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Mathematical modelling of 3D woven fabrics for CAD/CAM software

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Abstract

Weaving is one of the key technologies that are used in organising unidirectional fibrous materials into 2D sheet and 3D shaped geometrical architectures for applications such as textile composites. It has been demonstrated that the conventional weaving technology has the potential to produce textile assemblies which have many different types of 3D shaped fabrics, and this approach has obvious advantages in the provision of a sizeable quantity of 3D shaped fabric and in cost reduction. However, the design of such 3D shaped woven fabrics may be complicated especially when the shape and micro structures are complex. This paper reviews the mathematical modelling of different types of 3D weaves which have been successfully used in developing CAD/CAM software for 3D fabrics. The types of weaves described here include single-layer, 3D orthogonal, 3D angle interlock, and 3D cellular. Results from different CAD programmes are also demonstrated.

Keywords

3D woven fabrics, mathematical modelling, orthogonal, angle-interlock, cellular, CAD/CAM

Introduction

Textile assemblies already play an important role in technical applications, most notably as reinforcements and preforms to advanced fibre composites for aerospace, automotive and many other applications.[1] Unidirectional and 2D woven textiles have been widely used in creating composite components and they have demonstrated clear advantages over the traditional metallic materials in the performance to weight ratio. As an effort to eliminate composite delamination and to increase structural integrity, various 3D textile structures have received serious attention for composite and many other applications. In response to the demand of 3D textile structures, different methods have been used to create 3D textile assemblies, including weaving, braiding, warp knitting, and nonwoven.[2] In weaving, two general approaches are used for making the 3D textile structures. The first is based on the development of new weaving machines for making 3D fabrics. Examples of this include technologies developed by 3Tex[3] and Biteam.[4] Another approach for making 3D woven architectures is based on the conventional weaving technology. The University of Manchester[5] has been working in this area for many years and has developed techniques and tools for creating different categories of 3D woven fabrics. The advantages of the latter include readily available manufacturing technology and the flexibility of the 3D structures that can be produced. It is also claimed that the technology route using the conventional weaving leads to the low cost of 3D architectures.

Whilst the conventional weaving technology has the capability of making a large variety of 3D textile architectures, the design and manufacture of the 3D fabrics can be complicated. This paper presents the work and progress made in the mathematical modelling of woven structures and in establishing CAD/CAM tools for 3D woven architectures based on the use of the conventional weaving technology.

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Classification of 3D woven architectures

3D woven architectures may be classified according to many different criteria. According to the geometrical details, 3D woven architectures can be classified into 3D solid, 3D hollow, 3D domes and 3D nodal.[6]

3D solids refer to those woven architectures that have solid cross-sections either in a broad panel or in a net shaped preform. There are a number of different ways to form 3D solid architectures, each having its own structural features and mechanical properties.[7,8] Firstly, a 3D solid architecture can be made based on the multi-layer principle, where there are multiple layers of distinctive woven fabrics being stitched during the weaving process. The features of this type of 3D architecture are that (i) each fabric layer can be given a different weave to facilitate a 'hybrid' of properties through the thickness of the composite; (ii) all warp and weft yarns in the 3D solid textile architectures can be crimped to specified extents to suit the property requirements of the composite; (iii) the required amount of vertical stitching can be arranged between any layers of fabrics in the preform to enhance the through-the-thickness property; and (iv) the architecture can be further strengthened up by adding straight wadding yarns in any adjacent fabric layer in either warp or weft or both directions. The second method for making 3D solid woven architecture is the orthogonal principle.[7] The structural features of these types of fabric are that (i) all yarns in the three principal directions are laid straight, therefore they are able to take on the load directly and most effectively; (ii) required amount of vertical yarns can be arranged by the binding weave specification; and (iii) the interlinking depth can be altered easily within the same preform, leading to variable preform thickness. The third way for making 3D architectures is with the use of the angle-interlock principle, where the weft yarns are laid straight whereas the warp yarns are travelling diagonally.[8] This structure generally leads to more flexible 3D structures because of the reduced number of cross-over contact points. Wadding warp yarns can be introduced into the angle interlock fabric during weaving to increase the structural rigidity. Figure 1 illustrates the cross-sectional views of these solid architectures.

3D hollow architectures in this context refer to those having tunnels running in warp, weft, or any diagonal directions in the thickness of the 3D architecture. There are two different types of 3D hollow architectures,[9,10] one with flat surfaces and the other with uneven surfaces. The creation of the 3D hollow architectures is based on the multi-layer weaving principle to join and separate fabric layers in places as needed. For the flat-surface hollow fabrics, the lengths of some inner fabric layers are made longer than the surface layers. In the case of the uneven-surface hollow fabrics, the fabric layers in the same region in the cross-section are made to have the same length. The cell size determines the maximum opening thickness of the fabric. Figure 2 shows the two types of hollow architectures.

3D dome architecture can be achieved by weave combination, discrete take-up,[11] and moulding with fabrics which have a low shear rigidity.[12] Nodal architectures basically refer to woven tubes which are joined together.[13] Smooth opening-up of all joining tubes must be achieved. Figure 3 shows examples of domed and nodal architectures.

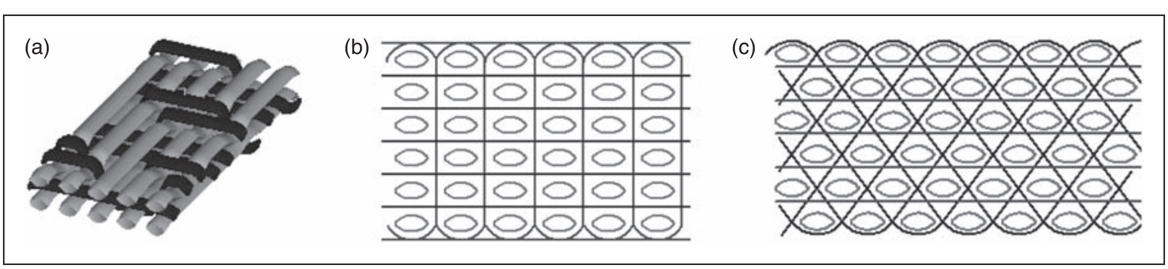

Figure 1. Cross-sectional views of 3D solid architectures.

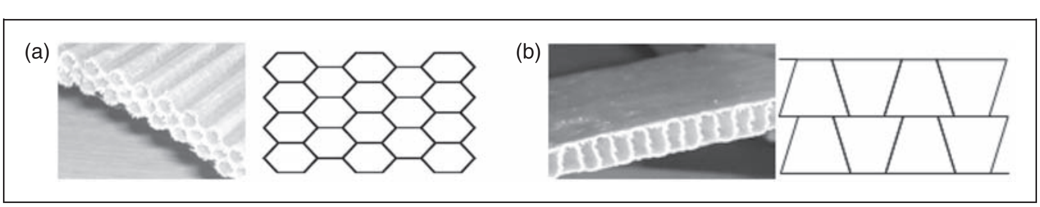

Figure 2. 3D hollow structures with uneven and flat surfaces.

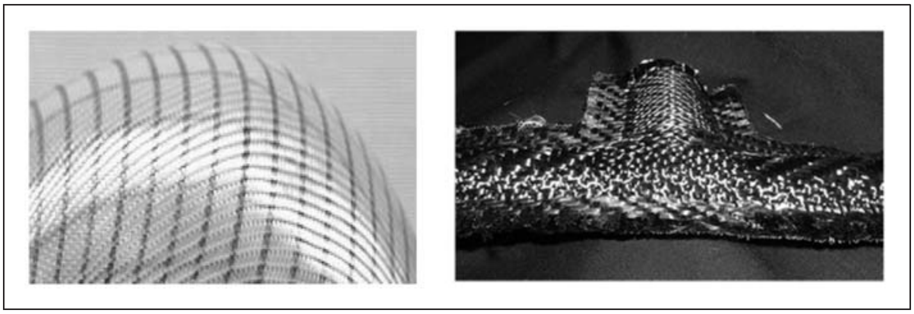

Figure 3. Domed and nodal 3D architectures.

Mathematical descriptions of 2D and 3D woven structures

2D weaves

Single-layer woven fabric is made from one set of warp yarns and one set of weft yarns. By arranging interlacement between warp and weft yarns, different weave patterns can be obtained. A 2D binary matrix has been used to represent these patterns.[14] Figure 4 shows a 2D binary matrix and the weave it represents.

In order for the computer to create weaves, weaves need to be parameterised. The parameters should be the ones that are commonly used by the weave designer and engineers. Based on the nature of the weaves, weaves are classified into regular and irregular. The former refers to weaves with constant float arrangement and step number within one complete repeat, and the rest are called irregular weaves. Many commonly used weaves are regular weaves. Let us discuss the mathematical description of the regular weaves.

For creating regular weaves, the input parameters are as follows:

N_f – the number of floats;

$F_i (i = 1, 2, 3, \ldots, N_f)$ – the lengths of the i^{th} float. If i is an odd number, F_i represents a warp-up float; and if i is an even number, it represents a warp-down float; and

S – the step number of the weave.

The weft repeat R_p of a regular weave can be obtained using the following equation:

$$R_p = \sum_{i=1}^{N_f} F_i \quad (1)$$

The step numbers, denoted by S, may be specified either in the warp or the weft direction. However, this work presumes that step numbers are specified in the warp direction only. The absolute value of step number should be smaller than the weft repeat, namely:

$$|S| < R_p \quad (2)$$

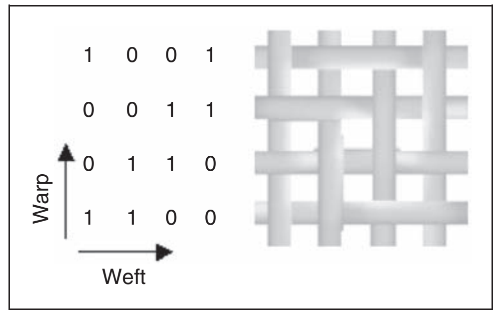

Figure 4. Weave and weave matrix.

A step number can be specified as either a positive or a negative integer. The positive step number indicates the 'Z' direction of the twill lines, and the negative step number indicates the 'S' direction of the twill lines. A negative step number, S_n, can be converted to a positive equivalence, S_p, by the following:

$$S_p = R_p + S_n \quad (3)$$

where S_p is the positive step number, S_n is the negative step number, and R_p is the weft repeat. The negative step number S_n will give the same effect to the weave as the positive step number S_p.

The warp repeat R_e of a regular weave can be calculated by

$$R_e = \begin{cases} R_p/|S| & \text{if } R_p \bmod |S| = 0 \\ R_p & \text{if } R_p \bmod |S| \neq 0 \end{cases} \quad (4)$$

The operator 'mod' in the above equation is the remainder operator. This operation returns only the remainder as the result. $|S|$ must be the smaller one between $|S_p|$and$|S_n|$.

The parameters needed for the construction of a regular weave are the number of floats, float length F_i (where i is an integer such that $1 \leq i \leq N_f$), and the step number S

A weave matrix, W, is used to represent the weave, and $W_{x,\,y}$ is the element of this matrix at co-ordinate (x, y), where $1 \leq x \leq R_e$ and $1 \leq y \leq R_p$.

The first column of the weave matrix is to be created first using the following equation:

$$W_{1,y} = \begin{cases} 1 & \text{if } i \text{ is an odd integer} \\ 0 & \text{if } i \text{ is an even integer} \end{cases} \tag{5}$$

where $y = (\sum_{j=1}^{i} F_j - F_i + 1)$ to $\sum_{j=1}^{i} F_j$ and $1 \le i \le N_f$.

The values of the rest of the matrix elements are determined as follows.

$$W_{x,z} = W_{1,y} \tag{6}$$

Where

$$z = \begin{cases} y + [S \times (x-1)] + R_p & \text{if } \{y + [S \times (x-1)]\} < 1; \\ y + [S \times (x-1)] & \text{if } 1 \le \{y + [S \times (x-1)]\} \le R_p; \\ y + [S \times (x-1)] - R_p & \text{if } \{y + [S \times (x-1)]\} > R_p; \end{cases}$$

and $2 \le x \le R_e$; and $1 \le y \le R_p$.

3D weaves – orthogonal[15]

In any orthogonal architecture, the relationship between the number of layers of straight warp, N_w, and number of layers of straight weft, N_f, can be explained as follows:

$$N_f = N_w + 1 \tag{7}$$

Warp and weft repeats of an orthogonal structure can be calculated according to the numbers of layers of straight warp and weft and the binding weave repeat.

$$R_e = (N_w + t) \times B_e \tag{8}$$

$$R_p = N_f \times B_p \tag{9}$$

where R_e = warp repeat of the orthogonal structure

$R_p =$ weft repeat of the orthogonal structure
$B_e =$ warp repeat of the binding weave
$B_p =$ weft repeat of the binding weave

$$t = \begin{cases} 1 \text{ in the case of an ordinary orthogonal structure} \\ 2 \text{ in the case of an enhanced orthogonal structure} \end{cases}$$

Therefore, in order to generate an orthogonal weave, it is necessary to provide the number of the straight warp layers (N_w) or straight weft layers (N_f), the binding weave, and the type of orthogonal structure, i.e., ordinary or enhanced.

Based on the provision of these parameters, the matrix for the non-interlaced body structure is generated as follows. If $(x-1) \bmod N_w < (y-1) \bmod N_f$ and $1 \le x \le N_w \times B_e$ and $1 \le y \le R_p$, $W^{ni}_{x,y} = 1$, otherwise $W^{ni}_{x,y} = 0$, where W^{ni} is the weave matrix for the non-interlaced body structure; $W^{ni}_{x,y}$ is the element of matrix W^{ni} at the x^{th} warp and the y^{th} weft.

The binding weave is introduced to integrate the non-interlaced body structure. Weft repeats of the binding weave and the inverse binding weave must be expanded to suit the straight weft repeat before the introduction using equation:

$$W^{be}_{x,y} = W^{b}_{x,j} \quad \text{for } 1 \le x \le B_e \text{ and } 1 \le y \le R_p \tag{10}$$

where $W^{be}_{x,y}$ is the extended binding weave matrix;

$W^{b}_{x,j}$ is the binding weave matrix;
$j = \{(y-1))\backslash N_f\} + 1.$

'\' is the integral division operator used for dividing two numbers. The result is rounded down and the operation returns an integer. For example, in the expression of $a = 17\backslash 3$, a is equal to 5.

For the inverse binding weave,

$$W^{ie}_{x,y} = W^{i}_{x,j} \quad \text{for } 1 \le x \le B_e \text{ and } 1 \le y \le R_p \tag{11}$$

where $W^{ie}_{x,y}$ is the extended inverse binding weave matrix;

$W^{i}_{x,j}$ is the inverse binding weave matrix;
$j = \{(y-1))\backslash N_f\} + 1.$

Then, the extended binding weave will be inserted into the non-interlaced body structure. Equation (12) and (13) are used for ordinary and enhanced orthogonal structures, respectively.

$$W_{x,y} = \begin{cases} W^{ni}a,\ y & \text{if } (x-1)\bmod(nw+1) > 0 \\ W^{be}b,\ y & \text{if } (x-1)\bmod(nw+1) = 0 \end{cases} \tag{12}$$

for every $1 \le x \le \mathrm{R}_e$ and $1 \le y \le R_p$

where $a = \{[(x-1)\backslash(N_w+1)] \times N_w\} + [(x-1) \bmod (N_w+1)]$; and $b = [(x-1)\backslash(N_w+1)] + 1$.

$$W_{x,y} = \begin{cases} W^{ni}a,\ y & \text{if } (x-1)\bmod(nw+2) > 0 \\ W^{be}b,\ y & \text{if } (x-1)\bmod(nw+2) = 0 \\ W^{ie}b,\ y & \text{if } (x-1)\bmod(nw+2) = 1 \end{cases} \tag{13}$$

for every $1 \le x \le \mathrm{R}_e$ and $1 \le y \le R_p$

where $a = [\{(x-1)\backslash(N_w+2)\} \times N_w] + \{(x-2) \bmod (N_w+2)\}$;

$$b = \{(x-1)\backslash(N_w+2)\} + 1;$$
$$c = \{(x-2)\backslash(N_w+2)\} + 1.$$

3D weaves – angle-interlock[15]

In an angle-interlock structure, warp yarns are interlocked through several weft yarns on the thickness direction. Variations in the geometry of angle-interlock structures can be achieved by varying the number of the weft yarn layers and varying the way the weft yarns are interlocked by the warp ends. The notation $[N_f, N_{ft}]$ has been used for the identification of angle-interlock structures, where N_f is the number of weft layers and N_{ft} is the number of weft layers interlocked by the warp ends. Naturally, N_f is always larger than or equal to N_{ft}.

In general, the warp ends in the angle-interlock structures can be divided into two groups, i.e. the interlocking warp ends and the non-interlocking warp ends. The interlocking warp ends refer to those that interlock through N_{ft} weft layers, whilst non-interlocking warp ends cover the ones that don't. The numbers of overall, interlocking and non-interlocking warp ends, denoted by N_w, N_{wi}, and N_{wn} respectively, can be calculated as follows:

$$N_w = N_f + 1 \tag{14}$$

$$N_{wi} = \begin{cases} k \times \left(N_{ft}+1\right) \\ \qquad \text{if } k \neq \left[\left(N_f+1\right)/\left(N_{ft}+1\right)\right] \\ \left(k - \dfrac{1}{2}\right) \times \left(N_{ft}+1\right) \\ \qquad \text{if } k = \left[\left(N_f+1\right)/\left(N_{ft}+1\right)\right] \quad \text{and} \quad N_f \neq N_{ft} \\ N_w \\ \qquad \text{if } k = \left[\left(N_f+1\right)/\left(N_{ft}+1\right)\right] \quad \text{and} \quad N_f = N_{ft} \end{cases} \tag{15}$$

$$N_{wn} = N_f - N_{wi} + 1 \tag{16}$$

where $k = (N_f + 1)\backslash(N_{ft} + 1)$

The warp and weft repeats R_e and R_p of angle-interlock weaves are given below.

$$R_e = N_w \tag{17}$$

$$R_p = N_f \times \left(N_{ft}+1\right) \tag{18}$$

The matrix representing the angle-interlock weave structure, W, can be generated from the structural parameters, N_f and N_{ft}, and the aforementioned calculated parameters. The element at the x^{th} warp and the y^{th} weft, $W_{x,y}$, is assigned using the following equation:

$$W_{x,y} = \begin{cases} 1; & \left[(y-1)\backslash N_f\right] \leq M_{\left[(y-1) \bmod N_f\right],x} \\ 0; & \left[(y-1)\backslash N_f\right] > M_{\left[(y-1) \bmod N_f\right],x} \end{cases} \tag{19}$$

for $x = 1, 2, 3, \ldots, R_e$ and $y = 1, 2, 3, \ldots, R_p$

3D cellular weaves[9]

This type of weave is created by linking and separating the fabric layer during the course of weaving. The basic idea is to create the cross-sectional view, and then assign a weave to each of the single and linked layers before the weaves are combined into a single weave. To generate a combined weave, two single-layer weaves need to be specified. These single-layer weaves will be converted into the form of a 2D binary matrix once the parameters of the weaves are specified. Then these two binary matrices will be combined together to generate the larger matrix representing the combined weave.

Let M_1 and M_2 be the matrices for two single-layer weaves. The lowest common multiple (*lcm*) is found first between the dimensions of these two matrices. Let d_1 be the dimension of M_1 and d_2 that of M_2. If $lcm(d_1, d_2)$ is not equal to d_1, M_1 will be enlarged so that M_1 has the dimension of $lcm(d_1, d_2)$. Let the enlarged matrix be ME The elements of this matrix are assigned as follows:

$$ME_{k(i,j)} = M_{k(i\,\%d_k,\, j\,\%d_k)} \tag{20}$$

where $i, j = 1, 2, \ldots, lcm(d_1, d_2)$, $k = 1, 2$

In order to combine the two enlarged matrices into the final weave matrix MF, the following equation is used:

$$MF_{(i,j)} = \begin{cases} ME_{1(i/2,j/2)} & \text{if } i\,\%2 == 0 \text{ and } j\,\%2 == 0 \\ 0 & \text{if} i\,\%2 == 0 \text{ and } j\,\%2 == 1 \\ 0 & \text{if } i\,\%2 == 1 \text{ and } j\,\%2 == 0 \\ ME_{2(i/2,j/2)} & \text{if } i\,\%2 == 1 \text{ and } j\,\%2 == 1 \end{cases} \tag{21}$$

Note that % is integer divisions, returning only the value of the integer part of the result.

3D trapezoid weaves[10]

Prior to generating the weave for the 3D trapezoid structure, the repeat unit must be determined. The structure within a single repeat is quite complex and therefore one repeat unit has to be subdivided into several 'areas', as shown in Figure 5. The structure subdivision is based on the structural features, defined by the node coordinates. For a cross-section of a repeat unit in the 2-dimensional (x, y) coordinate system with n nodes in the repeat unit, the number of areas is the number of nodes with different x coordinates. For the 3D trapezoid structure shown in Figure 5, the single repeat unit is subdivided into four areas, as there are four nodes with different x coordinates.

All three layers, of which the middle layer is longer, are woven simultaneously during weaving. The weft yarn distribution for the three layers must be arranged appropriately to reach the predefined cell geometry.

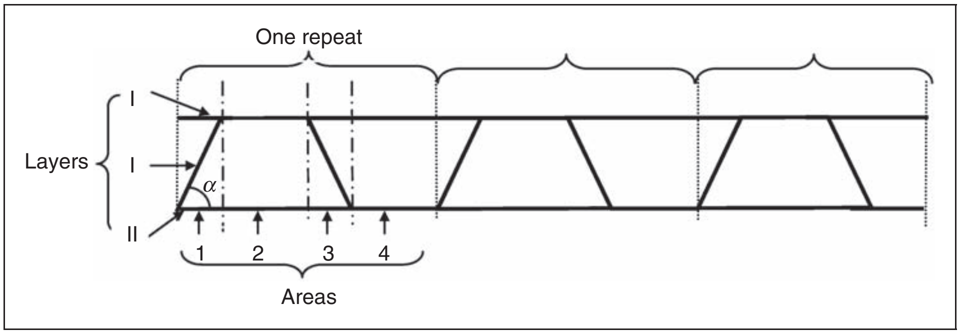

Figure 5. Subdivision of a repeat of a hollow structure.

The length ratio of these three sides in area 1 is defined as l_1:l_2:l_1. A convenient way to measure the fabric section lengths is to use the number of picks inserted into the fabric section when the fabric weft density is known. However, picks of weft yarns must be distributed as evenly as possible into the three fabric layers in area 1. It is necessary to divide the number of picks (weft yarns) for each section into the same number of groups so that the picks are introduced into different sections of fabrics evenly. Generally, the number of such groups is denoted by k. For a 3D trapezoid structure with m layers, group i of weft yarn distribution is recorded as w_{1i}:w_{2i}:w_{3i}:...:w_{mi} where all w_{qi} ($q = 1, 2, \ldots, m$ and $i = 1, 2, \ldots, k$) must be expressed as integers as they represent the number picks. When the weft density is taken into consideration, the following relation holds:

$$\sum_{i=1}^{k} w_{1i} : \sum_{i=1}^{k} w_{2i} : \sum_{i=1}^{k} w_{3i} : \sum_{i=1}^{k} w_{4i} : \ \ldots \ : \sum_{i=1}^{k} w_{mi} = l_1 : l_2 : l_1 : l_2 \ldots : l_1$$

The value of each w_{ri} is determined by using the length ratio among the fabric layers involved in area 1, and it is calculated as follows:

$$w_{qi} = \begin{cases} 1 & \textit{if q is odd} \\ round\left(i \times \frac{l_2}{l_1} - \sum_{j=1}^{i-1} w_{qj} \right) & \textit{if q is even} \end{cases} \tag{22}$$

In the overall weave for an area, a repeat unit must contain the smallest number of complete repeats for all constituent weaves. Different fabric sections in the same area may have different weaves, and each fabric section may have a different number of warp ends. Suppose there are n fabric sections in one area. The weave for section i is recorded in matrix M_i ($i = 1, 2, \ldots, n$), and the element of this matrix at the x^{th} warp and the y^{th} weft is $M_i(x,y)$ ($1 \leq x \leq r_{ie}$, $1 \leq y \leq r_{ip}$) where r_{ie} is the number of warp ends in M_i, and r_{ip} the number of weft picks in M_i. l_i is the length of section i. The warp dimension of all constituent matrices, r_{lcm}, can be found by calculating the lowest common multiple of the warp repeats of all constituent weave matrices. Accordingly, the warp dimensions of the constituent weave matrices are enlarged to match r_{lcm}. The enlarged weave matrix for the constituent section i is denoted by M_i' and its elements can be calculated by repeating the weave of a single section r_{lcm}/r_{ie} times:

$$M_i'(x,\ y) = M_i(x \ mod \ r_{ie},\ y)$$

The warp repeats r_{ie}' of the enlarged matrix M_i' are r_{lcm}, and its weft repeats r_{ip}' are still r_{ip}. The weave matrix for fabric section i will be changed from M_i' to M_i'' by repeating the rows of M_i' until its weft dimension is equal to the section length l_i:

$$M_i''(x,\ y) = M_i'\left(x,\ y \ mod \ r_{ip}\right)$$

where r_{lcm} and l_i are the warp and weft repeats of the enlarged matrix M_i'', i.e. $r_{ie}'' = r_{lcm}, r_{ip}'' = l_i$.

All constituent weave matrices M_i'' in this area will be merged together to generate the overall weave matrix W for this area. Considering the fact that all weft yarns from the upper layers go over the warp yarns from the lower layers and that all warp yarns from the upper layer go over the lower layer weft, the elements of matrix W, $W(x,y)$, are assigned by the following expression:

$$W(x,\ y) = \begin{cases} 0, \ \text{when} \ x > \sum_{i=1}^{i=m} r_{ie}'', \ \sum_{i=1}^{i=m-1} r_{ie}'' < y < \sum_{i=1}^{i=m} r_{ie}'', \\ \quad 0 < m < n+1 \\ 1, \ \text{when} \ \sum_{i=1}^{i=m-1} r_{ie}'' < x < \sum_{i=1}^{i=m} r_{ie}'', \ y > \sum_{i=1}^{i=m-1} r_{ie}'', \\ \quad 0 < m < n+1 \\ M_i''\left(x - \sum_{i=1}^{i=m-1} r_{ie}'',\ y - \sum_{i=1}^{i=m-1} r_{ip}'' \right) \\ \quad \text{when} \ \sum_{i=1}^{i=m-1} r_{ie}'' < x < \sum_{i=1}^{i=m} r_{ie}'', \\ \quad \sum_{i=1}^{i=m-1} r_{ie}'' < y < \sum_{i=1}^{i=m} r_{ie}'', \ 0 < m < n+1 \end{cases} \tag{23}$$

The warp repeat of matrix W is $R_e = r_{lcm} \times n$, and its weft repeat is $R_p = \sum_{i=1}^{i=n} l_i$.

CAD/CAM software and demonstration

The above mathematics is complicated, but it can be incorporated within software, in order to guide the user through an easy input of instructions. Based on the mathematical modelling and description of different types of 3D woven architectures, a suite of CAD software has been created to support the design and manufacture of 3D woven fabrics. The CAD suite established at the University of Manchester includes Weave Engineer®, Hollow CAD®, GeoModeller®, UniverWeave®, and Structra®.

Weave Engineer® is basically designed to support the design and manufacture of 3D solid fabrics. Its modules include the multi-layer, orthogonal, angle-interlock, backed, as well as the single layer fabrics. All designs are carried out based on the mathematical models described above. Therefore the design of 3D fabrics is speedy and accurate. For each category of 3D fabrics,

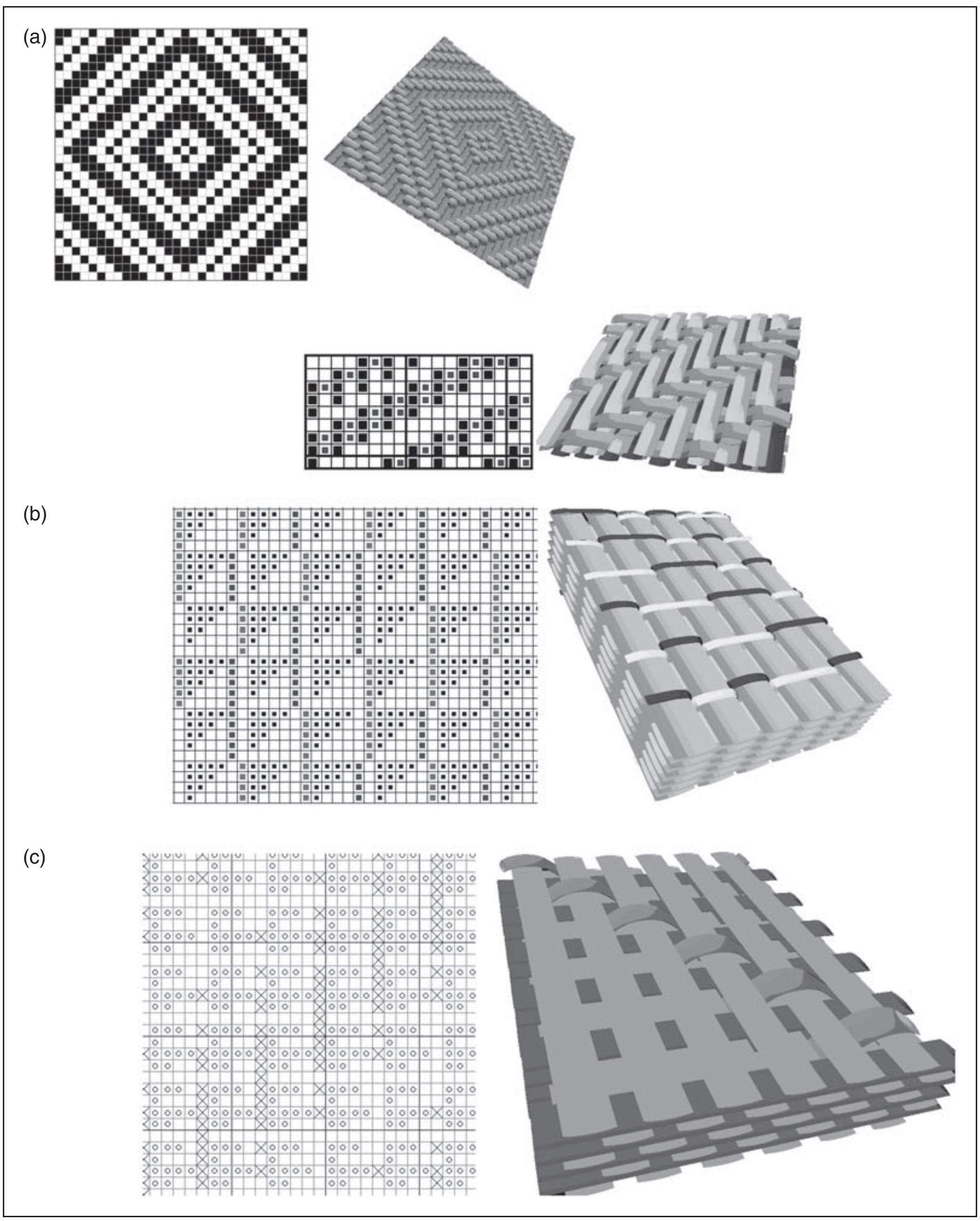

Figure 6. Weaves created using Weave Engineer®: (a) Single layer; (b) Warp backed; (c) Orthogonal; (d) Angle interlock.

there are a number of varieties which can be accommodated by the conventional weaving technology. Figure 6 shows the design of some of the 3D solid fabrics.

Hollow CAD® is dedicated for the design of 3D hollow woven architectures with uneven or flat surfaces when opened up. Figure 7 illustrates a design using the software tool. As for the other CAD programmes based on the mathematically modelling, the Hollow CAD® has been used in the investigation of lightweight textile composites.[18,19]

Discussions and conclusions

Mathematical models of various 2D and 3D fabrics have been established through the years and the resulting algorithms are used in the development of CAD/CAM software for the design and manufacture of 2D and 3D fabrics. The suite of software is now marketed by TexEng Software Ltd.[16]

Figures 6 and 7 show some of the designs created by the use of Weave Engineer® and Hollow CAD®. Both software programmes generate weaves using both the parametric approach and the free-hand editing approach aiming to maximise the flexibility for the software users. The former is specialised for 3D solid fabrics and the latter is for 3D hollow fabrics. The software is being expanded to cover more types of 3D structures for various applications. The software programmes are able to create the final weave and weaving instruction, and are able to provide visualisation of the designed 3D

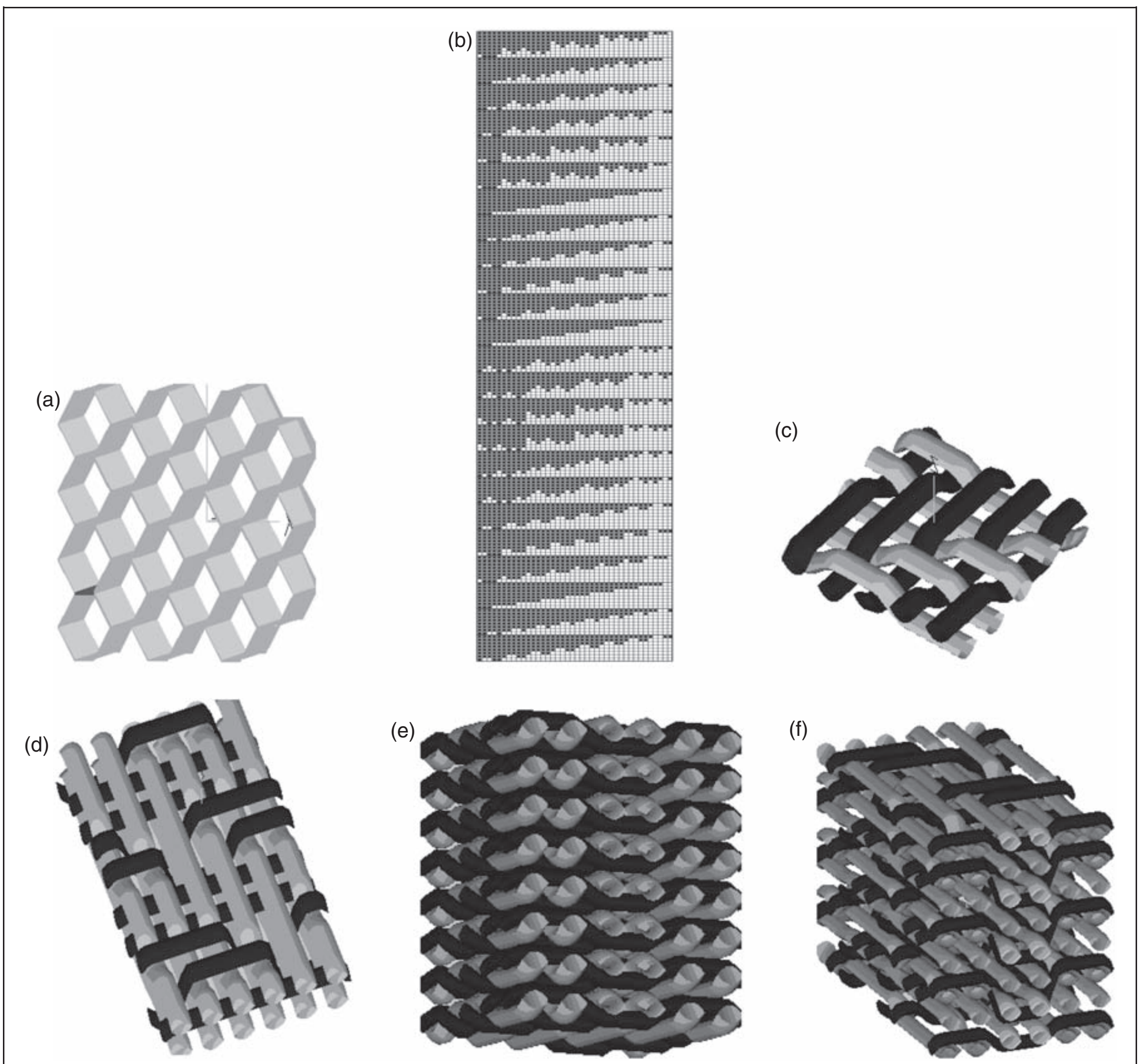

Figure 7. Design of 3D hollow architecture using Hollow CAD®: (a) The opened cellular structure; (b) The overall weave; (c) The weave used for the single layer sections; (d) The weave used for double layer sections; (e) 8 single layers; (f) single-(3 $\times$ double)-single layers.

textile architectures. The software programmes have been used in creating many 3D fabrics with different structural features and the 3D graphical models, if exported in suitable format, can be used to create FE models for the analysis of mechanical, fluid and other properties.[17]

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