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New Method of Weaving Multiaxis Three Dimensional Flat Woven Fabric: Feasibility of Prototype Tube Carrier Weaving

Abstract
A prototype of multiaxis three dimensional (3D) flat weaving was constructed, and the feasibility of this type of weaving was studied. Several multiaxis 3D woven and 3D orthogonal woven unit cells were developed and fabricated for the trial of the preforms. Multiaxis weaving units were described and implemented based on the initial trial period. The performance of each unit cell was tested, and important processing parameters were found to be related to the multiaxis unit cell. It was found that this kind of weaving could be achieved for certain types of unit cell, the results of which can be considered to be encouraging.

Key words: *multiaxis weaving, 3D weaving, bias fibres, multiaxis 3D preform, multiaxis 3D composites, tube carrier weaving.*

Introduction

For the last two decades, intensive research into textile structural composites has been carried out by Universities, research organisations and government laboratories for application in defence, space and civilian areas. Because textile structural composite materials are attractive specific properties compared to those of metals. For instance, the NASA–ACT program encouraged the researcher to initiate fibre-based advanced materials, as indicated by Dow and Dexter [1], as well as Dexter and Hasko [2].

Traditional textile structural composite materials show better strength and stiffness characteristics than those of metal and ceramics. However, they have a low delamination resistance which results in catastrophic failure, as reported by Chou [3], Sih and Skudra [4]. 3D woven preforms have been developed for composite materials which show a high delamination resistance and have fracture toughness properties due to z-fibre reinforcement, as reported by Mohamed [5], Brandt, Drechsler and Arendts [6], and Cox et al. [7]. However, it is understood that z-fibre leads to a reduction in some of its in-plane properties. To improve the in-plane properties, additional fibre, which can be called bias, should be introduced to the preform at an angle.

Dow [8], Dow and Tranfield [9] and Skelton [10] developed a fabric structure which has three sets of fibres, two bias fibre sets and a filling which are interlaced with each other to make a single layer triaxial woven. However, it has a single layer structure and is highly porous, which is not a result of the high fabric volume fraction or the lack of warp (axial) yarns. Lida et al [11] enhanced triaxial woven fabric in which additional axial fibre was introduced to single layer triaxial woven fabric; this was called a quadrilateral fabric structure. However, the structure is not multilayered in terms of the number of warp, filling and bias layers. Skelton [10] reported that the structure was open and has more isotropic properties compared to those of 2D traditional plain woven.

Multiaxis 3D woven preform and a method were developed by Anahara et al [12, 13]. But preform is not versatile in terms of the bias layer position in the preform and is limited in terms of the number of warp layers in the preform. Also the screw shaft system used in bias orientation is not effective due to ineffective bias yarn control during rotation. Kamiya, Popper and Chou [14] reported that instead of using the screw shaft system for indexing bias yarns, guide blocks were used in this technique to orient the bias fibres at ± 45°. This system fairly improves the bias orientation compared to that of the screw shaft system. Farley [15] developed a technique to make a multiaxis structure using individual eye needles. However, the structure lacks z-fibre, and only four yarn sets were interlaced with each other to provide structural integrity. Furthermore, bias insertion is not continuous and must be cut for each bias yarn insertion in the preform, which is not practical.

Mood [16] also developed multiaxis fabric and a method based on the jacquard technique. The structure has four yarn sets which are interlaced with each other to make multiaxis fabric. However, the structure has a single layer and lack of multiple warp and filling layers, which can find only limited application in technical textiles. Mohamed and Bilisik [17] developed multiaxis 3D woven fabric of many warp layers and a method in which tube carriers are used to orient bias fibres

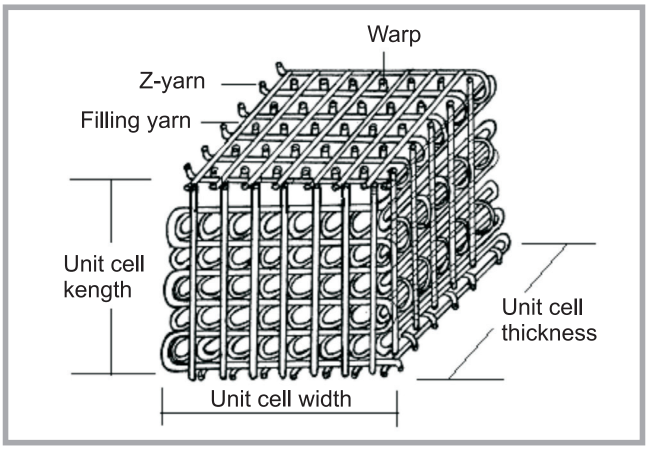

***Figure 1**. Schematic view of a 3D orthogonal woven preform unit cell.*

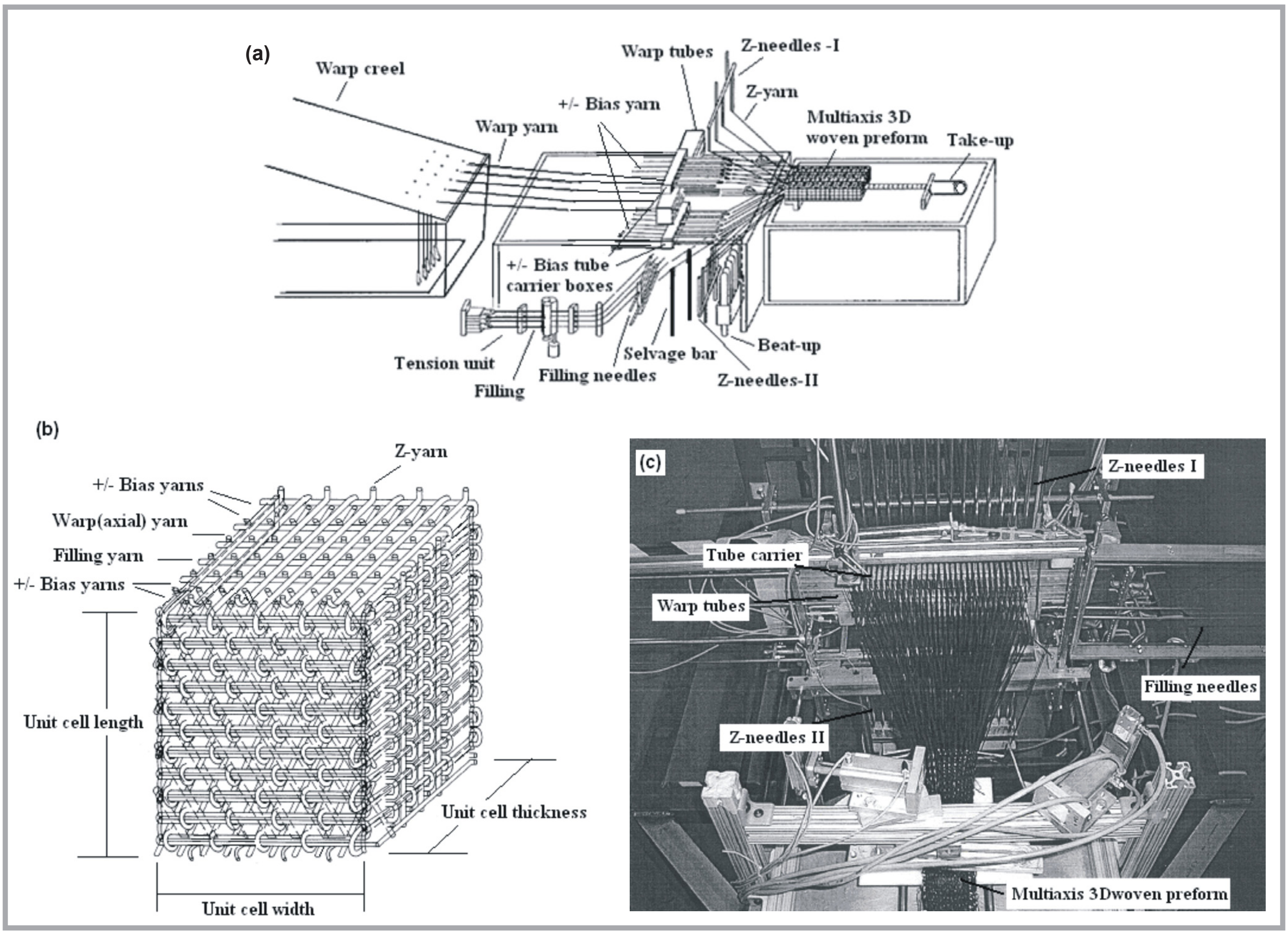

Figure 2. Schematic views of the multiaxis 3D weaving prototype (a), perspective views of the unit cell of the multiaxis 3D woven preform from tube carrier weaving (b), actual view of the multiaxis 3D weaving zone of the prototype (c).

at an angle. It was found the in-plane shear properties of the multiaxis 3D woven carbon/epoxy composite are better compared to those of the 3D orthogonal woven carbon/epoxy composite, as reported by Bilisik and Mohamed [18]. Uchida et al [19, 20] made a prototype of multiaxis 3D weaving based on Anahara's guiding block principles in which bias rotation was carried out using the chain-sprocket system, where some of the bias yarns came apart from the structure. Moreover, the z-fibre insertion system not only performs the insertion of z-fibres but also a beat-up action, which could damage brittle carbon fibres. This causes the decreasing of some of the mechanical performance of the preform associated with the final composite form. Recently, Bryn, Lowery and Harris [21], and Nayfeh [22] developed techniques to make multiaxis fabric for use in connectors and joint elements for defence related products. The fabric has four yarn sets that interlace with each other to form the structure. The fabric is single ply with no z-fibre reinforcement. The process by Bryn, Lowery and Harris has a discon-

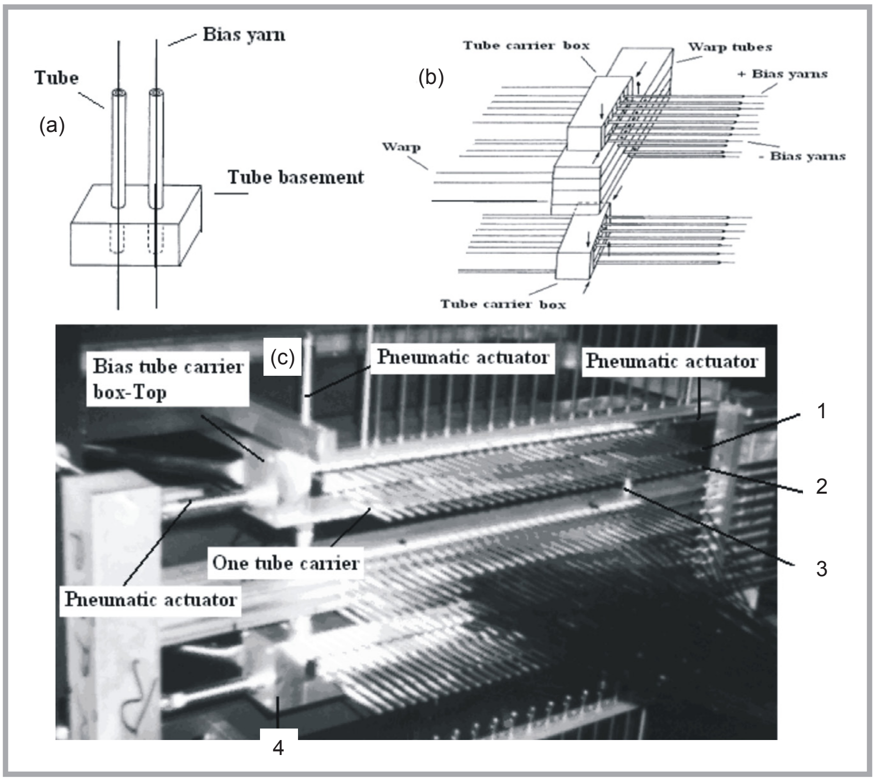

Figure 3. Schematic views of the one tube carrier (a), warp tube and bias tube carrier boxes (b), bias tube carrier box in the multiaxis 3D weaving zone (c); 1) +Bias layer tube carriers, 2) -Bias layer tube carriers, 3) Pneumatic actuator, 4) Bias tube carriers box-Bottom.

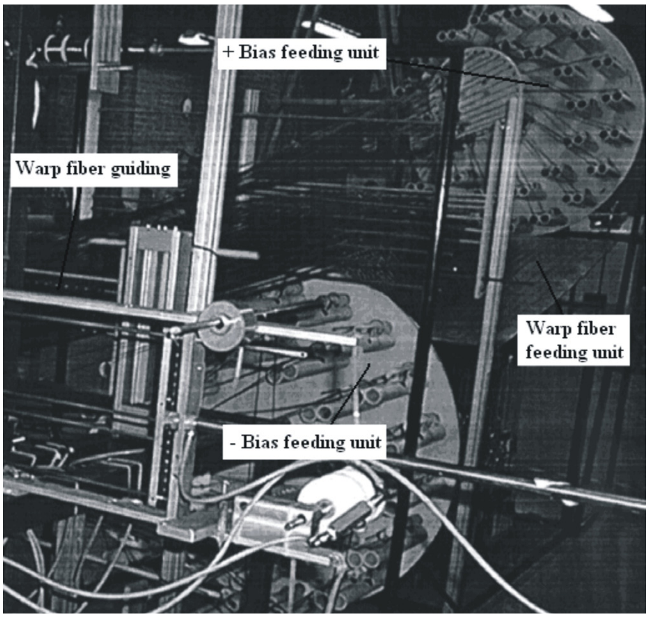

***Figure 4.** Bias and warp fibre feeding units.*

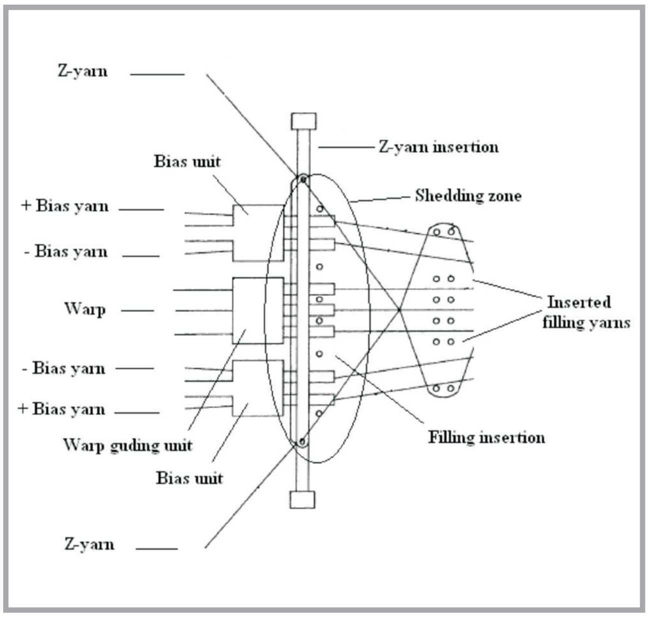

***Figure 6.** Shed formation in multiaxis 3D weaving.*

tinuous bias insertion. The process by Nayfeh has braider carriers for bias insertion, but the filling insertion and beat-up become impractical.

In this research multiaxis 3D weaving called "Tube Carrier Weaving" is further developed as part of an extension of previous work conducted by Mohamed and Bilisik [17]. Multiaxis and multilayer preforms were enhanced with regard to structure architecture and bias orientation. Multiaxis 3D weaving was prototyped and basic technical hurdles were identified and refined; thus its feasibility was tested. The results were considered to be encouraging for certain types of preforms.

Materials and methods

Basic concept of multiaxis 3D weaving

In traditional weaving, the basic method for 2D woven fabric is shed, pick and beat-up. Additionally, a let-off and take up unit is required to continue the weaving. Fabric has an interlacement (or crimp) between two fibre sets for structural integrity. In 3D weaving, the basic method for 3D woven fabric (or preform) is similar to that for 2D weaving, except for the warp and filling layers, which require Z-yarns in 3D weaving. 3D woven fabric has interlacements on the surface but none inside the structure. The three yarn sets are orthogonal to each other. The unit cell of 3D woven fabric is shown in ***Figure 1***.

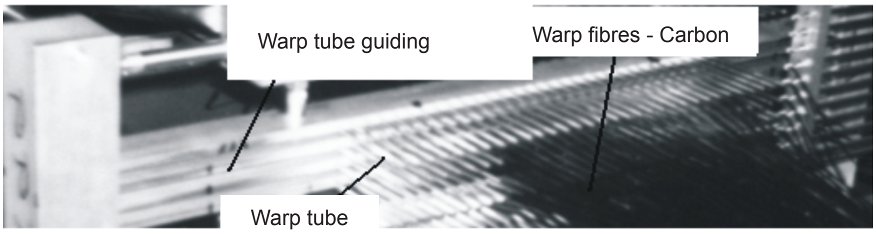

***Figure 5.** Warp tube guiding unit.*

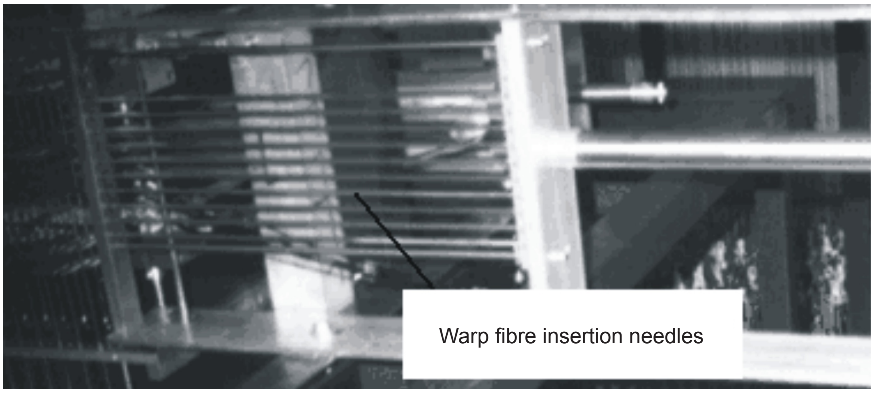

***Figure 7.** Filling insertion unit.*

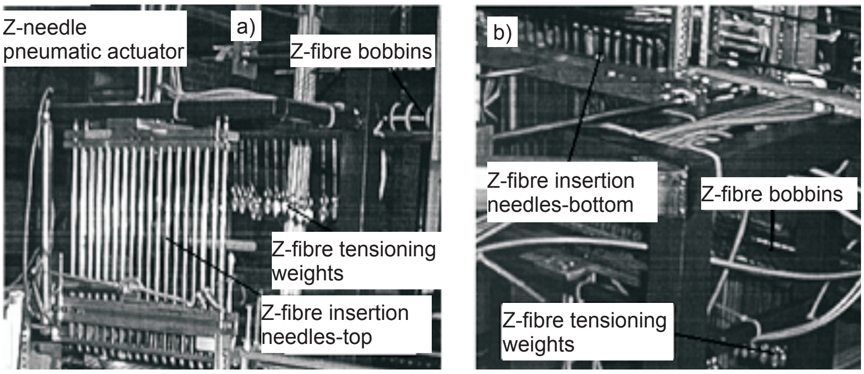

***Figure 8.** Top (a) and bottom (b) of the Z- fibre insertion unit.*

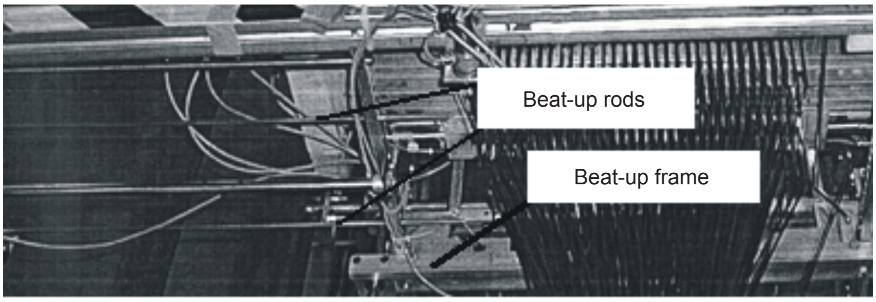

Figure 9. *Light beat up unit.*

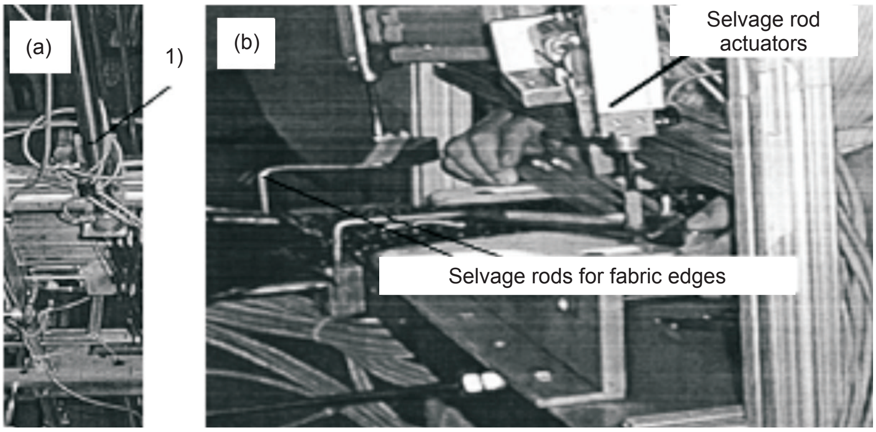

Figure 10. *Filling loop selvage needle (a), selvage transfer rods (b); 1 - Selvage for filling loops.*

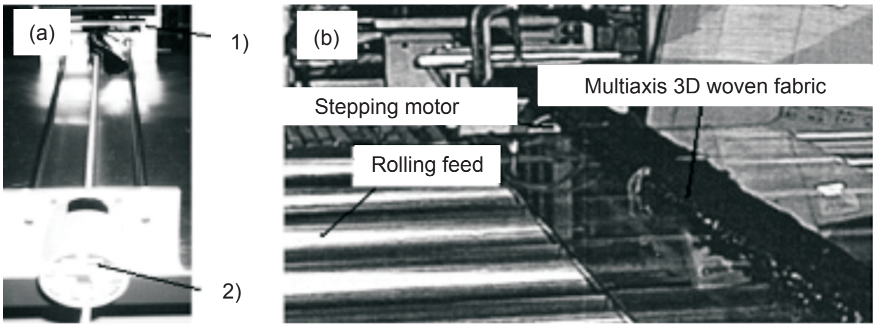

Figure 11. *Starting position of take-up (a), woven fabric delivered from weaving zone (b); 1 - Starting of weaving position for take up, 2 - Stepping motor.*

In multiaxis 3D weaving, the basic method for multiaxis 3D fabric is similar to that for 3D weaving, except for the ± bias yarn layers, which must be oriented at an angle to the structure plane; therefore a new element is added to the weaving. Thus, the basic method for multiaxis weaving depends on the bias, shed, pick and beat-up, as well as the let-off and take-up. A concept design of multiaxis 3D weaving is shown schematically in ***Figure 2.a***.

Multiaxis 3D woven fabric has bias layers which can be placed in any warp layer (structure plane), filling and z-fibre. The unit cell of multiaxis 3D woven fabric is shown in ***Figure 2.b***. Multiaxis 3D weaving is also capable of making a 3D orthogonal woven unit cell.

A multiaxis 3D weaving prototype was constructed to evaluate each unit of the weaving, as shown in Figure 2(c). Processing parameters related to the unit cell were identified for the prototype. This was a viable method of refining the weaving units in order to have an acceptable and consistent preform unit cell depending on requirements.

Process units of multiaxis 3D weaving

Bias tube carrier box

A bias tube carrier box was developed to orient ± bias layers depending upon the requirement. A bias box has many tube carriers depending on the number of bias yarns. Each tube carrier has two tubes where bias fibres pass through, as shown in ***Figure 3.a***. Each bias box had two rows of 32 tube carriers each rotating inside the bias box, as seen schematically in ***Figure 3.b***. In every weaving cycle the tube carrier at the edges of the row rotated and changed direction from the top to the bottom and from the bottom to the top of the bias box, which meant that one tube carrier at the edge of the box changed its position from bias(+) yarn to bias(-) yarn and from bias(-) yarn to bias(+) yarn. In each weaving cycle, the total number of tube carriers in each row remained the same. Tube carrier actuation was carried out by pneumatic cylinders. There were two bias tube carrier boxes placed on the top and bottom of the weaving zone, as seen in ***Figure 3.c***.

Bias and warp fibre feeding

Because of the intermittent bias rotation around the preform surface, a new method of rotational bias fibre feeding or creel was designed to eliminate fibre twist. Two bias feeding units were used for each bias box, as seen in ***Figure 4***.

Warp tube guiding

The warp fibre was a matrix arrangement and could have many rows and columns. There were four warp rows, each row having 32 columns equal to the number of bias tube carriers. Warp tube guiding was used to align the warp yarns in the weaving zone, as shown in ***Figure*** 5. Warp fibre was fed from the warp feeding unit, as seen in ***Figure 4***.

Shed Formation

In multiaxis 3D weaving there is a constant opening shed for filling and z-yarn insertions. The open space between each warp tube and bias tube row was used for the filling insertion, whereas the open space between each warp tube and bias tube column was used for z-yarn insertion, as seen in ***Figure 6***. The shedding in the 3D orthogonal woven preform is similar to that of multiaxis 3D weaving; the only difference being that bias tube carriers in the bias box remain stationary during weaving, and bias yarns in 3D orthogonal weaving become warp yarns.

Filling insertion

Multiple filling needles were developed to insert filling yarns between each adjacent warp layer. The filling needle was

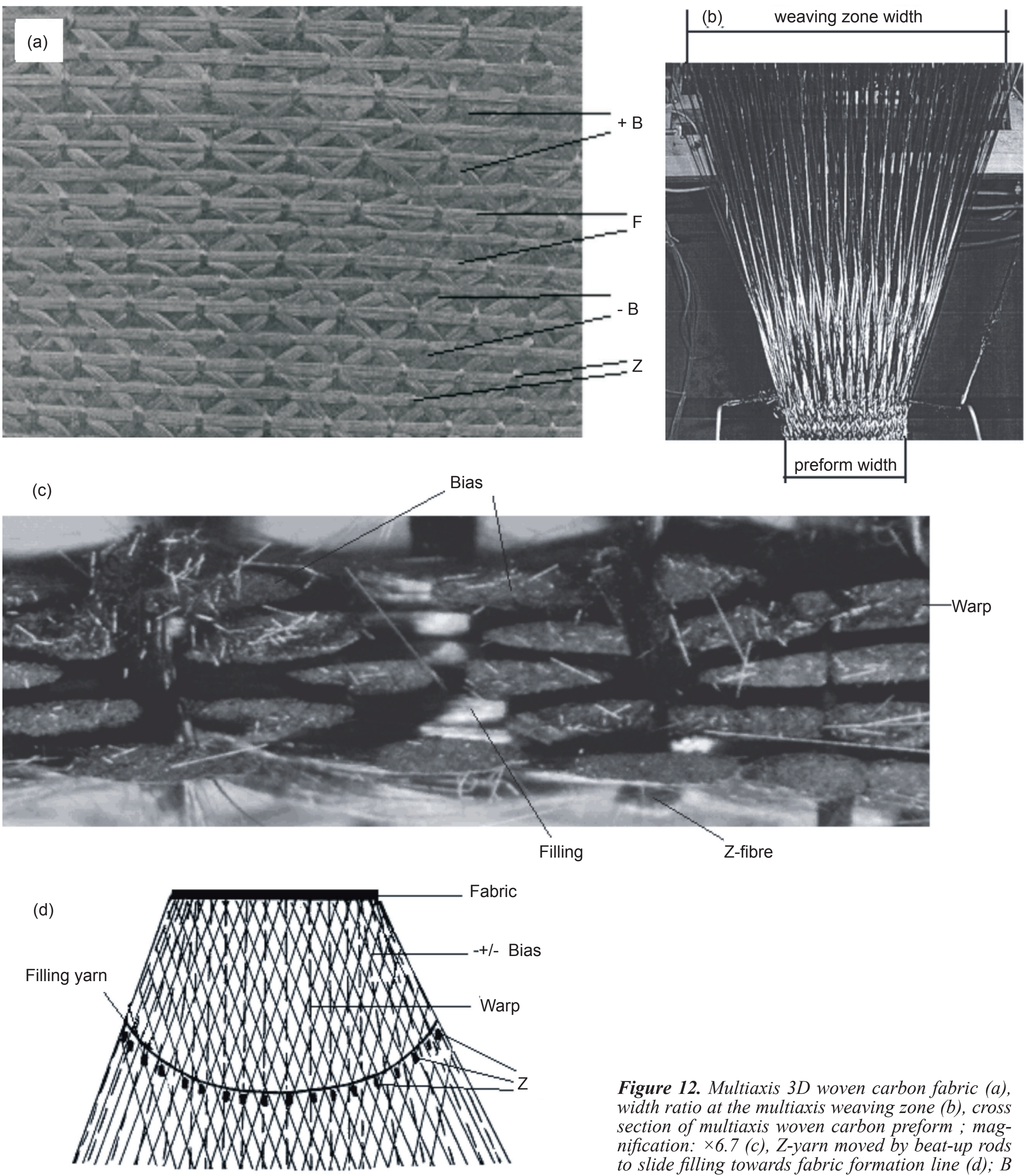

Figure 12. *Multiaxis 3D woven carbon fabric (a), width ratio at the multiaxis weaving zone (b), cross section of multiaxis woven carbon preform ; magnification: ×6.7 (c), Z-yarn moved by beat-up rods to slide filling towards fabric formation line (d); B - Bias yarns, F - Filling yarns, Z - Z-yarns.*

actuated by a pneumatic cylinder, as shown in ***Figure*** *7*.

Z-fibre insertion

Z-yarn locked the warp layer, filling layer and ± bias layers all together to provide structural integrity. There were two z-yarn units which looked open shed compared to traditional 2D fabric weaving. Each z-yarn was inserted into the structure by an individual eye needle. Z-yarn was fed by bobbins, and tension was provided by hanging weights on the z-yarns, as seen in ***Figures 8.a*** and ***8.b.***

The top z-needle and bottom z-needle were inserted into the weaving zone, in which each needle was arranged alternately from the top to the bottom z-fibre unit corresponding to each slot of the weaving zone thickness direction. Both z-needle units were actuated by pneumatic cylinders.

Beat up

The beat-up unit beat the inserted filling yarns against the woven zone to get a proper fibre volume fraction depending upon requirements. Two types of beat-up were developed: light beat-up and rigid beat-up. In light beat-up, two rods

Table 1. *Specifications of the multiaxis 3D and 3D orthogonal woven carbon preforms. [1] Polyacrylonitrile type (PAN) carbon fibres are used in both of the unit cells. Thornel T-300 Carbon fibre is a family of high strength carbon fibre. Carbon fibre density is 1.78 g/cm^3 and filament diameter 7 micron and ultimate elongation is 1.62%. It is sized with an epoxy resin to improve the handling characteristics and is compatible with epoxy matrix. Tensile strength and modulus of the fibre are 3792 MPa and 234 GPa respectively; [2]K = 1000 filament at the TOW.*

		Multiaxis 3D woven	**3D orthogonal woven**
Preform unit cells	Material type	Celion G 30-500 Carbon fiber[1]	
	Warp yarn	6 K[2] - HTA – 7E with EP-03 finish	
	Filling yarn	3 K - HTA – 7E with EP-03 finish	
	Z-yarn	3 K - HTA – 7E with EP-03 finish	
	+ /- Bias yarn	6 K - HTA – 7E with EP-03 finish	-
Preform structure	Warp	2 layers x 32 rows	6 layers x 32 rows
	Filling	3 layers (3 double picks/cm)	3 layers (3 double picks/cm)
	Z-yarn	32 ends (one z-yarn for every warp row)	
	+ Bias yarn	2 layers x 32 rows	-
	- Bias yarn	2 layers x 32 rows	-
	Bias angle (measured)	32°	-
	Cross section	Rectangular section	Rectangular section
Weave architecture in section		Z-yarn	Z-yarn
		90° - Filling	90° – Filling
		+45°- Bias	0° – Warp
		-45° – Bias	0° – Warp
		0° – Warp	0° - Warp
		90° - Filling	90° - Filling
		0°- Warp	0° - Warp
		+ 45° – Bias	0° - Warp
		-45° – Bias	0° - Warp
		90°- Filling	90° – Filling
		Z-yarn	Z-yarn

moved towards the weaving zone opposite the filling insertion direction and locked onto the beat-up frame. The beat-up frame moved to the woven formation line so that the filling inserted slides against z-yarns, which applied pressure to the filling yarns via crossed bias yarns. The beat-up frame and rods were actuated by pneumatic cylinders. In the case of rigid beat-up , beat-up bars were used corresponding to each slot on the warp column. It was manually actuated, and in this way a dense structure was obtained. Only the light beat-up unit is shown in ***Figure 9***.

Selvage

After the filling was inserted between warp layers to the warp row, the selvage needle held the filling loop and carried the loop when the beat-up frame moved to the woven formation line. The selvage needle was then placed on the top of the beat-up frame, as shown in ***Figure 10.a***. There were two selvage transfer rods placed on the top of the woven formation line, as can be seen in ***Figure 10.b***. When the filling loop was carried to the formation line, two selvage loop transfer rods held the filling loops in place, and excessive filling lengths were removed from the weaving and secured at the edge of the fabric.

Take up

The take-up was a linear motion assembly actuated by a stepping motor, delivering the filling inserted and z-yarns from the weaving zone to continue the weaving cycles. The take-up unit was the starting position, and after that weaving was proceeded, following many cycles, as seen in ***Figures 11.a*** and ***11.b***, respectively.

Process control of multiaxis 3D weaving

Each motion in the process was carried out by pneumatic cylinders, the motions being controlled by solenoid valves via a microprocessor. The stepping motor was also controlled by a microprocessor connected to a personal computer via an interface card, which was used as an input-output port. Motion control was governed by a simple Basic program through which each motion sequence and time was performed. The speed of the stepping motor was also adjusted to control the take-up rate.

Results and discussions

The multiaxis 3D weaving prototype developed was used to produce multiaxis 3D woven carbon fabric, as shown in ***Figure 12.a***. Specifications of the preform are given in ***Table 1***. The prototype fabricated both multiaxis and orthogonal architectural unit cells. The multiaxis prototype and the structure were assessed, and the following points were considered.

Width ratio

The multiaxis weaving width was not equal to that of the preform , as seen in ***Figure 12.b***. This difference was defined as the width ratio (preform width/weaving width). This was not currently the case in traditional 2D or 3D orthogonal weaving. The width ratio was almost 1/3 for multiaxis weaving. This was caused by an excessive filling length during insertion, which was solved by simply designing a selvage transfer unit. However, local filling curvature was observed in the preform.

Packing

During multiaxis weaving, fibre density and pick variations were observed. Some of the warp yarns accumulated at the edges were similar to those of the middle section of the preform. When the preform cross-section was examined, uniform yarn distribution appeared not to have been achieved for all the preform volume, as seen in Figure 12(c). A similar tendency was observed at the picks. These indicated that the light beat-up did not apply enough pressure to the preform, and the layered warp yarns were redistributed under the initial tension. In part, the crossing of bias yarn prevented the z-yarn from sliding the filling yarns towards the fabric line, in which the filling was curved, as seen in Figure 12(d). Probably, this problem is unique to multiaxis weaving. Hence, it can be concluded that rigid beat-up was necessary. This unique problem could be solved by a special type of open reed, if the width ratio is considered the main design parameter.

Tension

Fibre waviness was observed during weaving at the bias and filling yarn sets. The bias yarn sets did not properly compensate for excessive length during biasing on the bias yarns. Variable tensioning might be required for each bias bobbin. The filling yarn sets were mainly related to the width ratio and level of tension applied. A sophisticated tensioning device might be required for filling yarn sets. On the other hand, brittle carbon fibre characteristics must be considered.

Conclusions

Multiaxis 3D weaving was prototyped to test the feasibility of the process and the capability of producing various unit cell-based preforms. The basic processing parameters were identified related to the preform unit cell. The basic technical hurdle was the beat-up, in which open reed was required for bias orientation in the process, which must be differentiated during the packing action for the width ratio. It was concluded that the process and product of this investigation was considered to be feasible.

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