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Geometrical Analysis of 3D Integrated Woven Fabric Reinforced Core Sandwich Composites

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Abstract
The variability of the internal geometry parameters, such as the waviness of yarns, cross sections of yarns and local fibre volume fraction of 3-dimensional (3D) integrated woven core sandwich composites affects their mechanical properties. The objective of this study was to define the geometrical and structural parameters of 3D integrated woven core sandwich composites, including the fold ratio of pile threads, the fabric areal weight and the fibre volume fraction by changing the core thickness of 3D sandwich core fabric. 3D fabrics with different core thicknesses were used for reinforcement. It was confirmed that the pile fold ratio, slope angle and pile length increase with an increase in the core thickness of the fabric. The difference between the calculated and experimental areal weights of fabrics was in the range of 5-13%. A novel approach was also presented to define the fibre volume fraction of 3D woven core sandwich composites.

Key words: *3D integrated fabric, geometrical modelling, shape function.*

Introduction

The use of three dimensional (3D) integrated fabrics in the production of sandwich composites has presented a new concept in the composite industry [1-3]. These fabrics offer better resilience properties than classical two-dimensional textile fabrics and better mechanical properties, such as tensile, flexural and compression strength as compared to other materials like aluminium and magnesium for light weight construction [4]. Composites reinforced with 3D integrated sandwich fabrics show a high strength to weight ratio, damage tolerance and low manufacturing cost. These 3D composites have been widely used in boats, aircraft wings, the sandwich of oil tanks as well as in various floors and partition walls [5]. The 3D textile production methods have led to interesting developments in this area [6-8]. These integrated sandwich fabrics are manufactured using the velvet carpet weaving technique, where two parallel layers (top and bottom) are woven together using pile yarns [3], keeping a definite distance between the layers 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 main disadvantage of many core materials [9, 10]. The warp and weft yarns constitute the top and bottom layers, while the pile yarns create a hollow core section. The free length of pile yarns determines the core thickness. This sandwich fabric structure has the following advantages: (1) sandwich panels can be produced in a single step, and production costs are reduced in line with the shortened production periods; (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; (3) the hollow core section can be filled by several means, thus different functional capabilities can be given to the structure.

The fabric geometry influences the mechanical and end use properties of fabrics and reinforced composites [11]. The issue of variability of internal geometry is especially important for 3D reinforcements, and therefore attracts considerable attention. L. Tong, et al. [12] presented an extensive summary of the problems associated with the manufacturing of multi-layer 3D weaves, such as the lack of consistency and low quality of the products. Sandwich 3D fabrics have very complex geometry since they have two layers and binding yarns between them. This complex geometry makes it difficult to determine and interpret yarn folds, the fibre volume ratio, and their associated mechanical properties in composite materials made from these fabrics. In the light of the information available in the literature, the core behaviour can be partially determined by making simple evaluations for the core part in 3D integrated sandwich fabrics [13]. A unit cell model is developed in the study by Ding and Yi [13] to describe the fibrous structure of 3D woven structures and, consequently, to determine the contribution of different yarn systems inside the 3D structure to the fibre volume fraction.

3D integrated sandwich fabrics are more complicated in structure than other 2D and 3D textile woven fabrics used in the production of composite materials. In 3D integrated sandwich fabrics, fibre distribution in the skin and core is different from each other. Different yarn connections and crimp properties in the skin and core make it difficult to predict the mechanical properties of composites obtained from these fabrics. It is therefore necessary to identify the structural parameters of the skin and core geometry of 3D integrated core sandwich fabrics in order to determine the mechanical properties of composites produced from these fabrics. A geometrical modelling approach based on finite element modelling has been used to model the core behaviour of sandwich fabric [9].

In order to apply the property potential of 3D integrated sandwich fabrics in composites, a systematic study is necessarily required to understand the influence of the structural factors on their mechanical behavior. This will help in the proper choice of fabric structure, structural design and correct evaluation of performance properties to obtain composite parts with 3D integrated core sandwich fabrics [14-16]. The fibre volume fraction is an important parameter which directly affects the composite properties. A geometrical cell model was developed in a study to predict the volume fraction of fibre and the cellular part of 3D integrated cellular woven composites [17]. However, a totally different and novel approach was practiced in this study to determine the fibre vol-

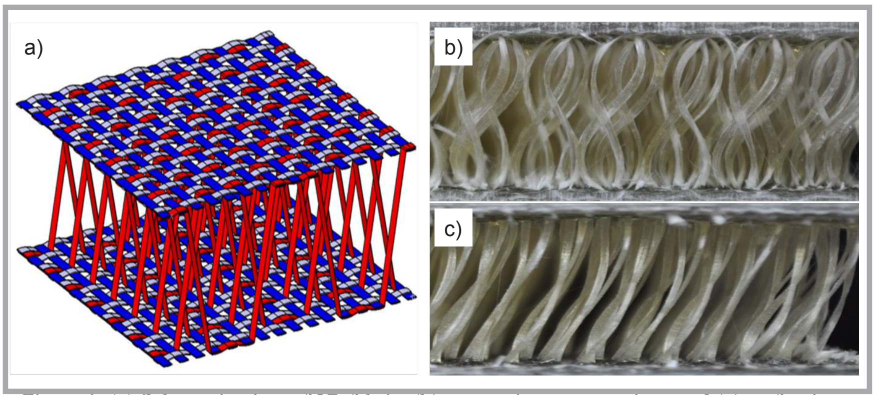

Figure 1. *a) Schematic view of 3D fabric, b) warp-wise cross section, and c) weft-wise cross section.*

ume fraction of composites reinforced with 3D integrated core sandwich fabric. So far, there has been no mathematical model available in literature to model the weight per unit area of 3D integrated core sandwich fabric and to determine the fibre volume fraction of their corresponding composite panels. Therefore it necessitates the introduction of a new model of 3D integrated core sandwich fabric panels. The objective of this paper is to explore the fibre architecture in a 3D integrated woven glass sandwich core composite by defining the parameters of the internal geometry for cross sections of the composite to model the weight per unit area of 3D integrated core sandwich fabric and to determine the fibre volume fraction of their corresponding composite panels.

Materials and methods

3D integrated fabrics

3D sandwich fabrics, supplied by Parabeam BV (NL), with a core thickness of 10, 15, 18 and 22 mm were used in this research. All four fabrics were identical in terms of their top and bottom skin layers, the yarns used and weaving architecture. The only difference is in their free pile yarn length and, thus, the core thickness.

Table 1. *General characteristics of fabrics used in the study.*

Core thickness, mm	Yarn	Yarn crimp, %	Yarn density, yarn/cm²	Fabric weight, g/m²
10	Warp	2.80	2.08	1430
	Weft	2.80	2.56	
	Z-thread	190	2.08	
15	Warp	2.40	2.08	1600
	Weft	4.40	2.56	
	Z-thread	251.80	2.08	
18	Warp	3.90	2.08	1720
	Weft	2.30	2.56	
	Z-thread	322.40	2.08	
22	Warp	4.40	2.08	1860
	Weft	2.40	2.56	
	Z-thread	298.20	2.08	

Figure 1 illustrates the typical weaving architecture and cross sectional view in the warp and weft directions of 3D integrated sandwich fabric. Accordingly there are binding yarns between the top and bottom skin layers of the structure in the pile direction which create the hollow core of the fabric. The structure of 3D integrated sandwich fabrics is different from that of conventional woven fabrics [18]. Therefore the fabric geometry was established based on the yarn intersections within the fabric to understand the fabric structure. Parameters taken from the fabric structure were yarn thickness, weave densities and the distance between yarns. Drawings were made using CATIA CAD software. Parameters of the fabrics used in the study are listed in ***Table 1***. All yarns in the warp, weft and pile directions consisted of E-glass fibres with a linear density of 300 tex.

Fabrication of 3D integrated sandwich composite panels

3D sandwich core composites were produced from 3D integrated fabrics. Atlac 580 AC 300 type vinylester urethane resin was used. A 6% cobalt naphthalate accelerator was added in a ratio of 0.25%. A 50% active methyl ethyl kethone peroxide catalyst was used with a mixing ratio of 2%.

All composite panels were manufactured with the hand lay-up technique using a glass plate and treating its surface with a releasing agent. Special care was taken to control the fibre volume fraction during the production of each panel. After applying the resin to the skins on both sides, it was ensured that the resin thoroughly penetrated the entire fabric and that all entrapped air was removed using aluminum impregnation rollers (***Figures 2.a, 2.b***).

After application of the resin, the laminate plates were kept for one day to com-

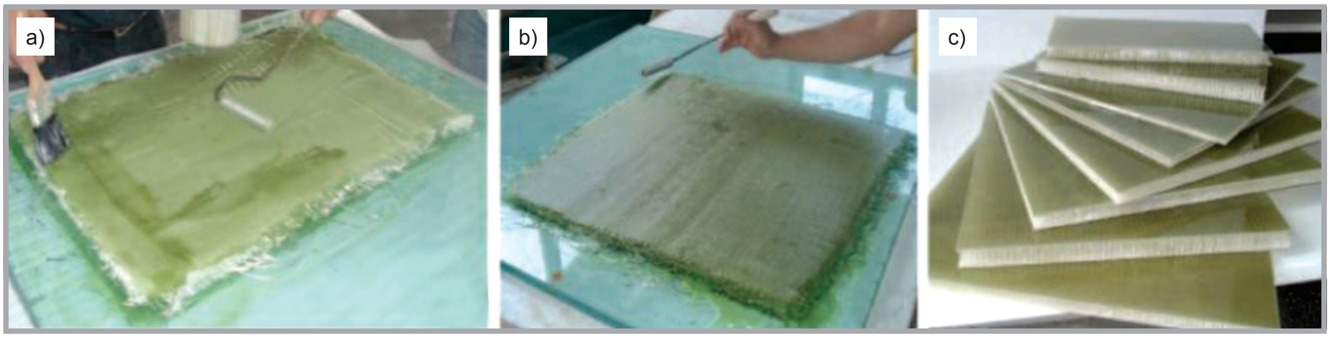

Figure 2. *a, b) Fabrication of 3D integrated composite panels, and c) view of finished plates.*

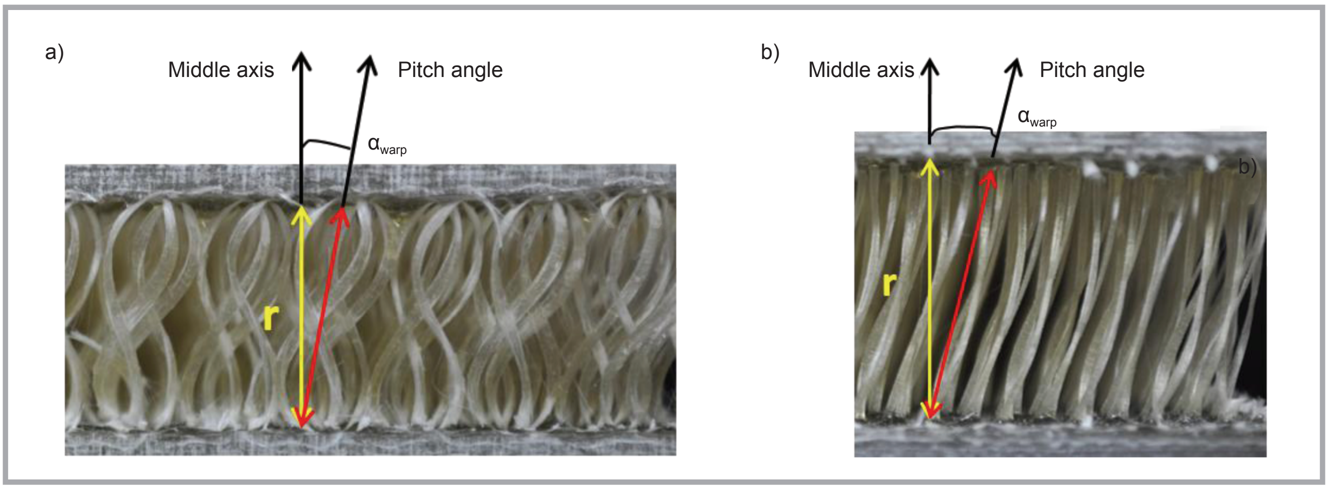

Figure 3. *Appearance of pile yarns in warp (a) and weft (b) directions.*

pletely cure. After that, specimens were cut from the plates. The appearance of the composite panels is shown in ***Figure 2.c***. Composite panels of the 3D integrated sandwich fabrics were prepared only for microscopic analysis. Cross sections of the composite panels were prepared with sandpaper of 120 grit roughness to get the precise position of the desired cross section. After that, sandpapers of 320, 800, 1200 and 4000 grit roughness were applied in ascending order for at least 15 min each (till the marks from the previous grade were removed). Finally diamond suspension with a 2 µm roughness was applied.

The cross sections were observed and images taken using (a) a scanner with a resolution of 4800 dpi, (b) a Reichert – ZETOPAN microscope (Austria), and (c) a Leica DMILM HC inverted microscope with image processing software (Germany). The image scale was calibrated in each case with an object of known dimensions.

Mathematical model

Pile fold (bending) ratio

The pile bending (fold) ratio is defined as the ratio of the direct length of the pile between the upper and lower skins (r) to the maximum possible pile thread length (L). This situation is presented in ***Figure 3***. If the pile thread has no curl, then it is directly tied to the lower and upper skins like a straight rod. But in reality, it has a certain curl in the form of an 'S' shape due to its slightly longer length than that of its core thickness. Due to this curvature, the pile thread forms a certain slope or pitch angle (α) with respect to the vertical (middle) axis (***Figure 3***). This angle (α) affects the fold ratio of the pile thread in dependence on its size. ***Figure 3*** shows angle α in both the warp and weft directions [7].

In this work, three different fold ratios of pile yarns are defined:

1 – The practical pile fold ratio neglects the slope angle and does not consider the length distributions between pile yarns. The practical fold ratio is given by ***Equation (1)*** [9, 19]:

$$\%S_{practical} = \frac{r}{L_{min}} \qquad (1)$$

Where L_{min} is the smallest pile length measured in the fabric.

In this measurement method, the smallest pile yarn is considered vertically oriented on the middle axis, and the slope angle is so small (less than 5 degrees) that it is neglected.

Figure 3 shows the state of the warp and weft directions of pile yarns on the sandwich panels. The practical folding ratio depends on the smallest pile yarn length in the structure, and the crimp in this smallest pile yarn is very low. L_{min} is determined by taking the maximum number of possible measurements from the fabric and assuming that there is no slope angle.

2 − The true fold ratio takes into account the slope angle, the relation of which is given by ***Equation (2)*** [9, 19]:

$$\%S_{real} = = \frac{r}{L}\sqrt{tan^2(\alpha_{warp}) + tan^2(\alpha_{weft}) + 1} \qquad (2)$$

Where 'L' is the average length of the pile, and 'α_{warp}' and 'α_{weft}' are the slope angles in the warp and weft directions, respectively.

3 − The average fold ratio is calculated by taking the length distribution into account and by putting the average length L in ***Equation (1)*** while neglecting the slope angle.

Fabric areal weight

To determine the fabric areal weight, the weights of warp, weft and pile yarns were calculated separately and subsequently added to get the total fabric weight. The weight of weft yarns was calculated using the relation given in ***Equation (3)***:

$$W_f = \frac{n_f.(100+C_f)}{1000.100} T_f \qquad (3)$$

Where, W_f is the weight per unit area (g/m^2), n_f the number of weft threads per unit length (threads/cm), C_f the crimp (%), and T_f is the linear density (tex) of weft yarns.

The same relationship applies to warp yarns:

$$W_w = \frac{n_w.(100+C_w)}{1000.100} T_w \qquad (4)$$

Where, W_w is the weight per unit area (g/m^2), n_w the number of warp threads per unit length (threads/cm), C_w the yarn crimp (%), and T_w is the linear density (tex) of warp yarns. The top and bottom layers of the fabric were woven with the same warp and weft yarns, thus the same yarn from the top layer is moved to the bottom. Therefore, while calculating the total fabric weight, the weight of warp and weft yarns must be multiplied by two.

Pile yarns have a different arrangement from that of warp and weft yarns. These yarns pass through the top and bottom layers and have a free length in the core.

Table 2. *Different parameters of pile threads.*

Core thickness, mm	r, mm	L, mm	α_{warp}, °	α_{weft}, °	$\%S_{real}$	$\%S_{practical}$	$\%S_{average}$
10	105	112	5	6	0.9375	0.94875	0.943125
15	152	171	6	8	0.888889	0.937778	0.913333
18	184	191	8	10	0.963351	1.040419	1.001885
22	225	232	10	15	0.969828	1.06681	1.018319

The total weight of pile yarns is calculated by dividing the fabric structure into three different sections: the top layer, bottom layer, and the core. Accordingly the weight of pile threads in the top layer can be calculated as follows:

$$W_{pt} = \frac{(n_{pt}/2).(100+C_{pt})}{1000.100} T_p \qquad (5)$$

Where, W_{pt} is the weight of the top layer per unit area (g/m^2), n_{pt} the number of threads of the top layer per unit length (threads/cm), C_{pt} the yarn crimp (%), and T_p is the linear density (tex) of pile yarns in the top layer. The same relationship applies to pile yarns in the lower layer:

$$W_{pb} = \frac{(n_{pb}/2).(100+C_{pb})}{1000.100} T_p \qquad (6)$$

Where, W_{pb} is the weight of the bottom layer per unit area (g/m^2), n_{pb} the number of threads of the bottom layer per unit length (threads/cm), C_{pb} the yarn crimp (%), and T_p is the linear density (tex) of pile yarns in the bottom layer. The weight of pile threads in the core is calculated using the following relation:

$$W_{pc} = \frac{n_{pc}.(100+C_{pc})}{1000.100} T_p \qquad (7)$$

Where, W_{pc} is the weight of the core layer per unit area (g/m^2), n_{pc} the number of threads per unit length (threads/cm), C_{pc} the yarn crimp (%), and T_p is the linear density (tex) of pile yarns in the core. Ultimately the total weight of pile yarns is calculated as follows ***Equations (8)*** and ***(9)***:

$$W_p = W_{pt} + W_{pb} + W_{pc} \qquad (8)$$

We can simplify the above expression to get ***Equation (10)***.

The total weight per unit area of the fabric is determined as follows ***Equation (11)***:

$$W_t = 2.W_f + 2.W_w + W_p \qquad (11)$$

By replacing ***Equation (11)***, we get ***Equation (12)*** and ***(13)***.

The yarn linear density (T), crimp% (C), and number of threads per unit length (n) used in the expressions above were determined experimentally (***Table 1***), and finally the values were put in ***Equation (13)*** to get the total areal weight of the fabric.

Fibre volume fraction

The fibre volume fraction is an important parameter that has a significant effect on the mechanical properties and performance of composites. Therefore it must be determined correctly. In the case of 3D sandwich composites, the fibre volume fraction is determined by a method different from monolithic plates. Because of the existence of gaps in the middle and presence of pile yarns in the upper layer, lower layer and core at the same time, it is necessary to consider the weights of individual (warp, weft and core) yarns in order to find the correct fibre volume fraction.

The fibre volume fraction can be calculated using the following relation:

$$V_{f-t} = \frac{V_w + V_f + V_p}{V_t} \times 100 \qquad (14)$$

Where is the total fibre volume fraction, V_w the fibre volume fraction of warp yarns, V_f the fibre volume fraction of weft yarns, V_p the fibre volume fraction of pile yarns, and V_t is the total volume of the panel.

The total volume of the panel can be easily calculated depending on the panel thickness. The values of V_w, V_f and V_p are calculated as follows:

$$V_w = \frac{W_w}{\rho}\ ; V_f = \frac{W_f}{\rho}\ ; V_p = \frac{W_p}{\rho}\ ; V_t = t.l.w \qquad (15)$$

Where 'ρ' is the density of glass fibre (g/cm^3), 'l' the composite panel length (mm), 't' the composite panel thickness (mm), and 'w' is the composite panel width (mm).

In this case, the total fibre volume fraction can be written as ***Equation (16)*** and ***(17)***:

$$V_{f-t} = \frac{2.W_w + 2.W_f + W_p}{\rho.l.w.t} \times 100 \qquad (16)$$

Results and discussion

Table 2 shows the different parameters of pile yarns measured experimentally and pile fold ratios (S) calculated using ***Equations (1)*** and ***(2)*** for all fabrics of different core thickness. The cross-sec-

$$W_p = \frac{(n_{pt}/2).(100+C_{pt})}{1000.100} T_p + \frac{(n_{pb}/2).(100+C_{pb})}{1000.100} T_p + \frac{n_{pc}.(100+C_{pc})}{1000.100} T_p \qquad (9)$$

$$W_p = \frac{[(n_{pt}/2).(100+C_{pt})]+[(n_{pb}/2).(100+C_{pb})]+[n_{pc}.(100+C_{pc})]}{1000.100} T_p \qquad (10)$$

$$W_t = 2.\frac{n_f.(100+C_f)}{1000.100} T_f + 2.\frac{n_w.(100+C_w)}{1000.100} T_w + \frac{[(n_{pt}/2).(100+C_{pt})]+[(n_{pb}/2).(100+C_{pb})]+[n_{pc}.(100+C_{pc})]}{1000.100} T_p \qquad (12)$$

$$W_t = \frac{2.[n_f.(100+C_f)].T_f + 2.[n_w.(100+C_w)].T_w + \{[(n_{pt}/2).(100+C_{pt})]+[(n_{pb}/2).(100+C_{pb})]+[n_{pc}.(100+C_{pc})]\}.T_p}{1000.100} \qquad (13)$$

$$V_{f-t} = \frac{2.[n_f.(100+C_f)].T_f + 2.[n_w.(100+C_w)].T_w + \{[(n_{pt}/2).(100+C_{pt})] + [(n_{pb}/2).(100+C_{pb})] + [n_{pc}.(100+C_{pc})]\}.T_p}{1000.\rho.l.w.t} \qquad (17)$$

Equations (9), (10), (12), (13) *and* ***(17).***

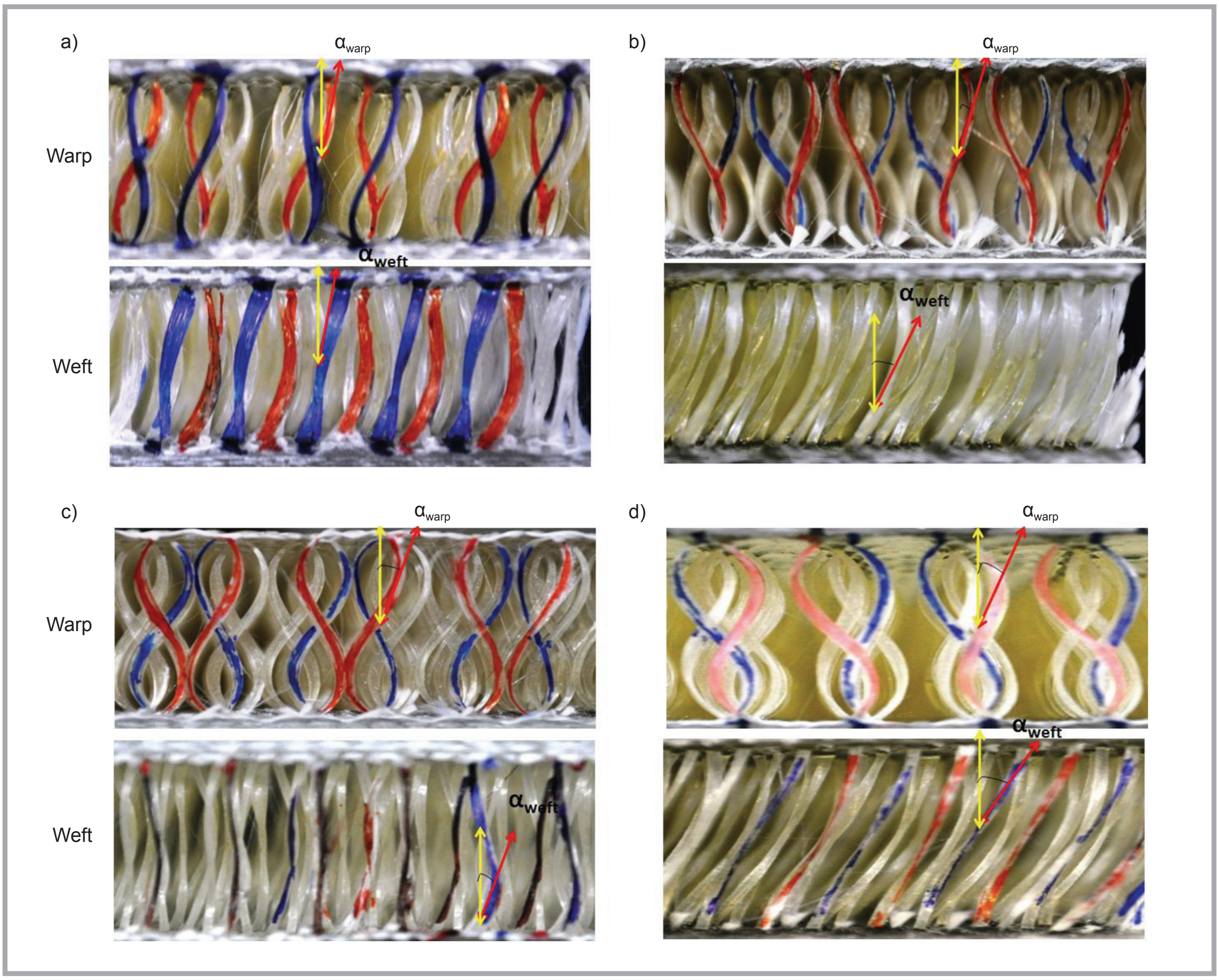

__Figure 4.__ Cross-sectional images of 3D fabrics for a) 10 mm, b) 15 mm, c) 18 mm, and d) 22 mm thicknesses.

tional shapes of the 3D integrated fabrics are also presented in ***Figure 4***. It is evident that the pile length, slope angles and pile fold ratios increase with an increase in the core thickness of the fabric. The possible reason for the increase in the slope angle and pile fold ratio may be due to pile length being greater than the core thickness.

The values of different geometrical parameters from ***Table 1*** and ***2*** were put in ***Equation (13)***, and the total fabric areal weight was calculated. The fabric weights calculated were about 1500, 1700, 1800 and 1750 g/m^2 for 10, 15, 18 and 22 mm core thicknesses, respectively. These values are approximately 87-95% in close agreement with the values measured, given in ***Table 1***.

The total fibre volume fractions of composite panels of different thickness were calculated using ***Equation (17)***, which were found to be 5.5%, 4.1%, 3.7% and 2.95% for panels with 10, 15, 18 and 22 mm core thicknesses, respectively. This may be due to the decrease in the volume of fibres in the core, as compared to the total free volume of the core resulting in a decrease in the volume fraction of corresponding composite panels with an increase in core thickness. It is also evident from ***Figure 4*** that when the core thickness increases, the length of the pile in the core as well as the total volume of the core increase, while the volume of fibres in the total volume of the core decreases. Hence the fibre volume fraction decreases in the composite panel with an increase in core thickness.

It can be estimated from ***Figure 1*** that the fibre volume fraction at the surface of the panel is different from that of the core. The value of the volume fraction will be maximum at the surface, while it will be minimum at the core due to the lower volume of fibres and greater hollow core in the middle. The results may be utilised as input data for geometrical modelling and meso-level 3D finite element analysis of this type of composite panel, thus enabling a more precise representation of the internal geometry with additional assessment of the scatter of processing parameters and prediction of the mechanical properties of 3D integrated core sandwich panels.

Conclusions

In this study, the geometrical and structural parameters of 3D integrated woven core sandwich composites, including the fold ratio of pile threads, the fabric areal weight and fibre volume fraction, were defined by changing of composite thicknesses. The results were as follows:

- The pile length, slope angles and pile fold ratios increase with an increase in the core thickness of the fabric due to the pile length being greater than the core thickness.

- The fabric weights calculated are approximately 87-95% in close agreement with the experimentally measured values.
- A novel approach is practiced to determine the fibre volume fraction of composites reinforced with 3D integrated core sandwich fabric. The total fibre volume fractions of composite panels were found to be 5.5%, 4.1%, 3.7% and 2.95% for panels with 10, 15, 18 and 22 mm core thicknesses.

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