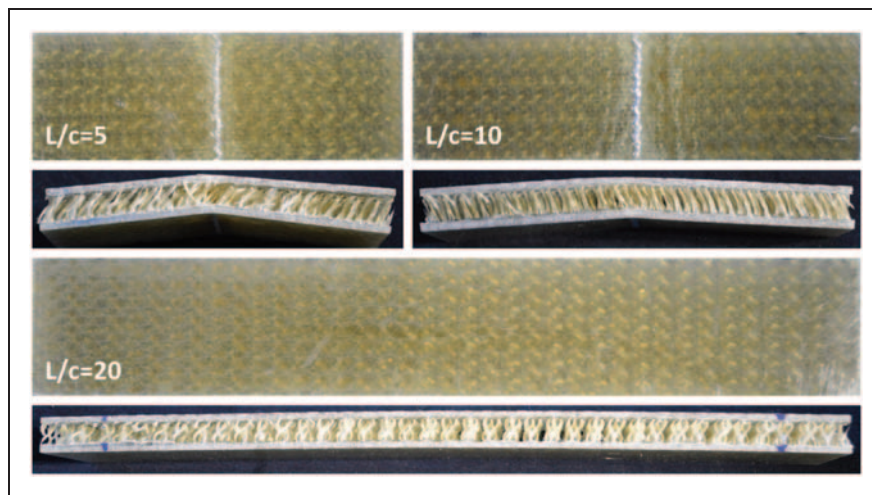


Figure 9. Display of upper skin and side sectional damages for A1 sample at varying span lengths.

samples without foam filling. As the core thickness and span length increase, the structure tends more to take its original form when the bending load is lifted. Skin damage does not occur because the core is so weak. Figure 9 shows upper skin and sectional damages for A1 sample at different span lengths.

The damage characteristics in foamed samples change considerably. Since the use of foam increases the shear resistance, the damage that takes place is a mixture of core breakage, skin breakage, extra skin-core delamination and shear deformation (Figure 10). The dominant damage mode changes according to span length, core thickness and foam density. Depending on the increase in core thickness and decrease in foam density, shear deformations can also take place in foam-filled samples. Figure 11 shows shear deformation occurred on foam-filled sample. In such cases, the foam core gets deformed initially at the parts close to the free

ends. Upper and lower skin layers slide away from each other with the effect of shear deformation. As core thickness decreases and foam density increases, shear resistance reaches its maximum level and the damages that occur consequently take place in the forms of core breakage, skin breakage or extra skin-core delamination. Shear deformation does not occur as the density of foam filling increases and as loading continues cracking of foam core can be observed (Figure 12). Cracking of the foam core generally starts from the mid section and spreads through the length of the whole sample. Due to the high shear loads in tests with short span lengths, delamination of the extra skin layers takes place. In this case, a sharp load decrease occurs and the load-bearing capacity of the structure is partially maintained. This was also the case even for samples with $L/c=20$ span length as the foam density increased (Figure 13). Characteristic of the damages

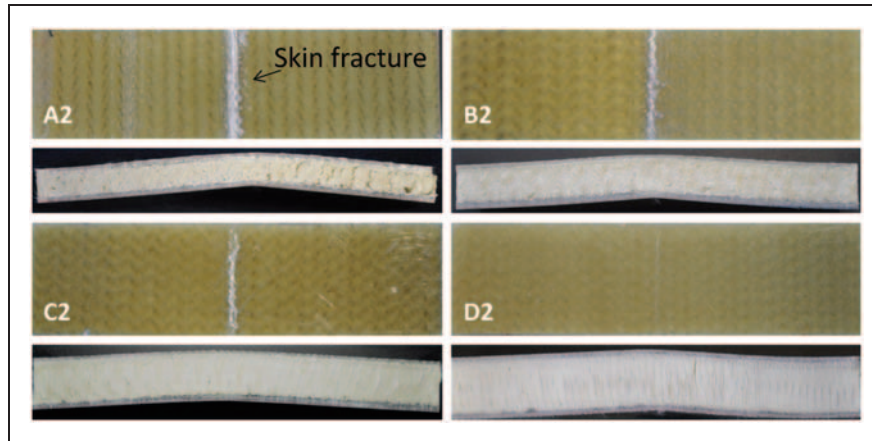


Figure 10. Display of the upper skin and side sectional damages for $L/c = 10$ foam-filled samples. L/c : length/core thickness.

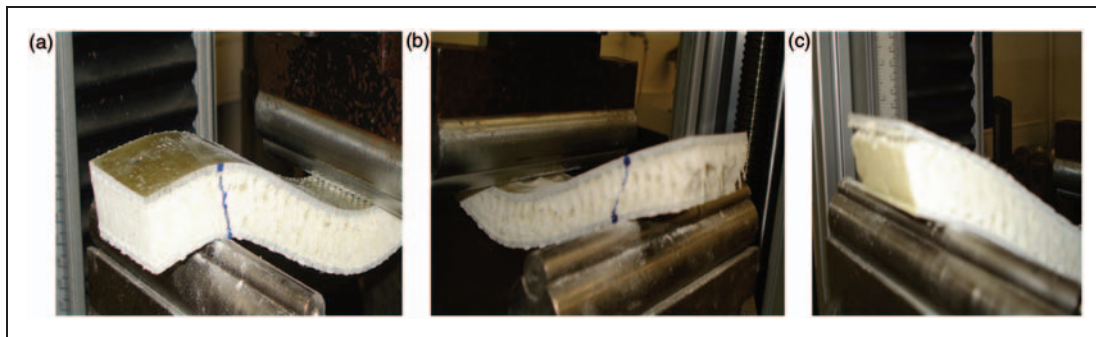


Figure 11. View of the shear deformations taking place on foam filled sample (b and c).

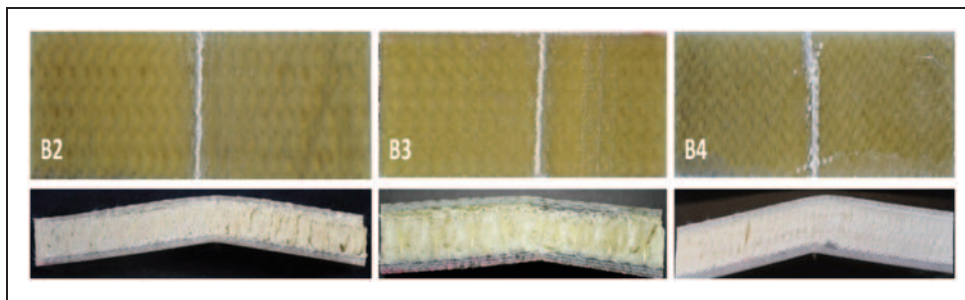


Figure 12. Display of damages that occur at different foam densities.

that occurred as the foam density increased did not show a significant difference, yet since less shear deformations took place the damages were usually in the form of skin breakage.

When the damages that occur on 3D integrated composites due to bending load are compared to those on conventional sandwich composites, it can be set forth that the load-bearing capacity of 3D sandwich composites can be sustained. In conventional foam core sandwiches, the foam core breaks near the loading point

under bending load and load-bearing capacity of the structure ends^{31,36,37} (Figure 14). The important point is that crack in the foam leads to unstable crack growth of this crack and sudden failure. Whereas no such form of damage occurs on 3D sandwiches and the pile yarns in the core and the foam filling support each other during loading. In a 3D sandwich, the pile fibers act as crack stoppers, and that means that there is a more gradual degradation. The damages that occur on the core are only in the form of local foam cracks and

they do not disrupt the integrity of the structure and exhibit that the load bearing capacity of the structure continues. But however the most important problem observed on 3D structures was the delamination of extra skins during loading especially for short span lengths.

Bending and shear modulus

In the determination of skin and core shear modulus, results of the bending test conducted with three different span lengths were used. In these measurements, while sample width was kept fixed (at 45 mm), sample length was changed according to the thickness of the

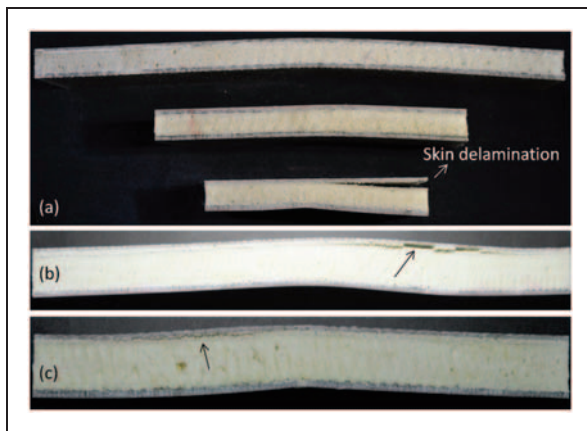


Figure 13. Damages that occur on foam-filled samples for different span lengths (a) and extra skin-core delamination that take place on the samples of $L/c = 20$ (b and c). L/c : length/core thickness.

panel as indicated in Table 3. This method is an alternative to the block shear test method used for determining core shear modulus and previously conducted studies demonstrated that the method is reliable and that there is no significant difference between the results obtained from this method and from the block shear test method.³⁸

Results of skin and core shear modulus are presented in Table 4. The effect of core thickness and foam-filling density on these properties is shown in Figure 15. It is found that the results of shear modulus follow the same trend with the results of bending modulus. Shear modulus increases with the increase of foam density and the decrease of core thickness.

It was determined by comparing the data presented in Table 4 that bending and shear modulus is higher on weft direction when compared to warp direction. As the thickness in samples without foam filling increases from 10 mm to 22 mm, bending modulus decreases from 5800 MPa to 510 MPa and shear modulus decreases from 12.66 MPa to 2.04 MPa for weft direction. On the other hand, in warp direction bending modulus decreases from 2543 MPa to 201 MPa and shear modulus decreases from 8.52 MPa to 1.72 MPa. The decrease in bending modulus during the increase of thickness takes place in accordance with the reduction of core shear resistance, based on the increase in the unsupported length of pile yarns in the core. Highest bending modulus and shear modulus in samples with no foam filling were obtained from the 10 mm sample, the one with the least thickness. On the other hand, bending modulus and shear modulus increased dramatically depending on the addition of foam filling. However, also the weight of the plates increase in line

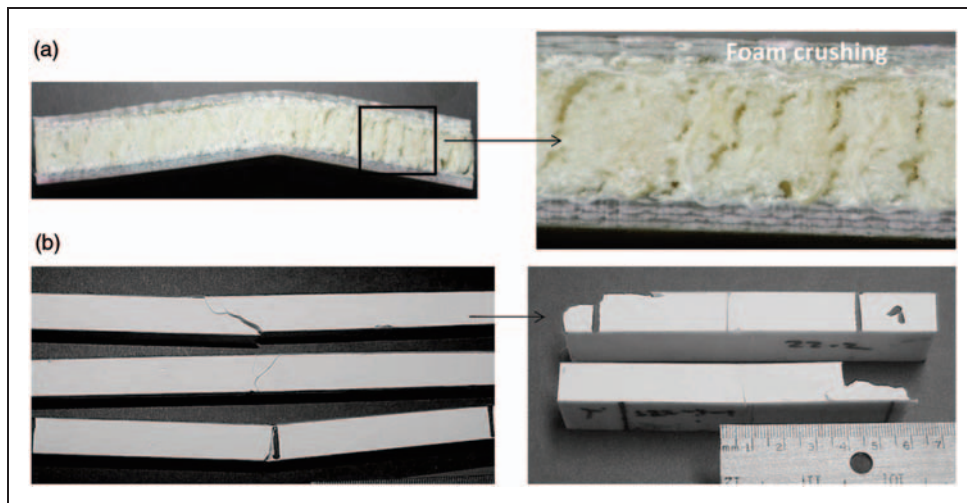


Figure 14. Display of the damages due to bending loading in 3D integrated sandwich composites (a) and conventional foam core sandwiches (b).³¹ 3D: three-dimensional.

Table 4. Three-point bending test results.

Samples	Test direction	Bending modulus (MPa)	Shear modulus (MPa)	Specific bending modulus (MPa. m ³ kg ⁻¹)	Specific shear modulus (MPa. m ³ kg ⁻¹)
A1	Fill	5800 ± 324	12.66 ± 0.80	864.38	1.88
	Warp	2543 ± 156	8.52 ± 0.49	378.98	1.27
A2	Fill	7170 ± 489	31.10 ± 1.62	925.16	4.01
	Warp	4355 ± 258	24.54 ± 1.30	561.93	3.16
A3	Fill	8600 ± 536	38.43 ± 1.86	1107.96	4.95
	Warp	4921 ± 312	30.52 ± 1.55	633.98	3.93
A4	Fill	9278 ± 508	40.10 ± 2.13	1187.90	5.13
	Warp	5321 ± 216	33.05 ± 1.62	681.30	4.23
B1	Fill	2466 ± 128	6.19 ± 0.37	353.24	0.88
	Warp	1077 ± 34	3.92 ± 0.21	154.27	0.56
B2	Fill	4148 ± 185	20.54 ± 1.10	502.05	2.48
	Warp	2511 ± 96	13.94 ± 0.76	303.92	1.68
B3	Fill	5678 ± 304	27.95 ± 1.46	665.49	3.27
	Warp	2855 ± 164	22.71 ± 1.53	334.62	2.66
B4	Fill	5963 ± 276	29.01 ± 1.65	689.60	3.35
	Warp	3092 ± 153	24.4 ± 1.41	357.58	2.82
C1	Fill	788 ± 36	2.59 ± 0.16	109.85	0.36
	Warp	467 ± 21	1.96 ± 0.60	65.10	0.27
C2	Fill	2167 ± 102	15.02 ± 1.01	247.37	1.71
	Warp	1155 ± 52	10.38 ± 0.62	131.85	1.18
C3	Fill	2865 ± 142	22.48 ± 1.20	315.66	2.47
	Warp	2062 ± 113	14.32 ± 0.84	227.19	1.57
C4	Fill	5963 ± 344	24.38 ± 1.39	330.00	2.64
	Warp	2158 ± 108	16.74 ± 1.10	234.10	1.81
D1	Fill	516 ± 23	2.04 ± 0.10	72.79	0.28
	Warp	201 ± 14	1.78 ± 0.50	28.35	0.25
D2	Fill	1870 ± 95	12.56 ± 0.90	201.44	1.35
	Warp	978 ± 46	8.92 ± 0.40	105.35	0.96
D3	Fill	2310 ± 12	18.65 ± 1.10	238.26	1.92
	Warp	1879 ± 98	12.63 ± 1.02	193.81	1.30
D4	Fill	2415 ± 108	20.72 ± 1.41	245.45	2.10
	Warp	2075 ± 101	15.21 ± 1.20	210.89	1.54

with the increase of foam density and it is more meaningful to carry out this evaluation on the basis of the increase in weight.

Compared to the sample without foam filling, in the plate of foamed 10 mm core thickness, specific bending modulus increased by 37% and 79% on weft and warp directions, respectively, while the increase in specific shear modulus on weft and warp directions were 172% and 233%. As for the sample B with 15 mm core thickness, while the increases of specific bending modulus on weft and warp directions were 95% and 131%, the increase in the specific shear modulus on the same directions were 278% and 402%, respectively. For the sample C of 18 mm core thickness, the

increases in specific bending modulus on weft and warp directions were 200% and 259%, while the increases in the specific shear modulus on the same directions were 632% and 564%, respectively. For sample D, specific bending modulus increased by 237% and 643% on weft and warp directions, respectively, and specific shear modulus increased by 631% and 515% on the same directions. As the core thickness increased, the effects of the foam filling on the bending modulus and shear modulus of the samples realized on a higher scale. This is primarily due to the excessive decreases of bending resistance and shear resistance that occur as the thickness of samples without foam filling increases.

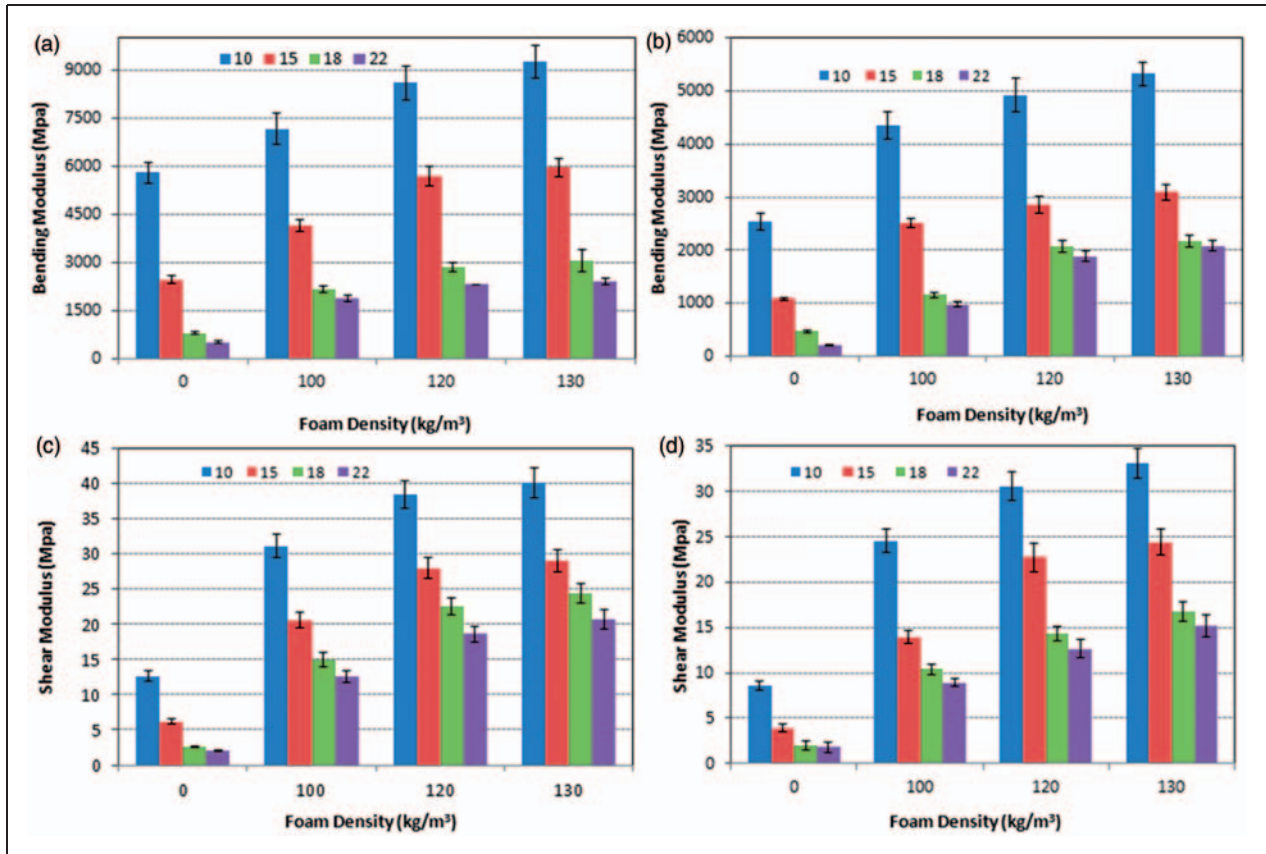


Figure 15. Variation of bending and shear moduli on the basis of the changes in foam density: (a and c) for weft direction and (b and d) for warp direction.

According to the three-factor analysis of variance (ANOVA) test conducted at 95% confidence level, it was determined that the test direction (warps and weft direction), foam density and sample thickness have significant effects on bending modulus and shear modulus values. It was also determined that the intersection of these factors also has effects on bending and shear moduli. The same trend was also detected for specific bending and shear moduli.

According to this, the results of each factor, obtained with 95% confidence level according to Student Newman Keuls analysis (SNK), are shown in Table 5. An arrangement of all of the factors according to their respective average values of bending and shear moduli and specific bending and specific shear moduli is presented here. The results of this arrangement can give an idea in terms of optimization of the results.

According to these results, in the evaluation made for all samples bending modulus and shear modulus on weft direction were, respectively, 44% and 25% higher than those on warp direction. As for the assessment made on the basis of unit weight, specific bending and shear moduli on weft direction were, respectively, 46% and 25% higher than those on warp direction. In the

assessment made for all samples on the basis of core thickness, when the samples of 10 mm core thickness were compared to those of 15, 18 and 22 mm core thicknesses, respectively, 42%, 63% and 74% higher bending moduli and, respectively, 32%, 50% and 58% higher shear moduli were obtained. In the assessment made for core thickness on the basis of unit weight, the specific bending modulus of the sample of 10 mm core thickness were obtained 47%, 74% and 80% higher than those of the samples of 15, 18 and 22 mm core thicknesses, while the specific shear modulus of the sample of 10 mm were 38%, 58% and 65% higher than that of the compared samples. As for the assessment made for all samples on the basis of core densities, for the samples with densities of 100, 120 and 130 bending modulus values increased by 76%, 125% and 162% in comparison to the sample without foam filling, while the increases in shear modulus were 245%, 372% and 413%. For the assessment made on the basis of unit weight, the specific bending modulus values of samples with densities of 100, 120 and 130 increased by 47%, 84% and 95% in comparison with the sample without foam filling, while the increases in the specific shear modulus values were 283%, 292% and 309%.

Table 5. Average bending, shear, specific bending and specific shear moduli values obtained with SNK analysis for different parameters.

Parameters	Bending modulus (MPa)	Shear modulus (MPa)	Specific bending modulus (MPa. m ³ kg ⁻¹)	Specific shear modulus (MPa. m ³ kg ⁻¹)
Test direction				
Fill	4249.80	20.27	502	2.42
Warp	2355.10	15.22	287	1.82
Core thickness (mm)				
10	6002.60	27.36	791	3.56
15	3473.70	18.58	419	2.21
18	2202.95	13.48	207	1.49
22	1530.50	11.52	161	1.22
Foam density (kg m ⁻³)				
0	1732.30	4.96	252	0.72
100	3044.04	17.12	371	2.76
120	3896.25	23.46	463	2.82
130	4537.30	25.45	491	2.95

The results indicate that decreases in core thickness and increases of foam densities have dramatic effects on bending modulus and shear modulus values.

Conclusion

In this study, static properties of 3D integrated sandwich woven composites under bending loading were examined in terms of the changes in core thickness and foam-filling density, and the following conclusions were obtained.

- In three-point bending tests, compression stress takes place on the upper skin of sandwich composite, while tensile stress occurs on the bottom skin and shear stress occurs in the core. The dominant stress among these changes on the basis of core shear resistance and this is related with span length, core thickness, use of foam filling and density.
- In the evaluation made after the three-point bending tests carried out on all samples on the basis of unit weight, it was determined that the specific bending and specific shear moduli on waft direction are 46% and 25% higher than those on warp direction.
- In the assessment made for core thickness on the basis of unit weight, the specific bending modulus of the sample of 10 mm core thickness were obtained 47%, 74% and 80% higher than those of the samples of 15, 18 and 22 mm core thicknesses, while the specific shear modulus of the sample of 10 mm were 38%, 58% and 65% higher than that of the compared samples.

- For the assessment made on the basis of unit weight, the specific bending modulus values of samples with densities of 100, 120 and 130 increased by 47%, 84% and 95% in comparison with the sample without foam filling, while the increases in the specific shear modulus values were 283%, 292% and 309%.
- When compared with conventional foam core sandwich composites, 3D sandwich composites have superior mechanical properties and due to the fact that the pile yarns and the foam in the core support each other when under bending load, no catastrophic core breakage takes place, as it does in conventional sandwich composites, and in this way load bearing capacity of the structure continues.

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