

3TEX PREFORMS - THE METAL ALTERNATIVE

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Summary

Topics of this paper are recent progress in 3-D orthogonal weaving, composites made with 3-D woven preforms, their mechanical properties and applications. The patented fabric combines no-crimp in-plane fiber reinforcement with integral through-thickness fiber reinforcement. The latter one enables to suppress delamination and substantially improve interlaminar strength and damage tolerance. 3-D orthogonal woven preforms are especially suited to composites processing using RTM technique. Also, such composites are characteristic with fairly predictable basic mechanical properties, allowing to apply conventional modeling and predictive analysis tools.

1. Introduction

There have been many publications on "3-D Weaving", and there are numerous patents on a variety of devices that may be used to make a "3-D Woven" structure. Complex, multilayer woven structures are known as a potential advantage in composite fabrication and performance for over thirty years, offering new preforming approaches and various types of through-thickness fiber reinforcement. Despite this potential, 3-D weaves have remained more or less a novelty, sporadically investigated and with few commercial applications. A long-standing limitation to greater 3-D woven fabric applications has been the lack of an efficient weaving process, capable of readily producing fabrics with acceptable cost, consistent quality and low weaving-induced fiber damage. The majority of the 3-D woven products that are currently commercially available, are formed by a 2-D weaving process that is used to build up a preform with fibers oriented in three dimensions. Recent advances (refs. 1-4), have led to a revolutionary, multiple insertion 3-D weaving technology, which is currently implemented on nine automated 3-D weaving machines that were designed and built by 3TEX, Inc., producing fabrics up to 180 cm wide and 6 cm thick.

Resulting fabrics are used both as stand-alone products (mainly in soft personnel armor applications) and preforms for 3-D composites with numerous applications in hard armor systems, transportation, marine, aerospace, infrastructure and recreation products. When processed into a composite form, 3-D woven preforms provide

significant improvement in the reinforcement quality and consistency, in resin transfer molding (RTM) ability, in many critical mechanical characteristics, and also substantially reduce labor cost over traditional methods of manufacturing laminated composites. 3-D woven composites offer a combination of essentially uncrimped in-plane fiber reinforcement and integral through-thickness fiber reinforcement, giving an impressive combination of in-plane and out-of-plane properties. Further, the regularity and predictability of the fiber architecture facilitates convenient and accurate design using available modeling and analysis tools. We will start here with describing the 3-D Weaving process and the resulting fabric structure, then will demonstrate how it can lead to unusual preforming options and improvements in composites processing. Further, E glass composites will be used to illustrate attractive in-plane mechanical properties of single-ply 3-D weave composites over 2-D textile laminates. Also, 3-D woven composites provide greatly improved multiple hit and repeated impact performance as illustrated in ref.5 and 6.

2. The 3-D Weaving Process, Its Advantages and Products

Weaving is defined as the formation of fabric by the "interlacing" of two sets of yarns, the warp and the weft (or filling). Conventional 2-D weaving inserts fill yarns singly. Yarns in the warp direction are passed through heddles, and must be pulled past neighboring warp yarns, above or below the fill insertion to form the fabric. This is a relatively high-speed process, and the loom speed is measured by the number of filling insertion actions per minute (or "picks per minute", ppm). There are relatively few composite preform weavers that service the composites industry with 3-D woven products. However, to our knowledge, all of those companies use single filling insertion. Those 3-D fabrics are thus built up one insertion (or one "yarn layer") at a time. Obviously, such process is economically inefficient. Contrary to the aforementioned, the patented 3-D Weaving process (ref. 1) enables to simultaneously interweave N multiple planes of warp yarns with $N+1$ planes of filling yarns (current 3-D Weaving machines weave up to $N=14$ layers of warp). A third set of yarns, called *Z-yarns*, then interlaces the fabric. This is illustrated in Fig. 1. Schematic of fiber architecture in 3-D orthogonal woven fabric is shown in Fig. 2. Fibers are oriented along the three Cartesian orthogonal coordinates, with the *Z-yarns* taking a path essentially perpendicular to the fabric mid-plane inside the fabric, and parallel to the warp direction

on the fabric surfaces. This unique combination of straight in-plane fiber reinforcement and integral through-thickness reinforcement gives the woven structures unique advantages in both composite fabrication and composite performance, as discussed below.

The simultaneous insertion of an entire column of filling yarns makes the linear productivity of the 3-D Weaving process independent of N . Thus, if all other process parameters are fixed, different product volumes can be made during some fixed machine operation time, depending on N value. As larger N (e.g., thicker the preform) as more fabric can be produced on a given 3-D weaving machine during the same time. In other words, in this process the production time is proportional to the fabric area, while in the aforementioned 2-D and single insertion 3-D processes the required production time is always proportional to the product volume. Additional considerations on this issue can be found in (ref. 4).

Another important distinction is that in 2-D weaving process, yarns in the warp direction are passed through heddles, and must be pulled past neighbouring warp yarns, above or below the filling insertion. Repeated motions through the heddles and through other planes of warp tend to abrade fibers, especially brittle technical fibers. In the 3-D Weaving process individual warp planes do not pass through heddles, and are not forced to repeatedly cross neighbouring warp planes; accordingly, weaving-induced fiber damage in this case is significantly reduced.

3-D Weaving is essentially the automated method of producing net-shape preforms; besides an obvious flat sheets of fabric, also various cross-sectional shapes, including "I", "T", " ", box, core, pile, etc., can be produced. Fig. 3 shows some examples of application-driven 3-D preform structures woven by 3TEX. It is also should be mentioned that various hybrid fabrics can be manufactured: different fiber types can be used in the warp, fill and z directions. Various fiber types: S-2 and E-glass, carbon, Kevlar®, Spectra®, metal wires, optical fibers, etc. have been recently used by 3TEX to weave 3-D orthogonal fabrics.

3. Processing 3-D Woven Composites

3-D woven structures made by the 3-D Weaving process provide several important advantages in composite fabrication, some of them even unexpected. The most obvious advantage of 3-D woven fabrics in fabrication is the reduced labor of preforming thick sections, as one or a handful of 3-D woven plies often replace tens or even hundreds of 2-D textile plies. This reduces cutting pattern complexity and reduces or eliminates the need for

intermediate stitching or tackifiers to stabilize the preform. The second advantage is the ability to integrally unite fibers of differing types, which might not adhere readily to the same resin in a composite, such as polyethylene and carbon or glass. A third advantage to composite preforming with 3-D weaves is the ability to weave opening or closing shapes directly into the fabric, leaving pockets or flaps in the warp and fill, which can be used to form blades, joints, or connections in the composite.

Naturally, it is anticipated that the processing advantages of thick 3-D weaves come at the expense of reduced shapability. However, our experimental work revealed that shapability of fabrics made by 3-D Weaving is much higher than initially expected. The absence of interlacing between warp and fill yarns allows these fabrics to bend and shear easily, without buckling within the in-plane reinforcement. Fig. 4 shows some of the large deformations possible when a rather thick and heavy (3.22 kg/m^2) E-glass fabric is molded without wrinkling into a small hemisphere.

Another unanticipated advantage of the 3Weave™ structure is its high permeability. The structural regularity of manufactured 3-D orthogonal woven fabrics, which is strictly defined by the Z-yarn placement, results in the amazing effect, repeatedly demonstrated by the experiments conducted at different organizations. 3-D orthogonal woven fabrics show substantially higher permeability than equal areal weight multi-layer stacks of thin 2-D fabrics, particularly 2-D weaves and reinforced knits. This effect is illustrated in ref. 5. This improvement in permeability over stacks of 2-D fabrics has been observed, repeatedly, across a variety of fabric designs, and tends to become even more pronounced in thick preforms. It is hypothesized that the Z-yarns act as capillary channels to transfer resin into the preform interior. In specific applications the improvement of permeability could reduce cost in VARTM tooling (by allowing longer distances between inlet and exhaust), and/or reduce production cost by greatly reducing part rejection rate caused by imperfect/incomplete resin transfer.

4. In-Plane Mechanical Properties of 3-D Woven Composites

Taking advantage of the in-plane crimp absence in 3-D weave composites may be defeated, at various extent, by decrease in in-plane fiber content caused by the introduction of through-thickness fiber. Static strengths of 3-D weave composites having around 2% of Z-fiber content, are generally better than those from competing 2-D weaves. Fig. 5 compares the strengths of 3WEAVE™ E glass with 0/90 reinforced knits and plain woven rovings in vinyl ester resins, prepared by vacuum

infusion. Fiber volume fractions of all composites were 49-52%. The 3-D woven structure appears about 50% stronger in short beam shear, as would be expected by its through- thickness reinforcement. The 3WEAVE™ composites also appear stronger in in-plane loading, including flexure, tension and compression. Such higher strengths may be due to the reduction of in-plane crimp afforded by the 3-D orthogonal woven structure.

5. Machinable Composites

The basic concept of 3CARBONBILLET™ and 3GLASSBILLET™ is to provide a relatively low-cost and thick composite with excellent mechanical properties that can be easily machined into components. Such a material in an off-the-shelf and ready-to-use plates form would be utilized in the same fashion as standard aluminum and steel bar and plate stock. There are many places (e.g. machine designers and bicycle manufacturers) with design engineers who would like to use composites, but don't have the experience nor resources to prototype and evaluate them. Design of simple components is often done by intuitive estimation and experienced judgment. In these cases rough calculations may be made, but geometrical and processing constraints, material size availability, etc. drive thickness and profiles. A short iteration between intuitive design and prototype testing can facilitate rapid product development. Extensive finite element analysis is often performed by large companies and engineers experienced with composites design, but there are many small businesses and/or divisions of large companies with design engineers who are not used to complex analysis on anisotropic materials. They are used to the quick turn around of using modern CAD/CAM to design a machined part, and then emailing the design to a CNC/machine center, and having the prototype part appear on their desktop, thus enabling a quick design-build-test cycle. By understanding how machining is done, and selecting appropriate sizes of plate and bar stock, material and machining time can be saved. In fact, with modern high speed CNC equipment, machined components are often used by OEM's on original production parts. For applications with a short product cycle (e.g. high performance sports equipment), machined components gives the greatest flexibility and speed to market. For such components, the cost of the material may be small compared to the cost of machining. Using machinable composites commercially available in standard forms avoids the hassles associated with the storage of resins and chemicals and expensive fabrication equipment such as presses, autoclaves, RTM pumps and tooling. Lead times may be reduced to hours when material is on hand.

Fabrication with these materials is very similar to practices used for aluminum. However, 3CARBONBILLET™ composites are more than 45% lighter than aluminum. Figure 6 shows real examples of the thick 3CARBONBILLET™, a machined bicycle crank arm (composite and aluminum) and rocker arm for an IC engine.

In general, standard plates and bars of 3CARBONBILLET™ and 3GLASSILLET™ materials will find use in application that demand light weight, high corrosion resistance, high fatigue life and excellent damping characteristics. There is also real value to the intangible market appeal of carbon fiber materials. There are products today which mimic the appearance of carbon fabric composites. The markets for thick 3-D woven composites include manufacturers of after-market-parts as well as OEM's in areas including Performance Auto/Cycle, Performance Marine, Sports and Recreation Equipment, Industrial Machine Manufacturing, and custom CNC fabricators. Such manufacturers regularly make their parts by CNC machining, are interested in using composites, but may not be equipped for nor have the time for composite fabrication (e.g. chemical storage, molding, infusing, curing and post-curing, etc.)

6. Concluding Remarks

The 3-D Weaving process enables cost-effective, characterized by industrial speed and volume capabilities, manufacturing of thick composite preforms, with minimal fiber damage during the manufacturing cycle. The resulting preforms offer many economic advantages in consolidation, foremost a reduction in resin infiltration times. Compared to 2-D textile laminates, 3-D weave composites can be designed to have comparable or even superior in-plane mechanical characteristics, while vastly improving through-thickness properties. Important manufacturing advantages of 3-D woven preforms and composites, combined with their unique through-thickness strength, crack resistance and damage tolerance, also promise numerous applications in the aerospace, marine, transportation, infrastructure and recreation products. Preforms made by the 3-DWeaving process are consistent in quality and predictable, allowing confidence in the respective composite design.

The concept of using a composite material as a standard engineering material can be made possible by combining relatively low cost with high performance and then making it commercially available in a finite set of standard bars or plates. This concept is being brought to reality with 3CARBONBILLET™ and 3GLASSILLET™ 3-D woven composite materials.

REFERENCES

1. M. Mohamed and Z. Zhang, US Patent 5085252, February 4, (1992), to North Carolina State University.
2. M. H. Mohamed, in Textiles Used in Structural Composites, Proc. Symposium sponsored by SAMPE and the Industrial Fabrics Association, March, 1996.
3. L. Dickinson, M. Mohamed and A. Bogdanovich, in Proc. 44th Int. SAMPE Symposium, May, 1999, p. 303.
4. L. C. Dickinson and M. H. Mohamed, in Proc. IMECE, Orlando, Florida, November, 2000.
5. M.H. Mohamed, A.E. Bogdanovich, L.C. Dickinson, J.N. Singletary, and R.B. Lienhart, in SAMPE Journal, 2001, Vol. 37, No.3, pp. 8-17.
6. Personal communication from Crystal Newton, Center for Composite Materials, Univ, of Delaware, Feb.2001.

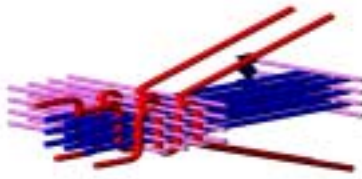


Figure 1. Illustration of the 3Weaving™ multiple insertion process.

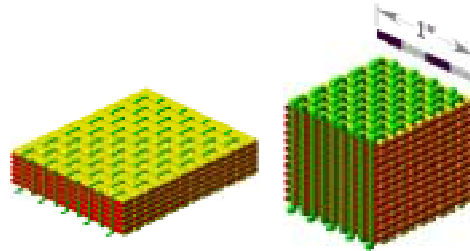


Figure 2 Schematics of thin and thick 3WEAVE™ 3D orthogonal woven preforms with small (~2% volume) and large (~15% volume) amounts of Z direction fiber.



Figure 3 Examples of net-shape and thick one-piece 3WEAVE™ preforms from carbon, aramid and E-glass fibers.



Figure 4. Demonstration of shapability possible with thick 3-D woven fabrics. Left: single fabric ply shaped into a hemispherical mold without wrinkling. Right: close-up of area of highest shear.