

Three-Dimensionally Reinforced Preforms and Composites

14.1 Introduction

Conventional fiber-reinforced polymer (FRP) laminates have a layered two-dimensional construction. The lack of reinforcement in the through-thickness or z-direction results in the laminates having low interlaminar strength and fracture resistance.

Laminated two-dimensional composites are not suitable for applications where through-thickness stresses may exceed the (low) tensile strength of the matrix (or matrix/fiber bond) and in addition, to provide sufficient residual strength after anticipated impact events, two-dimensional laminates must be made thicker than required for meeting strength requirements. The resulting penalties of increased cost and structural weight provide impetus for the development of more damage-resistant and tolerant composite materials and structures.

Considerable improvements in damage resistance can be achieved by using tougher thermoset or thermoplastic matrices together with optimized fiber/matrix bond strength. However, this approach can involve significant costs, and the improvements that can be obtained are limited. There are also limits to the acceptable fiber/matrix bond strength because high bond strength can lead to increased notch-sensitivity.

An alternative and potentially more effective means of increasing damage resistance and through-thickness strength is to develop a fiber architecture in which a proportion of fibers in the composite are oriented in the z-direction. This fiber architecture can be obtained, for example, by three-dimensional weaving or three-dimensional braiding. A much simpler approach is to apply z-direction reinforcement to a conventional two-dimensional fiber configuration by stitching; however, this does not provide all of the benefits of a full three-dimensional architecture.

In all of these approaches, a three-dimensional preform is first produced and is converted into a composite by one of the liquid resin molding techniques described in Chapter 5.

Even without the benefits of three-dimensional reinforcement, the preform approach has the important advantage that it is a comparatively low-cost method of manufacturing composite components compared with conventional laminating

procedures based on pre-preg. Indeed, preforms for resin-transfer molding (RTM) and other liquid molding techniques are often produced from a two-dimensional fiber configuration by stitching or knitting.

A summary of the main aspects of these and other approaches to three-dimensional reinforcement and preform manufacture is given in Table 14.1. Most of these are discussed in this chapter, which also includes a discussion on the relatively new topic of z-pinning.

14.2 Stitching

Stitching is best applied using an industrial-grade sewing machine where two separate yarns are used. For stitching composites, the yarns are generally aramid

Table 14.1 Description of Three-Dimensional Textile Manufacturing Techniques

Textile Process	Preform Style	Fiber Orientation	Productivity/Setup
Stitching	Complex preforms possible by combining several structures	Dependent on basic preforms	High productivity; short set-up time
Embroidery	Additional fibers incorporated onto basic fabric	Complex fiber orientations possible (e.g., maximum stress direction)	Moderate productivity; short set-up time
Three-Dimensional Weaving	Flat fabrics, integral stiffeners, integral sandwich structure and simple profiles	Wide range of through-thickness architectures possible but in-plane fibers generally limited to 0°/90° directions (except with advanced looms)	High productivity, long set-up time
Three-Dimensional Braiding	Open and closed profiles (I, L, Z, O, U, etc.) and flat fabrics	0° fibers; braiding fibers between 0–80° and 90° fibers possible	Medium productivity; long set-up time
Knitting	Flat fabrics and very complex preforms	Highly looped fibers in mesh-like structure	Medium productivity; short set-up time
Non-crimp	Flat fabrics and integral sandwich structures	Multi-axial in-plane orientation 0°/90°/ ± 45°, up to 8 layers possible	High productivity; long set-up time

(Kevlar), although other yarns such as glass, carbon, and nylon have also been used. A needle is used to perforate a pre-preg stack or fabric preform, enabling the insertion of a high-tensile-strength yarn in the thickness direction, as shown in Figure 14.1. The yarn, normally referred to as the needle yarn, is inserted from the top of the stack/preform, which is held in place using a presser foot. When the yarn reaches the bottom of the stack/preform it is caught by another yarn, called the bobbin yarn, before it re-enters the stack/preform as the needle is withdrawn from the stack/preform, thus forming a full stitch. The stack/preform is then advanced a certain distance between the presser foot and a roller mechanism before the needle is used to effect the next stitch. This process is repeated to form a row of stitches. Figure 14.2 shows the various types of stitches commonly used to effect z-direction reinforcement. Among the three stitches, the modified lock stitch, in which the crossover knot between the bobbin and needle threads is positioned at either laminate surface to minimize in-plane fiber distortion, is most preferred.

Apart from improving z-direction properties, stitching serves as an effective means of assembling preforms of dry two-dimensional tape or cloth, for example, attaching stiffeners to skin preforms, that are then consolidated using processes such as liquid molding.

14.2.1 Mechanical Properties

14.2.1.1 Out-of-Plane Properties. The most significant improvement resulting from stitching is the increase in the interlaminar delamination resistance of FRP laminates under mode I and, to a lesser degree, mode II loadings. To achieve this, the stitches need to remain intact for a short distance behind the crack front and restrict any effort to extend the delamination crack. As expected (with the enhanced fracture toughness), stitched FRP composites have a better resistance to delamination cracking under low energy, high energy, and ballistic impacts as well as under dynamic loading by explosive blasts. They also possess higher post-impact residual mechanical properties than do their unstitched counterparts,¹ as illustrated in Figure 14.3. It has been shown that the

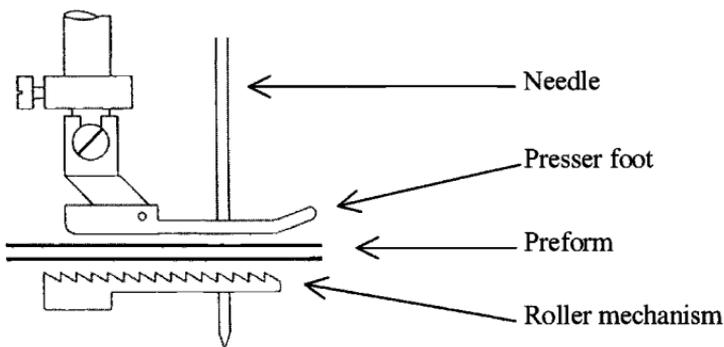


Fig. 14.1 Schematic diagram of the stitching configuration.

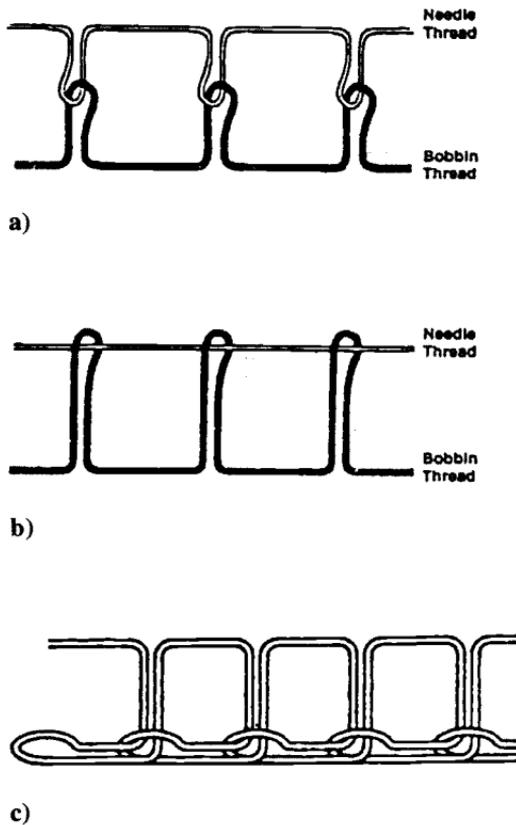


Fig. 14.2 Schematic diagrams of three commonly used stitches for z-reinforcement of two-dimensional composites: *a*) lock stitch; *b*) modified lock stitch; *c*) chain stitch.

effectiveness of stitching for improving residual strength is dependent on factors such as the stitch density, stitch type, and stitch thread. However, only in relatively thick laminates are significant improvements in compression-after-impact strength evident. Although it is noted that a toughened matrix could also provide similar improvement in residual strength² (Fig. 14.4), it is two or three times more expensive than stitching.

There have been, however, conflicting results that report that stitching does little (if anything) to improve either impact damage resistance or tolerance. In the cases considered, this is normally attributed to two factors: 1) the stitching yarns were insufficiently strong (both in terms of breaking strength and providing traction) to afford the necessary resistance to delamination growth; and 2) the bridging zone (of between 20–30 mm) needed for stitches to be effective, was not fully realized.

Undisputed, however, is the advantage of stitching for improved shear lap joint strength under both static and cyclic loading, largely due to reduced peel stresses. Stitches can delay the initiation of disbands and provide load transfer even after failure of the bond line. Therefore, stiffeners stitched onto a panel are

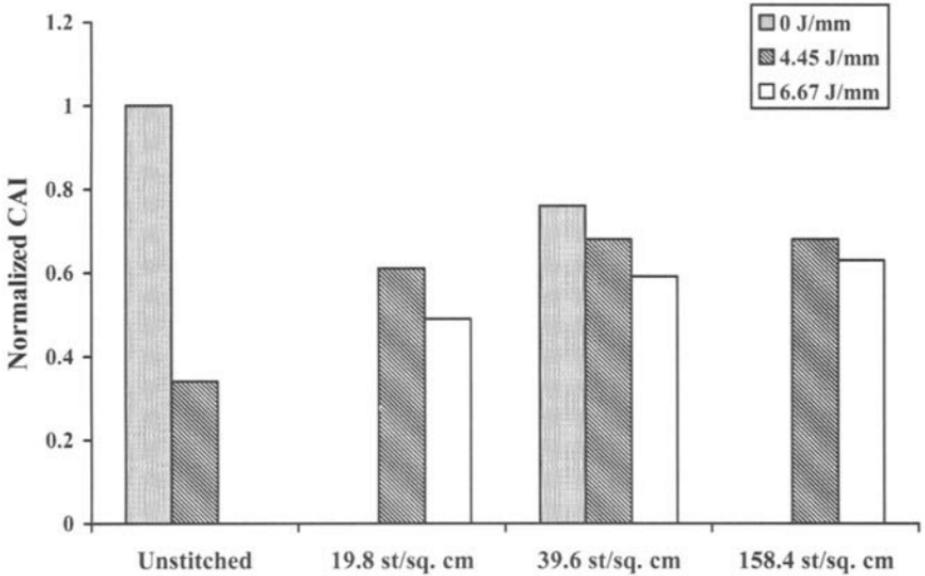


Fig. 14.3 Compression after impact (CAI) strength for stitched and unstitched laminates normalized with respect to undamaged compression strength.

more resistant to disbonding; improvements in load-carrying capability of approximately 15% have been observed. There is also evidence that stitching is effective in suppressing delamination due to free-edge effects.

14.2.1.2 In-Plane Properties. While attempting to improve the out-of-plane properties, the introduction of stitches into a two-dimensional composite laminate can also affect the in-plane performance of the stitched composite. This is due to induced defects in the final laminate introduced during needle insertion or as a result of the presence of the stitch yarn in the laminate. These defects may occur in various forms including broken fibers, resin-rich regions, and fine-scale resin cracking. Fiber misalignment, however, appears to have the greatest detrimental effect on mechanical properties, particularly under tensile and compressive loading.

To keep defects in stitched laminates to a minimum, careful selection and control of the stitching parameters (including yarn diameter, tension, material, stitch density, etc.) are necessary. Analysis of the effects of stitching on the basic mechanical properties of two-dimensional composite laminates in general have yielded contradictory results.³ These show that stiffness and strength of the composites under tensile as well as compressive loadings can be degraded, unchanged, or improved with stitching, depending on the type of composite, the stitching parameter, and the loading condition. The improvements in tensile and compressive stiffness are believed to be due to an increase in fiber/volume fraction that results from a compaction of in-plane fibers by the stitching. Any enhancement in compressive strength is attributed to the suppression of

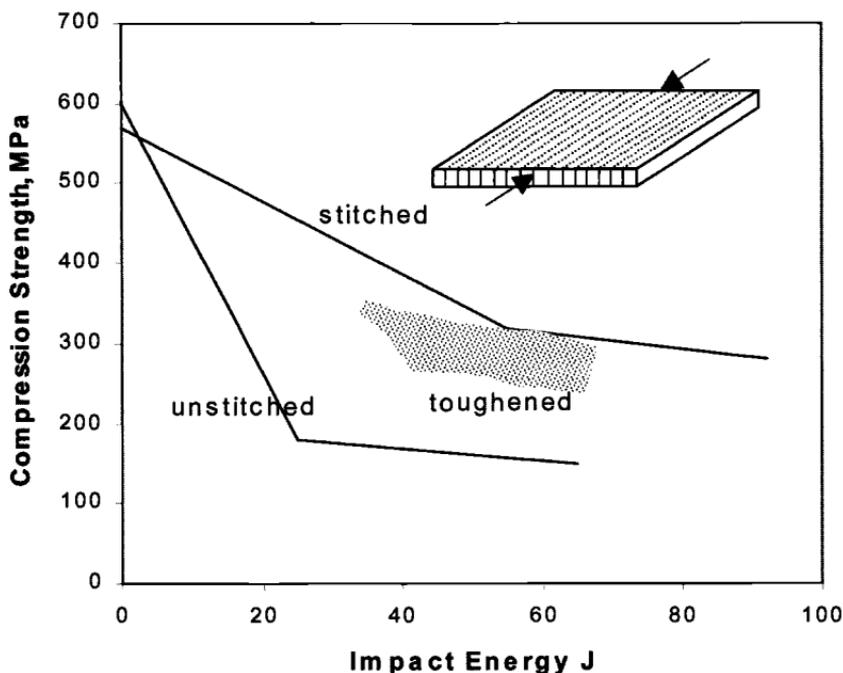


Fig. 14.4 NASA results for compression after impact for 48-ply quasi isotropic AS4/3506 laminates, either stitched or unstitched, and an unstitched laminate of similar configuration with a highly toughened matrix. Stitch pitch and spacing around 3 mm. Based on data provided in Ref. 2.

delaminations. The stiffness in tension and compression is mainly degraded when in-plane fibers are misaligned by the presence of the stitching yarn in their path.

Premature compressive failure can be triggered if stitches are too taut, which in turn can cause excessive crimping of the in-plane fibers. Conversely, insufficient tension of the stitching yarn can cause the stitches to buckle under consolidation pressures and render them ineffective as a reinforcement in the thickness direction, the purpose for which they were originally intended. Tensile strength, on the other hand, is normally degraded due to fiber fractures arising from damage by the stitching needle. Enhancement of tensile strength, which has been observed, is attributed to an increase in fiber/volume fraction resulting from compaction of in-plane fibers by the stitching.

It is also considered that the inferior fatigue performance observed for stitched composites under tension and compression loadings is due to the same failure mechanisms that are responsible for deterioration in their corresponding static properties.

Finally, it appears that the flexural and interlaminar shear strengths of two-dimensional laminates may also be degraded, unchanged, or even improved with stitching. In general, the conflicting effects of stitching, in increasing fiber content and suppressing delamination, on the one hand, and introducing

misalignment and damage to in-plane fibers, on the other, are possibly responsible for the reported behaviors.

14.2.2 Applications of Stitching: The Stitched Wing

To date, by far the most ambitious development of stitched composite structures is a NASA sponsored demonstrator program to develop a cost-effective damage-tolerant composite wing. A 28-m-long sewing machine,⁴ shown in Figure 14.5 was developed by Boeing to manufacture preforms with enhanced impact tolerance for the production of composite aircraft wing covers. The machine is able to stitch layers of carbon fabric of over 25 mm in thickness at a rate of over 3000 stitches a minute. In addition to stitching the skin preform, the blade stiffener flanges are also stitched to the skin. The stiffeners are formed by stacking tubular braided fabrics and partially stitching them together, leaving an unstitched region that is folded out to form the flanges before they are stitched to the skin.

After stitching, the flexible wing preform is placed on an outer mold-line tool pre-covered by film of partially cured resin; thereafter, the assembly is bagged and placed in an autoclave. Under heat and pressure, the resin melts and flows through the skin and stiffeners before curing. This process is known as resin film infusion (RFI) and is covered in Chapter 5. The resulting panel is claimed to be 25% lighter and 20% cheaper than an equivalent aluminum part.



Fig. 14.5 Boeing sewing machine for stitched wings.

14.2.3 Modified Stitching—Technical Embroidery

A version of stitching that can be used to provide localized in-plane reinforcement together with through-thickness reinforcement is technical embroidery. In this process, a reinforcement yarn is fed into the path of the stitching head and is thus stitched onto the surface of the preform (Fig. 14.6). With current computer-controlled embroidery heads, it is possible to place this in-plane yarn with high accuracy in quite complex paths, which allows high-stress regions of a component to be reinforced by fibers laid in the maximum stress direction. Improvements of 55% in specific bearing strength have been achieved through the use of this local reinforcement technique.⁵

14.3 Z-Pinning

Z-pinning is a simple method of applying three-dimensional reinforcement with several benefits over stitching. However, unlike stitching, z-pinning cannot

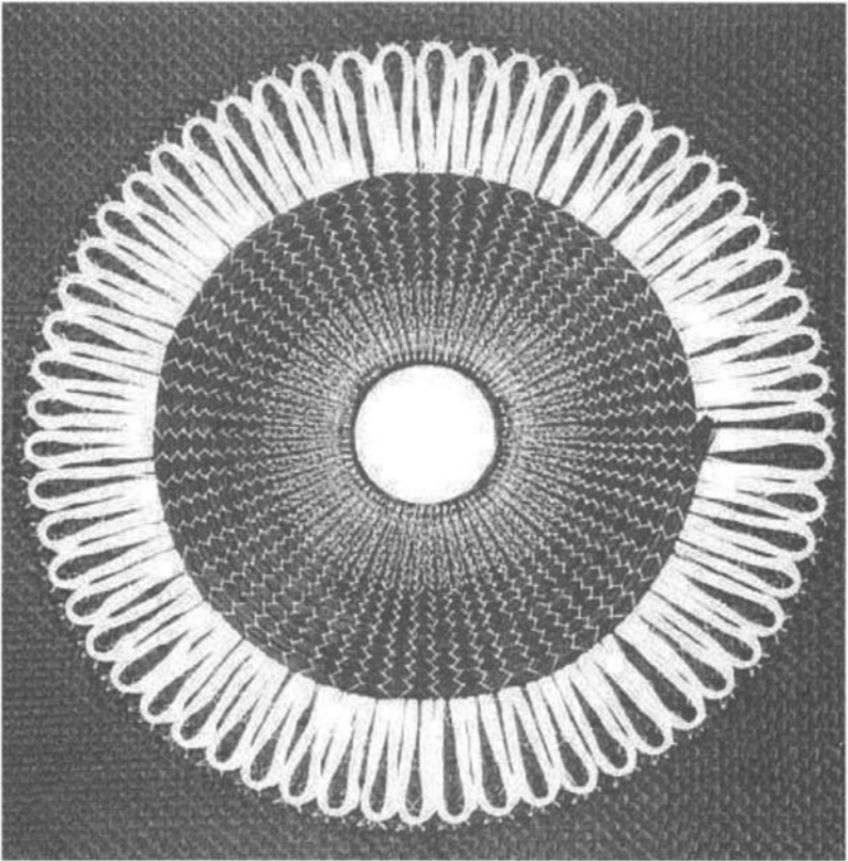


Fig. 14.6 Technical embroidery producing local, optimized reinforcement.

be used to make preforms. In the z-pinning process,^{6,7} thin rods are inserted at right angles into a two-dimensional carbon/epoxy composite stack either before or during consolidation. The z-rods can be metallic, usually titanium, or composite, usually carbon/epoxy. The composite rods are typically 0.25 mm and 0.5 mm in diameter, although slightly smaller or larger sizes are also available.

The rods are held with the required pattern and density in a collapsible foam block that provides lateral support.⁸ This technique prevents the rods from buckling during insertion and allows a large number of pins to be inserted in a single pressing operation. The rods are typically driven into the two-dimensional composite in one of two ways. The first technique (See Fig. 14.7) involves placing the rod-laden foam on top of an uncured pre-preg and autoclave curing. During the cure, the combination of heat and pressure compacts the collapsible foam layer, driving the rods orthogonally into the composite. When curing is completed, the residual foam preform is then removed and discarded, and rods sitting proud of the surface of the cured laminate are sheared away using a sharp knife.

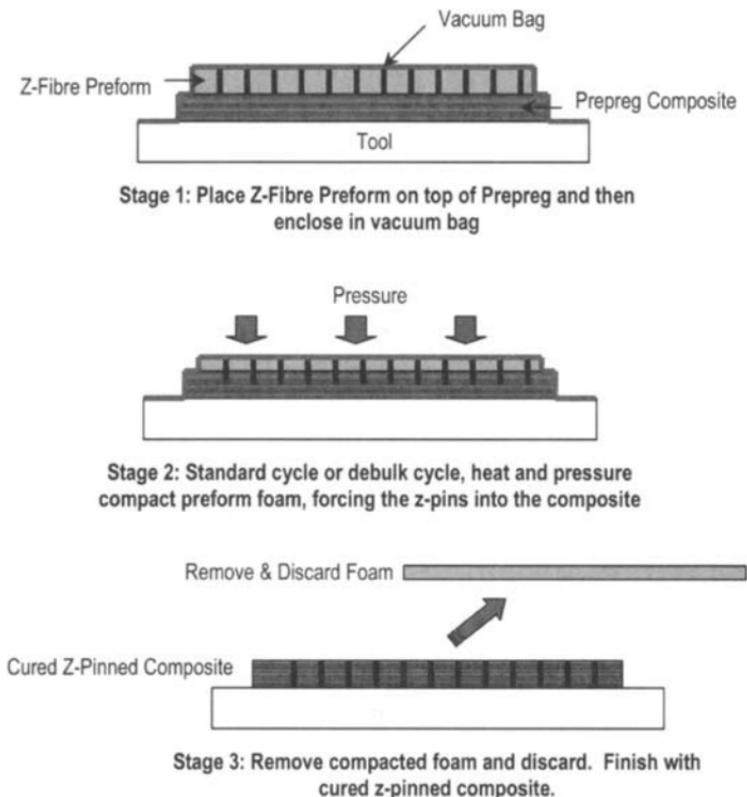


Fig. 14.7 Foam method of applying z-pins. Adapted from Ref. 6.

The second technique uses a purpose-built ultrasonic insertion gun to drive the rods into the two-dimensional composite. As shown schematically in Figure 14.8, this is a two-stage process whereby during the first stage the preform is only partially compacted using the ultrasonic horn, and hence the rods are not fully inserted. The residual foam is removed afterward and a second insertion stage is then carried out, also with the ultrasonic gun, to complete the insertion of the rods. If the rods are not flush with the part surface, the excess is sheared away. In principle, the part to be z-pinned could take on any shape provided there is an

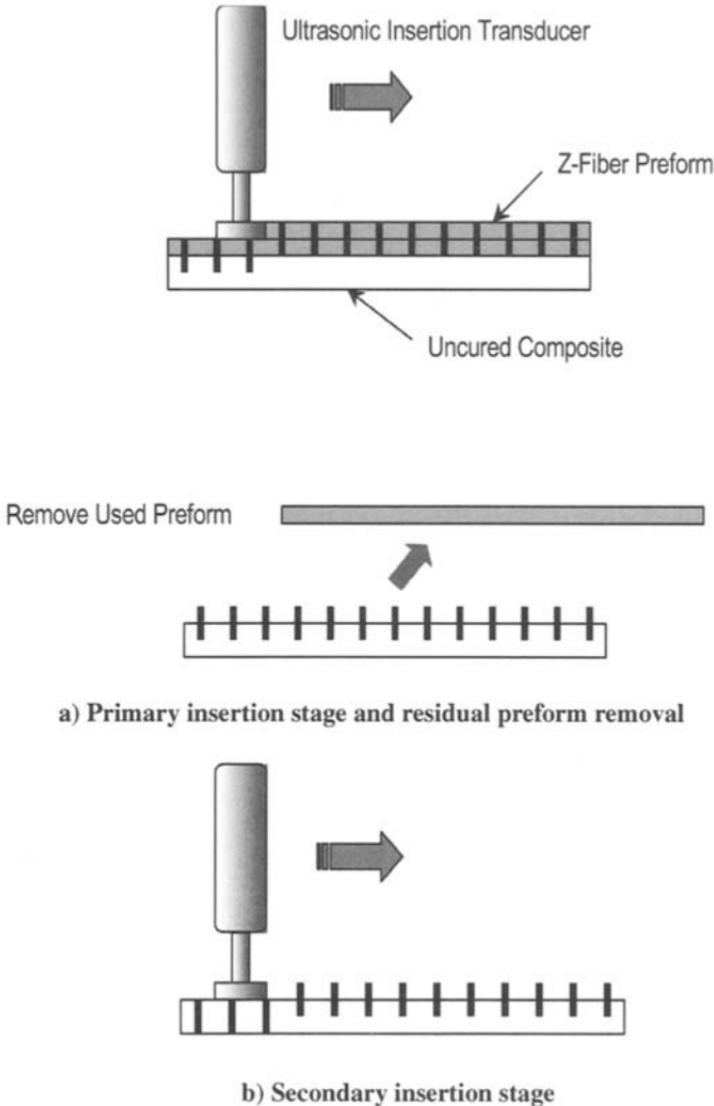


Fig. 14.8 Ultrasonic vibrator method of applying z-pins Adapted from Ref. 6.

appropriate ultrasonic horn. It is claimed that the ultrasonic insertion technique can be used to insert metallic pins into cured composites, a capability that could be used in the repair of delaminations in composites, although considerable damage to the parent material would result.

Between the two pin insertion methods, the vacuum bag route is perhaps more suitable when a large or relatively unobstructed area is to be z-pinned. On the other hand, localized z-pinning or difficult-to-access areas are more efficiently achieved using the ultrasonic process by configuring and shaping an appropriate ultrasonic horn.

14.3.1 Mechanical Properties

Relatively little work has been published on the mechanical properties of z-pinned composites. Based on available data,⁷ it can be deduced that significant improvements in both mode I and mode II fracture toughness are achievable through z-pinning, which in turn translate to superior damage resistance and tolerance,⁸ and improved skin-stiffener pull-out properties.⁹ There is evidence⁹ that these improvements in out-of-plane properties are achievable without much, if any, sacrifice to in-plane properties. Other work,¹⁰ however, shows that the pins can introduce excessive waviness to the in-plane fibers, causing compressive properties to be severely degraded. Clearly, in much the same way as in the case of stitching, the degree to which the in-plane properties are detrimentally affected, and the out-of-plane properties are improved, is dependent on the pinning parameters, such as density and configuration.⁹

14.3.2 Stitching Versus Z-Pinning

Research into the effects of z-direction reinforcement in traditional two-dimensional laminates on mechanical properties has been particularly extensive over the past decade or so. The impetus for this research is derived from the potential of stitching, and more recently, z-pinning to fulfil the need for a simple and cost-effective remedy for the poor out-of-plane properties of conventional two-dimensional FRP composites. The amount of z-direction reinforcement required to provide a substantial amount of out-of-plane improvement is small, typically no more than 5%.

The improvements in fracture toughness afforded by the two techniques mean that higher design allowables could be used in the designs of composite structures. In other words, stitched and z-pinned composites can be more readily considered as candidate materials for structures where impact damage (e.g., due to dropped tools), high peel stresses (e.g., in joints and at hard points), and cut-outs (e.g., edges and holes) are difficult to avoid. Stitching and z-pinning also provide the opportunity for parts integration to be incorporated into the production of composite components, thus improving the ease of handling, the potential for process automation, and the overall cost-effectiveness of the

manufacturing process. Further, when used in conjunction with a liquid molding technique, stitching can provide some pre-compaction of the preform and this can reduce mold clamping pressures required while ensuring a high fiber/volume fraction in the finished product.

A potential benefit of these reinforcement techniques is that post-catastrophic failure, they can hold fragments together—although stitches, compared with z-pinning rods, would be more effective in this respect. This benefit would be especially important in applications such as fan blades in aero engines, where fragments from a fractured blade, if unrestrained, could be swept into the engine and cause further damage. In fact, carbon/epoxy pins are already used in operational General Electric (GE90) fan blades to reinforce areas that require higher strength, and there are plans to increase the level of pinning in the growth version of these blades.¹¹ Z-pinning has also been used to produce high-performance sandwich structures. This is achieved by integrally connecting the skins through a foam core. It is claimed that, compared with traditional aluminum honeycomb sandwich structures, Z-pinned cores have three times the crush strength as well as superior damage tolerance. Although z-pinning is still inferior to mechanical fasteners in terms of pull-out failure load, it has good potential as an alternative shear attachment technique because its use would result in lighter-weight structures at a lower cost.

Stitching is inferior to z-pinning in three major ways. First, there are practical restrictions on the size and shape of the component that can be stitched, which usually can only be overcome with purpose-built stitching machines that demand large capital costs. Further, z-pinning is more appropriate than stitching for reinforcing regions with small radii of curvature. Second, the wrapping effect of the stitching yarn means that careful tension control has to be exercised so that in-plane fibers are not excessively crimped in the thickness direction. Each z-pin is independent of the others and hence does not pose this problem. Finally, to ensure minimal breakage, a limited number of fiber materials can be used as the stitching yarn. Alternatively, z-pins can be manufactured from a much wider range of materials, which can have large aspect ratios (l/d) to ensure good traction between the z-direction reinforcement and the base material.

14.4 Three-Dimensional Weaving

14.4.1 Process

Woven fabrics are made of warp (longitudinal) and weft (transverse) yarns interlaced in a regular order on mechanical looms. The process of weaving is already used extensively within the composite industry to produce the vast majority of the single-layer, broadcloth fabric that is currently used as a reinforcement. With minimal modification, the same standard industry mac-

hines can be used to manufacture flat, three-dimensional fabrics in a wide variety of yarn architectures.

Three-dimensional fabrics can be woven using almost any type of yarn, including carbon, glass, aramid, and ceramic fibers or combinations of these yarns. In addition, the proportions of the yarns in the x, y, and z directions can be controlled to tailor the properties of the composite for specific applications. Idealized examples of weave architectures that can be manufactured are illustrated in Fig. 14.9. In reality, the three-dimensional architectures that can be produced are significantly different from these idealized forms because tension in the binder yarns causes bunching up or crimping of in-plane yarns, as shown in Fig. 14.10 and Fig. 14.11. The path that the binder yarn follows as it traverses through the thickness of the woven preform plays an important part in controlling the final three-dimensional architecture and thus the resultant mechanical properties.

The main function of the z-direction yarns is to provide the composite with its improved impact performance. However, these yarns also bind the layers

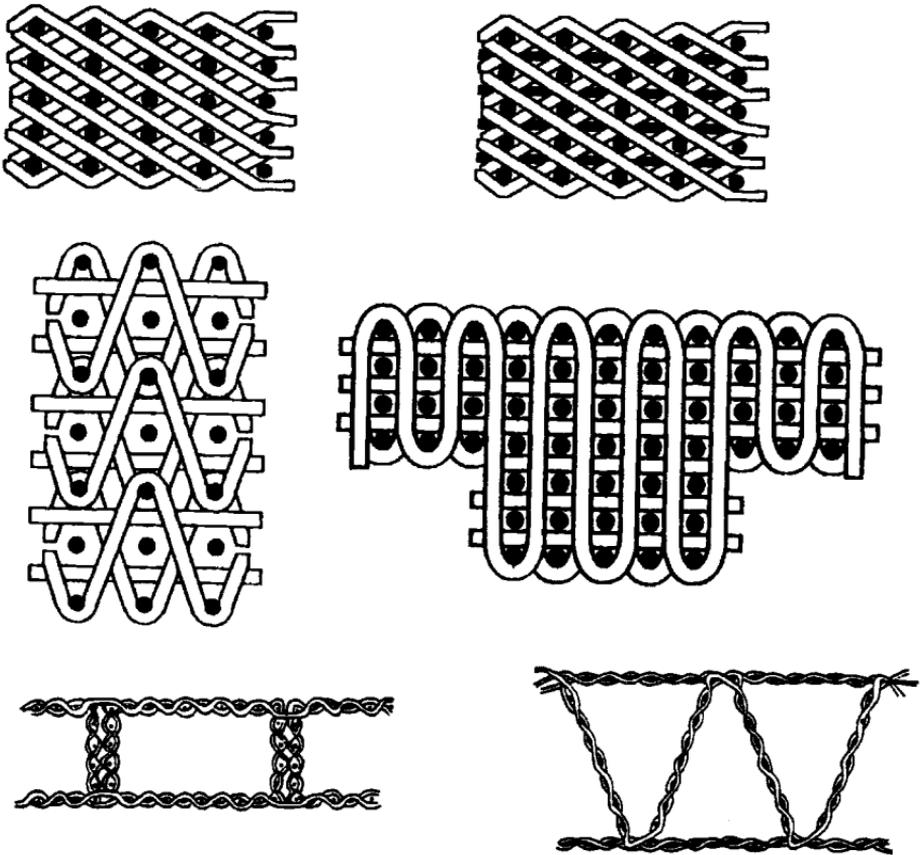


Fig. 14.9 Examples of three-dimensional weave architectures.

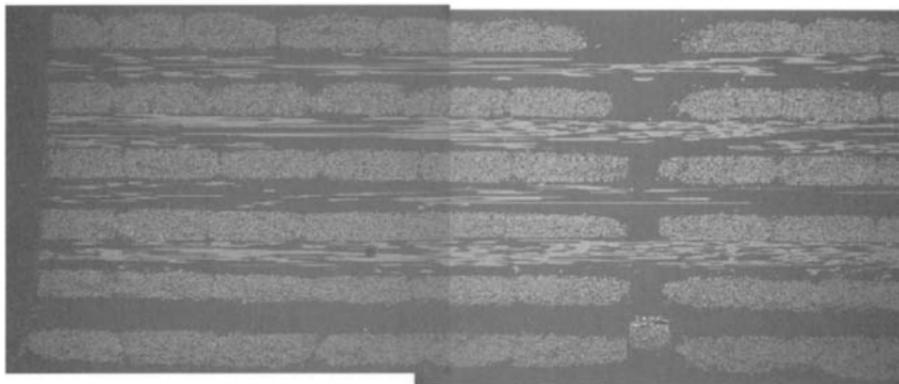


Fig. 14.10 E-Glass/vinyl ester three-dimensional orthogonal weave with warp yarns normal to the page. Courtesy of the CRC-ACS Ltd, Melbourne, Australia.

together to produce a net-shape preform that can be easily handled, reducing the manufacturing time associated with the lay-up of individual fabric layers. Importantly, three-dimensional woven preforms can also be designed to fold out into more complex shapes, for example, integrally woven blade-stiffened panels or I-beams, an ability that can help reduce costs in preform assembly.⁷

The main disadvantage of three-dimensional weaving is that standard looms cannot produce a fabric that contains in-plane yarns at angles other than 0° and 90° . This results in structures having very low shear and torsion properties, thereby making them unsuitable for use in most aircraft structures where high shear strength and stiffness are generally required. However, more specialized

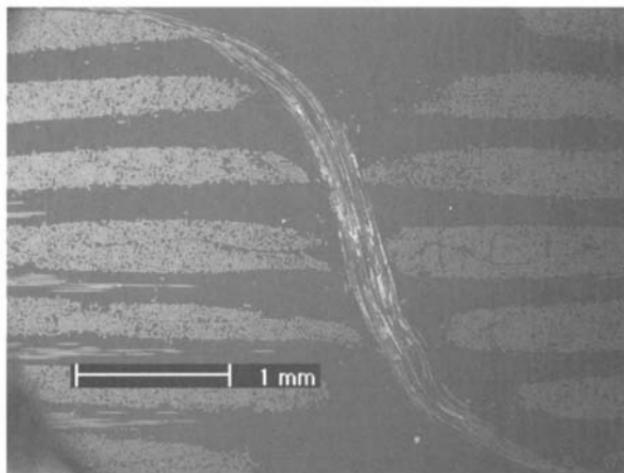


Fig. 14.11 E-Glass/vinyl ester weave (Fig. 14.10) with weft yarns normal to the page. Illustrates collimation of weft yarns by a binder yarn travelling in warp direction. Courtesy CRC-ACS Ltd, Melbourne, Australia.

looms have been in use since the early 1970s when the first was developed to produce three-dimensional woven carbon-carbon preforms for aircraft brakes.¹² These looms allow complex-shaped structures to be woven in the final shape without the need for folding operations and can produce fabric with yarns at angles such as $\pm 45^\circ$. Structures of such complexity are often difficult to manufacture using normal pre-preg technology, therefore the use of weaving technology can result in substantial cost savings in the production of complex composite structures.

14.4.2 Mechanical Properties

14.4.2.1 In-Plane Properties. The tensile and compressive properties of 3-D woven composites have been studied since the 1980s, but a clear picture of their in-plane performance and how it is affected by variables such as the weave architecture is still developing.⁷ Many of the studies on the performance of three-dimensional woven composites have been conducted with comparison to two-dimensional laminates manufactured with similar, but not always the same, parameters (fiber content, lay-up, etc.), and often these differences have prevented conclusive comparisons of performance being made.

Numerous investigations of the tensile properties of three-dimensional woven composites have led to conflicting results. Some researchers have reported the tensile modulus of three-dimensional woven composites to be reduced in comparison to similar two-dimensional laminates, whereas other researchers have reported an increase. However, in spite of this conflict in the reported results, it has been observed that (in the majority of cases) the tensile modulus of a three-dimensional woven composite is within 20% of the modulus of the comparable two-dimensional laminate. The studies have also shown that the modulus of the three-dimensional woven composite is not significantly influenced by the content of the z-direction reinforcement or the weave architecture. The explanation for the higher tensile modulus of some three-dimensional material is thought to be due to a slightly higher fiber content than the comparable two-dimensional laminate. The lower modulus in other cases is generally considered to be due to the increased waviness of the in-plane yarns caused by the presence of the z-direction reinforcement.

There is also no conclusive evaluation of the tensile strength of three-dimensional woven composites. The failure strength of three-dimensional woven composites has been found to be the same or (more often) less than the strength of a comparable two-dimensional laminate, but the difference is rarely more than 20%. As with tensile modulus, the strength of 3-D woven composites does not appear to be significantly affected by the z-direction reinforcement content or weave structure. The reduction in the tensile strength of three-dimensional woven composites is considered to be primarily due to the increased waviness of the in-plane yarns.

With regard to the compressive properties of three-dimensional woven composites, the modulus is generally reduced due to the z-direction yarns causing an increased waviness and local crimping of the in-plane yarns. A comparison of the compression strength of three-dimensional woven composites relative to similar two-dimensional laminates is more complex, and so far the findings have not been conclusive with both improvements and reductions in strength being observed. The compressive strength appears to be independent of weave architecture or the proportion of z-direction fiber. Degradation of the compressive strength is believed to be due to the kinking or microbuckling of the load-bearing yarns, which in turn is attributed to local waviness or crimping of the yarns as a result of the z-direction reinforcement. The occasional observed improvement in strength could be attributed to the initiation of delamination being suppressed by the z-direction yarn.

14.4.2.2 Out-of-Plane Properties. The most significant difference between the performance of three-dimensional and two-dimensional woven composites is apparent when examining their interlaminar fracture properties (delamination resistance) and their impact properties.⁷

Most interlaminar fracture studies have been performed in mode I, or tensile crack opening, conditions. The delamination resistance increases with the volume content, elastic modulus, tensile strength, and pull-out resistance of the z-direction yarn, but even a relatively modest amount of z-direction reinforcement can provide a large improvement to the delamination resistance. As with the other forms of z-direction reinforcement (stitching, z-pinning, etc.), the improvement in the delamination resistance occurs by the formation of a bridge of z-direction fibers spanning the crack faces behind the advancing crack tip, which restricts the further growth of the delamination.

The enhanced interlaminar fracture properties translate into improved impact properties. Impact performance has been extensively studied, and it has been found that in comparison with two-dimensional laminates, the improved delamination resistance of the three-dimensional woven composite results in a reduced area of impact damage over a range of impact energies. This superior impact damage resistance usually results in higher post-impact mechanical properties than that obtained from two-dimensional laminates, Fig. 14.12.

14.4.3 Applications

Three dimensional woven composites were used in the Beech Starship.¹² Woven H-joint connectors were used for joining honeycomb-sandwich wing panels together. The use of this woven connector was reported to be critical to the cost-effective manufacture of the wing and improved stress transfer at the joint, thus reducing peel stresses.

Three dimensional woven composites are used by Lockheed Martin for the air inlet duct in the F35 military fighter jet. In this example, the stiffeners are

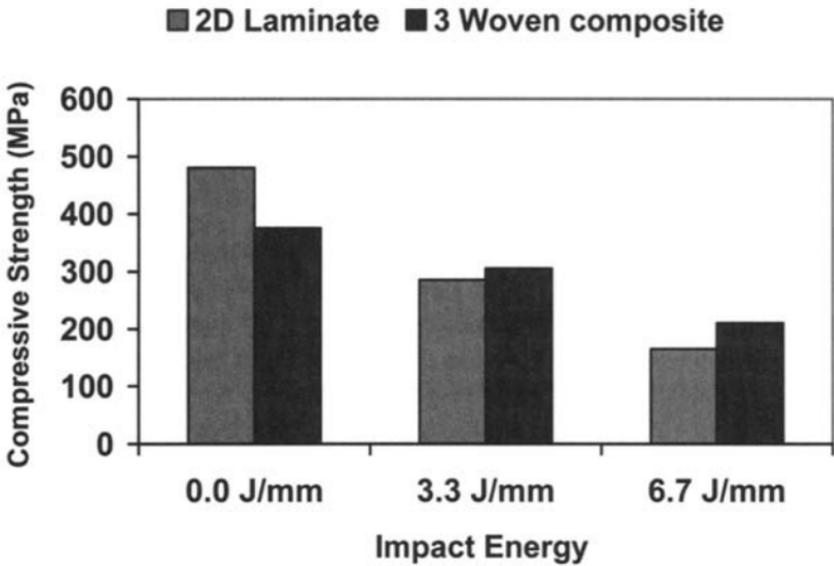


Fig. 14.12 Effect of impact energy on the compressive strength of two-dimensional and three-dimensional woven carbon/epoxy composites

integrally woven with the duct shell, reducing the need for secondary fastening. Ninety-five percent of the fasteners through the duct are eliminated, thereby improving aerodynamic and signature performance, minimizing the risk of fasteners being injected by the engine, and simplifying manufacturing assembly.¹³

Other, three-dimensional for woven composites have been investigated in a number of demonstration structures for aircraft including thrust reversers, rotor blades, engine mounts, T-section fuselage frames, stiffener gap fillers, and multi-blade stiffened panels.¹²

In more advanced applications, three-dimensional woven sandwich composites are also being used in prototype Scramjet engines capable of speeds¹⁴ up to Mach 8. The material is a ceramic-based composite consisting of three-dimensional woven carbon fibers in a silicon carbide matrix and is used in the combustion chamber. A key benefit of using a three-dimensional woven composite in this application is the ability to manufacture the chamber as a single piece and the consequent reduction in connection issues and leakage problems associated with conventional fabrication methods.

14.5 Braiding

Braiding is basically a textile process that enables the interweaving of two or more systems of yarn in the bias and longitudinal direction to form an integrated

structure referred to as the preform. Due to the interweaving of the yarns, braided preforms have conformability, torsional stability, and structural integrity as well as some degree of three-dimensional reinforcement (depending on the process), making them easy to handle and work with. The braiding process is capable of producing preforms of intricate shape; however, the size and length of the preform is generally limited to the size of the machine and yarn supply, respectively.

The adaptation of braiding to the composites industry has meant extensive research and development of the basic braiding process. This has focused on the hardware, production, and the geometric analysis of the braids, with the ultimate goal of complete automation and integration of machining and composite processing incorporating CAD/CAM (computer-aided design/manufacture) in aerospace factories.

Braided preform architectures can effectively be classified into two categories: two-dimensional and three-dimensional. Two-dimensional braiding has become well established over the past 15 years in the composites industry with a steadily growing database of knowledge and expertise. In contrast, three-dimensional braiding is still in its infancy.

14.5.1 Two-Dimensional Braiding Process

The traditional two-dimensional braiding process can be used to produce preforms of complex tubular shapes or in collapsed form, flat panels. The process of two-dimensional braiding can perhaps be best visualized by relating it to a maypole dance, in which the yarns are braided over a mandrel by yarn carriers that move in an interlinking rotational fashion around the mandrel. The simplicity makes it an efficient and cost-effective process compared with some other textile processes.

The braiding machine, shown schematically in Figure 14.13a, consists of three primary components: 1) yarn or fiber tow carriers, 2) interlinking mechanism and 3) take-up mechanism. The machine set-up involves placing the braiding fiber tow onto spools that are then loaded onto the carriers. The carriers (Fig. 14.13b) comprise a track follower, spool shaft, tensioning mechanism (weights or springs), and let-off mechanism (via hooks, loops, or wheels).

The carriers are connected to the braiding machine through “horndogs” and “horngears,” which propel the carriers into their interlinking rotational path as shown in Figure 14.13c. The usual yarn structure resulting from two-dimensional braiding is a simple regular biaxial braid where each yarn or tow in the two bias directions pass over and under two yarns in a repeat. The orientation (or braid angle, Figure 14.14) of these bias yarns typically range between 15° and 85° . By modifying the horn gears on the braiding machine, different braid patterns can be achieved. Hollow horn gears also allow the introduction of axial yarns in the braid that add to the stiffness of the preform. Two-dimensional braids, which contain longitudinal yarns, are referred to as triaxial braids (Fig. 14.14).

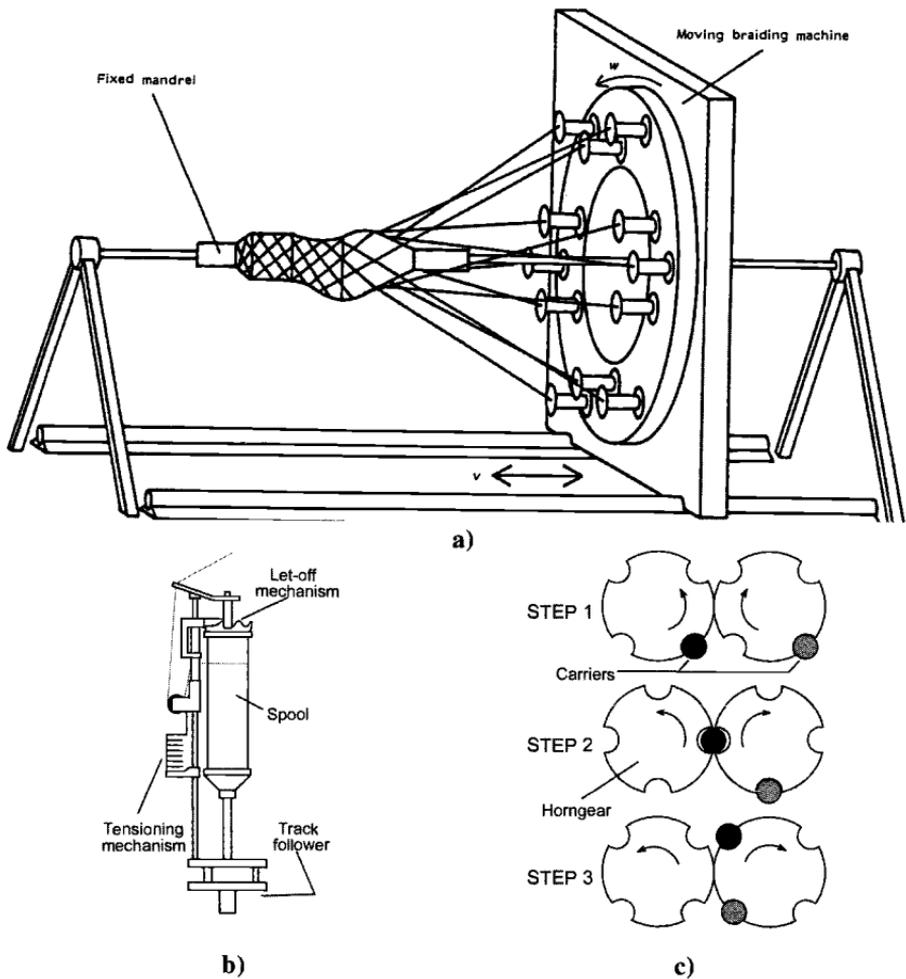


Fig. 14.13 a) Schematic diagram of a typical braiding machine; b) typical yarn carrier; c) horngear movement.

To form a continuous preform, a mechanism is also required to pull the fabric as it is formed. This is the take-up mechanism. Although there are several different types of take-up mechanisms, there are basically two systems that are applicable for braids intended for use in the aerospace industry. The first system involves a mandrel mounted on a gantry, allowing the mandrel to move back and forth while the braid is formed as shown in Figure 14.13a. The other system involves fixing the mandrel and allowing the braiding machine to move back and forth.

Research and development into the two-dimensional braiding process has focused on reducing the cost of the process and investigating its limitations and applications. Attempts at reducing the cost have resulted in the development of

high-speed automated braiding machines that can braid intricate shapes rapidly. The use of this type of machinery has been further assisted by the development of kinematic equations relating the machine parameters to the braid architecture that can be extended for use in CAD/CAM.¹⁵

14.5.2 Manufacturing Issues

There are a number of issues that must be considered when manufacturing braided preforms. A balance must be met between the design and manufacturing requirements. Although a particular braid angle may be required to obtain optimal structural performance, this angle may need to be modified to meet manufacturing requirements. That is, depending on the number of carriers, the size of the part to be braided, and the size of the tows, a particular fiber orientation may be unachievable. The reason for this is that either there will be jamming of the fiber tows, or at the other extreme, poor fiber coverage over the mandrel.

The mechanical properties are not only affected by the braid angle but also by the amount of crimp in the yarn. Fiber crimp, which occurs in the braider tows as they pass over and under other braider and axial tows, causes a reduction to the in-plane mechanical properties. This can be controlled to a degree by using smaller axial tow sizes and changing the braid pattern. A regular braid pattern has less crimp than a diamond braid (Fig. 14.14).

Issues related to the manufacture of two-dimensional braided preforms include preform quality, fiber orientation and coverage, fiber crimp, and mandrel design. The braided preform quality is highly dependent on the type of fiber being used. In the braiding process, the fibers are inevitably bent and twisted as they move from one machine surface to another. As the fibers are converted to the fabric structure, the process introduces stresses resulting from the interlacing and intertwining of the tows. This can cause damage to the fibers, degrading their properties. The amount of damage that takes place is dependent on the fiber stiffness, brittleness, diameter, coating (sizing), tow structure, and processing

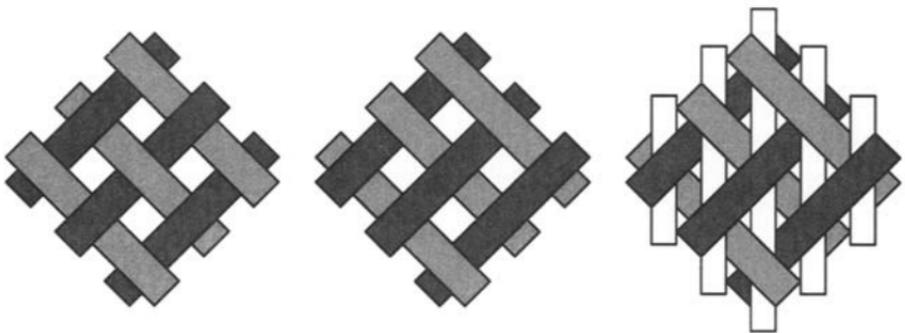


Fig. 14.14 Different braid patterns produced by two-dimensional braiding.

speeds. Carbon fibers have shown to be more susceptible to damage than aramid or glass fibers.

The mandrel forms an integral part in the fabrication of two-dimensional braided structural preforms. It not only provides the shape of the preform, but can also be used in the consolidation process and may also provide structural benefits. Mandrels may be rigid or flexible and are made from a number of materials such as metals (steel/aluminum), structural foams, and water- soluble or fusible casting compounds.

14.5.3 Design of Braided Composites

The design of braided composites needs to take into account the structural requirements of the part in question as well as the manufacturing issues outlined above and the limitations of the braiding process. Techniques used to design the braided preform may involve models that relate the geometric features of the braid architecture to the process parameters. Using such models enables the designer to accurately specify a braided preform with the desired fiber orientations. There is a range of analytical tools that can be used to predict the mechanical performance of the braided composite. Conventional techniques such as classical laminate theory and stiffness averaging have shown to work well in predicting stiffness. However, strength prediction is somewhat more difficult, as is the case for all composite structures. Traditional laminate failure theories do not work because they do not take into account the different failure mechanisms of these materials. Specialized methods that model these mechanisms should be used.

14.5.4 Mechanical Properties

Although the mechanical property database of two-dimensional braided composites is not as large as that for unidirectional tape or two-dimensional woven pre-preg, testing of these materials has shown that their properties compare favorably with other forms of composites. Two-dimensional braided composites have been shown to have similar stiffness and strength values compared with two-dimensional woven composites of similar lay-up. When compared with unidirectional tape, braids have also shown similar elastic properties; however, their strength values are reduced by as much as 25%. This discrepancy in strength is mainly attributed to the difference in fiber architecture e.g., fiber waviness that causes changes in failure mechanisms, particularly in compression.

With regard to damage resistance and tolerance, two-dimensional braids have been shown superior to both unidirectional and two-dimensional woven composites. Low-energy impacting followed by compression testing has revealed that braided composites can be significantly more resistant and tolerant to

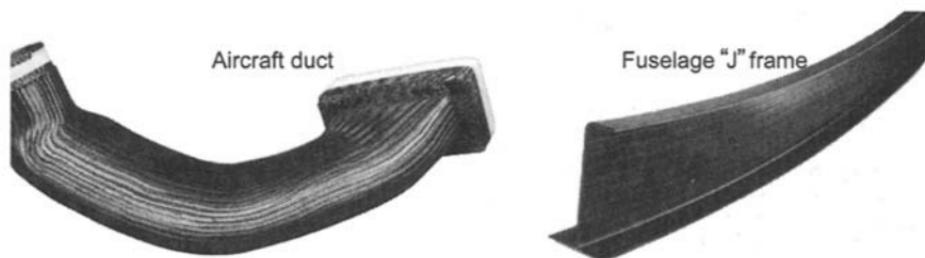


Fig. 14.15 Examples of parts fabricated using two-dimensional braiding. Courtesy Fiber Innovations Inc.

damage. This is a result of the slightly three-dimensional nature of the reinforcement architecture that acts to contain damage growth in the laminate.

14.5.5 Applications

By braiding over a diverse range of mandrels and increasing the size of the two dimensional braiding machine, it is possible to produce intricate tubular preform shapes of various sizes. There have been a number of low- and high-technology items manufactured this way that have been cited in open literature. Some examples, two of which are shown in Figure 14.15, include cellular stiffened panels, pressure vessels and drive shafts, aircraft propellers, truss joints, a monocoque racing car chassis, rocket launchers, aircraft fuselage frames, helicopter rotor blade spars. Metallic end fittings have also been attached to tooling mandrels and then braided over to produce an integrated preform.¹⁶ The braiding process not only makes it possible to manufacture these structures, but what is most important is that it is also able to provide the desired fiber reinforcement. When required, axial yarns are used to provide the tensile and compressive strength and stiffness, whereas the bias yarns supply adequate reinforcement for torsional or shear loads.

Braided preforms have generally been consolidated using liquid molding processes such as RTM and RFI; however, there have been cases where other infusion methods have been used. Preforms braided with commingled yarns (combination of fiber with thermoplastic) have been consolidated using compression molding techniques. There has also been the marriage of braiding with pultrusion, which enables the automated and continuous production of composite parts.

14.5.6 Three-Dimensional Braiding Process

With two-dimensional braiding, thick-walled structures are made by repeatedly braiding over the mandrel resulting in a multi-layer preform without significant through-thickness reinforcement. Some attempts have been made to

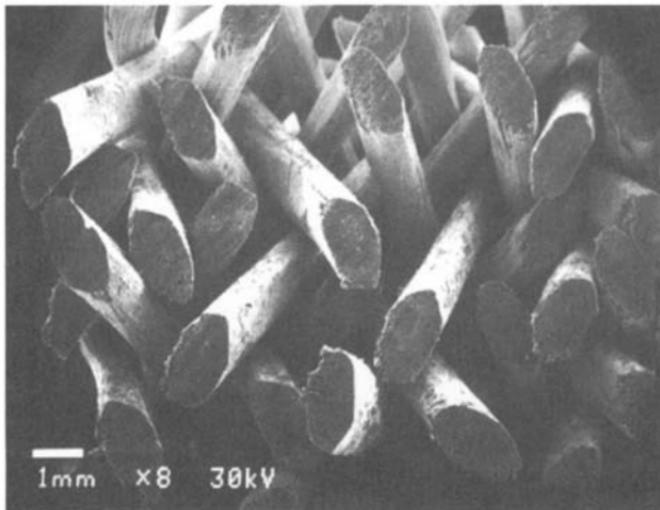


Fig. 14.16 Three-dimensional braid architecture. Courtesy Atlantic Research Corporation, Gainesville, VA.

overcome the lack of through-thickness reinforcement with multi-layer two-dimensional braids by interlocking the multi-layers with binding yarns. This has led to the development of three-dimensional braiding techniques that have provided new possibilities in the development of near net-shape preforms with added through-thickness reinforcement.

The first serious development of three-dimensional braiding, which occurred in the 1960s, was referred to as *four-step* (or row-and-column) braiding, a term given because of the four distinct operations in the braiding process. Since then other variations have been developed, along with some new techniques yielding three major styles of three-dimensional braiding: four-step braiding, two-step braiding, and multi-layer interlock braiding. Figure 14.16 provides an example of the type of construction that can be achieved with three-dimensional braiding.

Despite its advantages, the use of three-dimensional braiding has been limited. The maximum size of the preform is determined by the braiding machine size, and most industrial machines are only able to braid preforms with small cross-sections (less than 100 mm). Extremely large and expensive machines are required to produce preforms large enough for typical aircraft structures. Three-dimensional braiding machines are still at the research and development stage, and only a few machines are currently producing commercial preforms.

Three-dimensional braiding was developed in the late 1960s to produce three-dimensional carbon/carbon composites (Chapter 1) to replace high-temperature metal alloys in rocket motor components.⁷ These components achieved weight savings of 30–50% and demonstrated the ability of braiding to produce composite components of complex shape. The various styles of three-dimensional braiding can be tailored for specific structural applications and

can all be accomplished with a range of fiber materials: glass, carbon, aramid, ceramic, and metal. With three-dimensional braiding, it is possible to braid inserts or holes into the structure that have a greater stability than holes that have been machined. The braid pattern can be varied during operation so that a change in cross-sectional shape is possible, including introducing a taper to the preform. Thick-walled tubular structures can also be made by suitable arrangement of the braiding architecture and flat preforms can be made from these tubular structures by braiding splits into the preform then cutting and opening it out to the required shape.¹⁷ A bend is also possible as well as a bifurcation, which will allow junctions to be produced and these processes even allow 90° yarns to be laid into the preform during manufacture. This wide range of possible preform shapes makes three-dimensional braiding one of the most potentially versatile ways of producing a three-dimensional fiber reinforced preform.

14.5.7 Mechanical Properties Three-Dimensional Braided Composites

14.5.7.1 In-Plane Properties. The mechanical properties of three-dimensional braided composites have been studied since the 1980s, but in spite of this, the extent of the published literature only constitutes a small part of the information necessary to fully characterize this class of composite material. The current lack of detailed test data and an inadequate understanding of their mechanical behavior is limiting the use of three-dimensional braided composites in aircraft structures.

The most influential factor on the in-plane properties is the angle that the braided yarns (including the axial yarns if present) make with the loading direction. The braiding angle is set by the pattern to which the preform is being braided, and a closer orientation of the yarn to the load direction increases the mechanical properties in this axis but lowers the properties transverse to this direction. A similar result is obtained when some of the braiding yarns are kept fixed in the axial position or extra axial fibers are inserted. Because the braided yarns all travel to the specimen surface in the common three-dimensional braiding processes, any machining of the surfaces will result in the braiding yarns becoming discontinuous along the specimen length, with a resultant drop in performance.

Other aspects of the braided preform such as tow size and the type of three-dimensional braiding process used to manufacture the preform have also been seen to influence the in-plane properties.⁷ When compared with two-dimensional laminates with similar lay-ups and fiber contents, it has generally been observed that three-dimensional braided composites have inferior in-plane properties. This is because, as mentioned previously, the braiding process tends to crimp the yarns, lowering their performance relative to tape laminates.

14.5.7.2 Out-of-Plane Properties. There is, equally, a lack of published data on the impact performance of three-dimensional braids. A limited amount of work is published in the open literature. The results tend to indicate that, compared with conventional laminates, three-dimensional braided specimens suffer a much reduced damage area. Further, the residual compression strength after impact is also higher in the three-dimensional braided specimen than in the two-dimensional laminated material. However, the impact performance of two-dimensional braids is approximately the same as three-dimensional braids. This result is explained on the basis that even with an absence of z-direction yarns, the architecture of a two-dimensional braid is undulated with the layers significantly nesting with each other. This makes it very difficult for impact damage to propagate extensively within the composite when compared with the relatively straight crack paths available in tape laminates.

14.5.8 Applications

A variety of demonstrator parts have been made that clearly illustrate the versatility of the three-dimensional braiding process. C-, J-, and T-section panels, I-beams, bifurcated beams, connecting rods, airframe spars, F-section fuselage frames, fuselage barrels, and rocket engine nozzles have all been produced using this process, and examples of such products are shown in Figure 14.17. However, in spite of these successful manufacturing demonstrations, there is currently no reported aerospace use of a component manufactured using a three-dimensional braided reinforcement.

14.6 Knitting

Knitting refers to a technique for producing textile fabrics and preforms by intermeshing loops of yarns using knitting needles. A continuous series of

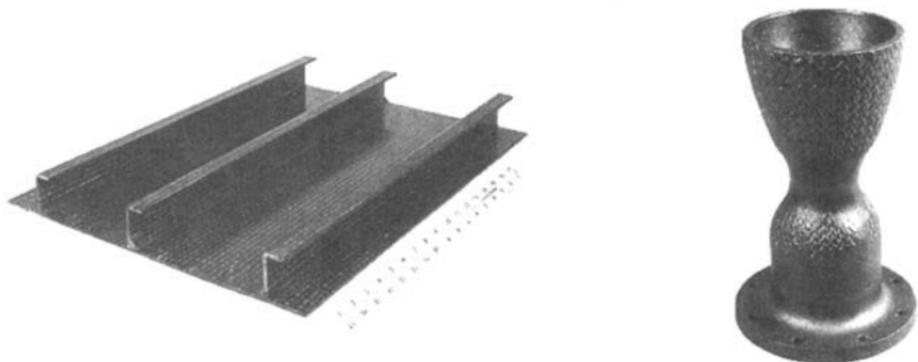


Fig. 14.17 Examples of parts that were fabricated using three-dimensional braiding. Courtesy Atlantic Research Corporation.

knitting stitches or intermeshed loops is formed by the needle, which, catching the yarn and drawing it through a previously formed loop, forms a new loop. In a knit structure, rows, known as *courses*, run across the width of the fabric, and columns, known as *wales*, run along the length of the fabric. The loops in the courses and wales are supported by and interconnected with each other to form the final fabric. Depending on the direction in which the loops are formed, knitting can be broadly categorized into one of two types—*weft knitting* and *warp knitting* (Fig. 14.18). Weft knitting is characterized by loops forming through the feeding of the weft yarn at right angles to the direction in which the fabric is produced. Warp knitting, on the other hand, is characterized by loops forming through the feeding of the warp yarns, usually from warp beams, parallel to the direction in which the fabric is produced. These basic knit architectures can be modified through the use of tuck and float loops to achieve specific macroscopic properties in the fabric. In general, the former makes a knitted fabric wider, thicker, and slightly less extensible, and the latter creates the opposite effect, as well as increases the proportion of straight yarns in the structure, which is an important consideration for many composites applications.

Since fibers are required to bend over sharp radii and maneuver sharp corners to form the knitted loops of the structure, knitting may not at first appear to be a manufacturing technique that would be suitable for use in the production of aerospace components. However, the knitted carbon and glass fabric that can be produced on current, standard industrial knitting machines has particular properties that potentially make it very suitable for certain aerospace composite components. Current machinery is also capable of producing preforms with up to four interconnected layers of knitted fabric. Therefore, although the process is not yet able to manufacture preforms with thickness dimensions as large as weaving or braiding, it is still able to produce three-dimensional fiber architectures.

Knit architectures result in a fabric of relatively low strength and stiffness compared with tape or woven cloth, but the knitted fabric is highly conformable

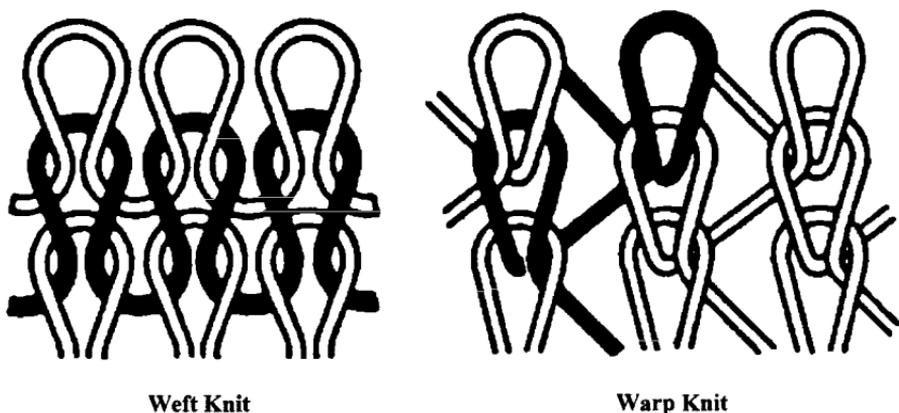


Fig. 14.18 Schematic diagram illustrating weft and warp knitting.

and is therefore ideally suited to manufacture non-structural components of complex shape. Layers of knitted fabric can be stretched to cover a relatively complex tool surface without the need to cut and overlap sections. This reduces material wastage and helps decrease the costs of manufacturing complex shape components such as fairings (Fig. 14.19).

More advanced industrial knitting machines are now capable of producing very complex, net-shaped structures at high production rates with little material wastage. Through careful knit loop control, structures that are very difficult to produce using conventional fabrics can be knitted to net shape, thereby further reducing manufacturing costs. These preforms can also incorporate oriented fibers in selected areas to improve the mechanical performance of the finished component.¹⁸

14.6.1 Mechanical Properties

14.6.1.1 In-Plane Properties. The in-plane mechanical properties of knitted composites are usually anisotropic. This is due to a difference in the relative proportion of fibers oriented in the knitted fabric, and is therefore a function of the knit structure as well as knitting parameters, such as stitch density. The knit structure is not only controlled by the choice of knit architecture but also by the amount and manner to which the fabric is deformed, thereby modifying the relative fiber orientation prior to consolidation. Similarly, knitted composite properties are also controlled by manipulating parameters such as loop lengths or

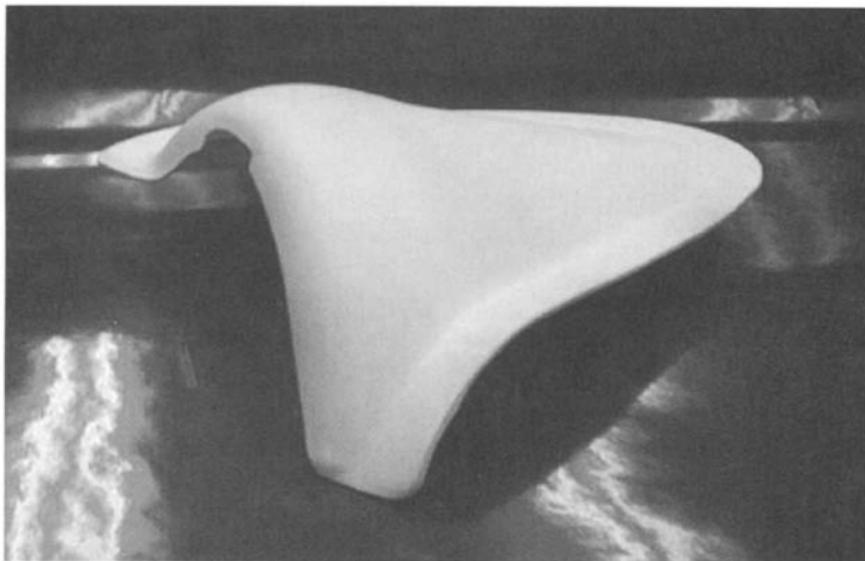


Fig. 14.19 Aerospace fairing constructed of knitted glass fabric. Courtesy CRC-ACS Ltd, Melbourne, Australia.

stitch density of a particular knit architecture. Nevertheless, the strength of knitted composites in compression is dominated by the properties of the resin.

The strength and stiffness of knitted composites are inferior to woven, braided and unidirectional materials having an equivalent proportion of in-plane fibers. This is due to the limited utilisation of fiber stiffness and strength resulting from the severely bent fibers in knit structures. Similarly, knitted composites are expected to have in-plane properties that are close to those of random fiber mats composites (Table. 14. 2).

Failure of knitted composites is a complex process with the yarn crossover points and the curved side legs of the knit loops being critical points at which failure occurs. Substantial microcracking from yarn-matrix debonding at these positions within the knitted fabric is also observed during failure.

14.6.1.2 Out-of-Plane Properties. The three-dimensional nature of knitted fabrics is effective in promoting fiber bridging to enhance Mode I fracture toughness where improvements over more conventional composites of up to 10-fold have been observed. These superior Mode I fracture toughness values are reflected in the energy absorption capabilities and impact penetration resistance of knitted composites. As illustrated in Fig. 14.20, under impact conditions, knitted composite materials are found to retain far higher proportions of their undamaged strength when compared with conventional two-dimensional composite reinforcements¹⁹.

14.6.2 Applications

The highly looped fiber architecture ensures that knitted fabrics are able to easily undergo significant amounts of deformation when subjected to an external force. Their formability raises the potential of knitted fabric for cost-effective composite fabrication of complex and intricate shapes. This advantage extends to permitting holes in a composite to be formed or knitted in, instead of drilled. As continuous fibers diffuse stresses away from the hole, the strength in the knitted/formed hole region is increased leading to notch strength and bearing properties

Table 14.2 Typical Mechanical Properties of E-Glass/Vinyl Ester Knitted Composites
Vf ~ 55% Courtesy of the CRC-ACS Ltd.

	Plain knit	Rib knit	Milano knit
Tensile strength (MPa)	165	114	135
Tensile modulus (Gpa)	13.6	14.3	14.8
Tensile failure strain (%)	2.7	1.7	2.3
Compressive strength (MPa)	138	169	168
Compressive modulus (GPa)	11.6	11.2	11.2
Compressive failure strain (%)	1.9	2.0	1.9

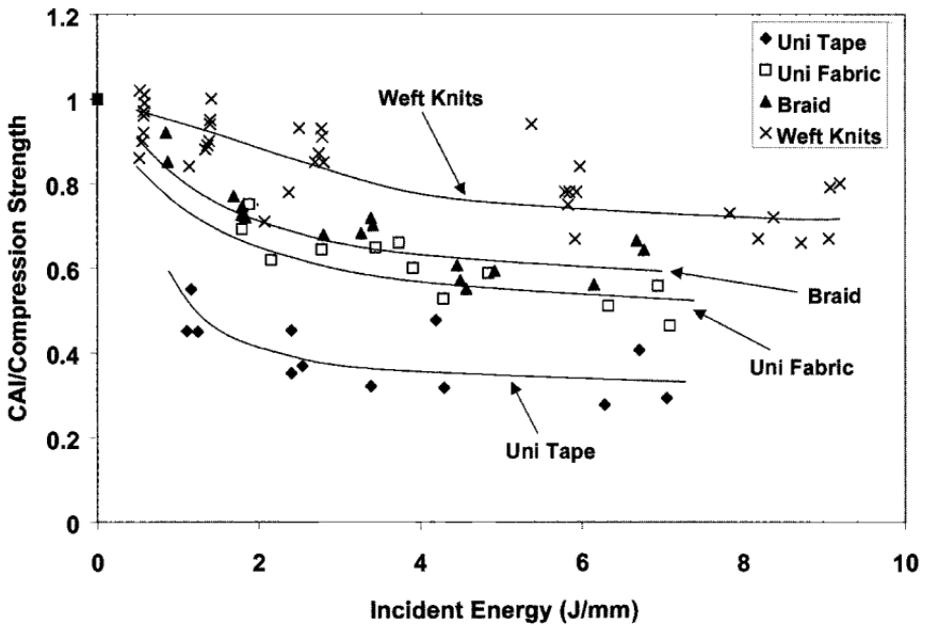


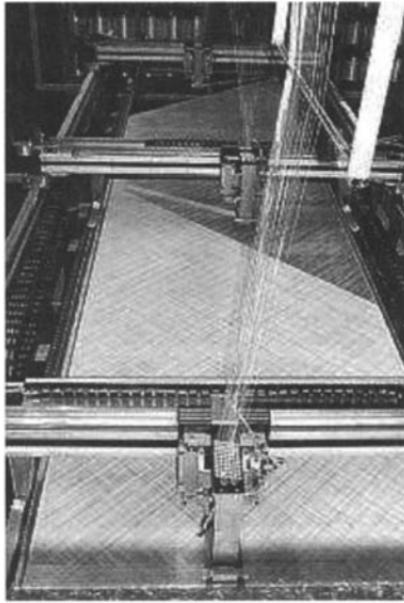
Fig. 14.20 Comparison of normalized retained compression strength after drop weight impact of various E-Glass reinforcements. $V_f \sim 55\%$.

that are relatively a higher proportion of un-notched strength than is the case for composites with a drilled hole. Generally, knitted composites are generally notch-insensitive.

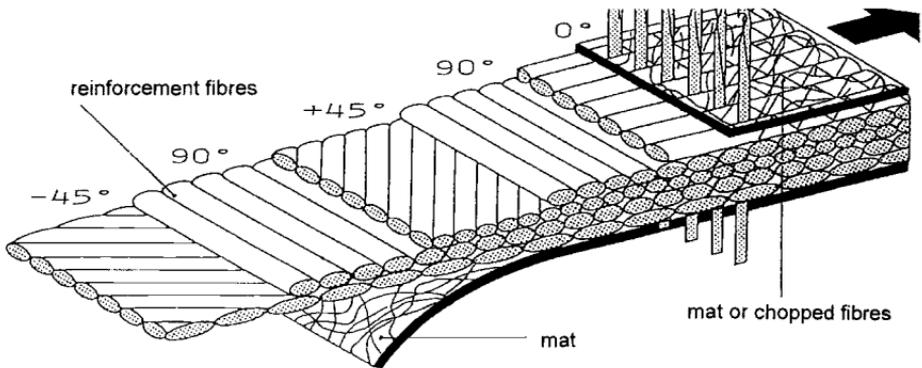
In general, flat knit and shape knit products have so far been used primarily as a demonstration of the ability of the knitting process to manufacture complex shaped components. Jet engine vanes, T-shaped connectors, car wheel wells and aerospace fairings have all been successfully manufactured,⁷ however the low mechanical performance of the knitted fabric is a deterrent to its wider use.

14.7 Non-crimp Fabrics

One application of knitting is the subject of intense interest within the aerospace industry. Using warp-knitting techniques in conjunction with fiber placement concepts, multi-axial, multi-layer warp-knit fabrics, more commonly known as non-crimp fabrics, can be produced with in-plane fibers that are relatively straight. These in-plane fibers are held in place by a stitched or knitted thermoplastic polymer (typically nylon or dacron) fiber or a flexible high performance fiber such as glass or aramid. The material is not crimped as in the case of woven material, and as such the fibers are arranged in a more optimal fashion (Fig. 14.21). The availability of heavy multi-layered fabric with the



a)



b)

Fig. 14.21 a) Non-crimp fabric being produced; b) typical non-crimp fabric. Courtesy of LIBA-Maschinenfabrik GmbH, Naila, Germany.

desired fiber orientations also has significant economic benefits in production because the reduced ply count required means that lay-up rates are much higher than for conventional lighter fabrics.

A reasonably wide variety of these non-crimp broadcloth fabrics are currently commercially available in glass and carbon yarn. They have three main

advantages. First, unlike multilayer woven preforms, the material affords cost-effective off-axis reinforcement. Second, like other multilayer textile preforms, this material has the potential to greatly reduce production cost through reducing the time taken to lay-up the composite component. Finally, this material has the potential to outperform traditional two-dimensional pre-preg tape laminates because it too contains nominally straight fibers but with the added advantage of having through-thickness reinforcement for improved out-of-plane properties. Although stitched two-dimensional laminates can also offer the same attributes, stitching is nevertheless a secondary operation, and there appears to be a general component size and cost restriction with this technique.

14.7.1 In-Plane Properties

In general, three-dimensional warp-knit non-crimp composites have slightly inferior in-plane properties when compared with unidirectional pre-preg tape laminates of similar lay-up²⁰ (Table 14.3). The tension control of the through-thickness component is of paramount importance to minimize any out-of-plane crimping (waviness) of the in-plane fiber yarns while maintaining good controllability of the preform. Similarly, the yarn size and stitch density will determine the degree of in-plane crimping and fiber damage in the load-carrying fiber yarns. The presence of any such crimping could render the non-crimp composites inferior under tensile, compressive, and flexural conditions, compared with two-dimensional woven composites. On the other hand, insufficient tension in the through-thickness yarns will cause them to buckle under cure pressure and hence, be ineffective at providing a crack closure force.

It should be noted that the in-plane properties could be degraded by the impalement of the non-crimp layers by the knitting needles. This impalement causes fiber distortion and damage, a phenomenon not dissimilar to that observed for stitched composites. A way to eradicate this is to ensure knitting needles are

Table 14.3 Comparison of in-plane mechanical properties for carbon/epoxy tri-axial layups manufactured from two-dimensional unidirectional pre-preg tape and 2 layers of tri-axial non-crimp fabric

	2-D Unidirectional		Non-crimp	
	Pre-preg Tape [45 ₂ , -45 ₂ , 0 ₆ , -45 ₂ , 45 ₂] _s		[{45, -45,0}, {0, -45,45}] _s	
Test orientation	0°	90°	0°	90°
Tensile modulus (GPa)	64.8	21.4	60.8	17.2
Tensile strength (MPa)	951	123	621	159
Compressive modulus (GPa)	59.9	19.6	54.7	16.5
Compressive strength (MPa)	852	215	574	236

inserted between tows of in-plane fibers. However, the gaps that are formed between the tows by doing this are potential resin-rich sites that are considered detrimental to some properties.

Microscopic analysis has shown that the knit structure in the non-crimp composite appears effective in constraining the delaminations and longitudinal splitting that are normally associated with unidirectional pre-preg tape laminate. Other than that, it seems that non-crimp and unidirectional pre-preg tape laminates have very similar failure mechanisms, essentially, multiple cracking in off-axis plies and delamination at $\pm 45^\circ$ interfaces.

14.7.2 Out-of-Plane Properties

The interlaminar fracture toughness of non-crimp composites is superior to that of unidirectional pre-preg tapes due to the knitting yarn acting to bridge the crack and restrict its further growth when subjected to out-of-plane loads. In spite of this, little improvement is observed in the suppression of delamination damage due to impact. The damage tolerance of non-crimp and unidirectional pre-preg tape composites is similar, although the former exhibits superior compression-after-impact strengths with increasing impact energy level.

The damage generated in non-crimp composites by low-energy impact is more complex than that in unidirectional pre-preg tape laminates. Instead of a collection of shear cracks linking delamination planes, which is normally observed in unidirectional pre-preg laminates, the impact damage created within non-crimp composites consists of an intricate array of cracks not dissimilar to that observed in more conventional knitted composites. This highly branched cracking links planes of delamination which also contain parallel matrix cracks that appear to coincide with the inter-fiber tow resin-rich regions. The presence of the z-direction reinforcement yarns in the non-crimp fabric should be very effective in reducing the amount of back face spalling compared with unidirectional pre-preg tape laminates. The level of performance improvement in this area would be linked to the mechanical properties of the z-direction yarns.

14.7.3 Applications

There are significant cost incentives to be gained with non-crimp fabric in comparison with unidirectional pre-preg tape composites. These include reduced wastage and labor, adaptability to automation, and virtually unlimited shelf life without the need for refrigeration. Limitations arise from issues such as relatively higher raw material cost, impracticality in terms of ply drop-offs, and restrictions on the number of fabric types available commercially. The overall cost implication is, therefore, an important consideration when deciding between the more traditional unidirectional pre-preg tapes and non-crimp composites. In spite of these issues, a great deal of effort is being devoted within the aerospace industry to develop these fabrics for use within secondary and primary structures

and components that have been demonstrated include wing stringers and wing panels. It is anticipated that a number of significant components on the Airbus A380 will be manufactured from non-crimp fabrics.

14.8 Conclusion

Stitching and z-pinning are applicable to current two-dimensional composites and provide improved damage tolerance and strength to bonded joints. They are also beneficial as manufacturing aids and may reduce the need for mechanical fasteners in some cases. The main issues are the increased costs and the need for specialised equipment. The reduction of some in-plane properties may also be an important issue.

Three-dimensional textile manufacturing processes are an emerging field and they offer similar advantages to two-dimensional processes, albeit not without their restrictions. Design or manufacturing criteria that favor the use of a particular textile process for one application may not necessarily be relevant for another. It is also possible that for some structures it may be necessary to combine a number of the textile processes to achieve a cost-effective product with the required performance. Of particular importance is the intimate connection between the textile manufacturing process, the required preform design, the cost, and the performance of the resultant composite. A large range of possible preform architectures can now be produced, each with its own mechanical performance and associated cost. It is, therefore, critical that in the design of any component, early consideration is given to the method of manufacture because only seemingly slight, relatively unimportant changes to component shape or required performance may result in significant changes to the cost of manufacturing a preform.

In spite of the relative youth of these manufacturing techniques, advanced textile preforms are beginning to be used in the manufacture of aerospace components. The potential savings in cost and improvements in performance that can be realized through the use of these processes are sufficiently attractive that extensive efforts are being put into further developing these processes. It is not yet clear how far these developments will go, but as designers and manufacturers become more familiar, and hence confident, with the advanced textile composites on offer, the use of these techniques will become more commonplace.

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