Computer-aided design of 3D woven composites with complex topologies

by

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Abstract

Three-dimensional woven fabrics with various structures have wide applications in many technical fields. These applications include aerospace, automotive, construction, medical, energy, military, and more. Due to the complex structures, the design process of 3D woven fabrics is time-consuming and error-prone. This report introduces a new algorithm of CAD/CAM tool to design 3D woven textile structures. This developed algorithm represents warp yarns paths and weft yarns paths using symmetric matrices. Hence it allows technical weavers to design woven fabrics in both weft plane and warp plane. Users provide input data by graphing the yarn paths precisely. The CAD/CAM design tool uses this data to generate weft matrices and warp matrices, then calculate a 2D binary weaving matrix automatically. This weaving matrix can be used to produce 3D woven fabric on a conventional jacquard weaving loom. This paper provides the design processes of various three-dimensional woven fabrics by using this CAD/CAM tool, such as T, Pi, I-beam, truss, tubular structure, and some other near-net-shape structures. Furthermore, this article discusses the assembly part of this algorithm. Weavers can assemble fabrics in both warps and wefts directions to generate more complex structure

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Acknowledgements

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Dedication

To my loving parents, my sister, my husband, and my unborn baby.

Chapter 1 – Introduction

1.1 Background

Weaving is a textile production method, which interlaces the warp yarns and weft yarns to form a fabric or cloth. The traditional weaving method, which is two-dimensional weaving technology, can trace back 12,000 years ago. In most 2D woven fabrics, weft yarns and warp yarns interlace in one layer, typically at two orthogonal directions. The definition of 3D woven fabrics is controversial. It is generally defined as a structure with warps and wefts interlacing not only in the X and Y directions but also in the Z direction.

Compared with the traditional two-dimensional woven fabrics, the three-dimensional woven fabrics has a variety application. These applications are not only in military fields such as bulletproof vests and steel helmets, but also in people's daily life, such as clothes, hats, and shoes.

1.2 Problem Statement

Due to the complex structures of 3D woven fabrics, the design of 3D woven fabrics is more complicated than for 2D woven fabrics. The design process is time-consuming and error-prone. In order to increase productivity, it is very essential to use CAD/CAM tools to design 3D woven textile structures.

Several CAD/CAM algorithms for 3D woven fabric structures have been developed. Ping and Lixin [1] presented an algorithm based on the Kronecker Product for designing double-layer woven fabric. This algorithm requires users to provide four matrices to describe the face and back basic weaves, and the interlacing status between these two weaves. The required two-layered woven fabrics can be automatically produced according to the algorithm. However, this method only applies to double weaves. Chen and Potiyaraj [2][3] developed several algorithms to generate different types of 3D woven fabrics and calculate the weave matrix. To generate a specific 3D woven fabric structure, these algorithms require users to determine some parameters of 3D multi-layer weaves, such as woven fabrics types (i.e. Orthogonal, Angle-interlock, etc.), the binding weave types, the interlacement type between the warp and weft. However, these algorithms are applicable to specific structures. Koltycheva, N. G. [4] described 3D multi-layer fabric structure with two matrices: a binary weave matrix and a binary structure matrix. They developed an algorithm to generate a transformation matrix between the two representation matrices. However, before conversion between the weave matrix and structure matrix, it is necessary to specify either one of them.

1.3 Objective

The primary objective of this study was to develop a CAD/CAM design tool with a new algorithm. The CAD/CAM design tool allows technical weavers to design 3D woven fabrics with complex structures and outputs machine-readable files to produce 3D woven fabric on a conventional jacquard weaving loom.

1.4 Report Outline

This report is divided into five chapters. Chapter 1 states the background, problem statement, and objective of the research. Chapter 2 describes the definition of fabric topology and weaving matrix. Chapter 3 presents the CAD/CAM Algorithm of this research. Chapter 4 discusses the 3D woven fabric design modes, and Chapter 5 summarizes the conclusions of this study.

Chapter 2 - Fabric Topology and Weaving Matrix

The design process of 3D woven fabrics with complex structures is complicated. It includes four steps: topology design, weaving process design, geometric shape prediction, and mechanical performance prediction [5]. To achieve a successfully woven fabric topology design, a technical weaver is required to have a deep knowledge of weaving machine structure and the weaving process, and then establish the relation between fabric topology and weaving action process.

2.1 3D Weaving Machine Structure

A weaving machine is a device that weaves yarn into fabric. The basic purpose of any weaving machine is to hold the warp yarns under tension to facilitate the interweaving of the weft yarns [6]. Figure 2-1 illustrates the basic structure of a 3D weaving machine. It includes a reed and a Jacquard head. It is the Jacquard head that connects to a great many hooks that allow the weaving machine to create complex 3D woven fabrics. During the weaving process, each hook lifts or lowers a heddle without interfering with each other. Each heddle relates to one warp yarn and lifts or lowers the warp to either the upper or the lower position. At each weaving step, all warps are moved to designated positions to enabling the insertion of weft to generate woven fabrics.

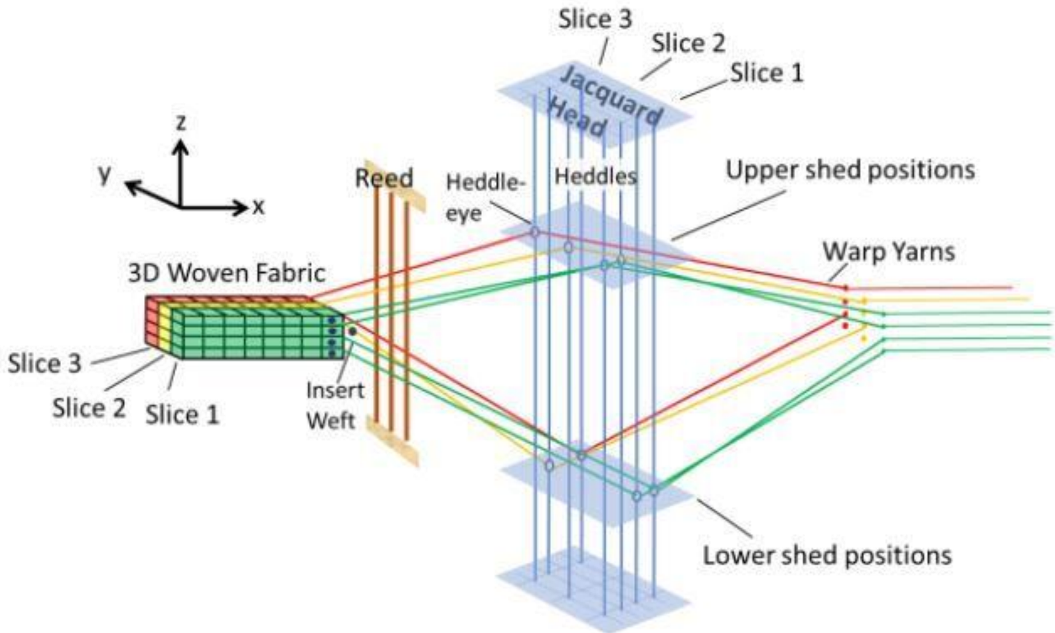


Figure 2-1. Illustration of 3-D weaving machine [5]

2.2 Jacquard Head Position Matrix

As shown in Figure 2-1, a Jacquard head is arranged in many slices, and each slice has a lot of hooks. Assume there are *n* hooks per slice and *m* slices, then a Jacquard head has *m*n* hooks in total. To define the Jacquard head position matrix during the weaving process, it is necessary to know each hook position in each weaving step (also known as the "weft insertion step"). For a 3D woven fabric, assuming there are *w* weaving steps in total during weaving process. Combined the number of total weaving steps with the total number of hooks, a 2D matrix with *w* rows and *m*n* columns can be obtained, this 2D matrix is called Jacquard head position matrix. Each element of one matrix row is corresponding to each hook. At one weaving step, if a hook lifts the warp in upper position, the corresponded matrix element is assigned as 1. If a hook lifts the warp in lower position, the matrix element is assigned as 0. Jacquard head position matrix during the weaving process can be defined by a 2D binary matrix [H] as follows:

$$\mathbf{H}[\mathbf{i},\mathbf{j}] = \begin{cases} \mathbf{1} & \textbf{if the hook is at upper position} \\ \mathbf{0} & \textbf{if the hook is at lower position} \end{cases} \qquad (\ 2\text{-}1\ )$$

where index *i* denotes the weft insertion number, i.e., the weaving step number, and index *j* denotes the hook number which is arranged by the Jacquard head. The Jacquard head position matrix is unique for each fabric. The Jacquard head position matrix is also known as the weaving matrix in textile industry.

2.3 Fabric Topology Matrix

There are two practical methods to design woven fabrics: one is the canvas method and the other is the yarn paths method.

2.3.1 Canvas Design Method

In the canvas method, as shown in Figure 2-2(a), a black-and-white grids design paper is employed. In this grids paper, the columns of the grids indicate the warp threads and the rows of grids indicate wefts, a black cell indicates that the warp thread is in the upper position than the weft yarn, while a white cell means the warp thread is in the lower position. If we assign 1s and 0s to black and white grids respectively, the weave pattern can be converted to a machine-readable binary matrix which is called topology matrix as illustrated in Figure 2-2(b). Though this canvas design method is widely used in 2D fabric design, in 3D fabric design, due to the complex shapes of 3D fabric structures, this method is error-prone and this display is not intuitive.

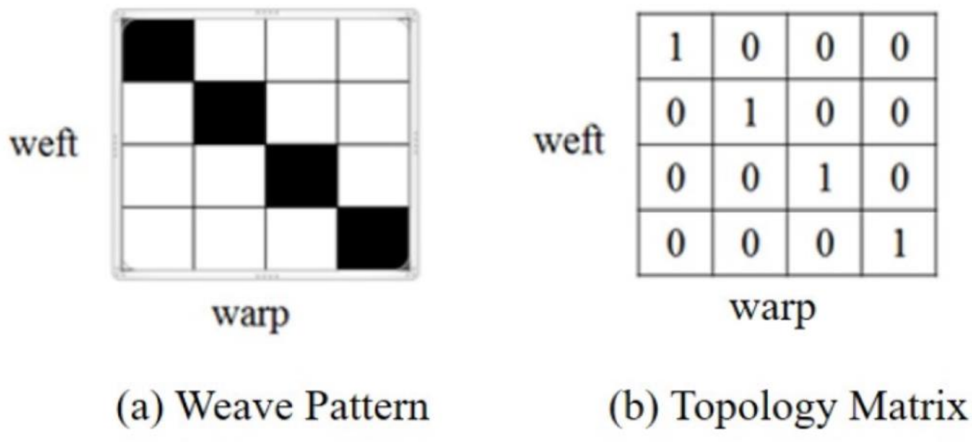


Figure 2-2. Fabric pattern and topology matrix [7]

2.3.2 Yarn Paths Design Method

In the yarn paths method, a plane which is perpendicular to the warp yarns is defined as the warp plane while a plane that is perpendicular to the weft is defined as the weft plane. Technical weavers design the weft yarn paths in warp plane or arrange the warp yarn filling paths in weft plane. For the Jacquard weaving machine, it is known that the shuttle carries the weft threads passing the warp yarns back and forth. Based on the operation principle of a weaving loom, the warp plane design is widely used in industry. As shown in Figure 2-3, technical weavers design the 3D fabric structures in warp plane by arranging the weft yarns filling paths. However, this method supposes the warp yarns to be straight and restricted the flexibility of design.

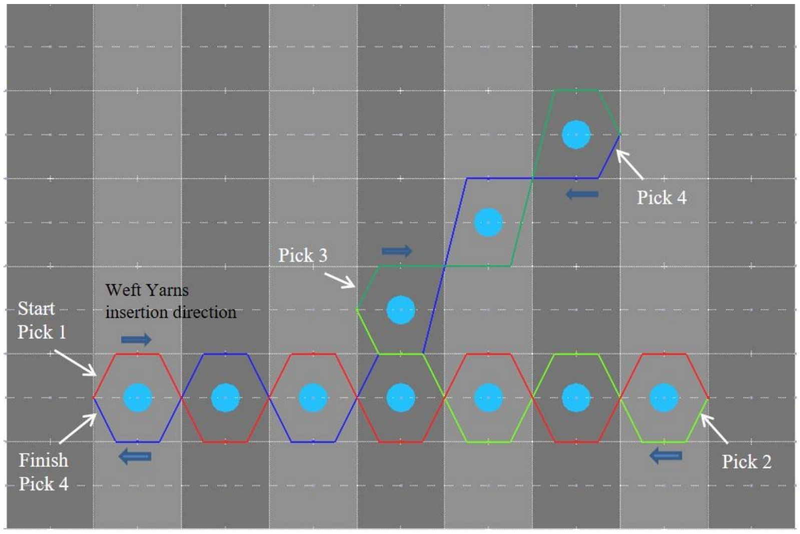


Figure 2-3. Weft paths design for T profile

2.3.3 Definition of Fabric Topology Matrix

The fabric topology matrix is briefly introduced in Section 2.3.1 and is introduced in more detail here for an integral view of the relation between fabric topology and Jacquard head position matrix. In weaving design activity, technical weavers usually assign each warp and weft a specific number, i.e., warp number and weft number. Both if hook numbers are identical to warp numbers and if weft insertion numbers are identical to weft numbers, the topology matrix is identical to the weaving matrix. However, in most cases, due to the variety of woven fabric and weaving loom configuration, warp numbers and hook numbers are not identical to each other [7]. To obtain the relation between fabric topology and Jacquard head position matrix, an additional vector is required to define the relation between hook numbers and warp numbers:

$$\text{Hook}\,[j] = k \qquad (2\text{-}2)$$

where “j” denotes the warp number and “k” the hook number. Then, the topology matrix and Jacquard head position matrix relations can be derived as:

$$T[i, j] = H[i, \text{Hook}[j]] \quad (2\text{-}3)$$

Technical weavers usually keep weft numbers identical to weft insertion numbers. However, in some cases, if these two numbers are not identical, another additional vector is required to define the relation between weft insertion numbers and weft numbers:

$$\text{Insertion}[i] = l \quad (2\text{-}4)$$

where “i” denotes the weft number and “l” denotes the weft insertion number. Then, the topology matrix and Jacquard head position matrix relations can be derived as:

$$T[i, j] = H[\text{Insertion}[i], \text{Hook}[j]] \quad (2\text{-}5)$$

As introduced in Section 2.2, the Jacquard head position matrix is unique for each fabric. The topology matrix is uniquely determined by the Jacquard head position matrix after the hook matrix is defined.

Chapter 3 – CAD/CAM Algorithm

This report introduces a new algorithm of CAD/CAM tool. A mixed weft-plane and warp-plane CAD/CAM design tool is introduced in this section.

3.1 Weft and warp matrices

The key issue of this algorithm is establishing the transformation between 3D woven structure and topology matrix. A matrices form description of the fabric geometry is proposed in this paper. Consider a 3D woven fabric contains multiple layers, columns, and slices which are connected by warp and weft yarns. As seen in Figure 3-1**,** a simple model which contains three weft layers, three weft columns, and three warp slices is derived to describe the algorithm of transformation between structure and topology matrix.

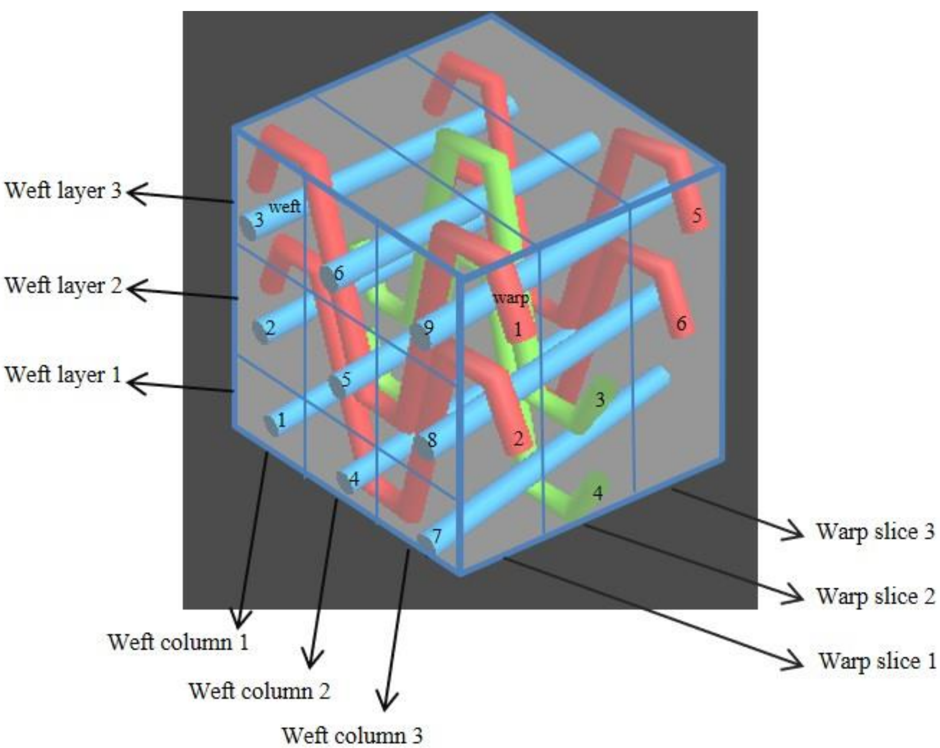


Figure 3-1. Fabric model with three weft layers, three weft columns, and three warp slices

In this model, two three-dimensional matrices, weft matrix E_{ijk} and warp matrix A_{ijk} are established to descript woven structure, as seen in Figure 3-2.

For weft matrix E_{ijk}, i denotes the weft number, which also represents the weft threads insertion order. The second subscript j denotes the slice number. The third subscript k can be 1 or 2. E_{ij1} represents the layer number and E_{ij2} represents the column number. For example, in this example model:

E_{811} = 2 means that the 8th weft yarn in the first slice locates in layer 2.

E_{822} = 3 means that the 8th weft yarn in the second slice locates in column 3.

Corresponding to the weft matrix, the warp matrix A_{ijk} which is symmetric to the weft matrix can be generated. In warp matrix A_{ijk}, the first subscript i denotes the warp number. The second subscript j denotes the column number. The third subscript k can be 1 or 2. A_{ij1} represents the layer number and A_{ij2} represents the slice number. For example, in this example model:

A_{211} = 2 means that the second warp yarn in the first column locates in layer 2.

A_{212} = 1 means that the second warp yarn in the first column locates in slice 1.

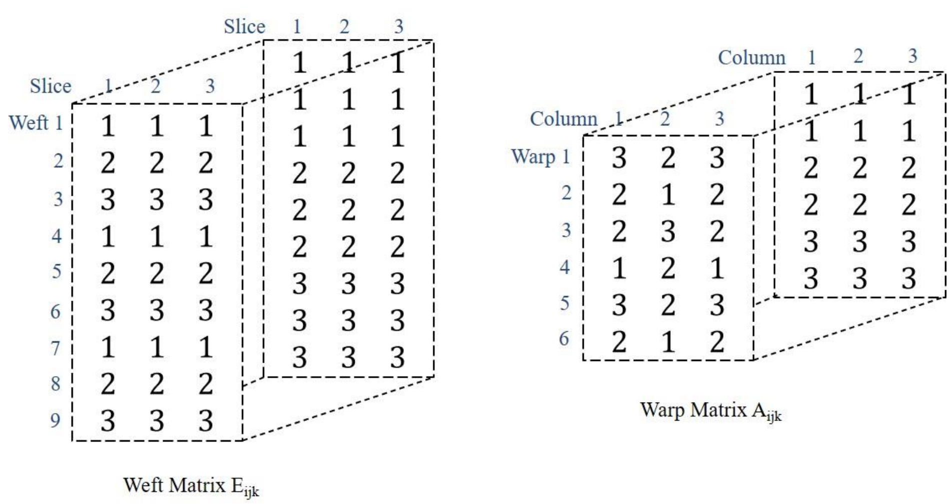


Figure 3-2. The corresponding weft matrix and warp matrix of the model in Figure 3-1

These two weft and warp matrices provide weft and warp yarns paths. Then the 3D woven structure can be generated based on these two matrices in the CAD/CAM software. Furthermore, these two matrices can be converted into a format to be read by the software Dynamic Fabric Mechanics Analyzer, which is used to determine the micro-geometry and mechanical properties of fabric.

3.2 Topology matrix calculation

Topology matrix is essentially the position relation between warp yarns and weft yarns. To calculate topology matrix, column number and slice number are needed to be specified first. Then by comparing the layer number of weft and warp yarns which are in the specific column and slice, topology matrix can be obtained.

For weft i and warp j, slice number p can be obtained by Jacquard head positions and warp/hook vector which is introduced in Section 3.3.3. Once slice number obtained, substitute this slice number into weft matrix E_{ip2} to get column number q. Thus, the topology matrix T can be calculated as follows:

$$T_{ij} = 1 \text{ for } (A_{jq1} - E_{ip1}) >= 0 \qquad (3\text{-}1)$$

$$T_{ij} = 0 \text{ for } (A_{jq1} - E_{ip1}) < 0 \qquad (3\text{-}2)$$

Where p is the slice number, q is the column number.

3.3 Fabric Assembly

In industry, a complex fabric consists of many different components. In consequence, it is essential to assemble multiple fabric segments to accelerate the design process. This new CAD/CAM tool allows technical weavers to create assemblies in the weft direction, the warp direction, or a combination of both directions.

3.3.1 Assembly in weft direction

Assembly in weft direction is to assemble two or multiple fabric segments along with weft yarns, which will change the number of warp slices and the number of warp yarns. Consider two fabric components which are assembled in the weft direction, the first component is expressed by the weft matrix $E_{ijk}^{(1)}$ and the warp matrix $A_{ijk}^{(1)}$, while the second component is represented by the weft matrix $E_{ijk}^{(2)}$ and the warp matrix $A_{ijk}^{(2)}$.

Now, the weft matrix $E_{ijk}^{(A)}$ and the warp matrix $A_{ijk}^{(A)}$ of the assembled fabric in weft direction are decided as follows:

$$E_{ijk}^{(A)} = [\, Eijk(1) \quad Eijk(2)] \tag{3-3}$$

$$A_{ijk}^{(A)} = \begin{bmatrix} Aijk(1) \\ Aijk(2) \end{bmatrix} \tag{3-4}$$

For the fabric model illustrated in Figure 3-1, the assembled weft matrix and warp matrix are shown in Figure 3-3. It's easy to know the number of warp slices and the number of warp yarns increased due to the assembly. The CAD/CAM software will enhance these numbers in the assembled matrices automatically.

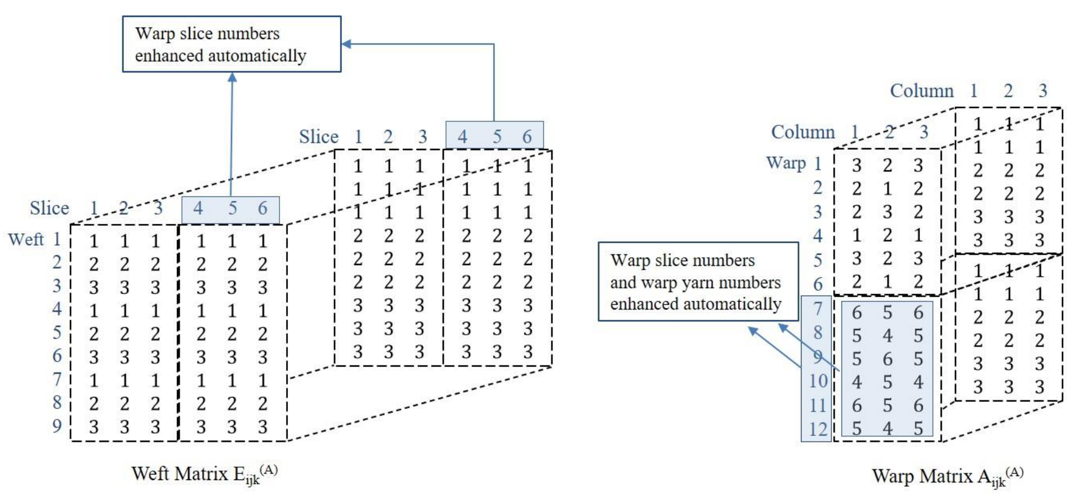


Figure 3-3. Assembled matrices in weft direction

3.3.2 Assembly in warp direction

Assembly in warp direction is to assemble two or multiple fabric segments along with warp yarns, which will change the number of weft columns and the number of weft yarns. Consider two fabric components which are assembled in the warp direction, the first component is expressed by the weft matrix $E_{ijk}^{(1)}$ and the warp matrix $A_{ijk}^{(1)}$, while the second component is represented by the weft matrix $E_{ijk}^{(2)}$ and the warp matrix $A_{ijk}^{(2)}$.

Now, the weft matrix $E_{ijk}^{(A)}$ and the warp matrix $A_{ijk}^{(A)}$ of the assembled fabric in warp direction are decided as follows:

$$E_{ijk}^{(A)} = \begin{bmatrix} Eijk(1) \\ Eijk(2) \end{bmatrix} \tag{3-5}$$

$$A_{ijk}^{(A)} = \begin{bmatrix} Aijk(1) & Aijk(2) \end{bmatrix} \tag{3-6}$$

Refer to the example shown in Figure 3-1, the assembled weft matrix and warp matrix are shown in Figure 6. The number of weft columns and the number of weft yarns are increased due to the assembly. The CAD/CAM software will enhance these numbers in the assembled matrices automatically.

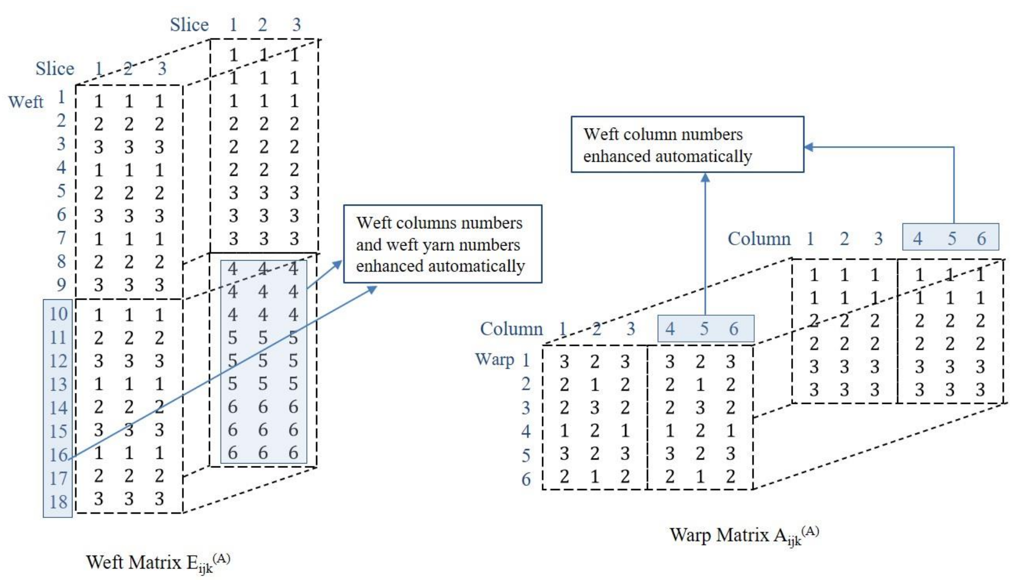


Figure 3-4. Assembled matrices in warp direction

Chapter 4 – 3D Woven Fabric Design

For 3-D fabric topology, a plane perpendicular to the weft direction is defined as the weft plane and a plane perpendicular to the warp direction is defined as the warp plane [7]. Technical weavers input yarn paths either in weft or warp planes. Based on the two symmetrical weft matrix and warp matrix which are introduced in Section 3.1, a combined weft-plane and warp-plane design mode is introduced for the technical weaver to input weft yarns and warp threads paths. This combined design procedure provides more flexibility when designing the woven preforms with complex shapes, such as structural panels reinforced in both the weft and warp directions.

4.1 Weft-Plane Design Mode

In weft-plane design mode, the weft yarns are assumed straight, technical weaver input the paths of warp yarns on the weft planes. A fabric topology generated by weft-plane design mode is shown in Figure 4-1. The weft threads (in blue) are arranged in 4 rows and 6 layers. The paths of warp threads (in red, green, and pink) are input on four weft planes. Each weft plane is defined as a slice. Each slice has 4 columns and 6 layers. Figure 4-2 shows the paths of warp yarns on the four slices.

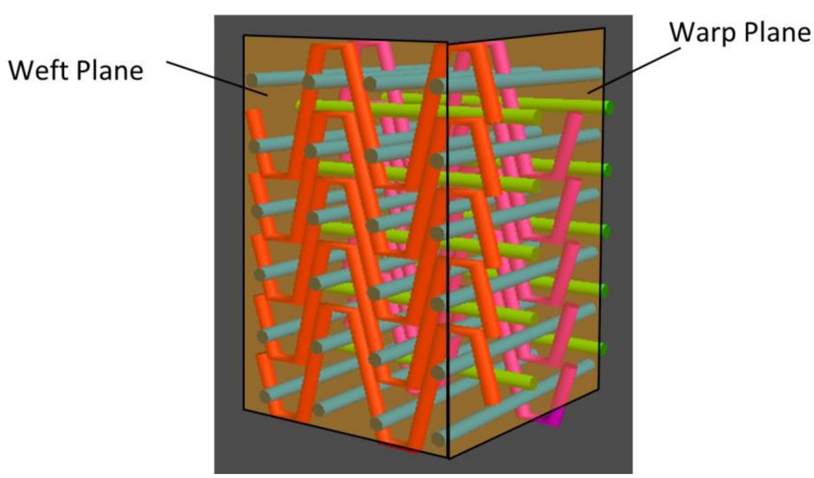
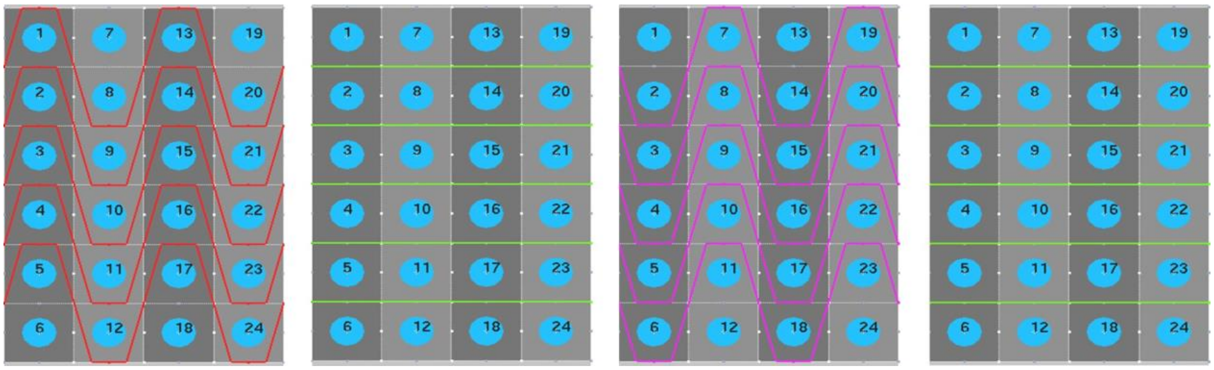


Figure 4-1. 3D woven fabric designed by weft-plane design mode [7]



Slice 1 Slice 2 Slice 3 Slice 4

Figure 4-2. Paths of warp yarns on weft planes

4.2 Warp-Plane Design Mode

In warp-plane design mode, the warp yarns are assumed straight, technical weaver input the paths of weft yarns on the warp planes. A fabric topology generated by warp-plane design mode is shown in Figure 4-3. The warp threads (in red, green, and pink) are all straight. The paths of weft threads (in blue) are input on four warp planes. Each warp plane is also known as a column. Figure 4-4 shows the paths of weft yarns on the four columns.

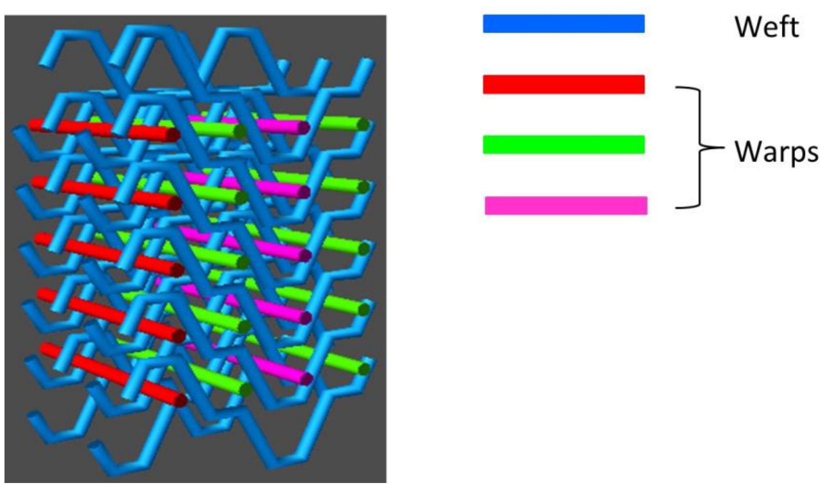
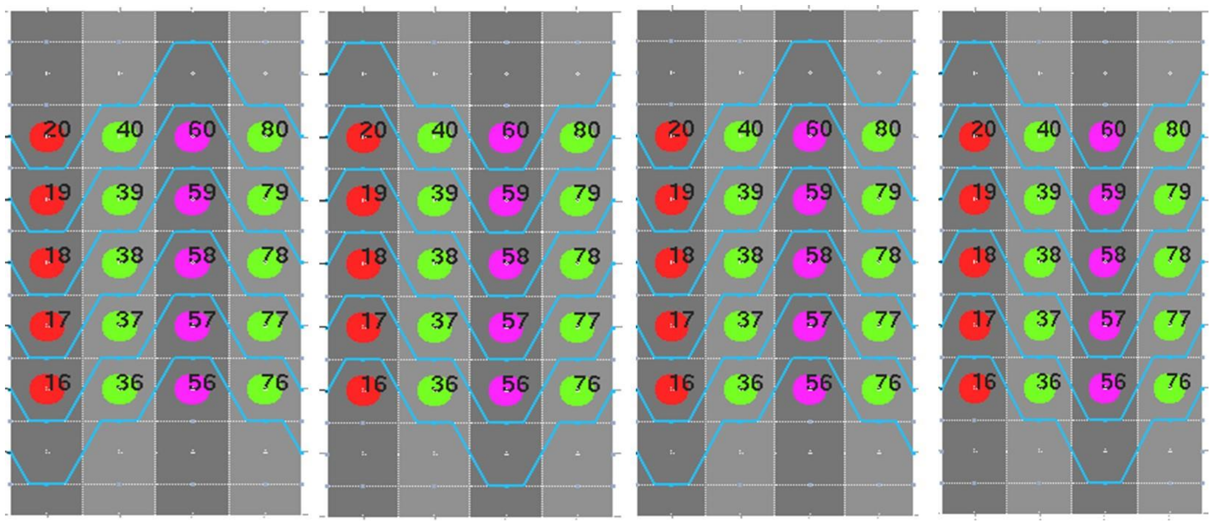


Figure 4-3. 3D woven fabric designed by warp-plane design mode [7]



Column 1 Column 2 Column 3 Column 4

Figure 4-4. Paths of weft yarns on warp planes

4.3 Combined Weft-Plane and Warp-Plane Design Mode

In combined weft-plane and warp-plane design mode, technical weavers input the paths of warp yarns on the weft planes and the paths of weft yarns on the warp planes. The warp threads and the weft threads are not required to be straight. A 3D woven fabric mode which is generated in the combined weft-plane and warp-plane design mode is shown in Figure 4-5.

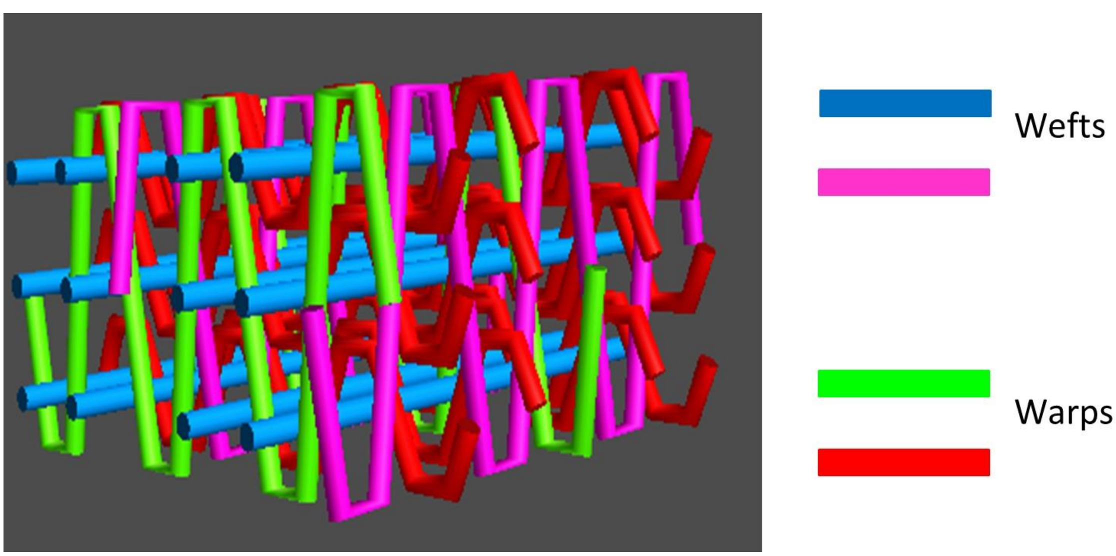


Figure 4-5. 3D woven fabric designed by combined weft plane and warp plane design mode [7]

4.4 3D Woven Fabric Design Examples

The design processes of a two-directional reinforcement fabric structure and a 3D tubular woven structure are provided in this section.

4.4.1 Fabric Design for Panels Reinforced in Both Weft and Warp Directions

The example in this subsection illustrates a design process using the CAD/CAM tool for an integrated woven panel reinforced in both weft and warp directions. The structure is shown in Figure 4-6. This weft and warp directional reinforcement preform is generated by the combined weft-plane and warp-plane design mode. The weave design is launched as follows:

1) In weft plane, input straight light blue yarns, which are wefts. Then input the paths of warp yarns (in red) to interlace wefts. Then a general single directional reinforcement panel structure is generated as shown in Figure 4-7(a).
2) In warp plane, insert the straight warp yarns (in dark red) in the other reinforcement direction to create the basic structure of the second directional reinforcement as illustrated in Figure 4-7(b).
3) In warp plane, input the weft yarn paths (in dark blue) to interlace the straight warp yarns as shown in Figure 4-7(c).

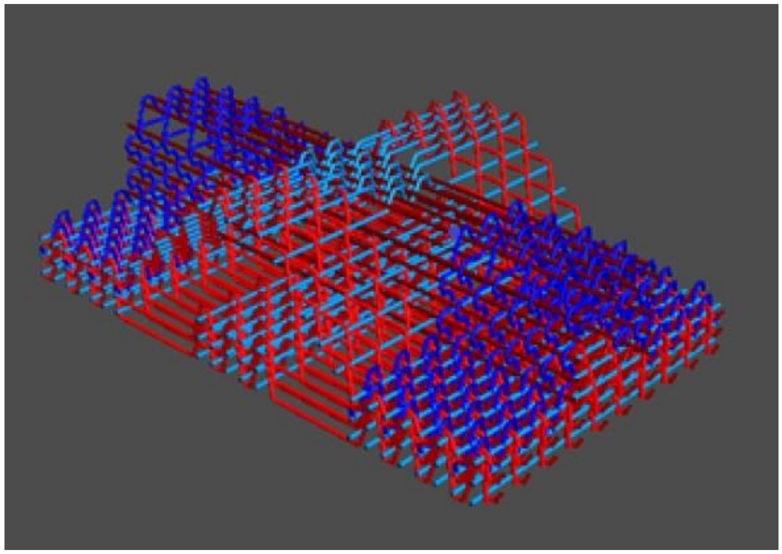


Figure 4-6. Integrated woven preform reinforced in both weft and warp directions

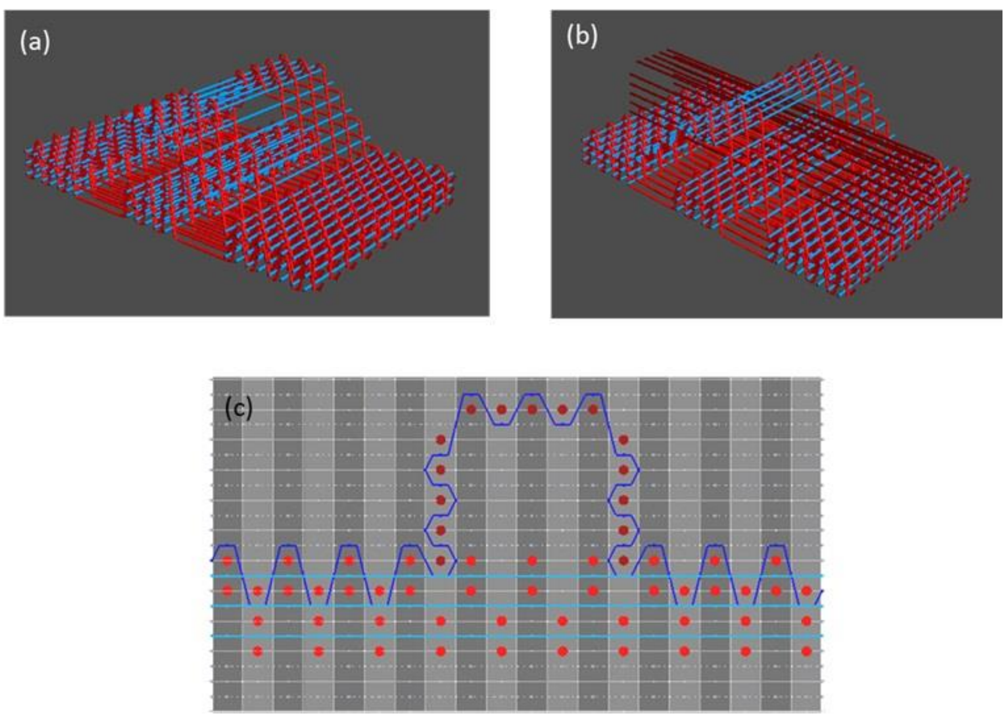
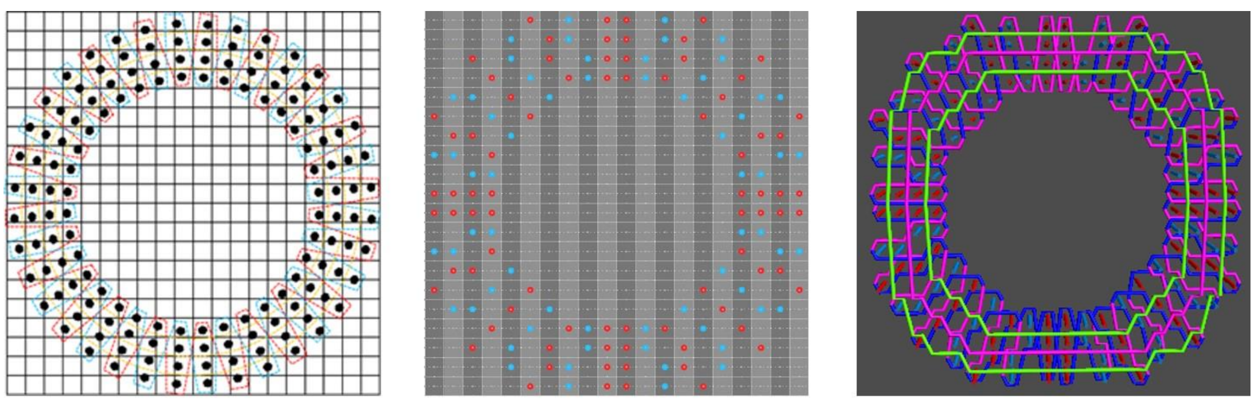


Figure 4-7. Two directional reinforcement preform design procedures

4.4.2 Fabric Design for Tubular Components

The 3D weaving method has been developed to produce 3D woven fabrics with three mutually perpendicular sections, such as I-shape, pie-shape, etc. For Jacquard weaving machine, it's known that the shuttle carries the weft threads passing the warp yarns back and forth. If the warp yarns are arranged in the radial directions while the weft thread is carried to pass the warp yarns in the circumferential direction, the 3D tubular fabric can also be produced.

The weaving design process for a tubular component with an axially symmetric structure is divided into 3 steps illustrated in Figure 4-8(a), (b) and (c), respectively. In the first step, the perfect tube topology is mapped into a Cartesian coordinate mesh. The second step is a warp relocation process. Each warp is moved to the closest location inside the Cartisian mesh as shown in Figure 4-8(b). The final step is to input paths of weft on warp planes as shown in Figure 4-8(c).



(a) Fabric pattern (b) Relocate Warps (c) Input wefts

Figure 4-8. Weaving design process for a circular tubular

Chapter 5 – Conclusions

The objective of this research was to develop a CAD/CAM tool with a new algorithm to design 3D woven near-net-shape structures based on the Jacquard weaving machine. This developed algorithm represents warp yarns paths and weft yarns paths using symmetric matrices. Therefore, it allows technical weavers to design woven fabrics in weft plane design mode, warp plane design mode, and combined weft-plane and warp-plane design mode. It enables technical weavers to graph the yarn paths precisely. The CAD/CAM design tool uses these yarn paths to generate weft matrices and warp matrices, then calculate a binary topology matrix automatically. This topology matrix can be used to weave 3D woven fabric on a conventional Jacquard weaving loom.

This report also provides the design processes of a two-directional reinforcement fabric structure and a 3D tubular woven structure. Once finish the design with the CAD/CAM tool, a machine-readable topology matrix can be determined by this CAD/CAM software.

References

[1]. Gu P. and Ding L. 1999. "Algorithms for computer-aided construction of double weaves: application of the kronecker product", Journal of the Textile Institute, pt. 1, vol.90, no.2, pp. 158-176.

[2]. Chen X and Potiyaraj P. 1999 "CAD/CAM of the orthogonal and angle-interlock woven structures for industrial applications", Textile Research Journal, 69: 648–655, DOI: 10.1177/004051759906900905

[3]. Chen X. and Potiyaraj P. 1999. "CAD/CAM for Complex Woven Fabrics. Part II:Multi-layer Fabrics", Journal of the Textile Institute, 90:1, 73-90, DOI: 10.1080/00405009908658692

[4]. Koltycheva N.G. and Grishanov S.A. 2006. "A systematic approach towards the design of a multi-layered woven fabric: Modelling the structure of a multi-layered woven fabric", Journal of the Textile Institute, pt. 1, vol. 97, no. 1, pp. 57-69.

[5]. Wang Y., Liu B., Li L., Tomich A., Yen CF. 2017. "CAD/CAM Tool for 3D Woven Textile Fabric Design," ASC 32nd Technical Conference, October 22-25, 2017.

[6]. Website, https://en.wikipedia.org/wiki/Loom

[7]. Liu B,. Wang Y., Yen CF. 2019. "Design and Fabrication of 3-D Woven Composite Preforms with Complex Topologies," ASC 34th Technical Conference, October 15-17, 2019.