11
Aerospace applications

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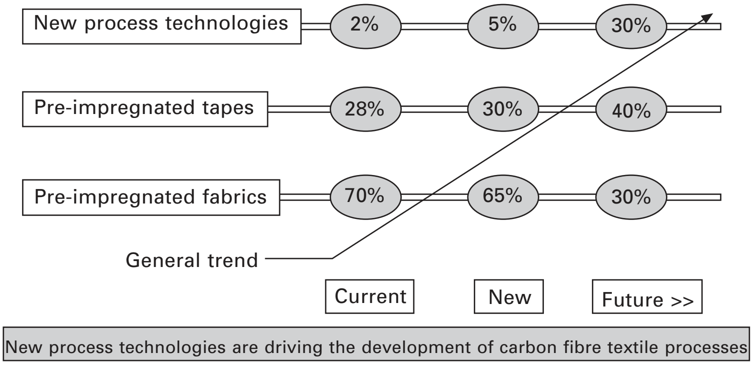
11.1 Introduction

The drive within the aerospace composites field over the last decade has been to reduce cost, increase component performance and reduce component weight. Composites have now gained an accepted position in aircraft design, while carbon fibre reinforced materials have become the mainstay of secondary components such as wing movables (flaps, spoilers, rudder, etc.) and have found their way into primary structural components such as complete horizontal stabiliser and vertical stabiliser structures.

This chapter is solely related to the use of carbon fibre reinforced textile materials, since the other widely used composite reinforcement fibres, glass and aramid have gained relatively limited use in the aerospace sector, owing to weight and lack of stiffness with regards to glass and to the problem of moisture absorption with respect to aramid fibre. Similarly applications concentrate on the use of epoxy resin systems, as these dominate the aerospace composites sector.

At the present time pre-impregnated materials are utilised for nearly all composite components for aerospace structures. The largest volume of materials use carbon fibre fabric, though in comparison carbon unidirectional prepreg is growing at a stronger pace. This trend is, however, beginning to change with the advent of reliable processing routes with resin transfer moulding (RTM) or resin film infusion (RFI) and a variety of other processing routes connected to these basic methods (Fig. 11.1). This trend has come about due to the textile processing improvements of using high tow count carbon fibres (i.e. larger 6K carbon fibre tow) for the preparation of textile fabrics and preforms. Applications for textile composites are usual where part consolidation is possible and overall sub-assembly construction cost is lowered against metallic components.

Lifetime costs for components are also a driver for these types of textile composites where the part cost may be similar or more expensive than metal components and the consideration of much higher fatigue life and lower in-



11.1 Expected change in usage of aerospace composites.

service cost is an overriding factor. All the major airframe manufacturers accept that higher component costs may be accepted if lower flying weight and the associated fuel savings can be achieved.

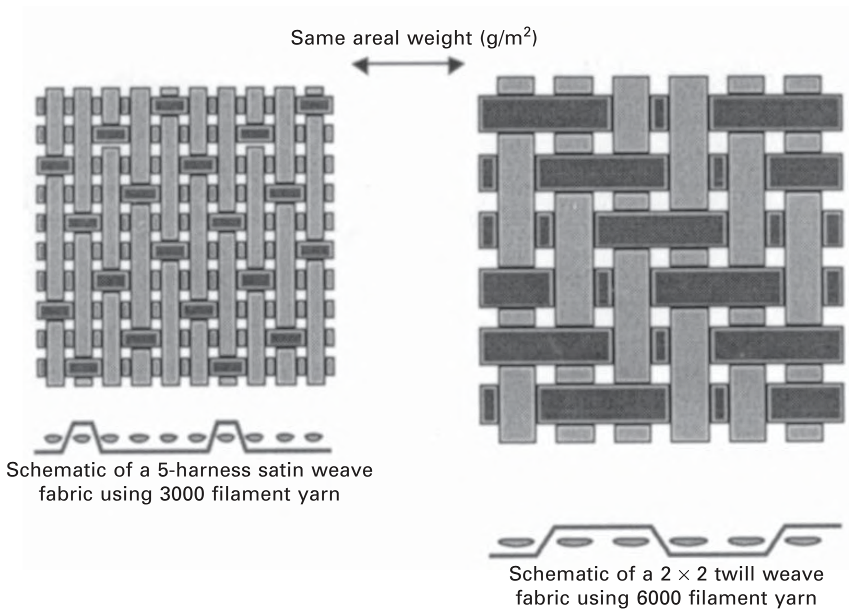
It has to be understood from the general process of manufacturing carbon fibre yarn that the production cost decreases with increasing tow count for the same type of yarn. In general the cost difference between a 7 μm diameter, 240 GPa modulus, 4000 MPa strength yarn can be approximated as follows: 3000 filaments, 3K (100%) > 6000 filaments, 6K (75%) > 12 000 filaments, 12K (50%). Carbon fibre yarn cannot be defined as a low-cost raw material and for this reason the textile development described in this chapter tends to describe material structures which have been developed to move away from the traditional carbon fibre fabric materials, based upon 3K yarns, towards more cost-effective 12K and 24K yarns.

In many applications the high cost of prepreg materials available from only a selected range of suppliers is driving composite textile development. At the present time, however, the lower properties of textile materials compared with prepreg restrict widespread use. The general material trends for the future will include the development of resins and other components to complement the carbon fibre textile properties and improve mechanical properties such as impact, compression and interfacial strengths, since these properties still lie below those attainable with advanced carbon fibre prepregs.

11.2 Developments in woven fabric applications using standard prepreg processing

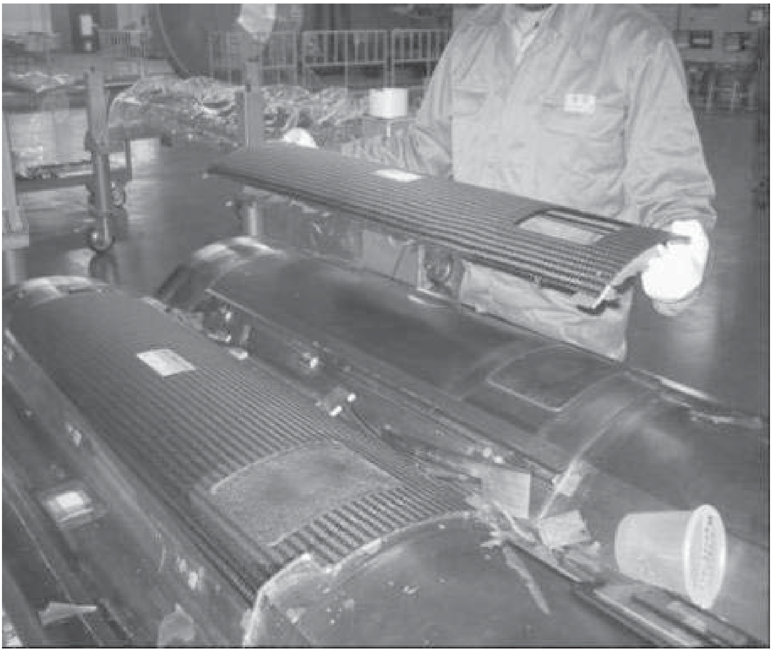
The main composite material used in the aerospace industry is pre-impregnated carbon fibre fabric. The development of these materials is evolving to accept the challenges of lower cost and improved or comparable material properties. For secondary sandwich structures, owing to the reasons of coverage and thickness (ply drop-offs), the industrial norm in has always been to use a minimum two-ply carbon fabric layer over honeycomb core (to be able to seal the structure). These layers have been traditionally 3K fabric prepreg in ply thicknesses of 0.2 mm (plain weave: 200 g/m^2), 0.25 mm (5-harness satin 285 g/m^2) or 0.4 mm (8-harness satin: 370 g/m^2).

In recent years the trend has been for the industry to search for lower-cost woven fabric solutions, moving from 3K to 6K prepreg fabrics. Owing to improvements in weaving techniques and technology it has been possible for the same fabric quality with the same coverage to be achieved moving from 3K to 6K yarns (Fig. 11.2). Most recently this trend has continued with a movement towards 12K fabric prepregs.



11.2 Achieving the same fabric weight and thickness with different carbon tow counts.

One of the first examples of has been achieved in Japan by Kawasaki Heavy Industries, where a 380 g/m^2 2 × 2 twill carbon fabric using Tenax HTS 5631 12K yarn using a special weaving technique is able to achieve complete coverage and the same ply thickness as fabrics woven with 3K or 6K carbon fibre yarns (Fig. 11.3). The prepreg developed using this fabric also exhibits self-adhesion to the honeycomb core, thus removing the requirement for an adhesive film to create filet joints between the honeycomb and the prepreg laminate. Several applications have already been found for this prepreg, including the Embraer ERJ 170 Inboard flaps, Embraer



11.3 Prepreg component manufacture using 12K carbon fibre fibric.

ERJ190 Outboard flaps and wing stubs and the Boeing 737-300 winglets (Fig. 10.4).

11.4 Boeing 737–300 winglet programme for Aviation Partners Boeing. Supplied by Kawasaki Heavy Industries (Japan); manufactured using KMS6115 style, Tenax HTS 12K fabric prepreg.

11.3 Carbon fibre multiaxial fabric developments

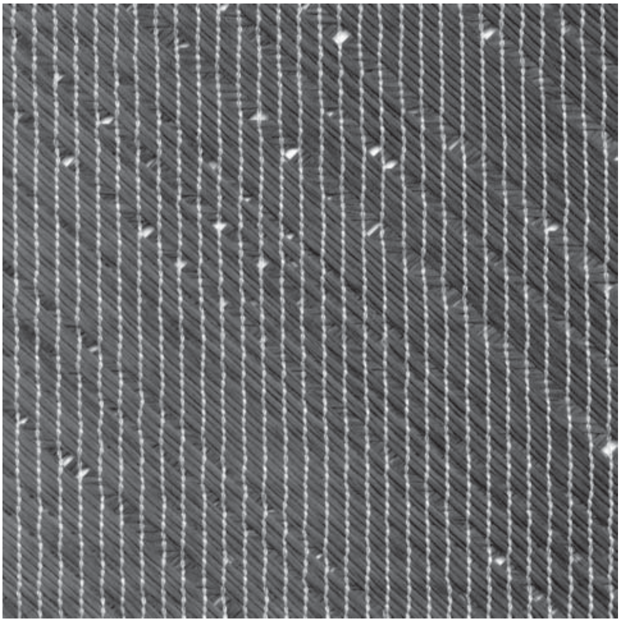
Multiaxial (non-crimp) fabrics using carbon fibre have been selected as they are seen to offer a textile solution to meet material properties similar to unidirectional prepreg while offering lower cost than established fabric solutions. During the late 1990s multiaxial fabric using carbon fibre yarn was the subject of many different development programmes, including the AMCAPS programmes funded by the UK's Department of Trade and Industry, several elements of the European-funded TANGO programme and the well-documented NASA composite wing programme (started by the Douglas Aircraft Company – now Boeing). These development programmes initiated and drove the improvement of the textile quality of the carbon multiaxial fabrics.

Initially the multiaxial fabrics manufacturing looms (two types are used within the industry, Liba and Karl Mayer-Malamo) were hydraulically driven, which caused the placement of the filaments to be inexact and the general movement of the laying-down heads to be clumsy and damaging to the brittle carbon fibre yarn. As a result, the earliest fabrics manufactured using this technology tended to exhibit poorly placed filaments, gaps and uneven stitching (Fig. 11.5a). Driven by the quality concerns of the aerospace industry, Liba in particular improved its multiaxial looms to use electronic controls and electrically driven motors. This has improved the accuracy of filament placement and has acted to reduce the damage of the carbon fibre yarn by controlling acceleration forces and using improved fibre handling mechanisms (Fig. 11.5b). This generation of machines, known as MAX3 Liba looms (Fig. 11.6), are the basis on which all present carbon fibre fabrics are produced for aerospace application and development programmes.

11.3.1 Fabric development

Nearly all the developments of carbon fibre multiaxial fabrics have concentrated on the use of 12K carbon fibre yarn, owing to the cost implications of using lower tow counts. During this time the major carbon suppliers have also realised that these developments require carbon fibre yarns that are supplied as ribbon-like (flat) tows, able to spread and provide easy coverage once the tows are knitted through with polyester yarn to create the multiaxial fabric. For this reason, carbon fibre yarns such as Tenax HTS 5631 12K or Toray T700 12K carbon have been developed, which are supplied as a flat tow without any false twists than can spread to provide gap-free fabrics.

Many problems still need to be overcome in the development of multiaxial fabrics. The mechanical properties of laminates produced using multiaxial textile fabrics are still lower than equivalent unidirectional prepreg laminates and the variation in properties is higher, dictating that the design properties are lowered. Limitation of low layer weights from multiaxial fabrics reduces design flexibility (due to large ply drop-offs) since at the present time individual layer weights are limited to approximately 200 g/m^2 (from conventional 12K carbon fibre yarn). The higher layer weights for thick constant section components are attractive, since the issue of high fabric thickness and the ability to apply triaxial or quadriaxial fabrics quickly is of great advantage when compared to unidirectional prepreg structures.



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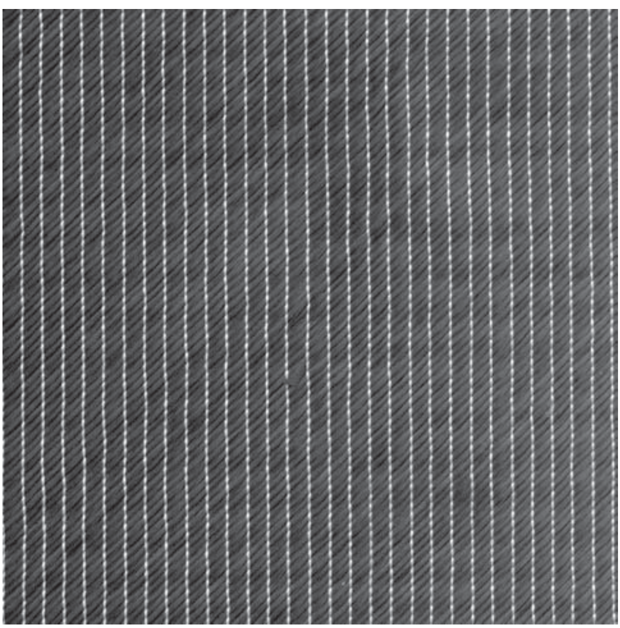
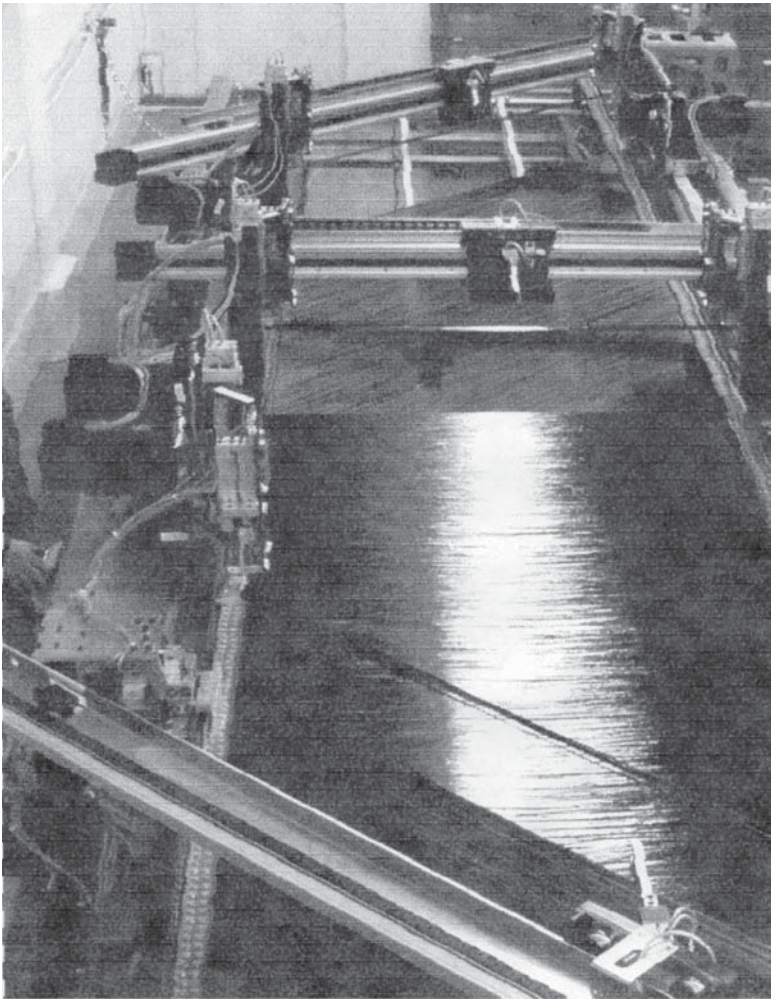


(b)

11.5 400 g/m^2 biaxial fabrics (±45°) Manufactured using (a) older and (b) the Liba multiaxial technology.



11.6 Liba multiaxial MAX3 machinery.

11.3.2 Stitching thread

An issue of great interest for the future is the development and improvement of stitching thread technology. The polyester stitching used as a processing aid in holding the fabric imparts an inbuilt flaw into the microstructure of the fabric. When the structure of the fabric is viewed closely, the carbon fibre filaments bundled by the stitching thread can be seen. This fibre bundling creates uneven fibre distribution at a microscopic level and is believed to be the cause of lower material properties in certain orientations. As such, the larger the stitching fibre used, the greater the fibre disruption, bundling and 'fish eyes' within the microstructure of the fabric.

Presently, the standard in the industry is to use a non-sized 80 dtex polyester multifilament yarn. Improvements are constantly underway, and recent technology available from Teijin Polyester Filament (Japan) allows the application of an unsized 33 dtex multifilament polyester yarn. The first fabrics being developed with these finer stitching yarns show promising improvements.

11.3.3 Quality control

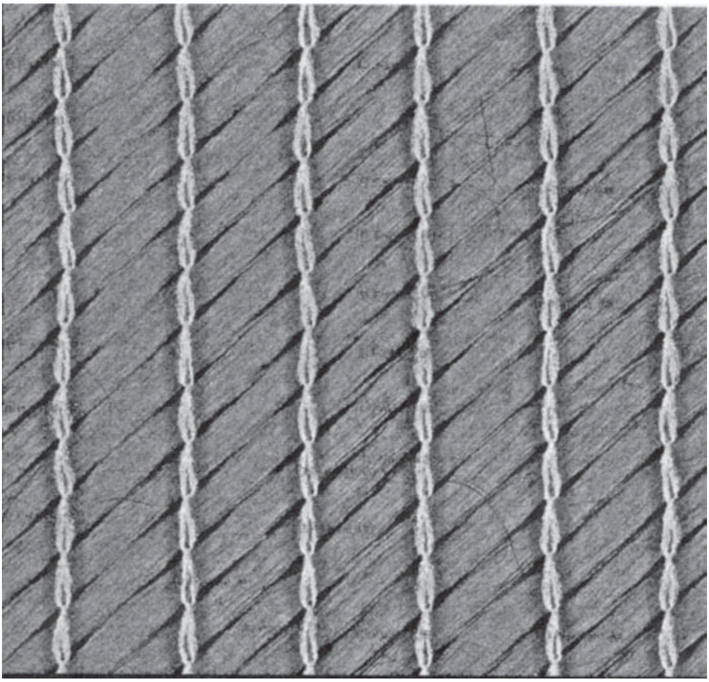
One of the most problematic issues for multiaxial fabrics is quality control. Many of the manufacturers of multiaxial fabrics have been used to supplying industrial or marine industries, which have much lower-quality requirements. The aerospace industry has the requirement for the highest quality control and product release specifications. The raw material standard, prepreg materials, have tended to require mechanical property testing (e.g. interlaminar strength and tensile strength) from specimens taken from random samples within a production run.

With multiaxial fabrics this type of quality control would be too difficult to organise, owing to the variety of processing routes and resins that may be used. As such, there are developments underway to implement quality detection using computer graphical detection methods. Images of randomly sampled fabric samples could be digitised, analysed and compared against an accepted standard (Fig. 11.7). In this manner it is hoped that by controlling the yarn orientation, coverage, stitching density, etc., the fabric can be released easily for aerospace fabrication without the need for costly mechanical testing.

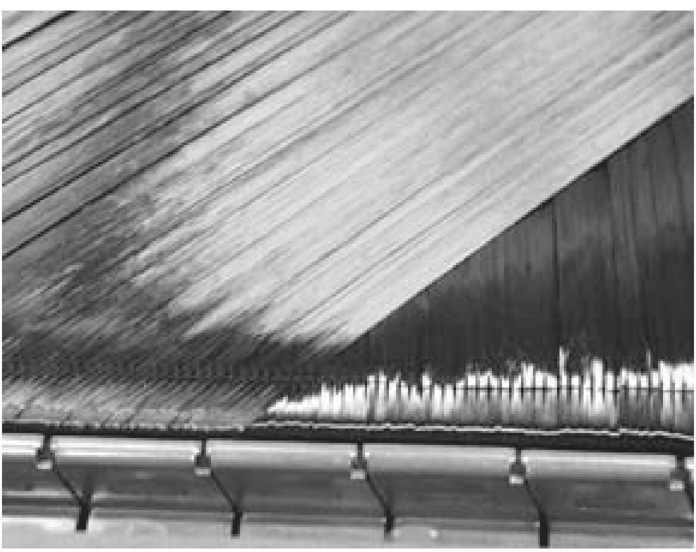
11.3.4 Lighter-weight fabrics

One of the most restrictive issues with carbon fibre multiaxial fabrics is to be able to produce very light-weight layers (i.e. lower than 150 g/m^2) using lower-cost 12K or 24K filament tows. In order to be able to spread the larger tows to create closed, gap-free unidirectional layers, Liba has modified the multiaxial loom (named MAX5) such that the yarns are spread and laid onto the fibre bed. The spread tows are clamped (Fig. 11.8) and held in place with a newly devised system instead of the usual pins around which tows are usually wrapped.

This type of multiaxial loom can also to pre-spread tows of carbon filament yarn. Using pre-spread tows manufactured either from 12K or 24K yarn, layer weights as low as 50 g/m^2 can be achieved. Widely spread carbon fibre tows are available from a variety of sources, most of these being in Japan. As such the Liba MAX5 is capable of manufacturing quasi-isotropic (quadriaxial) fabrics with areal weights as low as 200 g/m^2 (0.2 mm ply thickness).



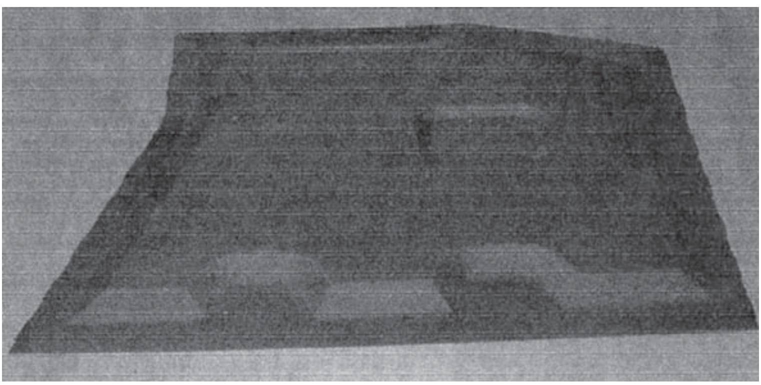
11.7 Digital graphical control of multiaxial fabrics. Digital image shows excessively large 'fish eyes' created by high knitting yarn tension.



11.8 MAX5 Liba multiaxial technology is able to clamp unidirectional tapes in position before assembling the fabric.

Example 1: *Multiaxial fabric components – using interleaved RFI*

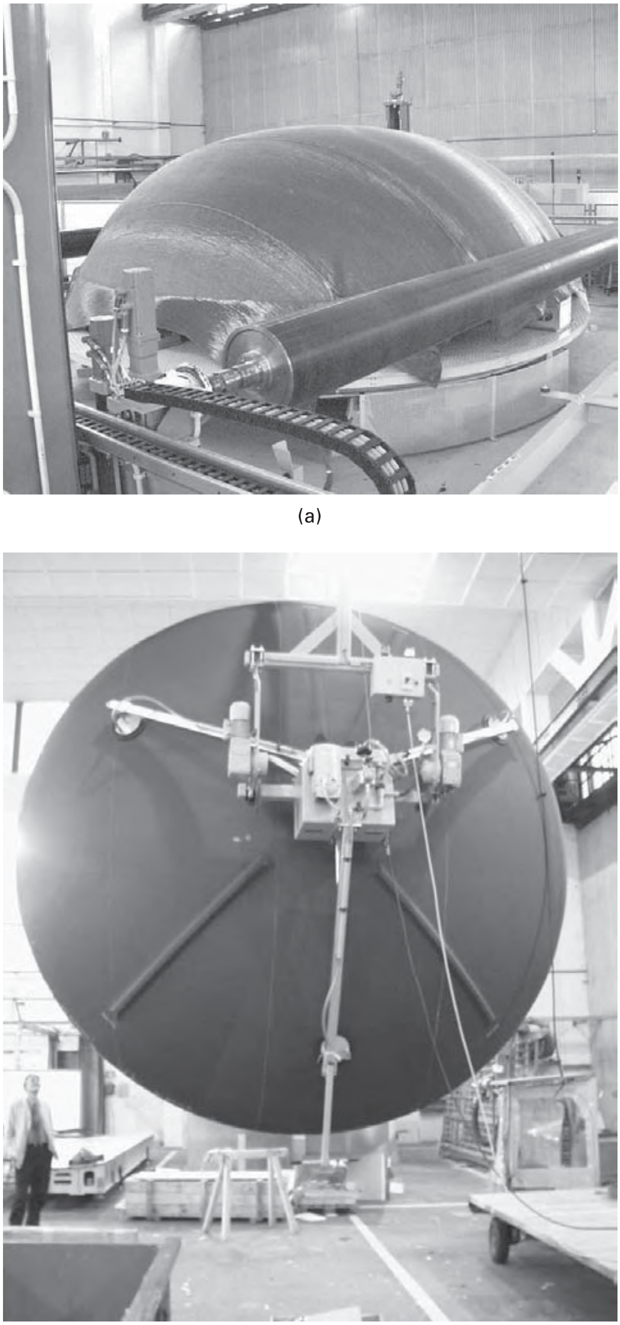
GKN Aerospace has started series manufacture of lower wing access panels for the Airbus A380 (Fig. 11.9) using a newly developed technology that involves interleaving layers of fabric with resin film (M36 epoxy film supplied by Hexcel Composites). The components use a 440 g/m^2 biaxial carbon fibre (Tenax HTS 5631 12K) multiaxial fabric (±45°) manufactured by Saint-Gobain (UK), stiffened by a honeycomb core. The manufacturing method requires no autoclave, merely vacuum and heat for the fabrication of these components. Also, owing to the viscosity of the resin film, no adhesive film is required to bond the laminate to the honeycomb. Because of the lower cost materials, reduction in lay-up times and the need for lower cost processing tools (i.e. no autoclave), the component manufacturing cost is estimated to be 30% less than a conventional fabric prepreg manufacturing route.



11.9 Airbus A380 lower wing access panels manufactured by RFI using biaxial (±45°) multiaxial HTS 5631 12K fabric supplied by Saint-Gobain (UK).

Example 2: *Multiaxial fabric components – RFI, using resin film blocks*

The pressure bulkhead developed for the Airbus A380 has been devised using carbon fibre (Tenax HTA 5131 12K) biaxial (0/90°) multiaxial fabrics manufactured by Saertex GmbH and is fabricated using resin film infusion with 977-2 resin film supplied by Cytec Engineered Materials (Fig. 11.10a). The bulkhead uses a fabric preform supplied by Saertex, which is assembled and stitched to form an assembly. This preform assembly is rolled onto a core unit, that is supplied to Airbus for component fabrication (Fig. 11.10b). The preform is rolled out onto a convex form that is pre-covered with the resin film. This assembly is vacuum bagged in the conventional manner and cured in an autoclave.



(a)

(b)

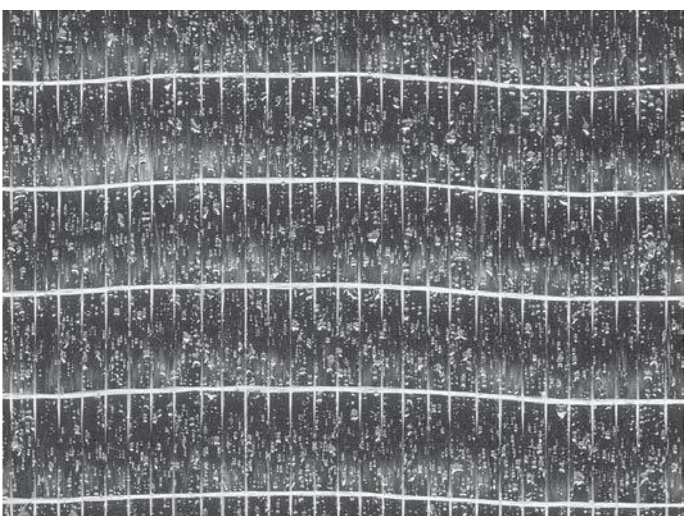
11.10 Rear pressure bulkhead or the Airbus A380. (a) Assembled multiaxial dry fabric preform and (b) finished component.

11.4 Improvement in standard fabric technology for non-prepreg processing applications

11.4.1 Unidirectional fabrics

Unidirectional (UD) fabrics are commonly used for adding stiffness in structures such as wing skins, spars or stiffeners (gliders, small general aircraft). UD fabrics also allow the lay-up of complex laminates in a similar fashion to UD prepreg tape structures. UD fabrics manufactured using Liba multiaxial looms tend to allow the filaments in the 0° direction to wander. Hence the resulting mechanical properties have been low in comparison with UD prepreg. Other UD materials have also been evaluated, such as dry UD tape held together with a fibre mesh backing, which is usually coated with an epoxy resin or a thermoplastic binder. The main problems with these types of UD tapes is that they have very poor impregnation properties, especially through-thickness.

To solve these issues and to be able to offer a UD fabric structure that exhibits repeatable quality, easy impregnation without excessive pressure and high mechanical properties, a new generation of fabrics has been developed using 12K carbon fibre yarns. In particular, advanced UD weaves using glass or thermoplastic (polyester) fibres in the weft direction to hold the carbon fibre yarns in place can be used as tape laid like products in similar manner to UD prepreg (Fig. 11.11). The scaffolding structure of the support yarns allows for good permeability of the fabrics for vacuum infusion processes



11.11 'Advanced Unidirectional Weave' (AUW) fabric supplied by Cramer (Germany) using Tenax HTS 5631 12K carbon fibre yarn. Epoxy powder binder is applied onto the fabric surface.

and the fact that the carbon filaments are not crimped allows the fabrics to exhibit high mechanical properties.

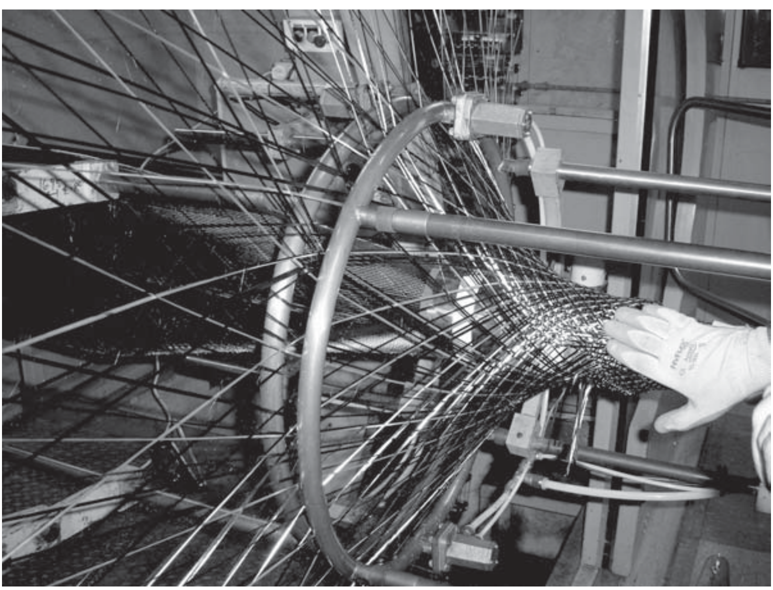
Since these types of fabric are manufactured on a conventional weaving loom, issues such as quality control and repeatability are well understood and accepted by the aerospace community. There are numerous development programmes presently underway to use the opportunities offered by these new types of materials.

11.4.2 Non-crimped biaxial fabrics

The type of non-crimp woven fabric described above is also available in biaxial form. As such there are development programmes and projects underway to qualify and use these materials in new component forms.

11.5 Braided materials

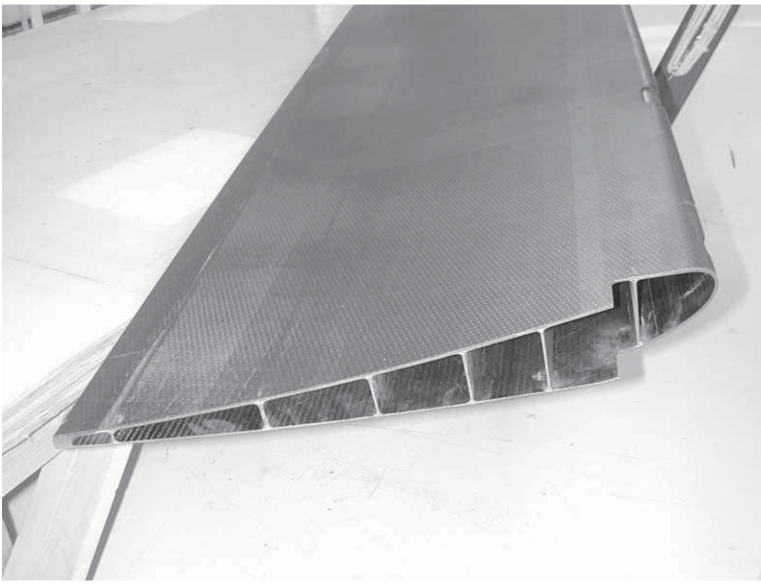
Braided carbon structures have been used for many years in aerospace applications. The best known applications are propeller blades (see Fig. 11.12) by Dowty-UK and Ratier-Figac-F. In recent years, braided materials have also been used in shear web stiffeners for applications such as landing flaps for the Bombadier-Shorts CRJ, in development programmes such as TANGO or for reinforcement of support struts for Airbus components



11.12 Over-braiding of a propeller fabric preform using Tenax HTA 5131 12K carbon fibre yarn.

(manufactured by SARMA, Lyon). In the USA the company Fibre Innovations manufactures complete cruise missile casing preforms in a complex braiding procedure.

Bombardier Aerospace has developed a process to manufacture outboard wing flaps for the Canadair regional jet (Fig. 11.13). The components replace metal outboard wing flaps, and are manufactured in a single injection process using HTA 5131 6K carbon fibre fabric in the skins, stiffened by braided ±45° socks folded to create shear webs.

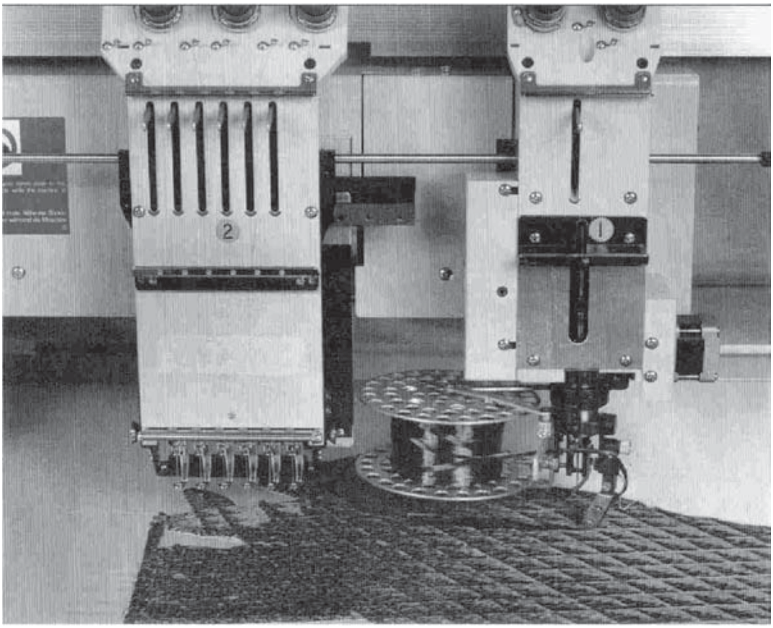


11.13 Outboard wing flaps manufactured by RTM using Hexcel RTM6, Hexcel Injectex Fabric, braid from 'A&P' using Tenax HTA 5131 6K carbon fibre.

11.6 Tailored fibre placement

Since 1995 there have been several well-documented development programmes to use textile embroidering technology to place carbon fibre tows, then stitch the tows into position using fine polyester monofilaments to produce complex preform structures (Fig. 11.14). The most successful of these developments has enabled the company Hightex (Germany) to offer complex preforms for specialist applications. Hightex has used this technology to construct a complex preform structure for Eurocopter. The first components to be selected are hoop-fuselage frames for the NH90 troop transport helicopter.

For these frames the preform is built up from a backing structure consisting of specially woven band fabrics onto which the tow is placed. The components are manufactured using the RTM process in a two-part matched metal tool.



11.14 Tailored fibre placement (TFP) uses a single carbon fibre yarn which is stitched in place to create a complex preform. Several placement heads are able to run in parallel.

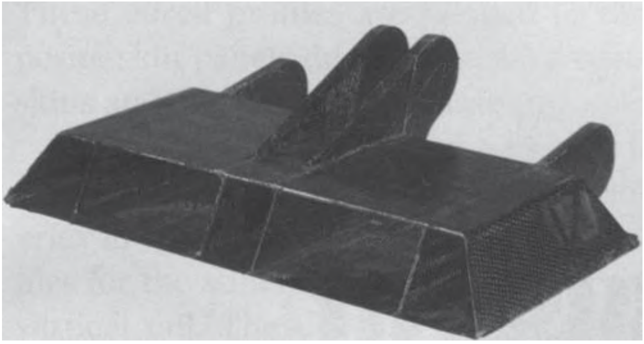
Even though the preform manufacturing process is expensive, the raw material cost is low and the waste material is estimated to be less than 5%. It is understood that the metal component that this composite piece replaced was 30% heavier and was more expensive to manufacture.

11.7 Preforming

11.7.1 Textile assembly

The company FACC (Ried Austria) has used new material and preforming developments from Cytec Engineered Materials, to develop a demonstration composite replacement part for a highly stressed aluminium spoiler centre fitting on the Airbus A340-400 (Fig. 11.15). Owing to the complexity of the component RTM was chosen. The high fibre volume content and the complexity of the preform meant that a low viscosity resin which could quickly and thoroughly impregnate the dry fibre preform was required.

However, for the high compression strengths necessary in this application, toughened epoxy resins containing high levels of thermoplastic additives are required. The thermoplastic additives increase the resin viscosity dramatically. This increased viscosity means that it is very difficult to permeate a preform



11.15 Spoiler centre fitting manufactured by RTM using a complex perform produced using Cytec Engineered Materials Priform Technology. Moulding by Fischer Advanced Composite Components.

without high injection pressures and temperatures. The 'Priform' system developed by Cytec Engineered Materials is said to overcome this problem by adding the thermoplastic toughener into the preform in the form of fibres, rather than including them in the resin system. The resin, a development of a widely used and aerospace-qualified toughened epoxy resin (977-2) is known as 977-20 and is a single pot system including hardener and accelerator agents.

The polymer toughening agent is spun into continuous fibres and is co-woven and added as a 3D stitching fibre into the fabric preform. The thermoplastic fibres are said to dissolve into the resin during cure at temperatures above 100 °C. The preform uses a standard aerospace type 370 g/m^2 HTA 5131 6K carbon fibre fabric. The component is manufactured using a matched metal RTM mould. Injection temperatures are initially low to avoid the thermoplastic component dissolving too soon, which would create variations in the thermoplastic contents throughout the moulding. This component, which is now due to be applied into full series production, weighs 30% less than the original metal component and has passed all required certification testing for aerospace application.

11.7.2 Preforming using heat-activated binder-coated fabrics

Thermoforming is the most well-known and accepted preforming assembly method either with the use of heated vacuum forming (Fig. 11.16) or heated press forming. In either case powder binders are applied to the fabrics to bond the layers together to produce a rigid preform. These binders are usually epoxy or thermoplastic based, and are compatible with the basic resin systems so that the binder does not adversely affect mechanical properties. Several

11.16 Heated vacuum performing facility used to form textiles coated with heat activated adhesive binders.

different binders are used, although each is coupled with its own resin system from specialised resin manufacturers (e.g. RTM6 from Hexcel Composites).

11.7.3 Preform assembly using stitching yarns

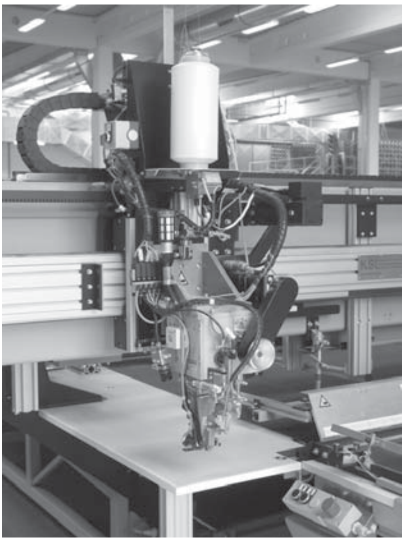
In very large preform structures such as the A380 pressure bulkhead, in order to be able to confection fabric textiles or to add extra localised reinforcement in certain highly loaded areas, specialised industrialised stitching/sewing machines have been developed and are used for a variety of aerospace preforming applications.

The choice of stitching thread materials are limited to a small selection of fibre types:

- Low tex carbon fibre (67 tex or 200 tex) yarn has been used for a variety of stitching applications. The major limitation with direct carbon fibre tow use is that the fibre has little knot strength and as such tends to filamentise when looped. Airbus is known to use direct carbon fibre tow to add reinforced stitching to preform stringers manufactured using RTM.
- Carbon stitching thread was supplied to the market up to the late 1990s by Toray, but is no longer available. However, new developments from the carbon fibre manufacturers could introduce a new carbon fibre sewing yarn into the aerospace market.
- Assembled carbon thread (stretch-broken assembled filaments from 12K/24K yarn). Thin assembled yarns are available for suppliers such as Schappe (France) who supply carbon yarns as low as 50 tex which can be used for stitching.
- Aramid threads or yarns are easily processed and give excellent out of

axis strength. Drawbacks include problems with ultrasonic inspection where the areas which have been stitched cannot be analysed since the signal range is too high. The second and most important factor for the lack of acceptance of aramid yarn for localised structural reinforcement is moisture absorption.

- Polyester yarn is used as an assembly aid. No strength is gained from the material. Saertex uses polyester yarn as a processing aid in the A380 preform (Fig. 11.17).



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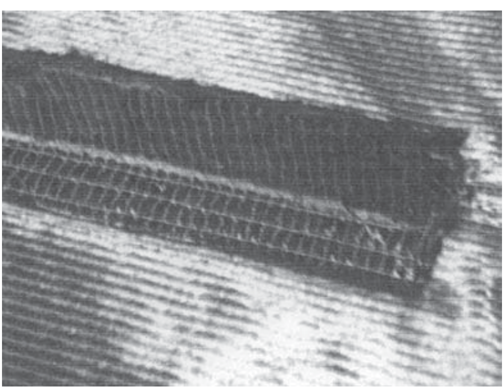

(b)

11.17 Preform assembly using stitching technology. (a) Stitching station used to assemble several layers of multiaxial fabric (Saertex, Germany); (b) stitched assembly of multiaxial fabric stringers onto a fabric skin.

11.8 Repair of fabric components

Repairing aerospace composite components has always been a hotly discussed topic. Through the mid-1990s to 2003 a programme involving all the major airframe manufacturers (Airbus, Boeing, Embraer, etc.) and many of the large aircraft users (British Airways, Air France, Fed Ex, United, American, etc.) devised design methodologies, repair techniques and qualification of material systems using a variety of repair methods. The system chosen was a plain weave fabric using 3K plain weave HTA 5131 carbon fibre and a two-part epoxy resin system Epocast 52A/B supplied by Huntsman.

The repair material is a ‘wet lay-up’ repair system that can be applied to a prepared damaged area using two laminating techniques, either the ‘squeeze-out’ or ‘vertical-bleed’ methods. Both methods use prepared layers of ‘wet’ resin impregnated patches to repair airframe structures, both for monolithic or sandwich laminates. The completed repairs are cured under vacuum conditions at 80 °C.

The repair system is now qualified to a universal specification and the certified data are available to all interested parties. As such there is now a material and laminating system that can be used in Aircraft repair stations worldwide. This fabric repair material can be applied to repair all epoxy-based aerospace components whether they are manufactured using prepreg or other material processing technologies.

12
Applications of textile composites in the construction industry

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12.1 Introduction

The use of textile composites offers attractive possibilities for the construction industry. Some potential advantages are the reduction of weight of construction, the (mass) production of complex form components, possible overall cost reductions thanks to industrialised off-site manufacturing processes, reduction in construction time, and production of multifunctional components. In addition, from an architectural point of view, textile composites offer variety of appearances: translucency, colour, surface texture, finish quality, etc.

Textile composites have been used in construction since the 1960s, and though they do not hold a prominent place compared with that of traditional construction materials, their use is on the increase. It is possible to categorise two different groups of textile composites used in construction: fibre reinforced polymers (FRP) (most commonly glass reinforced polyester (GRP), but also glass, carbon or aramid reinforced epoxides) and membrane structures (most commonly poly(vinyl chloride) (PVC)-coated polyester fabric and poly(tetrafluoro ethene) (PTFE)-coated (Teflon®) glass fabric but with other combinations such as silicone-coated glass, PVC-, PTFE- or silicone-coated aramid also being used).

12.2 Fibre reinforced polymers

The introduction and understanding of new materials in an industry sector is not a simple procedure. This is particularly true for the construction industry owing to its large segmentation. Nonetheless, there have been a considerable number of studies on applications and design guidance for FRP in construction. Even such early studies as those by Hollaway [1, 2] and Leggatt [3] are still very relevant today; it is normally suggested that architects or civil engineers not familiar with these materials should be aware of FRP composites having specific anisotropic properties, which means that existing design considerations may not be relevant. In addition, their mouldability and relatively low stiffness imply the use of structural surfaces and multifunctional elements. On one hand, the anisotropic nature of FRP, and the particularities of the manufacturing processes by which individual elements are produced, seem (on account of market constraints and building regulations) to call for levels of product development and industrialisation at which the non-standard building component cannot compete. On the other hand, their mouldability and the necessity (on account of relatively low stiffness) to adopt geometrical configurations of structural performance, confer a strong design character that makes it difficult for individual components to attain the flexibility that most traditional materials may offer.

Although these two main characteristics may appear contradictory from the traditional perspective of buildings as 'one-off' creations, there are plenty of opportunities for integration by adopting new approaches to the nature of the whole procurement process. One possibility would be to integrate adaptable design to production processes at early stages (e.g. mass customisation), thus avoiding the role of the architect as we know it. Perhaps these possibilities are the key to widespread use of FRP.

Even though FRP composites still do not hold a prominent position in building, they have attracted the attention of architects and engineers for many years. There was an initial rise in their application in construction during the 1960s and 1970s, a period during which a considerable number of buildings using FRP appeared. The reasons for the later reduction in their use are various, including the oil crisis (which importantly increased the price of resins), the low quality control exhibited by some manufacturers (which gave GRP a bad image) and the unsuccessful approach with which in early times the construction industry in general managed standardisation and prefabrication processes. In addition, because of the low structural requirements of the average component, textile FRP composites have only occupied a marginal place in the construction industry. The majority of FRP used have been chopped strand mat combined with glass reinforced polyester, using wet lay-up processes for (typically) cladding purposes. However, following advances in material technologies and owing to the economic need for industrialised production, new processes and applications have been found for composites in construction relying much more on the use of textiles as reinforcement, thus opening a completely new sphere for their use. Polymer composites are now employed to fulfil significant structural tasks such as concrete strengthening, concrete retrofitting and the production of entire lightweight structures such as pedestrian bridges.

Manufacturing processes such as pultrusion and pre-impregnation as well as the use of carbon and aramid fibres have gained significant importance in construction during the last decade. This has been especially the case in the area of infrastructure, where composites offer important advantages regarding durability (corrosion resistance) and ease of installation (light weight). These are crucial qualities at present, as a large proportion of the reinforced concrete infrastructure in the developed world is reaching the end of its life span. Examples of the various bridge decking systems using pultrusion processes are ACCS (Advanced Composite Construction System) from Maunsell Structural Plastics, ASSET (Advanced Structural System for Tomorrow's infrastructure) developed by a European consortium including Fiberline Composites and Mouchel Parkman, and Duraspan® developed by Martin Marietta Composites. An example of the use of pre-impregnated processes for strengthening and retrofitting is provided below as a case study. Another interesting field is the use of 3D textiles; a good example is Parabeam®, which uses velvet weaving techniques with E-glass, to produce an integral sandwich panel.

At the moment, the construction industry represents an important fraction of the total tonnage of composites being consumed, 11% being the figure for the UK [4] and 16.3% for the EU [5]. In both cases the construction industry represents the third major market for composites, but unlike other sectors where composites are used, in the construction industry plastics in general do not account for even 1% of the materials used [6]. Taking into account the size of the construction industry and the various current advantages of composites for building purposes, the above illustrates the enormous potential for a greater use of polymer composites in the construction industry. Accordingly, an increasing number of academic–industry projects and networks, such as Network Group for Composites in Construction (NGCC) and Polymer Composites as Construction Materials, on the use of composites in construction are being developed in the UK and abroad. The future of FRP composites in construction looks very promising.

12.3 Membrane structures

Coated textile membranes form a class of flexible textile composites that are used for small- to medium-span enclosures (usually roofs and air-halls), where their properties of lightness, translucency, high tensile strength, durability and fire resistance may be exploited. Here the textile is the primary load-carrying component of the composite while the flexible coating protects the textile from environmental degradation (e.g. the effects of UV light, moisture and pollutants) and creates a weather-tight enclosure.

Of the most commonly used yarn materials, polyester exhibits good tensile strength, flexibility and significant elongation before yield, while glass fibre shows brittle behaviour and low elastic strain [7]. Thus polyester fabric-based membranes have greater tolerance to dimensional errors in manufacturing, as they may be stretched more easily to fit on site, and they may be used in deployable membrane structures. Conversely, glass fabric-based membranes require more accurate manufacture and can be more easily damaged when folded.

The base fabric is generally woven in either basket or Panama weave, with the latter providing better mechanical properties [8]. One or more coatings are then applied, the most common being PVC for polyester fabric (usually with a top coat of acrylic lacquer, weldable or non-weldable poly (vinylidene fluoride) (PVDF) lacquer, or poly (vinyl fluoride) (PVF) film [9]) and PTFE for glass fabric (with, for example, a fluorinated ethylene propylene (FEP) topcoat to enhance impermeability, fungal resistance and weldability [10]). Other coatings are available, such as silicone, which is used primarily on glass fabric, giving a more flexible membrane than the more common PTFE-coated glass and offering greater translucency. Their perceived disadvantage has been a tendency to attract dirt more readily than the 'self-cleaning' PTFE material, although new surface treatments have overcome this, prompting renewed interest in their application.

Unlike the majority of conventional building materials, textile membranes display anisotropic, non-linear stress–strain behaviour, have negligible resistance to bending and low shear resistance. The structures for which they are used are geometrically non-linear under load. This requires a quite different approach to their design. To obtain some understanding of this difference, one might imagine the behaviour of a straight thread spanning between two supports. This is unable to resist loads applied to it (except loads applied in the direction of the thread) unless it deflects from its original straight profile[1] (i.e. the geometry changes). The profile of the deflected thread will also vary according to the applied load configuration. Equally, a textile membrane surface cannot remain perfectly flat if it is to resist loads applied out of the plane of the surface and will change its form according to the loading.

Snow (or rainwater) and wind are the most common external applied loadings in the case of textile membrane roofs. The former acts vertically downwards under gravity while the latter acts perpendicular to the membrane surface and can be either pressure or suction, depending on the wind direction and orientation of the surface. Both types of load are of much higher magnitude than the membrane self-weight, which is typically less than 1.6 kg/m^2. Thus to better resist the applied loads, textile membrane structures usually have double curvature and to reduce deformation under applied load the surfaces are prestressed. The curvature is anticlastic (Fig. 12.1) in the case of membranes tensioned externally (e.g. by masts, arches and edge cables) or synclastic, in the case of inflated and air-supported membranes, which are pretensioned by internal air pressure (Fig. 12.2). Hence, before carrying out an analysis to

[1] In theory, for a straight horizontal thread to resist vertical load (even its own weight), without deflecting from the original straight profile, would require an infinite tension to exist in the thread. The thread actually hangs in the shape of a catenary under its self-weight.

12.1 Simple anticlastic form of a small canopy, Millennium Garden, University of Nottingham, UK. The form has two high and two low points creating a classic saddle surface (photo: John Chilton).

12.2 Synclastic form of the air-inflated membrane tubes for the deployable roof of the Toyota Stadium, Toyota City, Japan (photo: John Chilton).

determine the stresses in the surface, the engineer must first determine the form of the membrane for the specified support (boundary) conditions. This process is known as 'form-finding' and is carried out using specialised software. Only once the membrane form is established can the stresses in the surface and forces in supporting elements be assessed.

A further peculiarity occurs because coated textile membrane material is produced in rolls of a specific width and length, the precise dimensions depending on the manufacturer. Therefore, as in the tailoring of garments, the cloth must be patterned and cut in such a way that individual planar pieces, when assembled, approximate to a double-curved surface. In the case of membrane roof structures this surface may be of considerable size. The pattern is normally arranged so that the warp and weft directions of the fabric follow the principal stress trajectories. Because the material is anisotropic and is also to be prestressed, it is essential that the correct allowance or 'compensation' is made in the cutting pattern for the stretch of the fabric under tension. Biaxial tensile tests are usually carried out to determine appropriate compensation factors for the material. An appropriate allowance must also be made for overlap at the seams. Therefore, all pieces are cut slightly smaller than established from the designed form and are then stretched to the required shape and size during erection, known as 'stressing-out'. This ensures that the form of the structure, as erected, is as close as possible to that originally designed and should avoid unsightly wrinkles. Owing to the translucency of the fabric, seam lines are a very prominent feature and the final pattern is often determined by both engineering and architectural considerations.

Extensive details of membrane material manufacturers, fabricators, designers and researchers and a wide-ranging database of projects, engineers and architects are provided by TensiNet [11], the EU-funded network for tensile membrane structures.

12.4 Case studies

12.4.1 Boots building, Nottingham (FRP strengthening)

The Boots Building in High Street, Nottingham (Engineer: Taylor Woodrow, Manufacturer: Advanced Composites Group; Fig. 12.3) is a historical building (Grade II listed) whose steel structure dating from 1921 had lost 30% of its section due to corrosion. For its recent refurbishment, the structure had to be able to carry loads superior to those specified by the original design. A particularly important problem was the flexural strengthening of the curved corner beams, for which (in two cases) FRP composites were used.

The solution chosen was a glass and high-modulus carbon fibre–epoxy low-temperature curing pre-impregnated system, maintaining fibre orientations at 0° and ±45° to the directionality of the beams. After installation (Fig. 12.4), the beams were vacuum bagged (Fig. 12.5) and heated to achieve a fibre volume fraction of 65%. The vacuum method also ensured a resin void content below 4%. The advantages of the solution include short installation time, no disruption to the refurbishment process, and minimal additional

12.3 Elevation view of the Boots Building, showing the curved corner section (photo: Advanced Composites Group Ltd).

12.4 Placement of a carbon prepreg layer around the flanges and web of a steel beam (photo: Advanced Composites Group Ltd).

12.5 A vacuum bag used to apply pressure on the composite material (photo: Advanced Composites Group Ltd).

weight or volume to the structure (about 5 mm in thickness). The latter allowed the position of the terracotta cladding to be maintained, thus complying with requirements from heritage authorities.

12.4.2 Inland Revenue amenity building, Nottingham (membrane structure)

Opened in 1995, the Inland Revenue complex (Architect: Michael Hopkins and Partners, Engineer: Ove Arup & Partners), in Nottingham, UK, has at its heart an amenity building (Fig. 12.6) which includes an indoor sports hall, covered by a single-layer, PTFE-coated glass fabric membrane. This is bounded on two sides by two-storey bar/restaurant facilities and by fully glazed façades to the north and south, partially shaded by the membrane. The sections of membrane are supported by lenticular windows suspended from four main masts and tensioned between the rigid edge frames of the windows and cables linking peripheral masts, (Figs 12.7 and 12.8).

12.5 Future developments

The built environment as an important part of and medium for cultural expression is now facing challenges of complexity to a hitherto unparalleled level. Digital computer-aided design (CAD) technologies, which allow for

12.6 Membrane roof at the Inland Revenue amenity building, Nottingham, UK (photo: John Chilton).

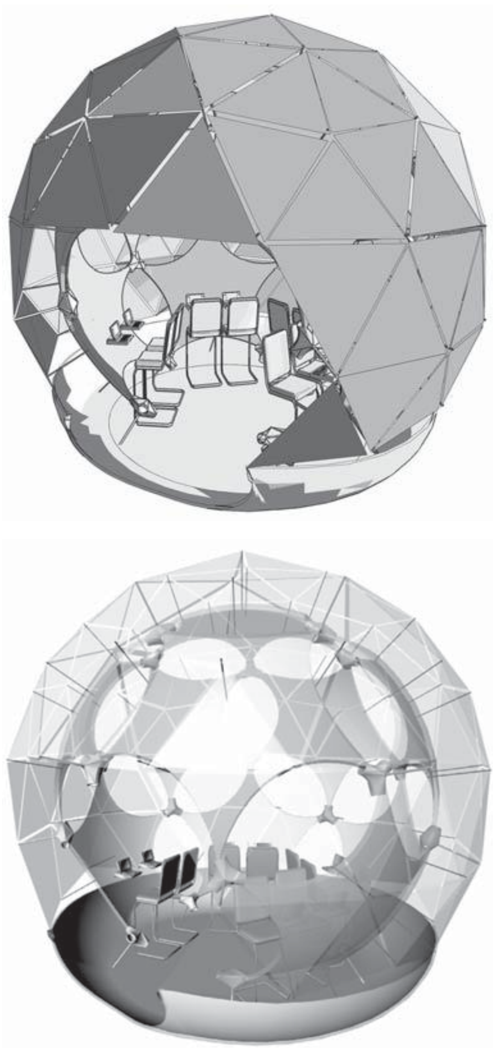
12.7 Stressing out the membrane at the Inland Revenue amenity building, Nottingham (photo: Alistair Gardner).

the development of 3D intricate configurations, along with the possibility of their direct linking to manufacturing processes (CAD/CAM), are now becoming standard in various industries. The implications of vast information availability, fast project development speeds and new techniques as mentioned, are already of importance to the way we think, and thus design and build. In this context, textile composites offer extensive opportunities due to high flexibility of physical configurations, and to the industrial nature of the processes involved in their production. One could easily imagine mass-customisation processes being employed by using for instance membranes, pre-impregnated composites

12.8 Cable and edge details, Inland Revenue amenity building, Nottingham (photo: Alistair Gardner).

or any other structural textile being automatically cut and sewn to form 3D structures that would comply with specific requirements. The textile reinforcements per se may have been tailored using different densities, directionalities and fibre types, to suit the individual structural and visual requirements for each part of the component they would form.

In the case of FRP composites particularly, there is a growing concern for the environmental impact of their production and end of life. There is significant interest in the development of biodegradable fibres and resins, very often based on the utilisation of natural substances. Recyclability issues have focused attention on the use of thermoplastic matrices in construction. However, taking a more realistic view of the immediate future, and understanding the issue of sustainability from a broader perspective, it is certain that present applications of FRP composites will continue to spread. Thanks to their efficiency, ease of transportation and assembly, they still will have much to contribute towards global economic growth and environmental welfare. The near future of construction is also likely to be marked by the emergence of new ways of using FRP composites, probably in combination with traditional materials (e.g. masonry, concrete, timber, steel and glass) to form hybrid structures. Furthermore, following an initial period of technical investigation and validation, a more liberal and creative use of the materials can be expected, where aesthetic values take foremost importance. An example of this is the F100 street station (Fig. 12.9), a glass–FRP hybrid structure being developed



12.9 F100 street station (design and 3D image: Rodrigo Velasco).

within the Architectural Construction Research Group (ACrg) at the University of Nottingham.

Tensile fabric membranes have, until recently, have been used primarily for canopies and/or temporary enclosures where environmental performance is not a high priority. However, with the increased use of textile membranes for permanent or semi-permanent enclosures, for example the Inland Revenue amenity building described above and the Millennium Dome in London, there is a move to improve, in particular, their thermal and acoustic properties. To achieve this, one normally needs to provide at least a two-layer system with or without an intermediate thermal and/or acoustic insulation layer. However, this tends to adversely affect the desirable property of translucency. Consequently, textile membranes are currently being developed with additional coatings designed to improve thermal performance, such as low-emissivity (low-e) coatings and surface treatments that selectively reflect certain wavelengths of solar radiation. Some of these materials are being used in the New Bangkok Airport Terminal, currently under construction [12].

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