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ADVANCED STITCHING TECHNOLOGY

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INTRODUCTION

In the design of textile composites, the selection of materials and constructional techniques must be matched with product performance, productivity, and cost requirements. Constructional techniques may vary from slow and expensive, hand laid-up batch manufacturing (one unit at a time) to very quick and cost effective continuous pull-through processing. No single textile material, resin system, textile assemblage, or constructional technique can be considered optimal for all applications.

A classification of various textile composite systems is given in Table I. In general, the chopped fiber system (Type I) is not suitable for structural composite applications because of fiber discontinuity, uncontrolled fiber orientation and a lack of fiber integration or entanglement. Linear filament yarn systems (Type II) are quite acceptable for structural components which are exposed to simple tension in their applications. To qualify for more general use as structural components, filament yarn systems must be multi-directionally positioned. With the most sophisticated filament winding and laying techniques, however, the Type II systems have limited potential for general load-bearing applications because of a lack of filament integration or entanglement, which means vulnerability to splitting and delamination among filament layers.

TABLE I. TEXTILE COMPOSITE SYSTEMS

Type	Reinforcement System	Textile Construction	Fiber Length	Fiber Orientation	Fiber Entanglement
I	Suspended	Chopped Fiber	Discontinuous	Uncontrolled	None
II	Linear	Filament Yarn	Continuous	Linear	None
III	Laminar	Simple Fabric	Continuous	Planar	Planar
IV	Integrated	Advanced Fabric	Continuous	3-D	3-D

The laminar systems (Type III) represented by a variety of simple fabrics (woven, knitted, braided and nonwoven) are especially suitable for load-bearing panels in flat form and for beams in a rolled up or wound form. The main features of simple fabric systems are fiber continuity, planar fiber orientation and planar fiber entanglement or integration, in general. The major vulnerability of simple fabric laminate systems is delamination between layers of the fabrics which tends to be more critical in flat panels than in rolled up tubular or rectangular configurations.

The totally integrated, advanced fabric systems (Type IV) are thought to be the most reliable for general load-bearing applications because of fiber continuity and because of controlled multiaxial fiber orientation and entanglement. Consequently, the risk of splitting and delamination is minimized and practically omitted. Type IV systems can be woven, knitted, braided or stitched through with very special equipment.

In general, multiaxial fabrics are classified as Type IV in Table I. A practical advantage of multiaxial fabrics is the elimination of much of the hand lay-up work in composite manufacturing which is so labor intensive and time consuming. Also, multiaxial fabrics are easier to handle because the various yarn orientations are held in a fixed position during manipulation. (1)

MULTIAXIAL FABRIC TECHNOLOGIES

Several alternate technologies are commercially available today for the conversion of yarn into multiaxial constructions for a variety of industrial fabric applications, but particularly for flexible and rigid composites. These multiaxial fabric technologies include adhesive bonding, triaxial weaving, triaxial braiding, weft insertion warp knitting, bias ply stitch bonding and bias warp knitting. Each multiaxial fabric technology has unique attributes and limitations, and accordingly, will find a place in the industrial fabric market on a cost/performance/availability/processability/machineability/join-ability/maintainability basis.

Adhesively-bonded multiaxial systems are easily produced by combining several layers of yarn or fabric at various angles (including skewed WIWK fabrics, bias woven, etc.). While the productivity is attractive, adhesive bonding does not provide resistance to delamination or to crack propagation. Another major limitation of adhesively bonded yarn and fabric systems is a lack of through-the-thickness strength. Adhesively-bonded constructions are classified as Type II if made directly from yarn or Type III if made by combining layers of fabric. By contrast, all of the following multiaxial fabric systems are classified as Type IV.

In triaxial weaving technology, three systems of yarns are interlaced at sixty degree angles (2,3). With two warps and one filling, the resulting orientation is $+30^{\circ}/-30^{\circ}/90^{\circ}$. While triaxial weaving technology has been developed for quite some time, triaxial woven fabric is commercially available in limited styles from Sakase Textile Company in Japan.

Triaxial braids incorporate one longitudinal yarn system with two helical or diagonal yarn systems. Consequently, the resulting yarn orientation can vary from $0^{\circ}/+30^{\circ}/-30^{\circ}$ to $0^{\circ}/+60^{\circ}/-60^{\circ}$, depending upon processing variables. Triaxial braids are particularly well suited for tubular applications.(4)

Weft insertion warp knit (WIWK) technology is well developed and established for a variety of industrial fabric applications. Biaxial WIWK fabrics are made by knitting 0° and 90° straight-laid yarn systems together. It is possible to produce quasi-quadraxial WIWK fabrics by adding two additional laid-in yarn systems in a counter zig-zag fashion in the machine direction, wherein each yarn continues for up to two inches in the $+45^{\circ}$ or -45° direction before reversing its path.(5,6)

Several companies are capable of producing quasi-quadraxial WIWK fabrics on LIBA or Mayer WIWK machines.

Multiaxial stitch bonded fabric preforms can be made by stitching together several layers of yarn at various angles or plies of skewed fabric. The stitching processes provides through-the-thickness strength and integrity. Stitching can be performed efficiently and with high productivity on any suitable multi-needle process capable of through-the-thickness penetration including sewing machines, Mali machines, warp knitting stitch-through machines, etc. The major advantages of multiaxial stitched-through fabric preforms are high density, control of yarn orientation in each layer, and the integration of the yarn/fabric layers by stitching. The major disadvantage is the impaling and localized dislocation of yarn during stitching which leads to reduced strength and to poor structural consistency.(7)

Several companies are presently involved in multiaxial stitch-through technology including Hexcel in Seguin, Texas; Bean Fiberglass Company in Jaffrey, New Hampshire; Brunswick Technologies in Brunswick, Maine; Bay Mills in Ontario, Canada; Chomarat in France; and others in Europe; each of whom has devised their own unique multiaxial orientation system. Commercial stitch-through machines without bias orientation capability are available from LIBA, Karl Mayer and Textima. Also, LIBA is presently marketing a machine called Copcentra-Multiaxial which coordinates multiaxial orientation with stitching through on a weft insertion warp knit type of machine. Multiaxial stitch-through fabrics are available in several plies of yarn systems oriented in the warp, weft and bias directions. Light nonwoven webs can be added, as a ply, if desired, and fabric widths of four to eight feet are possible.

All of the laid-in yarns are linear, are in a specific plane, and are continuous between fabric edges. Obviously, multiaxial stitch-through fabrics can be engineered for specific directional properties. Currently, most fabrics are composed of high modulus laid-in tow/yarn systems with a fine polyester stitching yarn system. Fabric constructions of the various ply orientations can be made up to approximately 1/4-inch thickness. Multiaxial stitch-through fabric weights vary according to construction but are often in the range between 12 and 48 ounces per square yard.

Multiaxial warp knit fabric technology has been developed recently by the Karl Mayer Textile Machine Company in West Germany. The process is officially known as multiaxial magazine weft insertion and informally referred to as the bias machine. As an alternate to multiaxial stitch-through technology, the Mayer bias machine precisely knits rather than punches the stitching yarn through the various layers of laid-in yarns. Consequently, no yarns are impaled and the texture is quite uniform throughout the fabric, leading to higher translation efficiencies. The major design limitation of the Mayer bias machine is a maximum of four yarn layers (0°, 90°, $+45^{\circ}$, -45°) plus a fiber web, if desired. Also, fabrics made from the Mayer bias machine tend to be somewhat more voluminous than comparable stitch-through multiaxial fabrics, which provides for easier resin penetration but slightly lower fiber volume fractions, potentially.(6) Milliken is the only company in the U.S. with a Mayer bias machine.(8) Nine other Mayer bias machines are in operation in Europe.

MULTIAXIAL FABRIC BEHAVIOR

The behavior of various fabric constructions under uniaxial stress in the machine (0°), crosswise (90°) and bias ($\pm 45^{\circ}$) directions are illustrated in Figures 1, 2, and 3, respectively. In-plane shear resistance is parallel to the direction indicated in each figure. With the variety of fabric constructional forms available, it is possible to have textile composite preforms behave according to any position desired on the performance maps illustrated in Figures 1 through 3, in general.(9)

When made from high modulus or fully drawn yarns, most multiaxial fabric constructions tend to have excellent dimensional stability and outstanding in-plane shear resistance in all directions (machine, crosswise, and bias) compared with regular woven, knitted, and braided constructions. Normally, dimensional stability and conformability are mutually exclusive. However, when made from partially oriented yarns (POY), multiaxial fabric constructions can be designed for directional conformability during 3-D draw-molding, 3-D draw-stamping or 3-D draw-wrapping with excellent omni-directional dimensional stability and shear resistance in the final 3-D configuration.

In many composite applications, isotropy (for performance) and porosity (for ease of resin impregnation) are quite important in composition preforms. A performance map plotting in-plane isotropy versus porosity for a variety of fabric constructional forms is illustrated in Figure 4. It can be readily seen that warp knitting technology (regular, weft insertion, stitched-through and multiaxial) offers the greatest range of design possibilities.

EXPLORATIONS IN STITCHING TECHNOLOGY

A number of multiaxial stitch-through samples have been made from a variety of high modulus yarns in recent years by hand orienting and stitching to simulate machine-made constructions. Typically, $0^{o}/-45^{o}/+45^{o}/90^{o}$ orientations have been made in 4, 8, 12, and 16 layers on tension frames of various dimensions and chain stitched at 2 or 3 wales per inch simulating a machine stitch-through operation. Yarn impaling/filament damage during hand stitching remains a problem especially with high density multiaxial orientations.

Most of the hand-made multiaxial stitch-through samples have been made with chain stitching in the 0^{o} (simulated machine) direction as straight and as uniformly as possible. Such an approach is appropriate for making large, thick, dense multiaxial preforms for planar applications requiring substantial, through-the-thickness strength and in-plane shear resistance. Currently, irregular stitching patterns with various stitching materials in various paths and angles are being explored in order to improve the conformability of large, thick, dense multiaxial stitch-through samples in adapting to non-planar applications.

In the analysis of 3-D textile composites, Norris Dow showed clearly that improvements in a given property are usually accomplished at the sacrifice of some other properties(10). He concluded that there is no magic configuration. Just as trade-offs are required to minimize the penalties for enhanced through-the-thickness properties, trade-offs are also required to minimize the penalties for enhanced conformability. Net shape textile preforms have received a great deal of attention in recent years, and rightly so. Perhaps advanced stitching technology will make as great an impact on net shape textile preforms in the near future as it has on planar multiaxial preforms in the recent past.

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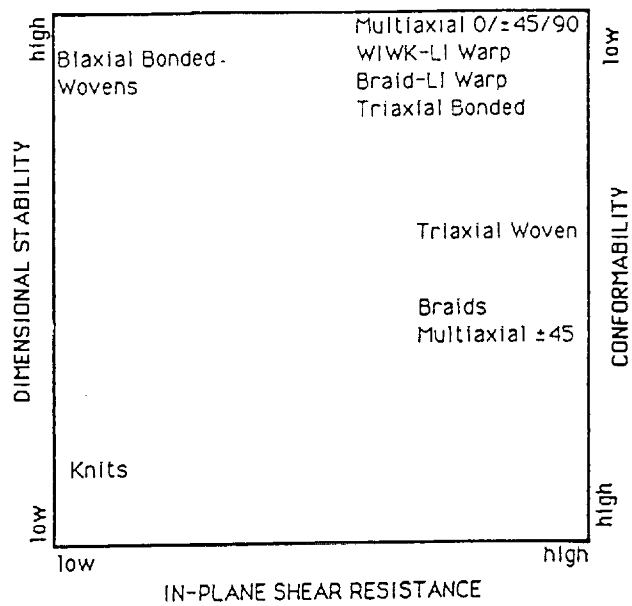

Figure 1. Behavior of Various Fabric Structural Forms Under Uniaxial Stress in the Machine (0°) Direction

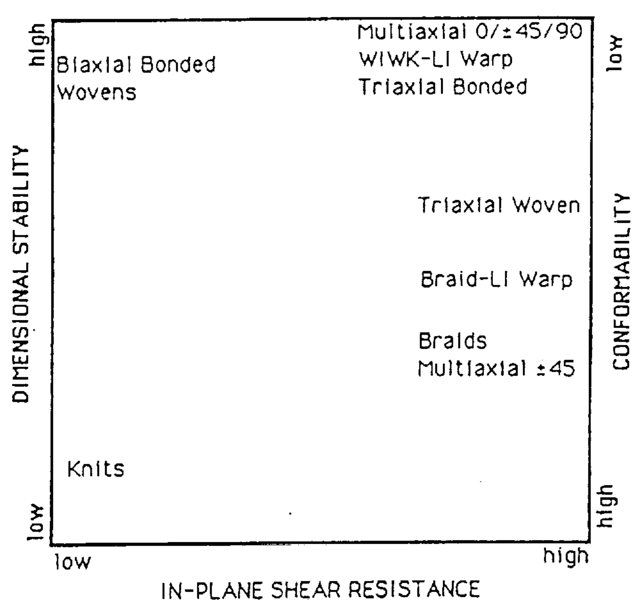

Figure 2. Behavior of Various Fabric Structural Forms Under Uniaxial Stress in the Crosswise (90°) Direction

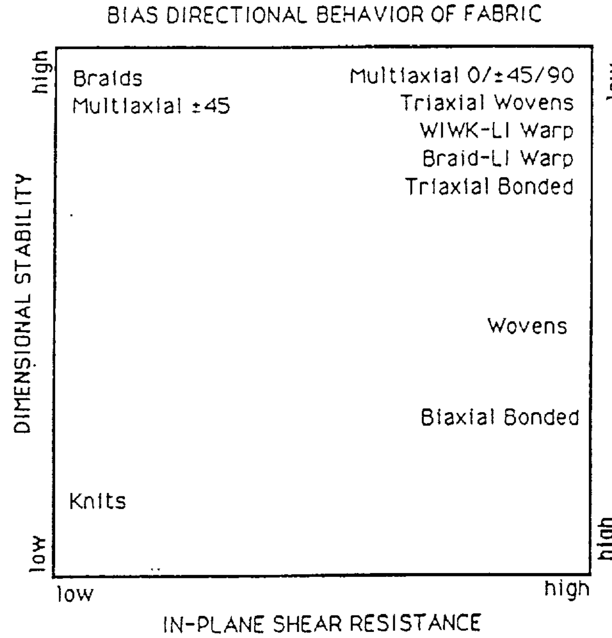

Figure 3. Behavior of Various Fabric Structural Forms Under Uniaxial Stress in the Bias (45° or -45°) Direction

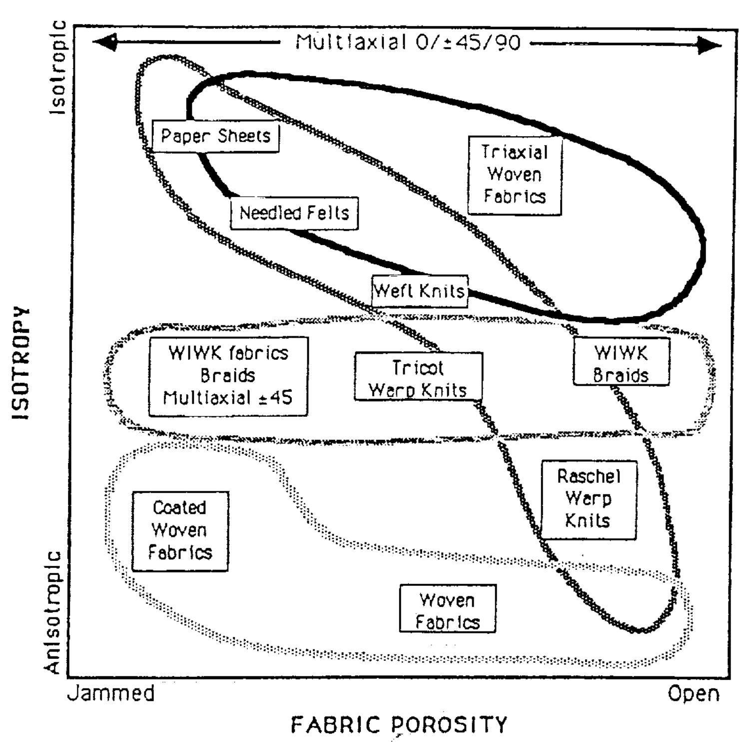

Figure 4. In-Plane Isotropy Versus Porosity for a Variety of Fabric Constructional Forms