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

DOI: 10.5604/01.3001.0012.7507

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 sand- wich 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-
3D integrated fabrics
3D sandwich fabrics, supplied by Para-beam 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 | 296.20     | 2.08                   |                     |

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-
completely cure. After that, specimens were cut from the plates. The appearance of the composite panels is shown in Figure 2c. 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]:

   \[
   \%S_{practical} = \frac{r}{L_{\min}}
   \]

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

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

   \[
   \%S_{real} = \frac{r}{L} = \frac{\tan^{2}(\alpha_{\text{warp}}) + \tan^{2}(\alpha_{\text{weft}})}{1}
   \]

   Where ‘L’ is the average length of the pile, and \(\alpha_{\text{warp}}\) and \(\alpha_{\text{weft}}\) 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):

\[
W_{f} = \frac{n_{f}(100+C_{f})}{1000.100} \cdot T_{f}
\]

Where, \(W_{f}\) is the weight per unit area (g/m²), \(n_{f}\) 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:

\[
W_{w} = \frac{n_{w}(100+C_{w})}{1000.100} \cdot T_{w}
\]

Where, \(W_{w}\) is the weight per unit area (g/m²), \(n_{w}\) 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 | \( t \) mm | L, mm | \( \sigma_{warp} \) | \( \sigma_{weft} \) | \%S_{total} | \%S_{practical} | \%S_{measured} |
|-------------------|------------|-------|-----------------|---------------|--------------|----------------|----------------|
| 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:

\[
W_{pt} = \frac{(n_{pt}/2)(100+C_{pc})}{1000.100} T_p \tag{5}
\]

Where, \( W_{pt} \) is the weight of the top layer per unit area (g/m²), \( n_{pt} \) is the number of threads of the top layer per unit length (threads/cm), \( C_{pc} \) is 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:

\[
W_{pb} = \frac{(n_{pb}/2)(100+C_{pc})}{1000.100} T_p \tag{6}
\]

Where, \( W_{pb} \) is the weight of the bottom layer per unit area (g/m²), \( n_{pb} \) is the number of threads of the bottom layer per unit length (threads/cm), \( C_{pc} \) is the yarn crimp (%), and \( T_p \) is the linear density (tex) of pile yarns in the lower layer. The weight of pile threads in the core is calculated using the following relation:

\[
W_{pc} = \frac{n_{pc}(100+C_{pc})}{1000.100} T_p \tag{7}
\]

Where, \( W_{pc} \) is the weight of the core layer per unit area (g/m²), \( n_{pc} \) is the number of threads of the core layer per unit length (threads/cm), \( C_{pc} \) is 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):

\[
W_p = W_{pt} + W_{pb} + W_{pc} \tag{8}
\]

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

\[
W_t = 2. W_f + 2. W_w + W_p \tag{11}
\]

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:

\[
V_{f-t} = \frac{2. W_w + 2. W_f + W_p}{\rho \cdot \text{t.l.w.}} \times 100 \tag{16}
\]

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:

\[
V_w = \frac{W_w}{\rho} ; V_f = \frac{W_f}{\rho} ; V_p = \frac{W_p}{\rho} ; V_t = \text{t. l. w.} \tag{15}
\]

Where ‘\( \rho \)’ is the density of glass fibre (g/cm³), ‘t’ the composite panel length (mm), ‘l’ 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 Equations (16) and (17):

\[
V_{f-t} = \frac{2. W_w + 2. W_f + W_p}{\rho \cdot \text{t.l.w.}} \times 100 \tag{17}
\]

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-

\[
W_p = \frac{(n_{pt}/2)(100+C_{pc})}{1000.100} T_p + \left( \frac{(n_{pb}/2)(100+C_{pc})}{1000.100} T_p \right) + \left( \frac{n_{pc}(100+C_{pc})}{1000.100} T_p \right) \tag{9}
\]

\[
W_p = \left[ \frac{(n_{pt}/2)(100+C_{pc})}{1000.100} T_p \right] + \left[ \frac{(n_{pb}/2)(100+C_{pc})}{1000.100} T_p \right] + \left[ \frac{n_{pc}(100+C_{pc})}{1000.100} T_p \right] \tag{10}
\]

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

\[
W_t = \frac{2. n_f(100+C_f) T_f + 2. n_w(100+C_w) T_w + \left[ \frac{(n_{pt}/2)(100+C_{pc})}{1000.100} T_p \right] + \left[ \frac{(n_{pb}/2)(100+C_{pc})}{1000.100} T_p \right] + \left[ \frac{n_{pc}(100+C_{pc})}{1000.100} T_p \right]}{1000.\text{p.l.w.t}} \tag{13}
\]

\[
V_{f-t} = \frac{2. W_w + 2. W_f + W_p}{\rho \cdot \text{t.l.w.}} \times 100 \tag{17}
\]

\[
E_{\text{quations (9), (10), (12), (13) and (17).}}
\]
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/m² 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 fibre in the core increases, 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.

**Figure 4. Cross-sectional images of 3D fabrics for a) 10 mm, b) 15 mm, c) 18 mm, and d) 22 mm thicknesses.**
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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Received 05.06.2017 Reviewed 02.07.2018

THE PLASTICS HERITAGE CONGRESS 2019
HISTORY, LIMITS AND POSSIBILITIES
29th-31st MAY 2019, LISBON, PORTUGAL