DEVELOPMENTS IN MULTIAXIAL WEAVING FOR ADVANCED COMPOSITE MATERIALS

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SUMMARY: There is an increasing demand within the composites industry for integrally-manufactured three-dimensional preform structures. Using and extending the basic principles of conventional weaving processes has allowed a wide range of such structures to be developed, as briefly summarised in this paper. Such integrally-woven preforms, however, lack reinforcing fibre in the bias directions (eg. ±45°) intermediate between the warp and weft. A detailed review of recent developments to overcome this limitation is presented in this paper, together with the type of integrally-woven multiaxial structure (eg. 5-axis) achievable. Although the details of implementation differ, these multiaxial weaving developments utilise the principles of lappet weaving, triaxial weaving, and cross-laying.

KEYWORDS: multiaxial, weaving, lappet, triaxial, cross-laying, bias, three-dimensional.

INTRODUCTION

The use of textile technology in the manufacture of preforms for advanced composite materials has and continues to be under intense investigation due to the potential of these processes, together with resin infusion techniques such as resin transfer moulding (RTM), to produce low-cost high-quality structures with improved mechanical performance. Perhaps foremost among these textile processes is weaving technology.

Using the basic principles of conventional weaving processes, as discussed below, a wide range of integrally-woven preform structures have been developed for the composites industry. Such structures, however, are generally limited to at most three directions of fibre reinforcement, viz. the orthogonal directions of warp, weft and through-thickness (binder) yarns. Inclusion of fibre reinforcement in the in-plane "bias" direction (eg. ±45°) still requires formation of a laminate structure. This restriction has led to interest in the use of multiaxial weft-inserted warp-knitted/stitch-bonded structures which can be manufactured on appropriate commercially available machinery. Such structures, however, suffer from limitations as regards potential channelling in the fibre architecture and the use of thermoplastic knitting threads to provide through-thickness reinforcement, as well as limited versatility for three-dimensional shaping during preform manufacture.

Recent years, however, have witnessed new developments in multiaxial weaving to overcome the above limitations. These developments are reviewed in this paper. Included in this is a brief outline of two special weaving techniques in which bias yarns can be introduced intermediate between the warp and weft directions in a woven fabric.

CONVENTIONAL WEAVING PROCESSES

Weaving is perhaps the oldest fabric-forming technology, with a rich history of technological development both in terms of machinery and fabric structures. It is essentially the action of producing a fabric by the interlacing of two sets of yarns (warp and weft) as schematically illustrated in Figure 1. The warp yarns run in the machine direction and are provided in a parallel sheet array, either from one or more warp beams or from individual warp yarn packages located in a frame known as a creel. The weft yarns run in the cross-machine direction and are typically introduced singly or in looped double-pick form. Weaving is characterised by three primary motions:

1. shedding - the separation of the warp sheet into an upper and lower layer, thereby creating a tunnel known as the shed;
2. picking - the insertion of the weft yarn (pick) into the shed;
3. beating-up - the consolidation of the inserted weft yarn into the edge of the fabric (known as the cloth fell).

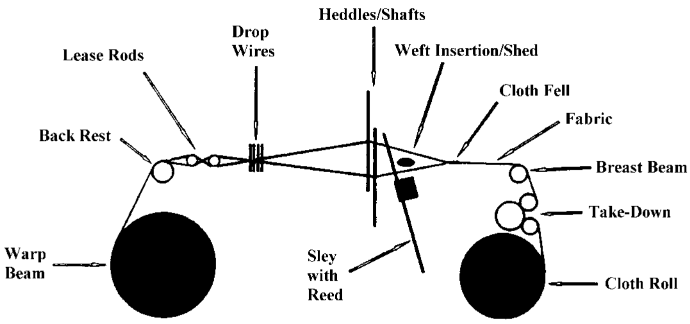


Fig. 1: Principles of conventional weaving

Secondary motions required for power weaving are warp let-off and cloth take-up. The former is the release of the warp yarn from its supply as weaving progresses, and the latter is the withdrawal of the fabric from the weaving zone as it is produced and its subsequent storage (eg. on a cloth roll). Additional auxiliary motions are associated with the continuity (and selection) of the weft yarn supply and the provision of various stop motions in the event of yarn breakage or other malfunctions; in the case of shuttleless weaving, selvedge forming devices are also required. Ideally, both yarn sets are under controlled tension regimes during the weaving cycle. Fundamental to the conventional weaving process is the use of heddles to effect shedding for individual warp yarns and of the reed to achieve beating-up; heddles are essentially (vertical) wires with an eye in the centre through which a warp yarn is threaded, while the reed is a comb-type device across the width of the machine - further, both devices maintain the lateral position of the warp yarns in the sheet array. Various mechanisms have been developed to implement and extend these motions and texts are available for the interested reader [eg. 1]. From these basic principles, an amazing array of woven fabric structures have been developed to satisfy various aesthetic and functional requirements for apparel, furnishing, and technical/industrial end-uses [eg. 2].

Extension to Textile Composite Preforms

Simple woven structures (eg. satin weaves) found early application as preforms in laminate structures. The poor impact performance and delamination resistance of such structures has led to the use of stitching techniques borrowed from clothing technology; in addition, the weave crimp is often considered to reduce the mechanical efficiency of the reinforcing fibres. The development of multilayer plate structures is a natural progression well within the scope of conventional weaving - indeed, they form the compound weave category of woven structures. Typical examples of such 3D woven fabrics are the simple angle interlock, warp interlock and orthogonal structures, which utilise binder warp and/or weft to provide through-thickness reinforcement and structural integrity to (ideally) straight warp and/or weft primary load-bearing yarns. In the patent literature there are various other plate-type structures developed for moulding into curved 3D surfaces [eg. 3] and for stiffened panels, including beams with various cross-sections [eg. 4]. In addition, the technique of face-to-face weaving, traditionally employed in the manufacture of cut-pile woven carpets, can be used to manufacture sandwich structures in which the “pile” yarn traverses between the two “backing” fabrics [eg. 5]. Further, this basic technique has been extended to manufacture core-type structures in which fabric “ribs” join the two surface layers [eg. 6]. Finally, the technique of contour or shape weaving has been utilised to weave 3D shell-type structures [eg. 7].

While recognisable weaving developments such as the above have been reported, other developments yielding structures sometimes referred to as 3D nonwoven orthogonal fabrics have also been undertaken [eg. 8]. Where the three primary motions of weaving are recognisable, such processes are in fact weaving developments. A typical example is the use of binder warp to provide structural integrity in an otherwise non-interlaced orthogonal array forming composite beams of various cross-sectional shapes [eg. 9].

MULTIAXIAL WEAVING PROCESSES

The inclusion of bias yarns at an angle (eg. $\pm 45°$) intermediate between the warp and weft directions for the development of multiaxial multilayer integrally woven preforms (eg. 5-axis 3D structures) requires that the constraints imposed by the heddles and reeds in conventional weaving be overcome. Before proceeding to such preform developments, it is instructive to first consider two special weaving techniques in which the same problems were encountered.

Lappet Weaving

Lappet weaving is a special technique in which extra warp threads are introduced traditionally to develop isolated design motifs on an open weave background [2]. Figure 2 illustrates the principles of the technique, which requires the use of a lappet (or needle) bar (D) positioned between the reed (V) and the cloth fell (A). The extra warp yarns (W) are threaded through the eyes of the needles of the lappet bar and do not pass through the reed; the extra warp is usually supplied from a separate warp beam to the normal warp (X), which is controlled by heddles (Y) in the usual way. The lappet bar has two directions of movement: a lateral (shogging) movement in the weft direction, thereby controlling the angular position of the extra warp yarns with respect to the principal directions of the fabric; and a vertical movement which allows the lappet bars to form a shed for weft insertion and to be clear of the reed during beat-up - the lappet bar can be considered similar to a guide bar in warp knitting. In principle, a standard weaving loom can be modified to incorporate the lappet system.

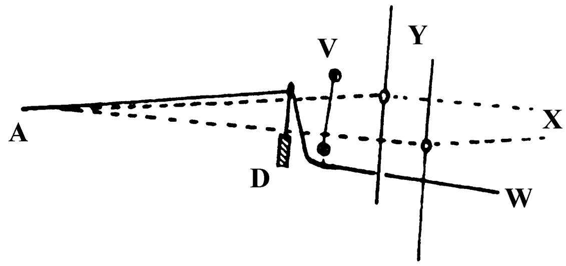


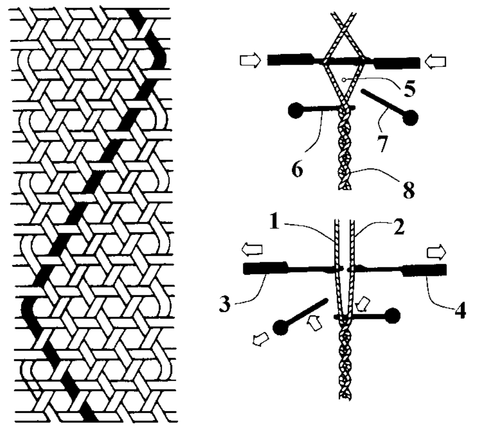
Fig. 2: Principles of lappet weaving

Clearly, lappet weaving has potential to manufacture integrally-woven multiaxial multilayer preform structures for composite materials. The extra warp yarns can be made to run at virtually any angle between (and including) the warp and weft directions, and can therefore be considered as bias yarns. These bias yarns are interlaced with the weft but held in position by the adjacent pair of normal warp yarns, and float on one surface of the fabric between successive weft interlacing points. Further, the bias yarns can be interlaced with weft yarns at any position within a multilayer structure, with the two extremes corresponding to the weft yarns at the same or opposite fabric surface; the latter would provide through-thickness reinforcement using bias yarns. However, such structures would have two main limitations: the location of the bias yarns would be limited to the outer surfaces of the preform structure; at some stage the lappet bars must reverse the direction of their shogging movement, thus limiting the extent to which an individual bias yarn can traverse the fabric width. The latter limitation, however, can be overcome with modification of the lappet system.

Triaxial Weaving

Triaxial weaving is another special weaving technique in which two sets of warp yarns and one set of weft yarns are interlaced in such a way that the three sets of threads form a multitude of triangles. Figure 3(a) illustrates a simple triaxial weave in which equilateral triangles can be seen as well as reversal of the (bias) warp yarns at the fabric selvedges. The latter ensures the continuity of an individual warp yarn across the full width of the fabric. Further, it clearly indicates that an individual warp yarn during one traverse (left-to-right, say) will be a member of one set of warp yarns but on the return traverse (right-to-left) will be a member of the opposite set of warp yarns.

The first specific patent of which the authors are aware was published in 1921 [10]. However, Mooney [11], in an excellent review of triaxial structures and manufacturing techniques, traces the history to the early 19th century. Interest in triaxial weaving was renewed in the 1960s due to its potential to manufacture stable fabric structures with excellent burst and tear resistance and with near-isotropic in-plane mechanical performance. Indeed, the 1960s and 1970s was a period of intense activity in which many patents describing structures and manufacturing techniques appeared [eg.



(a) Weave (b) Primary motions
Fig. 3: Principles of triaxial weaving

12,13] as well as various research papers describing mechanical properties [eg. 14]. The following summarises the basic features required in the triaxial weaving process, and as exemplified in the Barber-Colman TW-2000 triaxial loom [15].

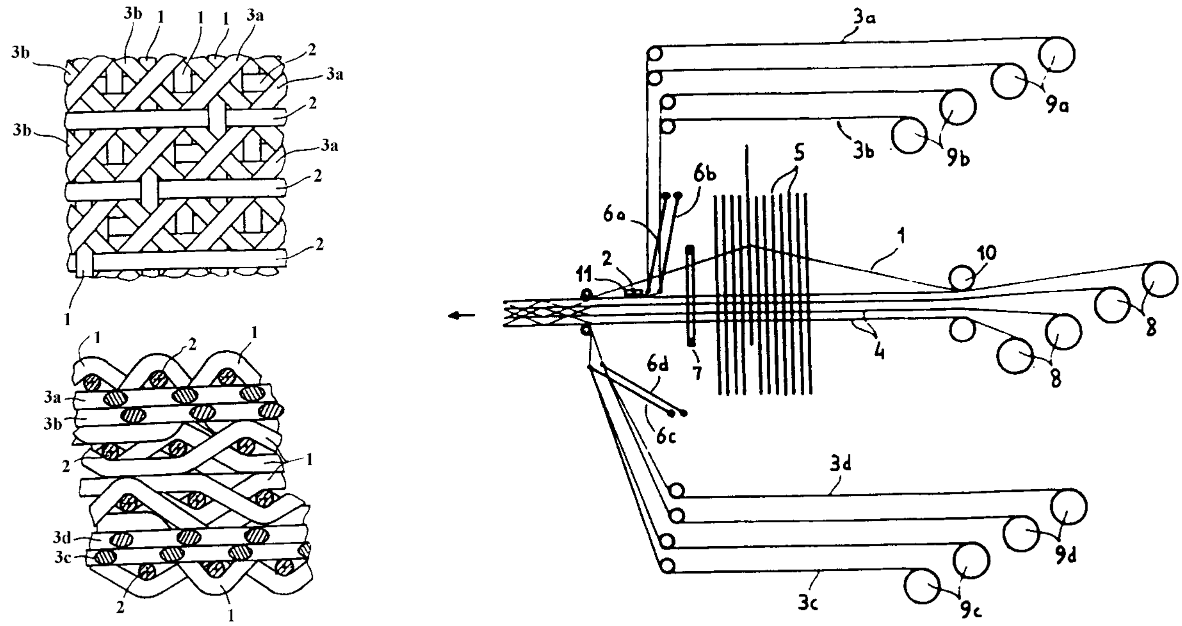
In order to achieve transverse positioning of the two opposing sets of warp yarns (1,2 in Figure 3(b)), including yarn transfer at the fabric selvedges, special heddles (3,4) circulating around a racetrack-type circuit [10,12] are used. These heddles are also used to form a shed for weft (5) insertion via a rigid rapier. The warp yarns are supplied on beams or individual yarn packages mounted on a rotating carousel [16]; alternate approaches are to use a warp beam in which the yarns form a flattened spirally wrapped sleeve [17] or to maintain the warp supply stationary and to rotate the machine. Beat-up is usually achieved through the use of two open reeds (6,7) working sequentially, with the fabric (8) formed in the same plane as the warp sheet. One reed maintains the position at the cloth fell of the traversing warp sets for the previous pick, while the second reed beats-up the newly inserted pick; the first reed is withdrawn immediately before the second reed reaches the cloth fell. On the next pick, the two open reeds reverse roles.

The potential of triaxial fabric structures for composite materials has been recognised with respect to their in-plane mechanical performance [18], conformability to curved surfaces [19], and a recent machine development for composite applications in shell-type structures [20]. It is clear from Figure 3 that inclusion of axial warp yarns as a third warp set in the basic triaxial process has some potential for the development of multilayer triaxial fabrics. However, modifying the conventional triaxial weaving process to incorporate such yarns would be a major engineering task. Rather, modifying the yarn guides to operate in a lappet weaving mode would be a simpler task - one which would overcome the second limitation of a traditional lappet weaving system as described in the previous section.

Multiaxial Developments for Textile Composite Preforms

The patent by Ruzand and Guenot [21] is the first patent to indicate how a standard loom can be modified for multiaxial weaving. Figure 4(a) illustrates the type of structure that can be obtained. The bias yarns (3a,3b) run across the full width of the fabric in two opposing layers on the top and back surfaces of the fabric, although they can be inserted on one surface only if desired. The bias yarns are held in position by selected weft yarns (2) interlaced with warp binding yarns (1) on the two surfaces of the structure. The intermediate layers between the two surfaces are composed of other warp (1) and weft (2) yarns which may be interlaced (as illustrated) or not.

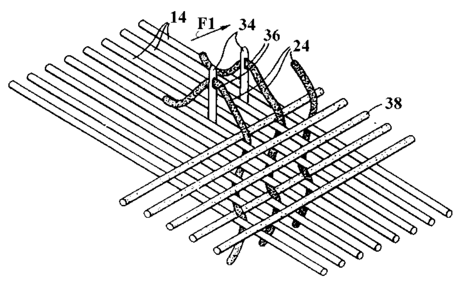
The basis of the technique is an extension of lappet weaving in which pairs of lappet bars (6a and 6b, 6c and 6d) are utilised on one or both sides of the fabric, as schematically illustrated in Figure 4(b). The lappet bars are segmented and of a length greater than the fabric width by one segment length. Each pair of lappet bars move in opposite directions, with no reversal in the motion of a segment until it fully extends past the opposite fabric selvedge. When the latter situation is reached, the segment is detached from the lappet bar, its yarns gripped between the selvedge and the guides and cut near the selvedge. The detached segment is then transferred to the opposite side of the fabric where it is reattached to the lappet bar and its yarns subsequently connected to that fabric selvedge. Since a rapier is used for weft insertion, the bias yarns can be consolidated into the selvedge by an appropriate selvedge-forming device employed for shuttleless weaving. The bias warp supply for each lappet bar segment must be independent of all other segments and not interfere with the yarns from other segments.

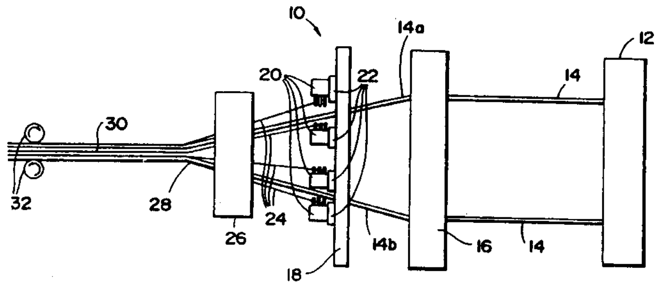


(a) Example weave *(b) Schematic illustration of loom cross-section*

Fig. 4: Multiaxial weaving development by Ruzand and Guenot [21]

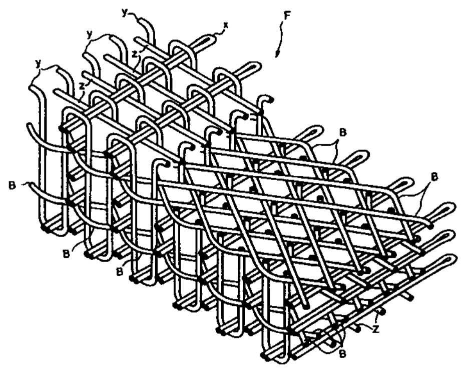
Another approach utilising lappet weaving principles has been described by Farley [22]; Figure 5 shows relevant aspects of his invention. In this case the lappet bars comprise slotted needles (34) positioned in transversely moveable needle holders (20) mounted on racks (22) placed in an assembly (18) which is positioned in front of a shedding mechanism (16); the latter controls the normal warp (14) which is drawn from warp beams or a creel supply (12). The bias yarns (24) are positioned in the slotted eyes (36) of the needles, with the yarn supply (eg. individual spools) attached to the needle holders; there is a plurality of such needle holders on any rack. The needle holders, and thus bias yarns, are moved transversely (F1) across the fabric width. At desired transverse positions, the needles are moved vertically to form a shed into which the weft yarn (38) is inserted by a special rapier (26) which also achieves beat-up through an attached inflatable membrane, thus negating the need for a reed. At the end of the traverse, a needle holder assembly is removed from its rack and repositioned at the opposite side (start) of the rack. The protruding ends of the bias yarns can be woven into the fabric selvedge or attached to a suitable clamping system moving parallel to the selvedge. According to the patent, a rack can be split into two halves so that each half can be separately withdrawn to opposite sides of the fabric to facilitate the weaving of complex preform structures, such as stiffened panels, without disrupting the continuity of the bias yarns. Examples of such preform structures, however, are not given, although it should be noted that the positioning of the lappet system together with bias yarn supply on racks permits the inclusion of bias yarn layers at any vertical position in the through-thickness direction.

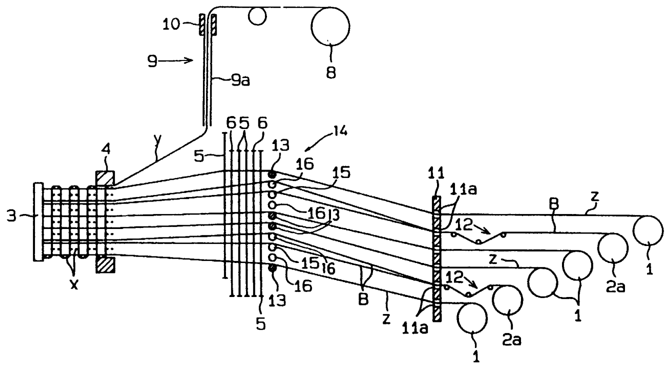




(a) Lappet weaving principles. *(b) Schematic illustration of loom cross-section*

Fig. 5: Multiaxial weaving development by Farley [22].





(a) Example weave *(b) Schematic illustration of loom cross-section.*

Indexing screw-shaft system

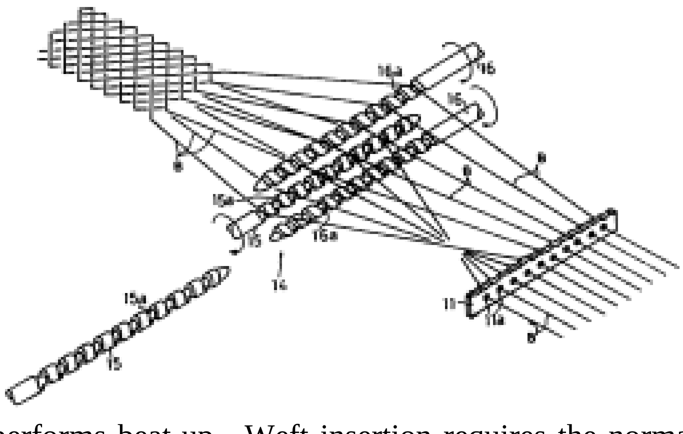
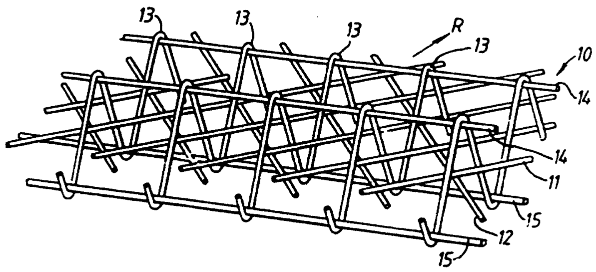


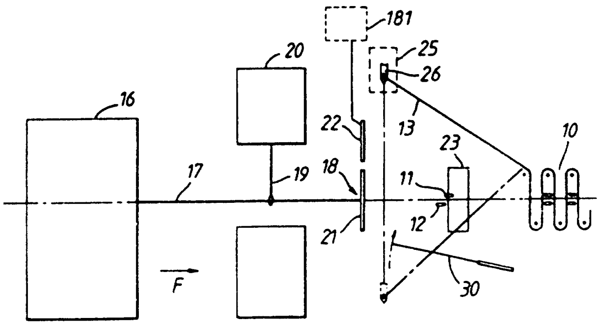
Fig. 6: Multiaxial weaving development by Anahara et al [23]

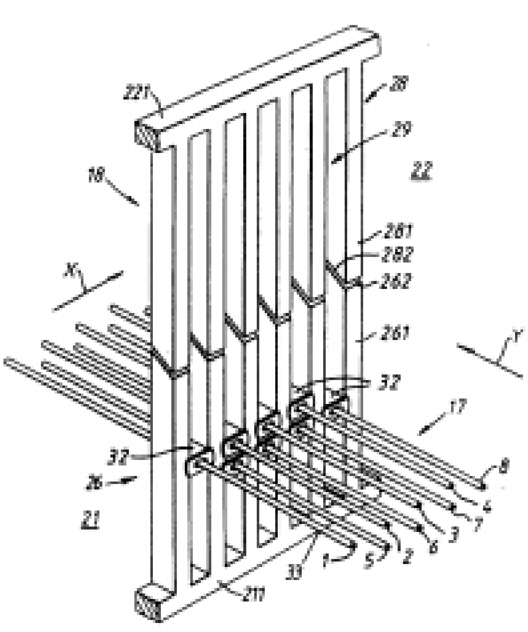
A multiaxial multilayer structure together with the manufacturing principles described by Anahara et al [23] is illustrated in Figure 6. The normal warp (z), bias (B) and weft (x) yarns are held in place by vertical binder yarns (y). The weft yarns are inserted as double picks using a rapier needle (not shown) which also performs beat-up. Weft insertion requires the normal warp and bias yarn layers to form a shed via shafts (5,6) which do not use heddles but rather have horizontal guide rods to maintain the vertical separation of these yarn layers. The binder yarns are introduced simultaneously across the fabric width by a vertical guide bar assembly (10) comprising a number of pipes with each pipe controlling one binder yarn. The bias yarns are continuous throughout the fabric length and traverse the fabric width from one selvedge to the other in a cross-laid/folded structure, as shown in Figure 6(a). Lateral positioning and cross-laying of the bias yarns is achieved through use of an indexing screw-shaft system (15,16), shown in Figure 6(c). As the bias yarns are folded downwards at the end of their traverse, there is no need to rotate the bias yarn supply as in triaxial weaving. Consequently, the bias yarns can be supplied on conventional warp beams (2a) or from a warp creel, but they must be appropriately tensioned (12) due to path length differences at any instant of weaving, although total yarn consumption will be equal for all bias yarns within a folded structure. It should be noted, however, that the folded structure of the bias yarns results in each layer having triangular sections which alternate in the direction of the bias angle about the normal warp direction due to bias yarn interchange between adjacent layers.

In total, Anahara's patent describes eight variations, in which the fabric structure achieved is the main emphasis. However, two of these variations also describe an alternate approach based on triaxial weaving principles. The bias yarns are threaded through individual guide blocks which are controlled by a special shaft to circulate in one direction around a rectangular path. Clearly, this also requires rotation of the bias yarn supply.



(a) Example weave
(b) Schematic illustration of loom cross-section





(c) Split-reed system

Fig. 7: Multiaxial weaving development by Addis [25]

Another approach is presented by Mood and Mahboubian-Jones [24] and extended by Addis [25]. While there are differences in detail, the prime features in these patents for control of the bias yarns are the use of special split-reeds together and a jacquard shedding mechanism with special heddles. Figure 7 illustrates the system developed by Addis together with an example of the type of structure that can be produced; the latter comprises bias yarns (11,12) sandwiched between weft yarns (14,15) with structural integrity provided by warp binding (13). A creel (16) supplies bias warp yarns in a sheet (17) to the special heddles (19) connected to the jacquard head (20). The bias yarns then pass through the split-reed system (18) which includes an open upper reed (22) and an open lower reed (21) together with guides (32) positioned in the reed dents. The lower reed is fixed while the upper reed can be moved in the weft direction. The jacquard head is used to position selected bias yarns in the dents of the upper reed so that they can be shifted transverse to the normal warp direction; it should be noted that correct positioning of the bias yarns requires a series of such lifts and transverse displacements and must ensure that there is no entanglement of the warp. A shed is formed by the warp binding yarn (13) via a needle bar system (25) and the weft is inserted at the weft insertion station (23), with beat-up performed by another open reed (30).

The earlier patent [24] utilised two split-reed systems, positioned on either side of the jacquard head, and required the bias yarns to be detachably engaged by the special heddles (eg. latch needles) for selective raising and lowering of yarn. Normal warp yarns were also controlled by the jacquard head and beat-up could be performed by the open lower reed of the split-reed system. It would appear that the yarn guides (32) in the later system were introduced to overcome problems of yarn abrasion and other failures. Nevertheless, the basic approach described in these two patents appears to have potential for the manufacture of unique structures, due to the use of the jacquard head, but clearly requires further exploration. However, as the warp supply is not rotated, reversal in the direction of the bias yarns must be governed by “cross-laying/folding” considerations which are not discussed in the patents.

A multiaxial multilayer nonwoven (non-interlacing) development has also been described in a second patent by Anahara et al [26]. The aim is to ensure that such structures are symmetrical about an imaginary central plane. The various layers are assembled from individual yarns laid around perpendicular pins in a frame. The pins are subsequently replaced by vertical binding yarn in a stitching action.

CONCLUDING REMARKS

The textile industry has a rich history of innovation and invention to meet consumer demands and increase productivity through automation of fibre/yarn manipulation processes - indeed, the development of a Dutch 12-piece ribbon loom in 1604 was, according to Karl Marx, the harbinger of the Industrial Revolution. The composites industry is one consumer of growing importance to the textile industry. The need for integrally-woven three-dimensional preform structures for advanced composites has seen many developments in recent years extending conventional weaving processes, as briefly summarised in the early part of this paper. The increasing demand for integrally-woven multiaxial structures (eg. 5-axis reinforcement), in which bias yarns complement the orthogonal directions of warp, weft and through-thickness binder reinforcement, has been the main focus of this paper. Developments in this area were reviewed in detail, together with the special techniques of lappet weaving and triaxial weaving. It is clear that lappet weaving principles have been incorporated in two of these developments [21,22] while a third patent [23] has offered a number of variations based on triaxial weaving principles and cross-laying principles. The fourth development [24,25] would appear to have potential for the manufacture of unique structures through the use of a jacquard shedding mechanism but this requires further exploration as cross-laying is implicit for bias yarn traverse across the full width of the fabric. The fifth development [26] is not a weaving technique but combines the assembly of non-interlaced yarn layers with subsequent binding via stitching. The authors are currently considering the feasibility of alternate weaving developments to the above and will report the principles of these in the near future.

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