14
Textile structures for load-bearing applications in automobiles

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Abstract: Various textile reinforcement structures are available for use in automobiles as composites. These structures can be realized using a wide range of textile technologies. One major focus of current developments is therefore load-bearing applications for structure elements. Their low weight in combination with very good impact behaviour in the event of a crash makes them an interesting alternative to conventional materials such as steel and aluminium. This chapter gives an overview of current production technologies for these kinds of textile structures, of joining and assembling techniques, and describes typical applications that are already in use.

Key words: composites, 3D textiles, preform, joining, cutting.

14.1 Introduction

Various textile reinforcement structures are available for use in automobiles as composites. The complexity of textile structures increases with dimension. These structures can be realized using a wide range of textile technologies. At present, textiles are used in automobiles for comfort, safety and structural components. This amounts to approx. 13 kg of textiles per vehicle and is expected to increase to 30 kg within the next decade.

Airbags, safety belts and seats as well as interior and acoustic structures are state-of-the-art but under constant development. Textiles for car tyres have been in use even since the 1930s. One major focus of current developments is therefore load-bearing applications for structural elements. Their low weight in combination with a very good impact behaviour in case of a crash makes them an interesting alternative to conventional materials such as steel and aluminium. Textile composite structures have already been put into practice in Formula 1 racing cars and also in several small series sports cars but are still far from being a mass production application. Considerable effort has to be put into that subject in order to reach higher productivity of the processes involved and also a higher degree of automation in order to meet the high quality demands of the automotive manufacturers.

Fibres used for load-bearing applications in vehicles are exposed to various stresses during processing (tensile stress, bending stress, fibre-fibre friction, fibre-machine friction). Bending and shear forces especially can cause fibre damage when brittle high-performance yarns made of glass or carbon fibres are used. Thus, only textile processes that induce a low deflection in the reinforcement fibres are suitable for this kind of application. Textile processes with warp- or weft-insertion (in weaves or knits), fibre-placement and overbraiding technologies are therefore well suited for the processing of carbon rovings.

Complex textile reinforcement structures in near-net-shape form (textile preforms) can be produced in one-step or multi-step processes, using one-step preforming technologies such as 3D braiding, 3D weaving, contour warp knitting or net-shape weft knitting. Usually, at least sub-preforms are manufactured that are processed in further preforming steps. In many cases 2D textile structures are used to create structures of higher complexity by forming and assembling several plies in multi-step preforming processes. An alternative technology is the use of 3D textile structures and preforming technologies. The relevance of textile and preforming technologies for use in automotive applications is discussed.

14.2 Latest advances in technologies for producing 2D and 3D textile load-bearing structures for automotive applications

For load-bearing applications in vehicles, 2D or 3D textiles can be used. To simplify the use of the expressions 2D textile and 3D textile, a definition was proposed by Gries and co-workers [1]:

> *A textile is defined as 2D if it does not extend in more than two directions, neither in yarn architecture nor in textile architecture. A textile is defined as 3D textile if its yarn architecture and/or its textile architecture extends in three directions, regardless of whether it is made in a one-step-process or a multiple-step process.*

High performance textiles for automotive applications usually consist of high performance fibres, yarns or rovings. Typical materials are carbon, glass and aramide. In most cases, twisted and untwisted multifilaments, the so-called rovings, are used. Twisting the roving slightly improves its processability significantly and decreases the risk of filament damage.

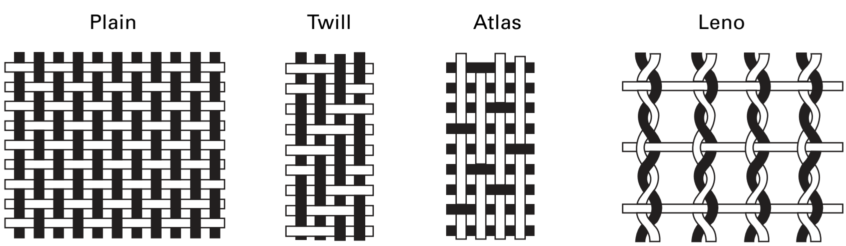
For the use of textile structures as reinforcement in composites, it is often important to realize a yarn position that is as straight as possible because non-crimped fibres can bear the highest loads and induce the highest stiffness. In other applications fibre crimp is needed, for example to achieve high damage tolerance or high energy absorption. Therefore each application requires its own textile structure.

14.2.1 2D textiles

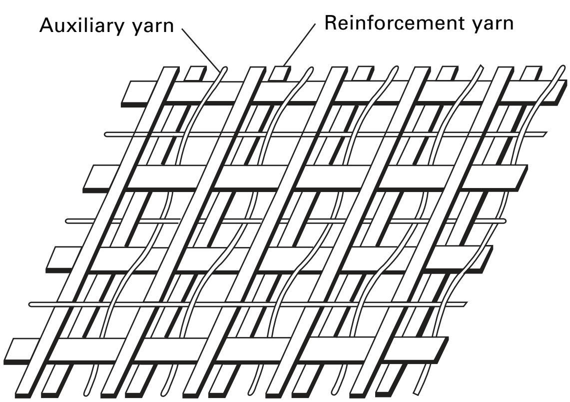
Woven fabrics

Woven fabrics are defined as fabrics which are made of rectangular crossed yarns of at least two yarn systems, warp and weft, by shed formation [2]. The manner of crossing the weft and warp yarns is called pattern. The pattern type has a strong influence on various fabric properties such as drapability and shear stiffness. There are three basic patterns: plain weave, twill weave and atlas weave and special pattern types like leno weave (Fig. 14.1).

There are also special non-crimp woven fabrics available that use thin auxiliary yarns to avoid bending of the reinforcing yarn. The bending, which is caused by the weaving process, is induced only in the auxiliary yarn because its bending stiffness is much lower than that of the reinforcing yarn. Figure 14.2 shows a biaxial non-crimp weave with auxiliary yarn called 'Advanced Syncron Weave' from the company ECC GmbH & Co. KG, Heek, Germany. In comparison to the unidirectional reinforcement structures, the handling and drapability of fabrics is good but the wave-like yarn crimp influences the mechanical properties of the consolidated textile-reinforced structure. Strength as well as stiffness of fabric-reinforced composites are



14.1 Weave patterns.



14.2 Non-crimp fabric.

therefore lower than with unidirectional reinforcements. Choosing a proper weft and warp density as well as suitable patterns, like Atlas, Advanced Syncron or leno weave, can minimize these effects by reducing the fibre crimp. Also the spreading of the yarns to a thin tape helps to reduce the yarn crimp.

The processing of brittle fibres to woven fabrics is possible but 'yarn-friendly' patterns (e.g., Atlas, Advanced Syncron or leno weave but not plain weave) and suitable machine set-ups must then be chosen.

Braids

Braids are defined as textile structures of regular appearance with closed selvedges. They consist of at least three yarns (healds) or at least two yarn systems (tubular braids), whose yarns are intertwined and cross diagonally to the edges of the textile (Fig. 14.3(a)).

The angle between the selvedges (that is the production direction) and the braiding yarns is called braid angle (Fig. 14.3(b)). This angle can be varied between 20° and 80°. Braids with a braid angle of 45° look quite similar to woven fabrics. They do have a comparable yarn architecture regarding yarn crimp due to the intertwining of the braiding yarns. The most common braid pattern is called regular braid. It is comparable to a 2/2-twill woven structure. Other braid patterns are the diamond braid (1/1) intersection repeat and the hercules braid (3/3) intersection repeat [3].

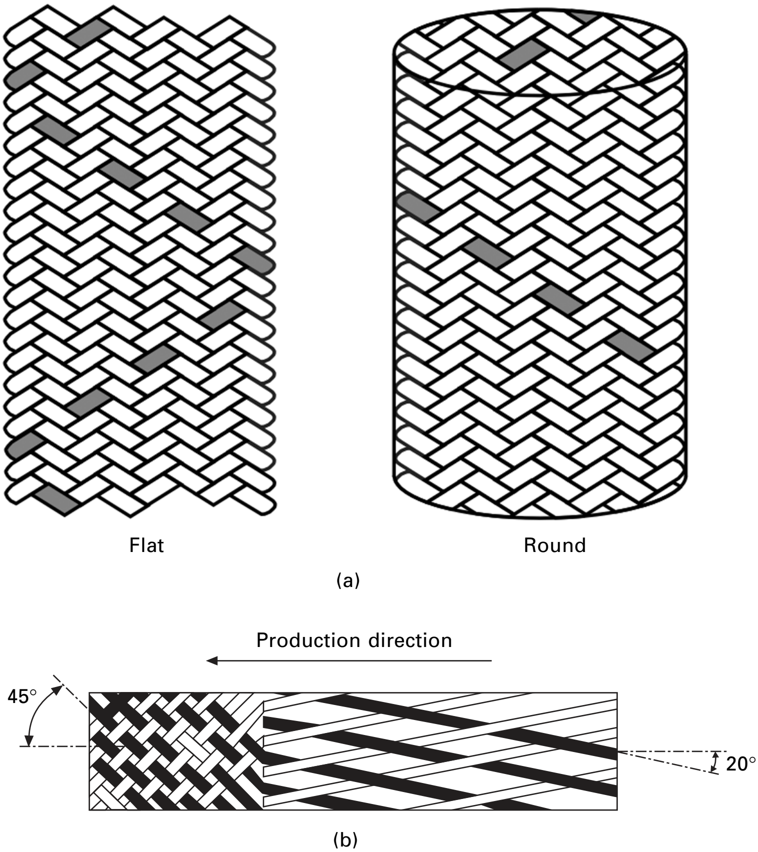
In addition to the braiding yarns, axial yarns (0°) can be added inside the braided structure. These yarns are inactive during the production process and are enclosed by the braiding yarns. While the braiding yarns are crimped, the axial yarns remain in straight position. Braids with axial yarns enclosed are called triaxial braids. Braids without axial yarns are called biaxial braids. The drapability of triaxial braids is worse than that of biaxial braids due to the friction between axial and braiding yarns.

For the reinforcement of flat, narrow automotive parts, 2D braids made of carbon fibres are used.

Knitted fabrics

Knitted fabrics have been discussed in Chapter 3. Due to the arrangement of the yarns in loops, these structures provide neither high tensile strength nor modulus. They are therefore not used as load-bearing applications in automobiles but solely in interior applications.

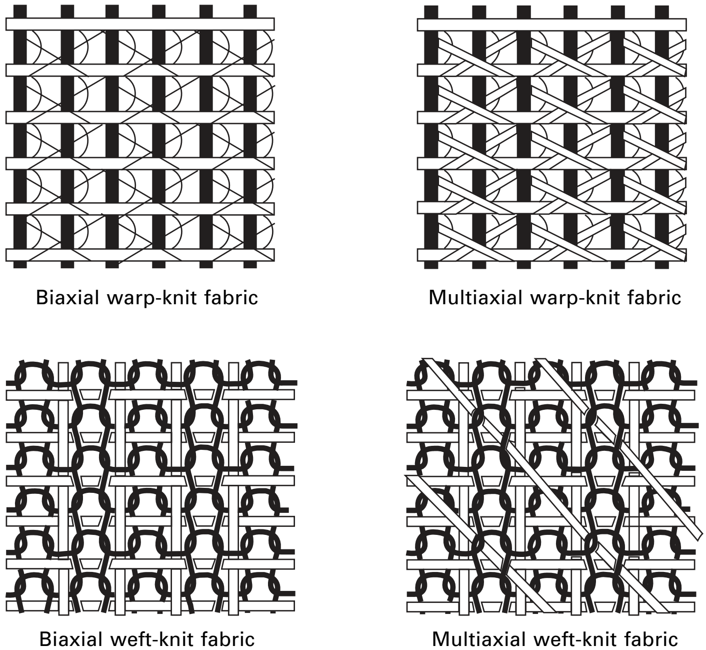
Nevertheless, weft-knits and warp-knits are of high importance for the reinforcement of composite structures when modified. Knitting allows the insertion of straight reinforcing yarns in warp and weft direction during production. Mono-, bi- and multiaxial weft- and warp-knitted fabrics can therefore be realized in economic production processes (Fig. 14.4).



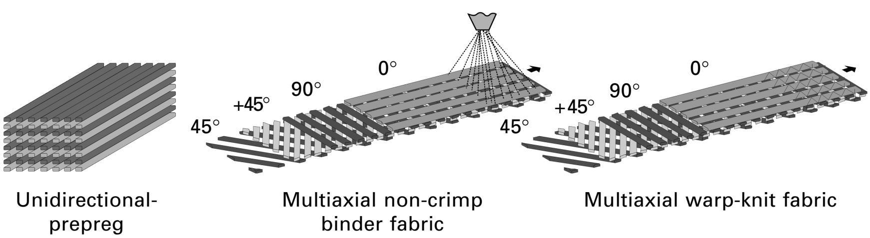
14.3 (a) Types of 2D braids and (b) braid angle.

Using knitting technology, every warp and weft yarn is bound with a single knitting loop. Compared to other technologies, the rovings therefore remain undisturbed. As knitting yarn, an auxiliary yarn made of thermoplastics like polyethylene or polyamide can be used. The insertion yarns are not subject to high load and abrasion during production, which allows the use of brittle materials such as carbon. Therefore this technology is very suitable for the production of reinforcing textiles for automotive applications.

A special weft-knitting process with warp and weft insertion which enables the production of near-net-shape knitted fabrics has been developed by Institut für Textil- und Bekleidungstechnik der TU Dresden, Dresden, Germany (ITB) [3, 4]. The innovative process is based on conventional flat-weft-knitting technology. Near-net-shape structures like disks with polarorthotrop reinforcing yarns can be realized [5].



14.4 Knits with reinforcing yarns.



14.5 Non-crimp fabrics.

Non-crimp fabrics

Non-crimp fabrics (NCF) are defined as textile structures which consist of one or several parallel layers of straight, unidirectional yarns that are not crimped [6]. Multiaxial NCF are 2D textiles consisting of at least two layers of unidirectional reinforcing yarns (Fig. 14.5). These layers are joined by being preimpregnated with resin, by fixation with adhesives or using warp-knit seams. Adhesives for the joining of non-crimp fabrics are used in the form of fluid, powder or nonwoven hotmelt. In a multilayer non-crimp fabric the layers can have different orientations. Possible orientations are 0°, 90° and orientations between 20° and 70°. Furthermore, the yarn count and the kind of material used in each layer can be varied. Industrial production machines can today process up to eight layers plus the introduction of two surface fabrics like nonwovens. In non-crimp fabrics joined by warp-knit seams the knitting pattern can be varied. The three patterns chain stitch, tricot lap and cord lap influence the drapability of the fabric [7]. Owing to the high standard of the machine technology, the processing of brittle high-performance yarns like carbon rovings is possible without much fibre damage. Only the joining process using warp knitting can be critical for very brittle yarns because the needles punch directly through the yarns. This can create filament breakage and yarn deflection. Nevertheless, a lot of non-crimp fabrics with different yarn architecture made of glass, carbon and aramide rovings are available today. In automotive applications, mainly carbon and glass are used as roving material.

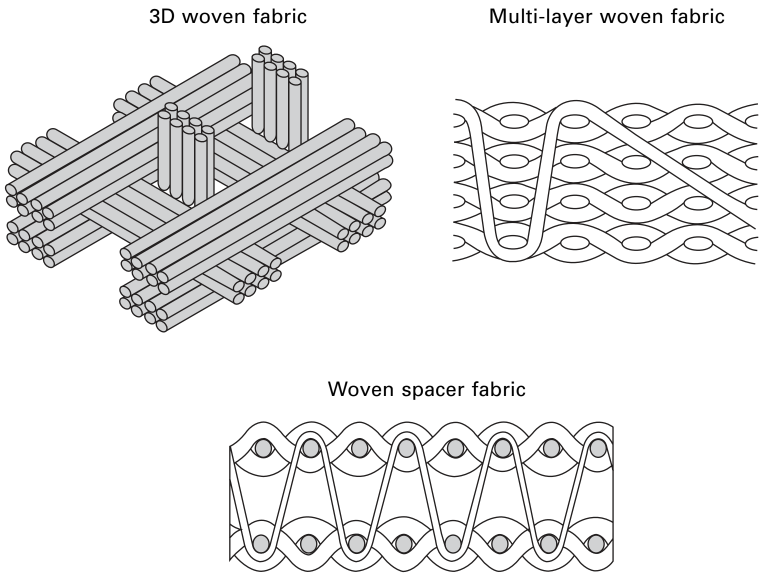
14.2.2 3D textiles

Processes for the production of 3D textile structures often allow the realization of textile preforms in one production step. Many production processes to create 3D textiles have been invented over the last two decades and development has not ceased yet. The most relevant technologies are described in the following.

3D woven structures

Different types of 3D woven structures exist. Figure 14.6 gives an overview of some types that are described in this section.

Three-dimensional woven fabrics are manufactured by inserting two picks with double shed opening, being perpendicular to each other. The yarns are fed in 0° and 90° direction and an additional yarn is positioned orthogonally towards the two others in z-direction. Three-dimensional fabrics feature quasi-isotropic properties, a high tensile and compression strength as well as a good bending stability and a very good impact behaviour [8–11]. The distribution of the reinforcement fibres is very uniform in all three dimensions. The drapability and the elongation behaviour of three-dimensional fabrics, however, is very poor. Three-dimensional fabrics are applied in fibre-reinforced composites with high thermal impacts as well as for structural parts for cars and aircraft. Another kind of three-dimensional fabric structures are the so-called *multi-layer woven fabrics*. These are manufactured by the composition of several fabric layers without any spacing between. The layers are fixed by interlocking or warp knitting. The yarns are oriented in 0° and 90° direction and the yarns in z-direction are variable. Multi-layer fabrics can be draped well, having very good elongation behaviour and good tensile, compression and bending stability. These fabrics are applied in impact charged multi-



14.6 3D woven structures.

layer composite structures, like automobile floor components [12, 13]. Among others, 3Tex, Cary NC, USA produces these kinds of fabrics.

Woven spacer fabrics also have a three-dimensional structure. They are manufactured by weaving-in upright pile warps, and their properties are comparable to those of multi-layer fabrics, but their drapability is poor. The distance between the two layers can be adjusted individually. These textiles show a high resistance against perforation. They are applied in sandwich structures, for example in composite lightweight design applications [10, 14]. Another process to produce 3D-textiles is called Shape Weaving process and was developed by the company Shape 3 Innovative Textiltechnik GmbH, Wuppertal, Germany [15]. The integration of warp and weft yarns of different lengths during the weaving process is the principle of this technology. Due to these extra yarn lengths the textile expands into the third dimension. This enables the configuration of textile fabrics to a certain shape during the weaving process [16]. This technology has great potential but is currently not being used for automotive textiles.

Braided structures

Braided structures in automotive applications have mostly been used to realize cable trees. Hereby several isolated wires are joined together by surrounding them with a tubular braid. The wires are therefore protected against mechanical damage and the car assembly process is simplified. Nowadays, as the use of composites in automotive applications is increasing, braided structures are also used for structural parts like bumpers and crash absorbers. For the production of these structures, overbraiding technology is used. But the 3D rotary braiding technology might also gain importance for very specialized parts.

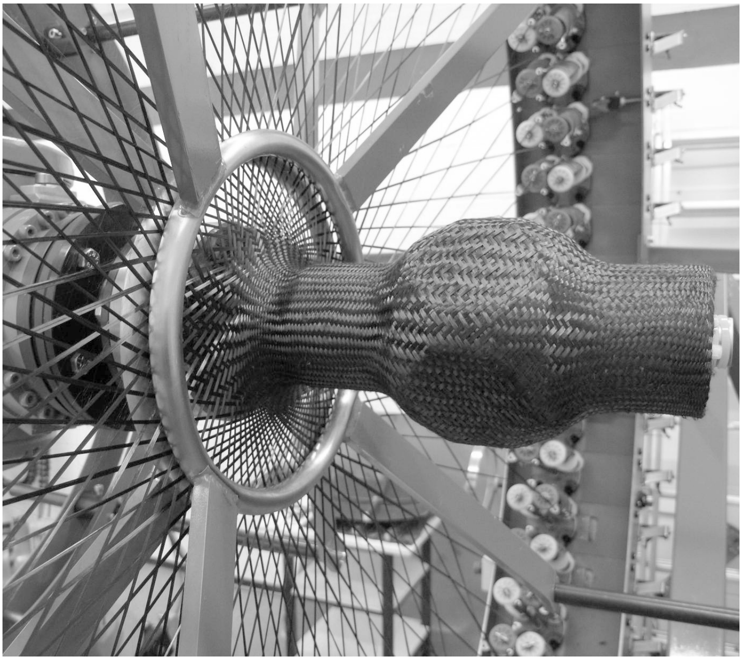
Overbraided structures

One possibility to create 3D textiles or textile preforms using braiding technology is overbraiding, a special kind of circular braiding. The creation of the textile is similar to circular braiding but the tubular braid is directly laid down on a net-shape mandrel. Several layers can be braided on the mandrel with individual starting points and end points of each layer. Similar to circular braiding, each layer can consist of a triaxial yarn architecture and braid angles can be varied between 10° and 80°. The orientations of the braiding yarns can be varied in each layer [17]. Also the formation of a layer that only consists of 0° yarns is possible. Because the yarn carriers can be equipped with different materials, the production of hybrid structures is possible. New developments use the initial division of the two yarn systems of braiding yarns to set up one group with reinforcing yarns and the other with auxiliary yarns. Choosing a suitable auxiliary yarn (for example, an elastic thermoplastic yarn), non-crimp structures can be realized, so-called unidirectional braids (UD braids). This technique not only leads to minimized filament damage of the reinforcing yarn, it also leads to structures which can concur with UD non-crimp fabrics.

Because the yarns support each other, orientations can be realized away from the geodesic line on the mandrel (Fig. 14.7). The braided structure remains stable as long as it stays on the mandrel. Depending on the mandrel concept, the braid can either be removed from or remain on the mandrel, which can become part of the composite. For the moving of the mandrel a multiaxis take-up can be used as well as an industrial robot. Therefore an automated production of textile preforms of complex geometry in one process step can be realized. This is of crucial importance for automotive applications where large lot sizes are common.

Recent developments of August Herzog Maschinenfabrik GmbH & Co. KG, Oldenburg, Germany (Herzog) led to a special design of the overbraiding machine. Instead of moving the yarn carriers on the front of the machine body, they are led on the inside of a circular machine body (Fig. 14.8). The orientation of the yarn carriers in the radial direction is the reason for the name of this machine type ‘radial overbraiding machine’.

This design leads to reduced filament damage during the braiding process due to a minimization of yarn movement along yarn guiding elements and reduced yarn-yarn interaction. The result is a high production speed and a



14.7 Overbraiding.

14.8 Radial overbraiding machine.

reliable production process. A prominent application so far are the bumpers of the BMW M6 made of carbon fibre reinforced plastic (CFRP), that are realized using overbraided preforms [18]. Other CFRP products realized using overbraiding technology are crash tubes, rocket engine nozzles and others [19, 20].

3D braided structures

3D braided structures do not only expand in the third dimension, they also contain an integral yarn architecture with a three-dimensional yarn course. Several 3D braiding technologies do exist such as the square-braiding technology, the 4-step braiding technology and the 3D rotary-braiding technology, which has the highest potential for application in automotive engineering.

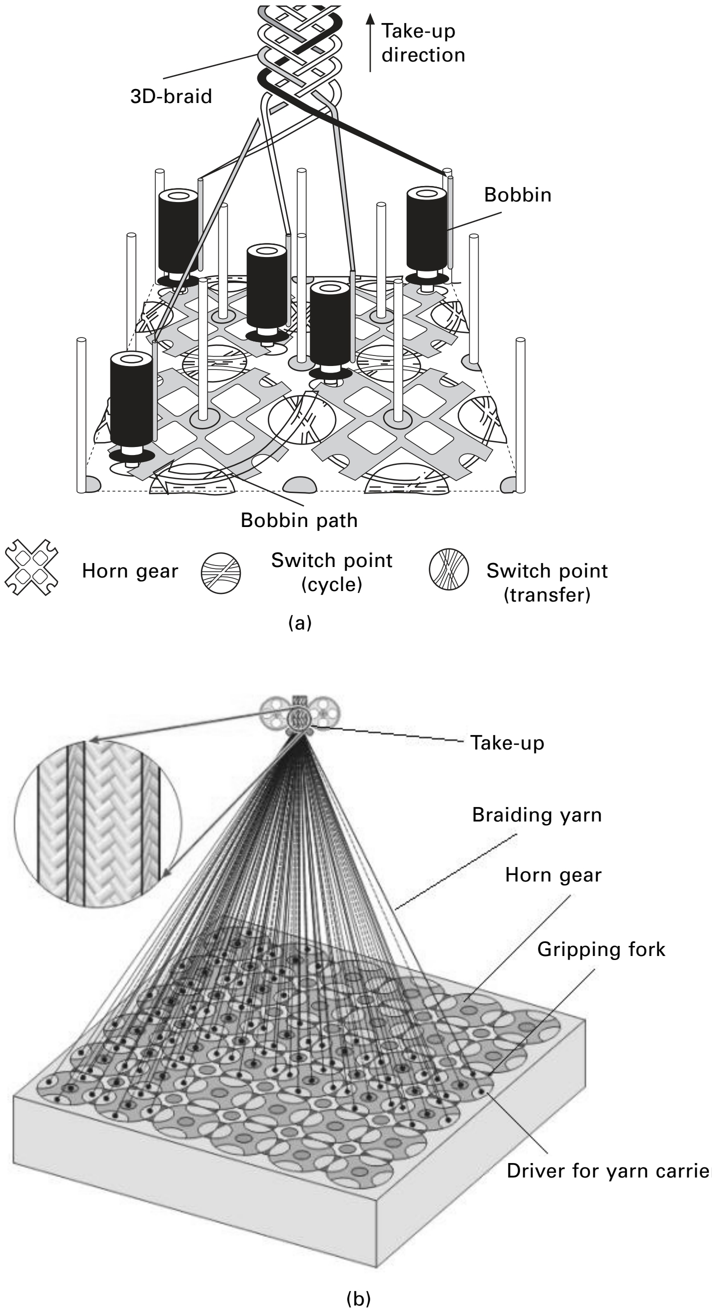
The newest generation of 3D braiding technology is 3D rotary braiding. Two different technologies exist. The ITA-Herzog 3D rotary braiding technology invented by Institut für Textiltechnik, RWTH Aachen University, Aachen, Germany (ITA) and Herzog (Fig. 14.9 (a)) and the 3TEX 3D rotary braiding technology invented by 3TEX, Cary, NC, USA (3TEX, Fig. 14.9 (b)). In both technologies the transport of the yarn carriers is realized by rotating horn gears that turn in counter direction.

With the ITA-Herzog principle, the yarn carriers are guided inside grooves that are cut into the machine table. Through switches located between the horn gears, it can be decided whether a yarn carrier is to be transferred to the next horn gear or whether it is to remain on the initial horn gear. Since every switch and every horn gear can be controlled individually, an individual path of each carrier over the machine table is possible [21]. The machine is computer controlled. Therefore complex and variable yarn architectures as well as complex and variable textile architectures can be realized in an automated production process.

The 3TEX 3D rotary braiding principle is similar to the ITA-Herzog 3D rotary braiding principle. But instead of switches, so-called gripping forks are located between the horn gears. This allows two yarn carriers to stay between two horn gears at the same time. At this position it can be decided whether they should swap places or rest on their respective horn gear [22].

The 3TEX technology can use more yarn carriers on the same area than the ITA-Herzog technology. On the other hand, the yarn carriers of the ITA-Herzog technology are bigger and have more yarn capacity than those of 3TEX. The 3TEX technology is faster than the ITA-Herzog technology but it does not offer the same freedom in design of braid design.

3D rotary braiding technologies enable the manufacture of textile preforms with integral yarn architecture and continuous changes of cross section geometry and dimension in one process step (Fig. 14.10). The processing of



14.9 3D rotary braiding principles.

14.10 3D braids.

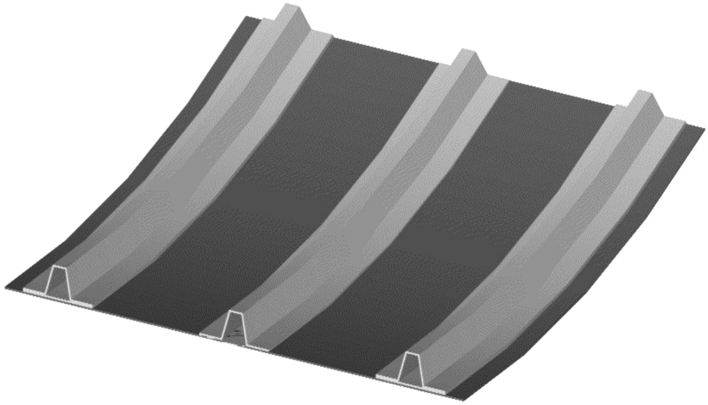
carbon and glass rovings is state-of-the-art. Those braided structures can be used for stiffening purposes or in energy absorption applications.

14.3 Processing textiles using preforming and prepreg technology

In today's processing of textile reinforced plastics (TRP) two ways of processing yarn architectures are mainly used: the processing of rovings or textile fabrics which are pre-impregnated with the resin (prepreg technology) and the processing of dry textile preforms which are impregnated in a second step, in the shape of the final part (preforming). In contrast to prepreg manufacturing, preforming creates a dry textile reinforcement structure which already has characteristics concerning geometry and fibre orientation required in the final part. This means that the rovings need to be formed and fixed via textile handling and assembly processes to achieve the geometry to later bear the load on the component.

For the creation of this inherently stable textile structure, several technologies are available. There are technologies which generate the three-dimensional structure from the yarns in one process step (e.g., 3D braiding, overbraiding, 3D weaving, contour knitting with weft insertion). These processes are referred to as one-step preforming. However, these technologies are limited to a certain degree of complexity concerning the reinforcing textile and thus the geometry of the final part. Examples of typical component geometries which are created with one-step preforming technologies are profiles, panels, sandwich structures and hollow parts used for, e.g., a car body.

For the realization of components of high complexity, the yarns are processed in multi-step processes. At first, 2D textiles like multiaxial non-crimp fabrics or woven fabrics and/or three-dimensional subpreforms like the above-mentioned 3D braids are manufactured. These textiles are subsequently processed to complex preforms via handling and assembly processes. A practical example for a complex composite component is the so-called rib stiffened panel (see Fig. 14.11). Rib stiffened panels consist of a flat shell (plane, unidirectional or multiaxial curved) and of stiffening profiles (e.g., top-hat-, T- or L-profile). These kinds of components are frequently used to



14.11 Panel with reinforcing profiles.

function as self-supporting outer skin in lightweight constructions such as automobiles and aircrafts.

Intermediate textiles for the shell are the above-mentioned flat textiles which are available as rolled fabrics. For the ribs, both 2D intermediate textiles as well as subpreforms can be used.

In order to process these textiles, the following steps are required:

- cutting
- handling and draping
- joining and conditioning.

These technologies are proven for the processing of carbon textiles for automobile parts.

14.3.1 Cutting

For an automated cutting of textile fabrics made of brittle high-performance yarns, computer controlled cutting machines which use different cutting techniques are available. Depending on the material, the fabric type and the fabric thickness that has to be cut, the suitable cutting device has to be chosen. These range from rotating cutting disks, oscillating knives to laser cutting. The cutting disks are supported by ultrasonic movement and roll along the path which has to be cut. Oscillating knives can be moved with high frequency or supported by ultrasonic movement. If necessary, the fabric can be fixed to the cutting table with the help of vacuum which is applied by covering the fabric with a sheet. Cutting using water-jet proved to be unsuitable for the cutting of dry textile fabrics. Owing to the computer-controlled movement of the cutting head, even complex contours can be cut out of the rectangular base.

14.3.2 Handling and draping

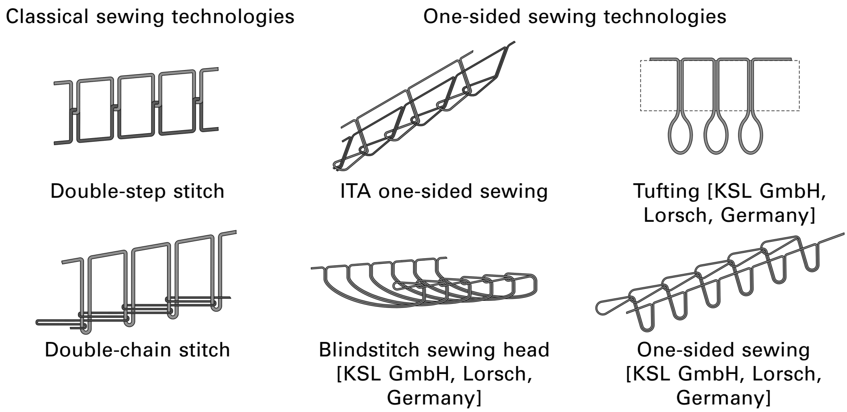
The handling and draping of textile fabrics, structures and subpreforms is at present mainly done manually. Several methods for gripping and transporting textile structures have been invented so far, e.g. needle gripping, vacuum-supported gripping, electrostatic gripping or ice gripping techniques. But no gripping or handling technology has been found so far that is suitable for the whole range of materials and applications.

14.3.3 Joining technologies

The most important joining technology for textiles besides gluing is still sewing. Sewing technologies will play an important role in the processing chain of future manufacturing of textile reinforced components. Their importance concerning cycle time reduction as well as cost savings can be regarded in line with those of qualified consolidation procedures [23]. The tasks of the sewing techniques within the preforming process range from the insertion of flat reinforcements as well as the fixation of individual components of a preform for the subsequent process steps to the manufacturing of load-compatible seam areas. Different sewing technologies are applied in differing process steps within the multi-step preform production. Sewing technologies are chosen according to the function of the seam, the preform geometry and the component loads [24].

The sewing of reinforcement textiles is both a textile and a load-compatible joining process. Thus a force-flow in form of an upright reinforcement is achieved in the seam area. Local reinforcements can be applied. Flat textiles are converted to 3D reinforcement structures. Via the application of reinforcement textiles within a component, several special mechanical properties can be realized. Additionally, the application of sewing technologies allows the production of near-net-shape textile structures. Both conventional (e.g., double-step stitch) and one-sided sewing technologies (tufting, blind stitch, ITA sewing technology) are applied [21, 25]. Figure 14.12 shows the seam architecture of relevant sewing technologies. The one-sided sewing technologies have the advantage of good automation and the possibility of sewing in a 3D mould as they are mountable to an industrial robot. The infiltration behaviour of the textile is improved because of the permeability caused by the seams.

Although seams enable high strength and drapability, there are also disadvantages, e.g. the disorientation of reinforcing yarns through the sewing thread. Therefore alternative joining processes, such as adhesive bonding, are also applied. Apart from the mentioned joining processes, the so-called tailored fibre placement (TFP) is used with reinforcement textiles. The reinforcing yarns can be put down purposefully (CAD operated) on a 2D



14.12 Seam types.

textile. Parallel to placing the fibres, they are stitched on the textile with a thin thread. This technology can be used for additional local reinforcements, e.g. for fittings or holes in the TRP part.

14.3.4 Mechanical properties of the final textile reinforced plastics structure

The reinforcing yarns are to be placed in a near-net-shape geometry that should be consistent with the strains that occur during use of the final structure. Different degrees of complexity in the textile structure can be realized with preforming technologies.

Disorientation or damage of the yarns in the reinforcement textile can be caused by mistakes in handling, forming or assembling processes. This decreases the mechanical properties of the final TRP structure. According to the mechanical requirements of the TRP structure, preforming technologies should be rated by their tendency to yarn disorientation and damage.

14.3.5 Productivity and production process complexity

The introduced preforming technologies are strongly differing in productivity and process complexity. According to the requirements of the TRP structure, a compromise of mechanical and geometric properties of the structure and of the productivity of the production process must be found.

There are numerous woven fabric variants of interest for textile reinforced automotive composite applications. These include amongst others multi-layer woven fabrics, three-dimensional woven fabrics as well as flat woven fabrics with three-dimensional design features. Regarding industrial usage, flat fabrics are widespread because of the good mechanical properties and the fast production process and thus their attractive price. Owing to its high productivity while creating near-net-shape textile structures, overbraiding technology is gaining importance for automotive applications.

14.4 Applications of textile structures in automobiles

Formula 1 car bodies consist of carbon textile structures. This reduces weight and improves crash behaviour considerably. Especially car noses and monocoques are made from carbon textile structures as these are crucial parts of the automobile in a crash.

Sports cars are often tuned with parts made from carbon fibres, e.g. aprons and spoilers. A serial application is the bumper which again decreases weight and improves the load take-up in case of a crash (e.g., BMW M6, Lotus Elise). These elements consist of braided carbon fibre structures [18]. The crash beams of the McLaren SLR car are located in longitudinal direction of the car, similar to crash elements in ordinary vehicles, and take up the load in a frontal and diagonal crash. They consist of foam cores overbraided with carbon rovings.

Another application is the car roof of the BMW M6 which consists of a TRP in sandwich design which reduces weight and leads to a lower centre of gravity of the car. It consists of carbon woven fabrics which are left visible from the outside on the upper surface. In Mercedes upper class cars, trunk hatches are made of SMCs (sheet moulding compound, consisting of resin and short fibres) to reduce weight and to integrate antenna for radio, etc. This is not a structural element in the true sense.

14.5 Future trends

- Development trends with reinforced structures go to more and more complex structures. This contradicts the trend to further automate the production process and to design more load-conforming TRPs. This dilemma must be solved.
- With the exception of Formula 1 racing cars, serial car frames are not made of TRPs yet. This would allow a significant reduction in the car weight and can therefore be expected to be realized in the near future.
- Another important trend is the development of processing techniques to manufacture 3D reinforcing structures from flat textile fabrics.
- New economical manufacturing processes for infiltratable and near-net-shape preforms with complex geometry become more and more essential. Great importance lies in an economic, automated preform manufacturing to be able to realize large-scale composite production. By using automated textile production technologies to manufacture complex textile preforms

made from high performance yarns, uneconomic manufacturing steps can be eliminated and production costs can be decreased dramatically.
- A further trend is the integration of different functions into composites. An example of this is the combination of energy-absorbing elements with structure composites.
- A further point could be continuous health monitoring of composites, in order to recognize structural failure at an early stage.

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Textile composites for automotive structural components

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Abstract: In this chapter, after a review of textile structures for composites, the role of fiber architecture in the manufacturing of automotive composites components is discussed. The various textile preforms are classified according to fiber architecture and manufacturing technology. The Sunrise™ electric vehicle program is used as an example to illustrate the design procedure and the feasibility for large-scale manufacturing of automotive structural composite components at targeted weight and affordable cost. Specifically composite pillars and wheel wells are used as examples to demonstrate the procedure in the integrated design for manufacturing (IDM) of automotive structural composites based on the Fabric Geometry Model (FGM). The chapter concludes with a summary and discussion of future trends in the use of textile composites for automotive structural components

Key word: textile structural composites, electric vehicle, textile preforming, fiber architecture, integrated design for manufacturing, B-pillar, wheel well.

15.1 Introduction

Textile structural composites represent an important class of affordable advanced materials, which are reinforced by textile preforms for primary structural applications. Making use of the unique combination of lightweight, flexibility, strength and toughness, textile composites found early applications in the 1950s in space re-entry vehicles. The need for higher damage tolerance, especially through the thickness strength requirements, led to the rediscovery of the merits of textile composites in the 1980s. The popularization of liquid molding processes and the demand for affordability in the 1990s added a new dimension to the interest in textile composites. As the needs for composites are being expanded to large-scale structural components, textile reinforcements have increasingly been considered for providing adequate integrity as well as shape-ability for low cost near-net-shape manufacturing. Textile composites are uniquely suited for automotive composite components because of their capability to address the uncompromising need of automotive composites for the combination of strength and toughness; scale-up manufacturability; and low cost manufacturing.

The increasing awareness of energy shortage and environmental impact caused by the pollution generated by fossil fuel-based automobiles in recent years has re-energized the awareness of the need for clean and energy-efficient vehicles. There is a global effort to seek energy saving solutions. One of them is to use lightweight composite materials [1, 2]. Because of their wide availability at low cost, textile composites have invariably been identified as a preferred reinforcement strategy to meet automotive structural composite needs [3]. In the US, in addition to earlier technology demonstration projects such as Ford Motor's million dollar all composite car, we have witnessed at least three generations of national (government/industry) programs in the US aimed at advancing the technology of composites for automobiles starting from the Automotive Composite Consortium (ACC) [2] wherein the three major auto companies in the US worked closely together with their industry suppliers and academic research partners to target selected structural components such as the cross-members and the crash rails. While the earlier program proved the feasibility of building a composite car, the ACC program demonstrated the feasibility of cost reduction via textile composites because of significant part consolidation for selected structural components.

Following ACC was the Partnership for the New Generation Vehicles Program (PNGV) championed by then Vice President Al Gore. The goal of PNGV was to achieve three times the fuel efficiency or 80 miles/gallon (at the 1993 level) by reducing the weight of the car body and chassis by 50% [2]. This must be accomplished with reduction in manufacturing cost and emission level. The Freedom CAR program replaced PNGV in 2002 with the long-term aim to develop petroleum free cars using "leap frog" technologies that will provide America with greater freedom of mobility and energy security while lowering costs and reducing impact on the environment. A significant component of this five-year program starting in 2006 is the materials technologies subprogram aiming at the development and validation of the enabling advanced materials and manufacturing technologies to achieve the goals of Freedom CAR [4]. Composite materials are identified as key components to achieve structural weight reduction of automobile body and chassis components by at least 60% and overall vehicle weight by at least 50% compared to 1997 passenger vehicles.

It is of interest to observe that many solutions to the weight reduction problem proposed in the Freedom CAR program were already available in 1997 as demonstrated in the Sunrise^{TM} electric vehicle (EV) program sponsored by the Department of Commerce [5]. The Sunrise^{TM} team, through strategic use of textile composites, demonstrated that a full size electric vehicle equivalent to a Ford Taurus in interior room but weighing 40% less at 159 kg (350lb.) can be built for a market competitive selling price of $20,000 at an annual production of 20,000 units. The Sunrise^{TM} EV has a combined city/highway range of 290 km (179 miles) and achieved 38.5 km per liter (90.5 miles per gallon) equivalent of gasoline with an average energy efficiency of 57 watt-hours per km (91watt-hours per miles) [5] proving that the Sunrise^{TM}

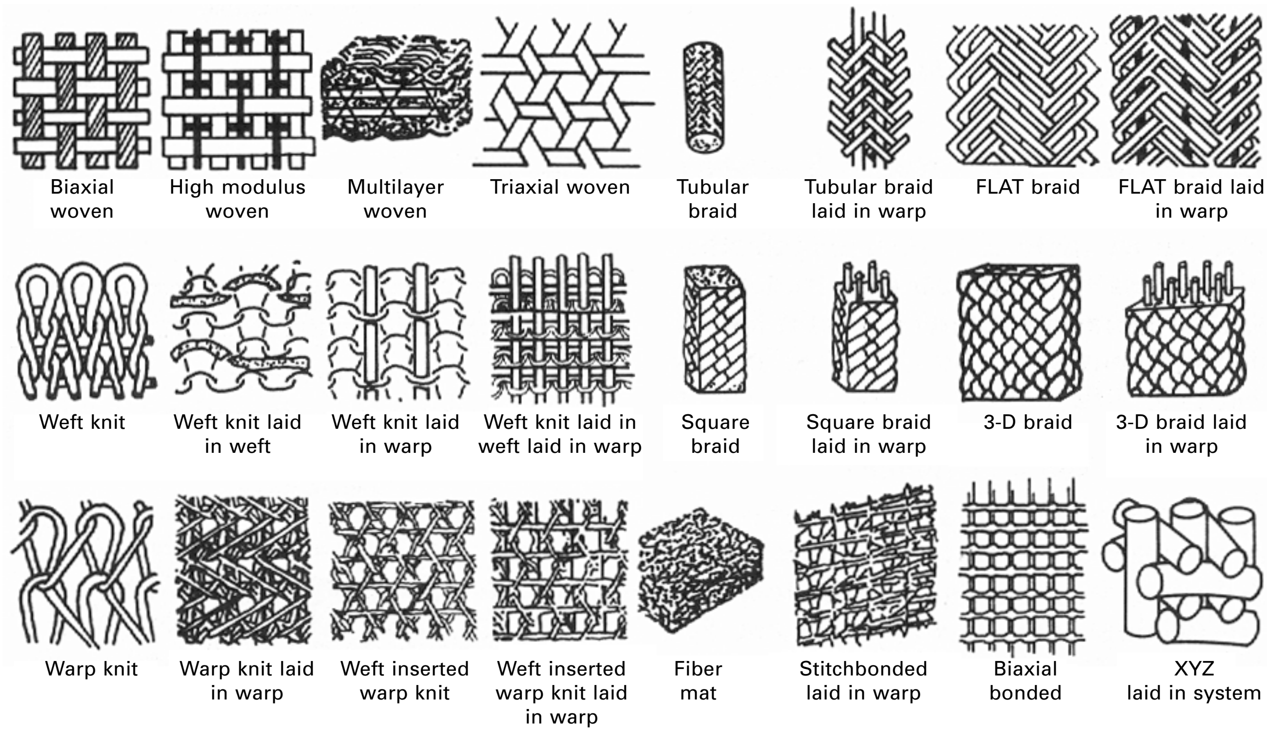
technology already exceeded the PNGV target of 34 km per liter (80 miles per gallon) of gasoline. Of course, with gasoline price at $1.25/gallon there was not an "energy crisis" then! Thus further scale-up production of the Sunrise™ electric vehicle was put on hold due to lack of funding from the government and from the private sector. The lesson learned from the Sunrise™ program was that technology alone is a necessary but not sufficient condition to take the clean vehicle to the consumer market. The ambitious goal and urgency of the Freedom CAR program is largely driven by the rapid rise of gasoline prices in the recent years and the increasing evidence of environmental impact of automobile pollution on health and global climate change.

In this chapter, after a review of textile structures for composites, the role of fiber architecture in the manufacturing of automotive composite components will be discussed. The various textile preforms will be classified according to fiber architecture and manufacturing technology. The Sunrise™ electric vehicle program is used as an example to illustrate the design procedure and the feasibility for large-scale manufacturing of automotive structural composite components at targeted weight and affordable cost. Specifically, composite pillars and wheel wells are used as examples to demonstrate the procedure in the integrated design for manufacturing (IDM) of automotive structural composites based on the Fabric Geometry Model (FGM). The chapter will conclude with a summary and discussion of future trends in the use of textile composites for automotive structural components.

15.2 Textile structures for automotive composites

The ultimate goal of manufacturing a composite structure for automotive components is to meet design requirements including performance and cost. How successfully the goal can be met depends on the effective use of the reinforcement material, architecture and processing technology. As illustrated in Fig. 15.1, there is a large family of textile structures available for structural reinforcement of composite vehicle components [6]. Preform fiber architecture plays a key role in composite manufacturing by facilitating the forming and resin infiltration processes. The properties of the composite will also be influenced by fiber architecture. Fiber orientation (θ) and volume fraction (V_f) are key engineering parameters influencing textile composite formability, permeability and mechanical performance. The key criteria for the selection of textile preforms for structural composites center around the capability of the technology to provide (a) in-plane multiaxial reinforcement, (b) through thickness reinforcement and (c) formed-shape and/or net-shape manufacturing. Depending on the processing and end use requirements, some or all of these features are required.

Based on the fabric formation techniques through fiber entanglement or yarn twisting, the fiber architectures shown in Fig. 15.1 are created by



15.1 Textile structures for composite reinforcements.

interlacing, interlooping, and intertwining or multiaxial fiber placement. While most textile preforms are converted from yarn to fabric (YTF) structures, some preforms, such as fiber felts, are converted directly from fiber to fabric (FTF) structures. In Table 15.1 the four basic fabric formation techniques are compared.

While weaving, braiding and knitting can produce planar or 3-D structures; nonwoven fabrics can be a 2-D planar system with random or organized fiber orientation, as well as the orthogonal 3-D system. The 2-D and 3-D fabrics are distinguished by yarn orientation distribution and the number of yarn diameters in the thickness direction. A 2-D fabric consists of two to three yarn diameters in the thickness direction with fibers oriented in the x–y plane. A 3-D fabric, consisting of three or more yarns in the thickness direction, is a fibrous network wherein yarns pass from surface to surface of the fabric in all three directions. Depending on the fiber architecture, the orientation and packing density of fibers, the fiber volume fraction varies. The theoretical range of fiber orientation angle and fiber volume fraction for each fabric preform-system and their components commonly used for composite reinforcements are shown in Table 15.2 [7].

It should be noted that, although the achievable range of fiber volume fraction is restricted by theoretical fabric geometric limits due to yarn jamming, it is possible to achieve higher fiber volume fraction in reality because of the compressible nature of the preforms. By forcing the preform into a smaller mold, a higher fiber-volume-fraction composite can be made, but this is done at the expense of introducing fiber misalignments and dried fibers.

Through geometric modeling of textile preforms a quantitative communication link has been developed between the preform manufacturer, composite fabricators and product design engineers [7]. By defining fiber architecture and textile preforming processes in terms of engineering and processing parameters V_f, θ, and η, rational composite design procedures and process control guides can be established.

Table 15.1 A comparison of fabric formation techniques

Preforming technology	Yarn introduction direction	Formation technique
Weaving (YTF)	Two (0°/90°) (warp and fill)	Interlacing (by selective insertion of 90° yarns into 0° yarn system)
Nonwoven (YTF or FTF)	Three or more (orthogonal)	Mutual fiber placement, fiber bonding
Knitting (YTF)	One (0° or 90°) (warp or fill)	Interlooping (by drawing loops of yarns over previous loops)
Braiding (YTF)	One (machine direction)	Intertwining (position displacement)

Table 15.2 Process engineering parameters for textile preforms

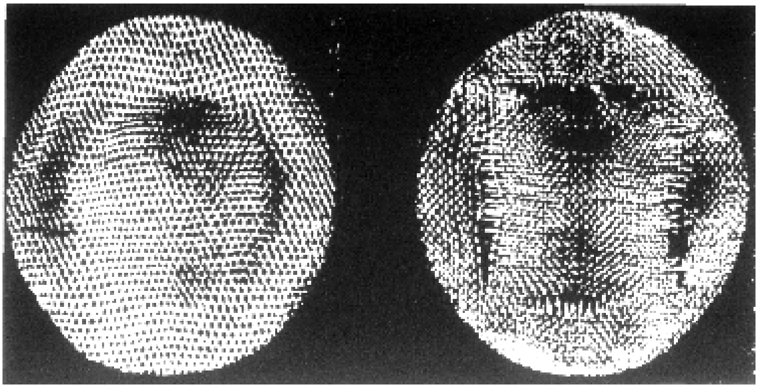
Preform	Fiber orientation, θ (°)	V_f	Processing parameter
Linear assembly	θ – yarn surface helix angle	0.6 ~ 0.8	bundle tension,
		0.7 ~ 0.9	transverse
	θ = 0		compression, fiber
Roving	θ = 5 ~ 10		diameter, number of
Yarn			fibers, twist level
Woven	θ_f – yarn orientation in fabric plane		fiber packing in yarn, fabric tightness factor,
	θ_c – yarn crimp angle		yarn linear density
2-D Biaxial	θ_f = 0/90, θ_c = 30 ~ 60	~ 0.5	ratios, pitch count,
2-D Triaxial	θ_f = 0/90/±30~60, θ_c = 30 ~ 60	~ 0.5	weaving pattern
3-D Woven	θ_f = 0/90, θ_c = 30 ~ 60	~ 0.6	
Non-woven	θ_x – fiber/yarn orientation along *x* axis	0.2 ~ 0.4	(2-D Non-woven) fiber packing in fabric,
2-D Non-woven	θ_y – fiber/yarn orientation along *y* axis	0.4 ~ 0.6	fiber distribution (3-D Orthogonal)
3-D Orthogonal	θ_z – fiber/yarn orientation along *z* axis		fiber packing in yarn, yarn cross section,
	θ_{xy} – fiber distribution on fabric plane		yarn linear density ratios
	θ_{xy} = uniform distribution, θ_z		
	θ_x, θ_y, θ_z		
Knit	θ_s – stitch yarn orientation		fiber packing in yarn,
	θ_i – insertion yarn orientation		fabric tightness factor,
2-D Weft knit	θ_s = 30 ~ 60	0.2 ~ 0.3	yarn linear density ratios, pitch count,
3-D MWK	θ_s = 30 ~ 60, θ_i = 0/90/±30 ~ 60	0.3 ~ 0.6	stitch pattern
Braid	θ – Braiding angle		fiber packing in yarn,
2-D Braid	θ = 10 ~ 80	0.5 ~ 0.7	fabric tightness factor,
3-D Braid	θ = 10 ~ 45	0.4 ~ 0.6	braid diameter, pitch length, braiding pattern, carrier number

15.3 The role of fiber architecture in composite performance

Preform fiber architecture plays a key role in composite manufacturing, influencing the productivity and quality of the composite. The properties of the composite will also vary depending on the fiber architecture. Fiber orientation (θ) and volume fraction (V_f) are key engineering parameters for textile composite formability, permeability, and performance.

15.3.1 Formability

The manufacturing of composites often requires transformation of the fiber reinforcements into various structural shapes through net shape fabrication or formed shape processing. While 3-D textile preforming is more suitable for the creation of net structural shapes, 2-D textile preforms are usually formed into shapes by molding or stitching. One of the earlier studies of fabric formability in composite manufacturing [8] showed that total available deformation could be imposed on the fabric uniformly and that the modes of deformation are important parameters for fabric formability. Potter [8] demonstrated that weft knitted fabrics are significantly more conformable than biaxially woven fabrics because deformation of the knitted fabric in the axial, transverse and bias direction are 50%, 50% and 26%, respectively, compared to 0%, 0% and 45% for the woven fabric. The same point can also be illustrated in a comparison of the shear resistance of biaxially and triaxially woven glass fabrics [9]. Comparing the strain behavior of plain woven and triaxial basic fabric of similar areal density (282 vs. 285 g/m^2), under biaxial loading, it was found that the shear deformation of the triaxial fabrics is considerably more uniform than that of the biaxial fabrics (Fig. 15.2). As a result of this study, it was found that triaxial fabric is more adaptable to 3-D draw molding than biaxial fabrics made from the same yarn. In quantifying the formability of fabrics, Dow [10] suggested that yarn slippage and low yarn jamming angles are required for fabric conformability. Accordingly, in fabric formability modeling, fiber volume fraction distribution, fiber orientation and fiber interlacing intensity as well as the limit of geometric deformation (all of which are governed by the architecture created by specific textile preforming techniques) must be considered.



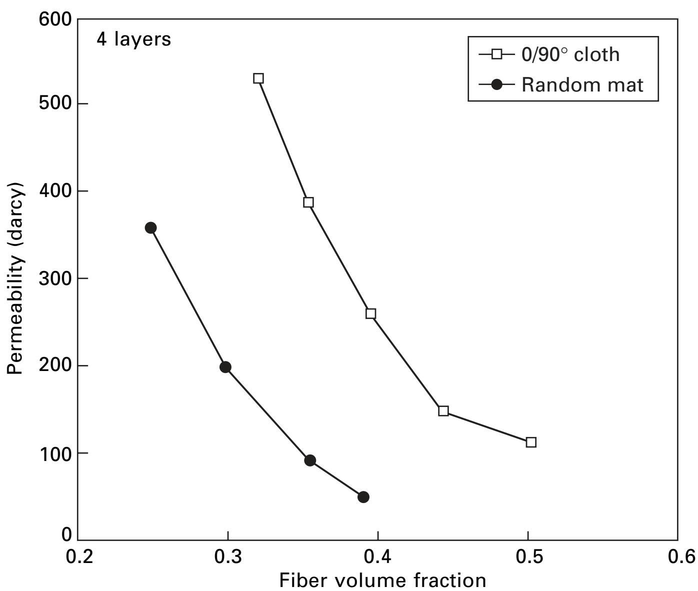
15.2 Effect of fiber architecture on formability of fabrics.

15.3.2 Permeability

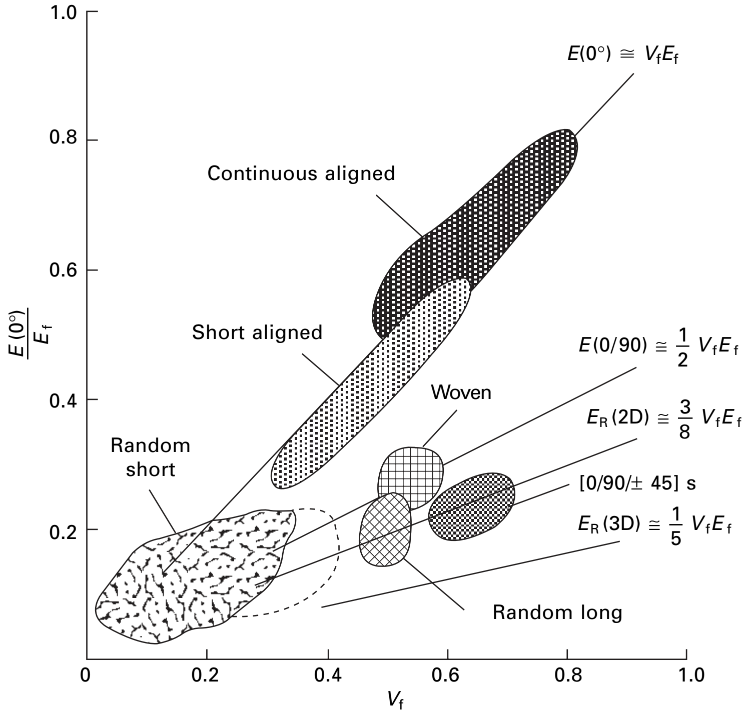
Fluid flow permeability of textiles is an indication of how easily and uniformly a matrix can be infiltrated into the fibrous assembly. McCarthy and Kim [11] concluded that the permeability of textile preforms is affected by the dynamic interaction of fiber architecture and fiber volume fraction (Fig. 15.3). In the same figure, it can be noted that, for the same fiber volume fraction, ordered structure such as 0/90° woven fabrics have higher permeability than disordered structures such as discrete chopped fibers. Loos *et al.* [12] also observed the dependence of permeability on fiber volume fraction in their study of carbon multiaxial warp knit performs. It was found that the introduction of through thickness fibers significantly increased the permeability of the preforms, especially for preforms with high fiber volume fraction.

15.3.3 Mechanical properties

Fiber architecture plays an important role in the translation of fiber properties to the composites as well as controlling the level of matrix infiltration. Figure 15.4 illustrates the dynamic interaction between material (fiber), fiber architecture and processing [13]. It can be seen that fiber architecture affects fiber packing and hence the maximum obtainable fiber volume fraction. As a result the translation efficiency of fiber properties to the composite is strongly influenced by fiber architecture. It can be seen that the highest fiber



15.3 Effect of fiber architecture on fabric permeability.



15.4 Fiber property translation efficiency as a function of fiber architecture and fiber volume fraction.

volume fraction is obtainable for aligned continuous filaments as in the case of filament wound structures. Aligned short fibers, on the other hand, have lower maximum fiber volume fraction than those of the aligned continuous filaments. For the same fiber volume fraction, the 0/90° woven and the random long fibers (as in the case of sheet molded compounds) will have lower fiber property translation efficiency.

15.4 The Sunrise™ electrical vehicle program

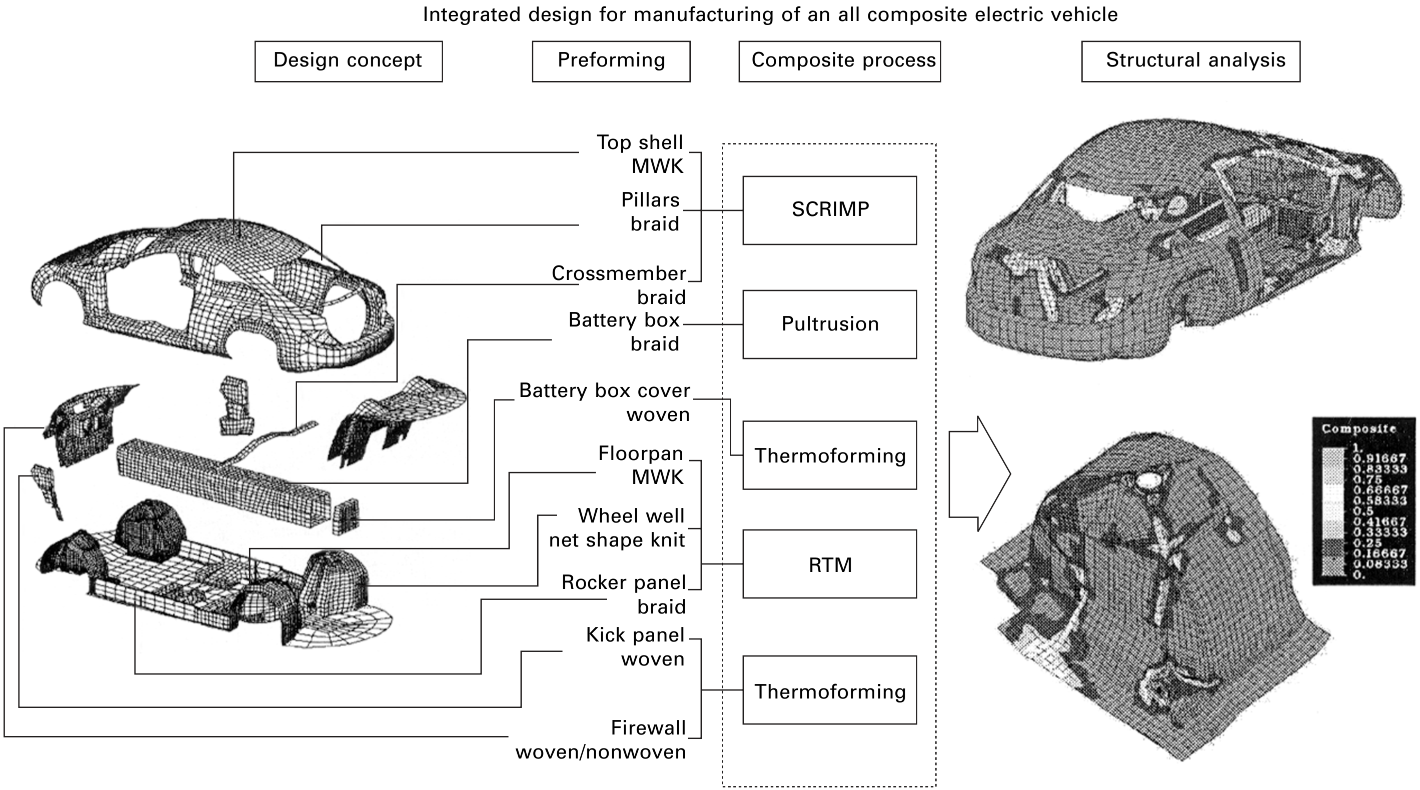
There are numerous examples of applications of textile composites for automotive structural components ranging from net-shape braided crash rail, to braided cross-members, to racing car seat backing, to door frames, tire belts, brake pads, to connecting rods and torsion bars as well as the monocoque body of formula racers. The most extensive integrated use of textile structures for automotive structural components is the Sunrise™ electric vehicle. Therefore the Sunrise™ is used in this article to illustrate the strategy and design methodology for producing automotive structural components. It is felt that this textile-based composite material's design for manufacturing platform is also applicable to other types of vehicles and many other non-automotive structural applications.

The Sunrise™ electric vehicle program is an Advanced Technology Program (ATP) co-funded by the National Institute of Standards and Technology (NIST) in 1996 along with a consortium of eight industry partners. This program calls for the development of the technology and pilot production tools capable of producing the Sunrise™ monocoque body/chassis cost-effectively at 20,000 units per year. With a target body-in-white (BIW) weight of 159 kg (350 lbs), this vehicle must also meet Federal Motor Vehicle Safety Standards (FMVSS).

One of the major tasks of this program was to organize the vehicle into components for distributed manufacturing by way of modular design. Figure 15.5 provides an overview of the extensive use of textile composites for the car body. The goal was to make the part integration as high as possible, while maintaining ease of manufacture, both in preforming and in the final composite consolidation phase.

In the design of the Sunrise™ vehicle, several technical issues were addressed. These issues include the level of part integration, the integration of various textile preforms, and the integration of local fiber architecture into the global structural design. Taking advantage of the wide availability of fiber architecture as shown in Fig. 15.1, all types of textile preforms, including woven, knitted, braided and nonwoven fabrics were used along with appropriate corresponding composite processes including RTM, SCRIMP, pultrusion and thermoforming. These combinations of fiber architecture and processes are the result of the consideration of the coupling effects of vehicle structural geometry and preform fiber architecture as well as the fiber architecture-composite processing interaction.

For example, during the effort of demonstrating resin transfer molding (RTM) for the integrated lower body shell (ILBS) of the Sunrise™ vehicle (Fig. 15.5), the design concept evolved from a highly integrated belly pan design to a more reasonable integration of components by modular manufacturing. Several parts of the previously existing belly pan configuration had to be removed to reduce tooling complexity. These parts include the battery box, the lower firewall, the passenger and driver kick panels and the rear cross-car beam. Some of the elements that were removed became candidates for different high rate manufacturing processes. Such an example is the battery box, which is a constant cross-section highly structural component of the vehicle body. Braiding was selected as the optimum preforming method for this part, based mainly on the off-axis fiber requirements of the lay-up and the continuous process potential of braiding. Having a constant cross-section, the battery box was also amenable to pultrusion. Combining braiding and pultrusion gives us continuous in-line preforming and high rate molding operation for the battery box. A quarter-scale battery box profile was



15.5 Composite parts breakdown of Sunrise™ BIW according to textile preforming processes and composite manufacturing processes.

successfully braid-truded in this program, while a full-scale battery box was braided and infused to validate the mechanical properties of the braided laminate.

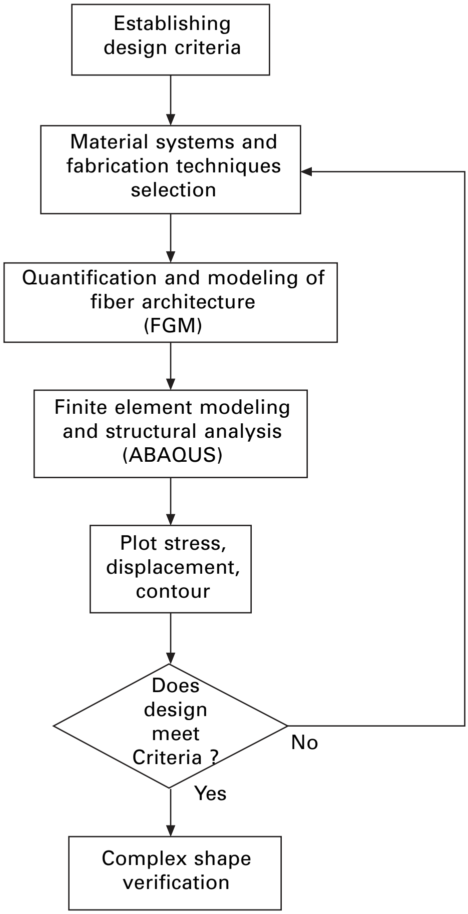
15.4.1 Integrated design for manufacturing

In order to reflect the contribution of local fiber architecture effect in the structural analysis of the vehicle, an integrated design for manufacturing methodology (IDM) was used. Figure 15.6 shows the logic flow of the methodology.

The heart of IDM is a fiber-architecture-based model – the Fabric Geometry Model (FGM) that provides a quantitative link between the manufacturing process and the design strategy and structural analysis. The FGM is a volume averaging homogenization method, which takes into consideration the volumetric angular distribution associated with fiber architecture via well-established coordinate transformation methodology. The procedure of FGM and related models have been detailed elsewhere [14–16]. The system stiffness matrix generated for a given fiber architecture provides the necessary input file for finite element structural analysis. Our strategy was to establish the initial design according to the logic flow shown in Fig. 15.6 for a given laminate schedule. The fiber architecture design is then mapped to the structural performance established with the laminate schedule.

The overall structural analysis of the body-in-white (BIW) begins with the assumption of a monocoque body with stress skins [17]. The skin thickness was tailored to provide necessary stiffness and strength. The fibers in the skins were oriented to follow projected load paths. Cores were used in panels that required additional stiffening. Most importantly, the design of a centrally located battery box tube was utilized in achieving high body stiffness. Additionally, large closed cross-section rockers were incorporated in the body design for stiffness purposes. This design made the battery box and the rockers the major paths for all body loads and the laminates were developed specifically to optimize the performance of these components.

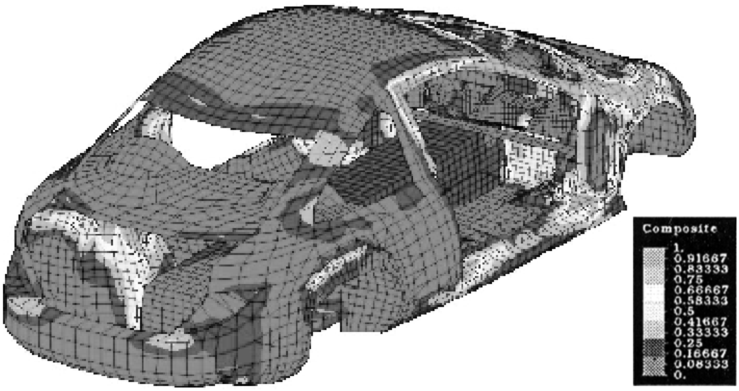
The suspension system of one of the early prototype vehicles was instrumented and tested under a wide range of driving conditions in order to obtain external driving loads to the body. These experimentally obtained suspension loads were checked against calculated load values with acceptable agreement between them. These loads were then used to develop the laminate schedules for the highly loaded parts of the BIW. The Algor [18] finite element analysis (FEA) program was utilized, along with standard composite engineering practices to optimize the laminate schedule and minimize weight in the vehicle. The highest externally loaded parts of the vehicle are the wheel wells, which directly accept the suspension loads. Several iterations of analysis and laminate design were performed (see Fig. 15.7).



15.6 Logic flow of the integrated design for manufacturing methodology.

The BIW main load path components were designed to sustain external crash load, carry the road loads locally and to provide for the targeted torsional and bending stiffness of the BIW. FEA was used in both cases, along with test results, to validate the FEA input. In the case of the load from crash conditions through the BIW, strain gage readings from the frontal impact tests were used to compare to battery box and rocker stresses and the values were in good agreement.

In the case of the BIW torsional and bending stiffness, one of the prototypes was used to evaluate those numbers. Both torsional and bending stiffness evaluation tests [19, 20] were performed on the body shell. The tests were repeated after bonding the firewall, battery box, inner rockers, kick panels and seat rails, cross car beams and rear bulkhead to the shell.



15.7 Stress contour from body torsion finite element analysis [16].

The results provide the design and manufacturing team a good understanding of the contribution of each of these components to the BIW performance. The assembled vehicle results were also compared to FEA results of body torsion and bending. The experimental and test results indicated similar contributions from the different BIW components to the body stiffness. The torsional stiffness of the assembled prototype BIW measured during these tests was 6000 ft-lbs/degree with the FEA results indicating 10 000 ft-lbs/degree. The bending stiffness was measured to be 17 000 lbs/in with the FEA results indicating 24 000 lbs/in. The torsional rigidity value exceeded the original lowest design limit of 4000 ft-lbs/degree, but the bending stiffness was lower than the lowest desired value of 35 000 lbs/in. The FEA model was reconstructed using composite material elements, and the FEA of the new BIW model resulted in stiffness of 6370 ft-lbs/degree and 18 600 lbs/in in torsion and bending respectively. These results, being within 10% of the tested values in both torsion and bending, provided the necessary confidence in the body FE model for subsequent studies. Using this model, the laminate sequence of the BIW components was reconstructed to improve both the torsional and bending stiffness of the BIW. Concurrently textile preforms enabling lower cost and simplified assembly were selected and designed to match the properties of the laminates.

15.4.2 Design and manufacturing of vehicle components

Selected components of the vehicle that are highly loaded were analyzed. The pillars and wheel wells represent two of the most highly loaded components in the top body shell and the lower body shell respectively. The mapping of material properties and fiber architecture are illustrated using the pillars and wheel wells. The requirements for high torsional and bending stiffness makes triaxial braid a suitable candidate for the pillars. The required fiber orientation and fiber volume fraction to meet the design criteria quantified in the laminate analysis were reduced to braiding machine control parameters such as braiding point location, braiding speed and take-up speed for programming the braiding machine for automated braiding process. On the other hand, the complexity in geometry and the large dimensions of the wheel well preclude the use of most of the preforming methods. Net shape fiberglass knitting with strategic placement of carbon fiber stiffeners was shown to be the most cost effective. The fully-fashioned knitting was performed on a computer-controlled knitting machine. The most challenging task for the knitted wheel well was the demonstration of their structural worthiness, for they are the highest externally loaded part of the vehicle. The design consideration and the selection of preforming strategy that is compatible with the RTM molding cycle for structural components of the ILBS have been detailed by Brachos *et al.* [21].

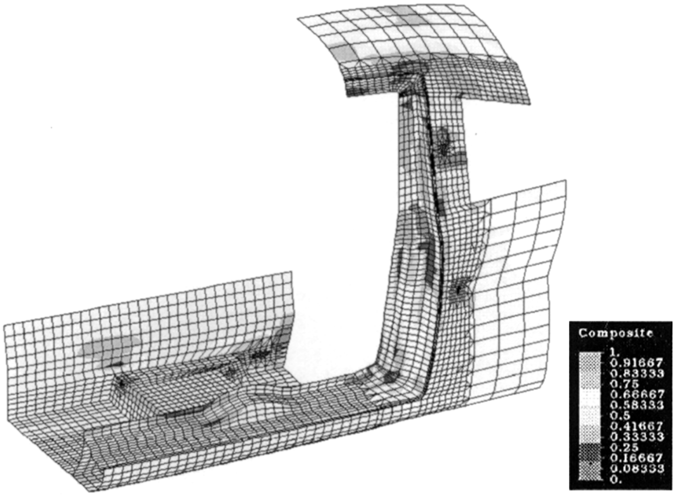
15.5 Examples of composite structural components

For illustration purposes the B-pillar and the rear wheel well are used as an example to show how a low cost textile preform can be designed for low cost manufacturing of automotive structural components. The pillars are the structural backbone of the upper body shell (UBS) whereas the wheel wells are the highest externally loaded parts of the vehicle [21, 22]. The wheel wells directly transfer the loads between the suspension of the wheels and the body shell. The wheel wells also play an important role in the structural performance of the entire integrated lower body shell (ILBS) and thus the overall car body. The upper body shell (UBS) was attached to the ILBS via the edges of the wheel well caps.

15.5.1 Braided B-pillar

The pillars are the structural backbones of the top body shell of the electric vehicle. For example, the B-pillar/seat-rail structure experiences a high seat-belt load in a crash situation. The laminate in that area was designed to sustain seat-belt loading resulting from frontal and rear impact based on the FEA analysis shown in Fig. 15.8. The laminate schedule for the B-pillar calls for a symmetrical lay-up of 2 mm thick carbon uni-tape and 1 mm thick fiberglass multiaxial warp knit (MWK) sandwiched with a foam core. The predicted composite properties are: E11 = 88.3 GPa (12.8 Msi); E22 = 8.3 GPa (1.2 Msi); E22 (flange) = 26.2 GPa (3.8 Msi); and G12 = 4.8 GPa (0.7 Msi).

To reduce the assembly time, triaxial braided structure was designed and built by mapping the laminate properties to the braided composite properties generated by the FGM. The first step in the FGM is to design the fiber



15.8 Finite element analysis of the B-pillar.

architecture according to the following relationship between fiber volume fractions and the braid angle [5]:

$$V_f = \frac{\kappa w_y N_c}{4\pi R_m \cos\theta}$$

where κ is the fiber packing fraction, w_y is the yarn width, N_c is the number of braiding carriers, R_m is the equivalent radius of the mandrel, and θ is the orientation angle of the braiding yarns.

The analysis suggested a combination of 2 mm of 15° triaxial carbon braid overbraided with 1 mm of 70° hybrid braid consisting of 80% glass braid and 20% carbon axial yarns. Figure 15.9 shows the B-pillar foam core and the braided B-pillar preform.

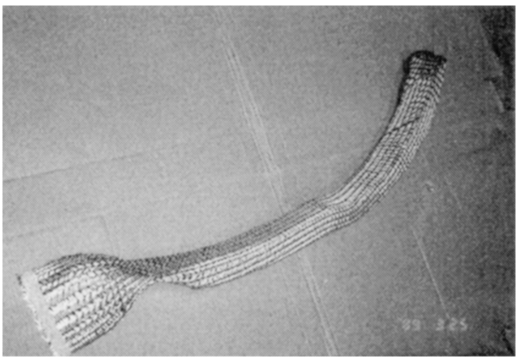
The following braided composite properties were generated by the FGM analysis: E11 = 85.6 GPa (12.4 Msi); E22 = 14.5 GPa (2.1 Msi); E22 (flange) = 29 GPa (4.2 Msi); and G12 = 9.7 GPa (1.4 Msi).

Figure 15.10 shows the predicted and experimental tensile moduli for the various pillars, indicating reasonable agreements between theoretical predictions and experimental results. This provided confidence in the selection of braided fiber architecture according to the processing window prescribed in the volume fraction-braiding angle relation.

15.5.2 Fully-fashioned knitting of front passenger wheel well

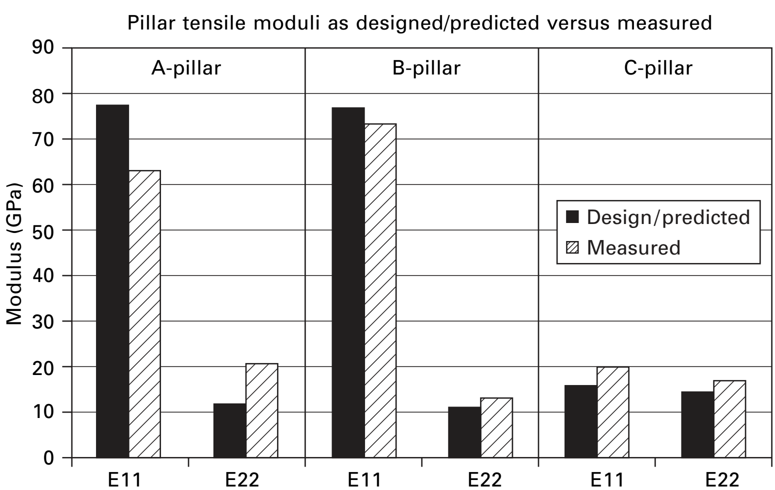
Both front and rear wheel wells have the form of a dome to cover the wheels. The major design loads are tensile and compressive loads in the radial direction

(a)



(b)

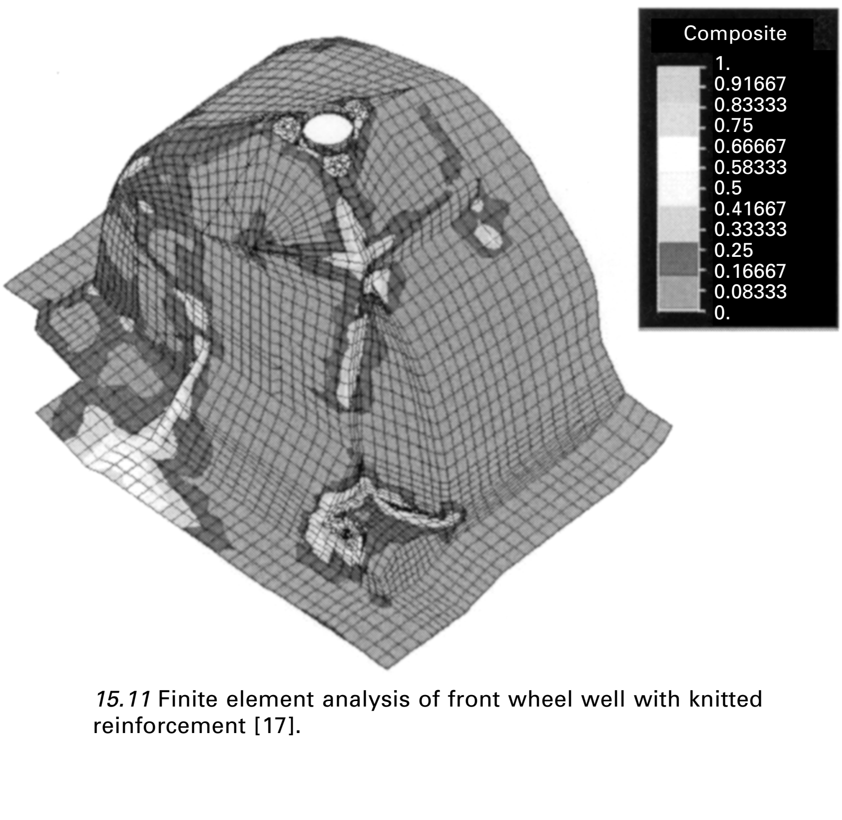
15.9 (a) Foam core fabricated by injection molding.
(b) Braided B-pillar preform.



15.10 Comparison of the experimental and predicted moduli of the A, B, C pillars.

of the dome. Loads on the wheel wells are transferred to the floor pan via the mount areas, which thus have to be the highest reinforced areas. To eliminate local stress concentrations, metal inserts were used in both front and rear mounts, in locations where other connections with the suspension are present. Figure 15.11 shows an example of the front wheel well loaded in a worst case, complex, combined loading condition [17]. For the bulk of the structure a material with dominant properties in the radial direction of the dome of the wheel well is required. In the other directions minimum requirements under tension, compression and in plane shear exist. In selected locations of the wheel well, such as the corners, high stiffness and strength are required to transfer the major loads from the top of the wheel well tower to the floor mounts. The FEA results prescribed a laminate schedule based on a multi-axial-warp-knit (MWK) material for the entire structure plus unidirectional carbon strips placed in the corner area. Although the wheel well fabricated according to the laminate schedule meets the property requirements, it would be too laborious to manufacture and thus fails to meet the required production economics of the Sunrise™ program.

To improve manufacturability it was determined that a weft knitted preform be used in order to take advantage of the conformable nature of weft knitted fabrics and the net-shape manufacturing capability of fully fashioned knitting.



15.11 Finite element analysis of front wheel well with knitted reinforcement [17].

Using the fully-fashioned knitting technology, net-shape or near net-shape fabrics can be produced with a high productivity and reproducibility on computer-controlled knitting machines. A further advantage of the knitted material for this application is that straight (non-crimp) fibers can be laid-in in the radial direction of the dome during the knitting process to create the directional reinforcements as required. Accordingly, mapping of the laminate design to knit design was carried out on the geometric and material property level. Geometrically, as shown in Fig. 15.12, a weft knitted fabric was transformed from a planar structure to the three-dimensional wheel well geometry with the unidirectional laid-in carbon fibers placed in the selected locations. By optimization of the knitted stitch construction, sufficient mechanical performance of the knitted fabric reinforced composite was developed in the non-radial directions of the wheel well.

The added cap and mount reinforcements in the wheel well preform were produced as sub-preforms in semi-automated lay-up stations. The layers were cut automatically using carefully designed patterns. The preforms were consolidated with a binder material under vacuum pressure as in diaphragm thermoforming [21]. The complete preform can also be laid up in a semi-automated lay-up station. The knitted fabrics, sub-preforms and metal inserts were integrated to form the final wheel well assembly. A picture of a finished front and rear wheel well preform, ready for placement in the RTM mould, is shown in Fig. 15.13.

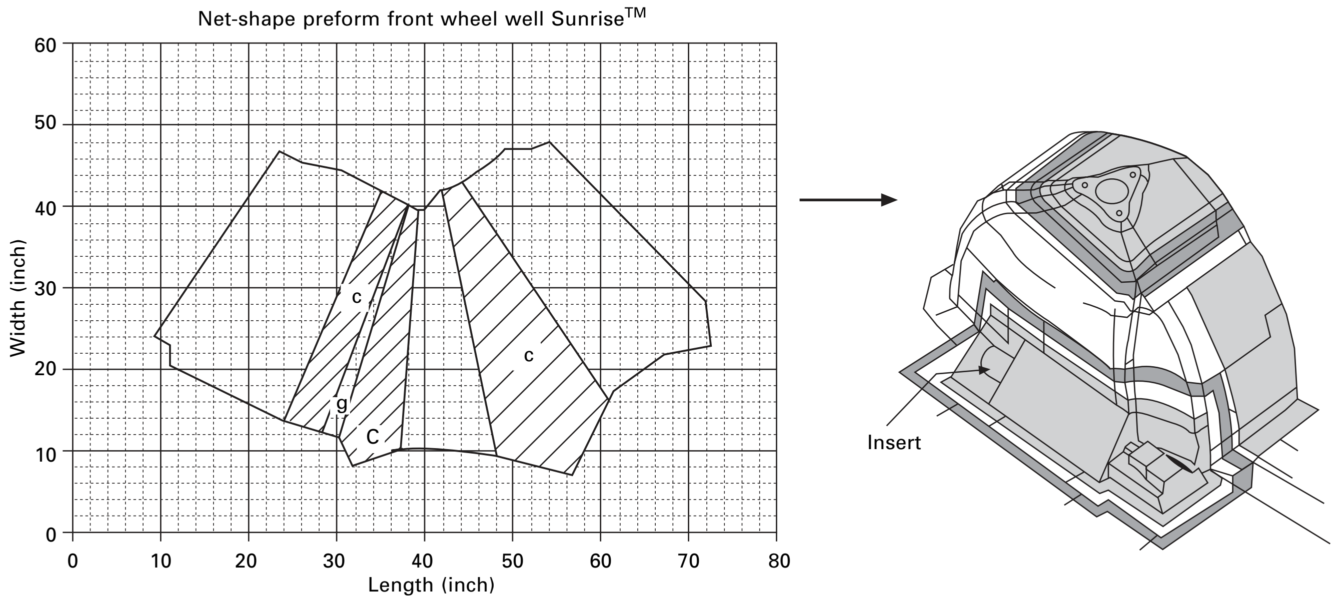
RTM production trial runs of the complete lower body shell preform with the knitted preforms integrated, have confirmed that the knitted preforms also have good permeability for liquid resin flow, which allows the removal of additional flow mats, that would have to be added to the wheel well preforms with traditional reinforcements [21, 22].

Following a similar approach shown in the design of the braided pillars, the relationship between fiber volume fraction and knit geometry were established. The predicted knitted composite properties are shown in Fig. 15.14 comparing to experimental results with good agreement.

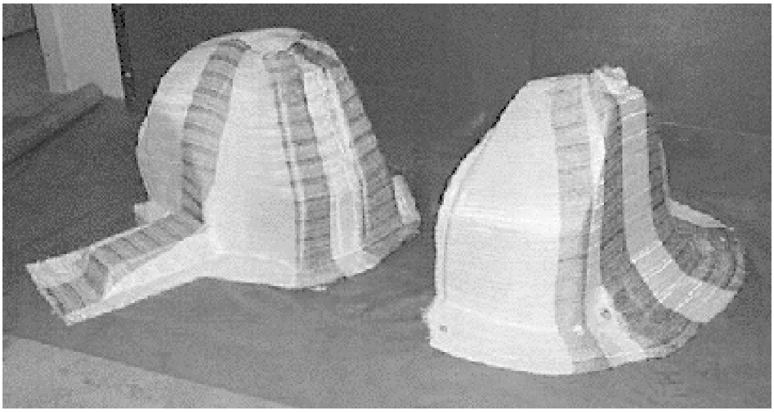
Besides meeting the mechanical property requirements, the use of near net-shape knitted preform fabrics for the basic wheel well construction has shown promising potential for a significant cost reduction for the formation of the total wheel well preform due to the high conformability of the knitted material. The overall labor time saving (including knitting time) of more than 30% was realized in comparison to the use of broad goods for the prototype wheel well performs [21, 22].

15.6 Summary and future trends

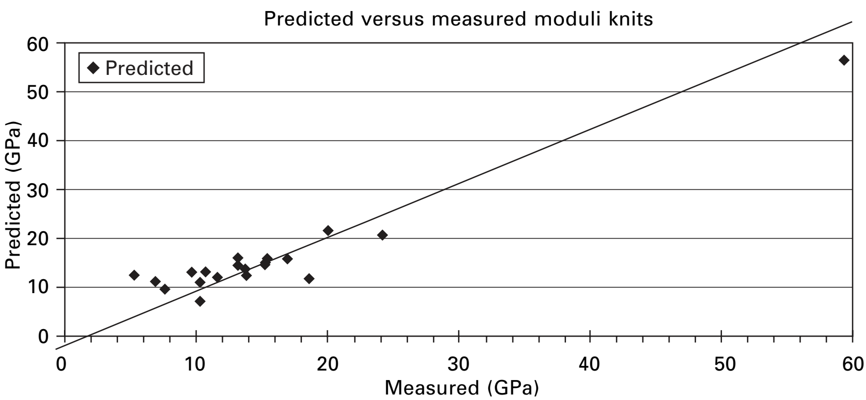
Composite materials have long been recognized as the ideal candidate to address the need for weight reduction for automobiles. The concern with



15.12 Net-shape 2D knitted preform for the front wheel wells; the fabric drapes around the mold easily produce the complex shaped part; the UD carbon reinforcements are integrated strategically into the preform during the knitting process.



15.13 Picture of finished rear and front wheel well preforms, with near net-shape knitted fabrics encapsulating cap and mount sub-preforms. The black strips are selective carbon yarn laid-in according to structural requirements.



15.14 Predicted and experimental tensile moduli of the knitted composite wheel well.

production economic of composite materials and the lack of a sense of urgency in the need for clean energy source has impeded the adoption of composites for structural automotive components. With the alarming increase in gasoline price and the increasing global awareness of the environmental impact caused by fossil fuel-based vehicles in recent years, there is renewed interest in clean and energy efficient automotives. However, the uncompromising needs of the automotive industry for low cost, large-scale manufacturing capability while meeting the structural and stringent safety criteria remain unchanged.

With a rich history of textile craftsmanship and wide availability of production facilities in the industry, textile technology can be used effectively to create the fiber architecture to meet the processing, performance and cost requirements for automotive composites. The availability of structural design and process control tools coupled with a large family of advanced fiber materials has led to textile structural composites being recognized as a promising class of composites characterized by high conformability, high toughness and high affordability. Depending on the product geometry and the required fiber volume fraction and fiber orientation, there is a wealth of fiber architectures at our disposal.

To facilitate communication, the large number of fiber architectures was classified according to manufacturing technology. The role of the fiber architecture in influencing composite processing and mechanical performance was discussed. The extensive use of textile preforms in large-scale composite product manufacturing was illustrated using the Sunrise™ all composite electric vehicle as an example. The implementation of the concept of integrated design for manufacturing (IDM) was illustrated using two structurally demanding components – the B-pillar and the rear wheel well in the upper body shell and lower body shell respectively. Through the Sunrise™ program a new paradigm of agile manufacturing of structural composites was demonstrated wherein multiple suppliers, each with special capability in producing particular components for the vehicle, were organized in a way similar to how the supply chain of structural components is being managed in the commercial aircraft and electronics industries today. The question of the optimum degree of structural integration was also examined in this program. It was found that the level of structural integration depends on the coupled effect of vehicle geometry and reinforcement geometry; the process-fiber architecture interaction; and production rate compatibility of various textile preforming and composite fabrication processes.

With the increasing usage of textile composites for automotive structural components and for other structural applications, there is a need for a comprehensive database and quality control measures for textile composites. The shortening of the supply chain due to part consolidation will place more responsibility for quality assurance on the textile preform manufacturers. As the need for multifunctional products is likely to increase, future composite products will need to integrate many types of materials and fiber architectures. With the explosive growth of nanotechnology it is inevitable to include nanomaterials as a component of textile reinforcement materials. This in turn will affect composite process control and requires design methodologies capable of integrating the local effects in global structural analysis and for composite process modeling. The linkage of fiber architecture-based design with structural performance through the FGM will provide a means to bridge the communication gap between designers and manufacturers, therefore resulting in a more efficient translation of design concepts to product reality. The integrated design for manufacturing (IDM) platform of textile structural composites is applicable not only to electric vehicles but also to various vehicles powered by different energy sources ranging from methanol, ethanol, bio-fuel, natural gas, reformulated gasoline, hybrid gasoline/electric as well as other non-automotive structural components.

Finally, there are encouraging signs that there is a shift of global interest in addressing the vehicle efficiency issues as demonstrated by the US and China, two of the most energy-hungry nations in the world. This is evidenced by the signing of a five-year agreement between the US Department of Energy (DoE) and China's Ministry of Science and Technology (MoST) in September 2007 to promote large-scale deployment of next generation vehicle efficiency technologies in the US and China with a specific focus on electric, hybrid-electric, fuel cell, and alternative fuel technologies. Accordingly, it is felt that the conditions are more favorable for global market acceptance of composite intensive vehicles in general, and for electric vehicles in particular than ten years ago. With the availability of new materials such as nanomaterials, improved control processing technology, increased efficiency of alternative energy and vehicle technology, coupled with more environmentally friendly clean air legislation, there is ample opportunity for textile structural composites to contribute to the next generation of clean, smart, safe, and energy-efficient automobiles.

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