13

Textile reinforced composites in medicine

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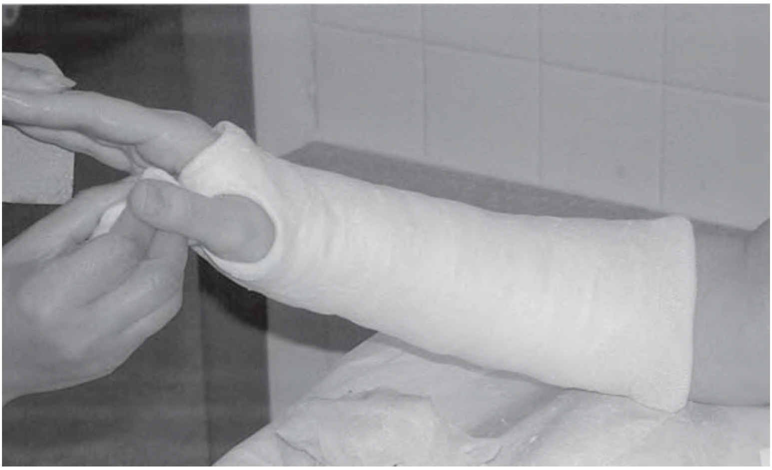
13.1 Splinting material

Splinting materials for the repair of broken bones are not only the largest medical market for textile reinforced composites, but the oldest. The use of plaster of Paris was certainly known by the 10th century as a support for fractures and other bone injuries of limbs. Because of the brittle nature of plaster of Paris, it is probable that it was reinforced with textile materials from a very early stage. However, the modern plaster of Paris bandage, still very extensively used, was not patented until 1851 by Antonius Mathysen, a Dutch military surgeon.

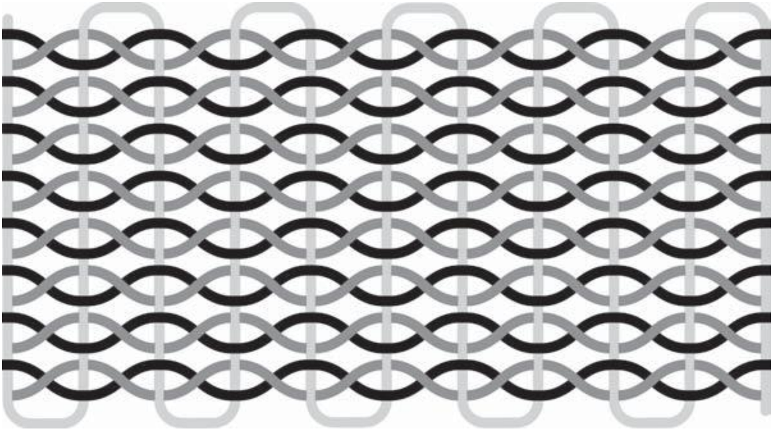
Many orthopaedic surgeons strongly believe that plaster gives a much better moulding to the limbs than other products. Plaster of Paris casts (Fig. 13.1), however, tend to have a high failure rate and have to be reapplied or repaired. Patient comfort is as important as having a light-weight, strong



13.1 Plaster of Paris cast.

cast; not only does plaster of Paris fail in this regard but is also sensitive to water, which means that the patient cannot conveniently shower, and bathing may be almost impossible.

The requirement for a splinting material is a high degree of stiffness combined with conformability. This fabric reinforcement must be capable of being moulded around the awkward contours of limbs. The fabric is required to be of open construction to allow impregnation with a large quantity of plaster. These requirements can conveniently be met by a leno woven construction where the warp yarns cross over one another, locking the weft into place (Fig. 13.2). Such a fabric is also less inclined to fray when cut.



13.2 Woven construction of splinting material.

Similar characteristics can also be obtained with various warp knitted and some weft knitted constructions. A number of fibres have been used in conjunction with plaster, particularly cotton, although modern bandages on the market contain combinations of elastomeric yarn and polypropylene, polypropylene and polyester, or even glass. Glass has fallen into disfavour particularly among casting technicians, mainly because of the glass contained in the dust produced during cast removal. Other casting materials also include polyurethane-coated fibreglass and 100% polyester and polypropylene reinforcing fabrics.

In most modern casting products, the product is delivered to the plaster technician as a packaged product that requires dipping in warm water. This will then harden after wrapping around the limb of the patient within 3 or 4 min (Fig. 13.3). A cast is formed that is sufficiently strong, even capable of taking the patient's walking weight, within 20 min. Not only is this external support splinting system commercially valuable in its own right, but it has led to the technique of 'bandaging' bridge support pillars with textile reinforced materials when they are assessed as being too weak for anticipated loads.

13.3 Wetting the casting product.

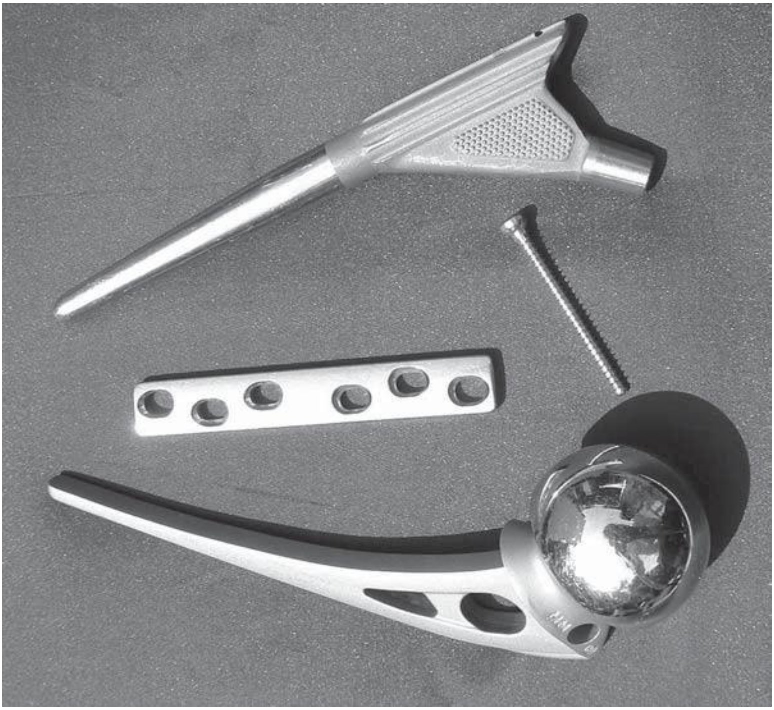
13.2 Walking support frame

Walking support frames provide vertical support for patients who have dysfunctional lower limbs. They provide a rigid support to assist in both standing and walking. Conventionally, metallic frames have been used, but because of the comparatively low stiffness of metallic materials the weight of metal needed frequently inhibits use of the frame by the patient, who typically suffers from cerebral palsy. The reduction in both weight and volume of a carbon fibre reinforced orthosis has led to marked improvements in the continuity of walking as well as an obvious enhancement to the quality of life of the user.

Because of the greater stiffness and hence rigidity of the frame and its increased strength, larger patients are able to use composite orthoses more conveniently and continue to experience improved walking capability. Although carbon-based materials have brittle failure characteristics, the mode of failure of such devices is of progressive collapse and is therefore inherently safe. The use of composites in smaller orthoses, such as knee braces, is limited, because metallic knee braces are required to be available in only a limited range of sizes to reduce stock holdings. They are not customised to the same degree and metal can readily be bent into shape to fit the patient. Such a facility is not normally available with thermoset resin-based materials.

13.3 Bone plates

In orthopaedic surgery, bone plates and screws are often used to treat fractures, particularly of the long bones. Most bone plates are made of stainless steel, cobalt chromium and titanium alloys (Fig. 13.4). However, the elastic modulus of these metals is much higher than the elastic modulus of human bone (110–220 GPa in comparison with 17–24 GPa for human bone). Because there is a stiffness mismatch, the normal healing process of the bone tends to modify itself, changing the whole cycle of the formation of a callus around the broken section, the conversion of the callus to bone (in the process known as ossification) followed by the union of the broken bones. Therefore, development has moved on to consider the use of thermoplastic polymer-based composites and further to thermoplastic polymer composites for bone plate applications.



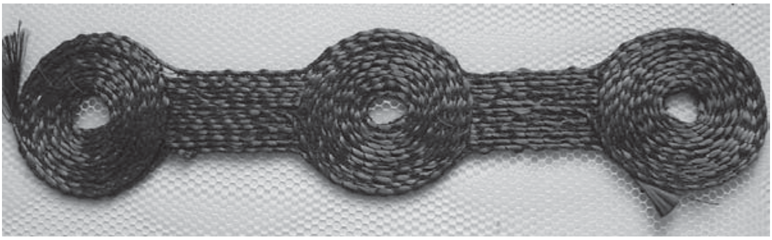
13.4 Metallic implants: hip prostheses (top and bottom) and bone plate and bone screw (middle).

Possible toxic effects (particularly from unreacted monomers) of all implanted polymeric products is of major concern. This, combined with the fact that thermoset bone plates cannot easily be bent to shape in the operating theatre, makes composites of limited attraction. Combinations of carbon/polystyrene, carbon/poly propylene, carbon/nylon, carbon/poly-(methylmethacry late) and carbon/poly (etheretherketone) for bone applications have all been considered. Manufacture has been by the conventional fabrication methods for thermoplastic textile composites, including film stacking (whereby layers of matrix and reinforcing fabrics are hot pressed to melt them together), co-mingling (where mixed yarns of reinforcing and matrix fibres are made into fabrics), hot pressing and the use of powders of matrix materials in between stacks of reinforcing fabrics.

One of the difficulties with composite bone plates is the necessity to provide screw holes within the plate to allow fixation to the bone. Drilling holes reduces the composite load-carrying capacity owing to the damage caused to the reinforcing fibres by drilling. However, if the hole is formed during the impregnation stage or earlier without significant damage to fibres, the loss of strength can be minimised. Computer aided design/manufacture (CAD/CAM) fibre placement technology, as is possible using conventional embroidery machinery, has been suggested for these applications (Fig. 13.5). Biodegradable materials have also been examined, but there are ongoing concerns particularly about the possible toxicity of degradation products as the materials are absorbed into the body.

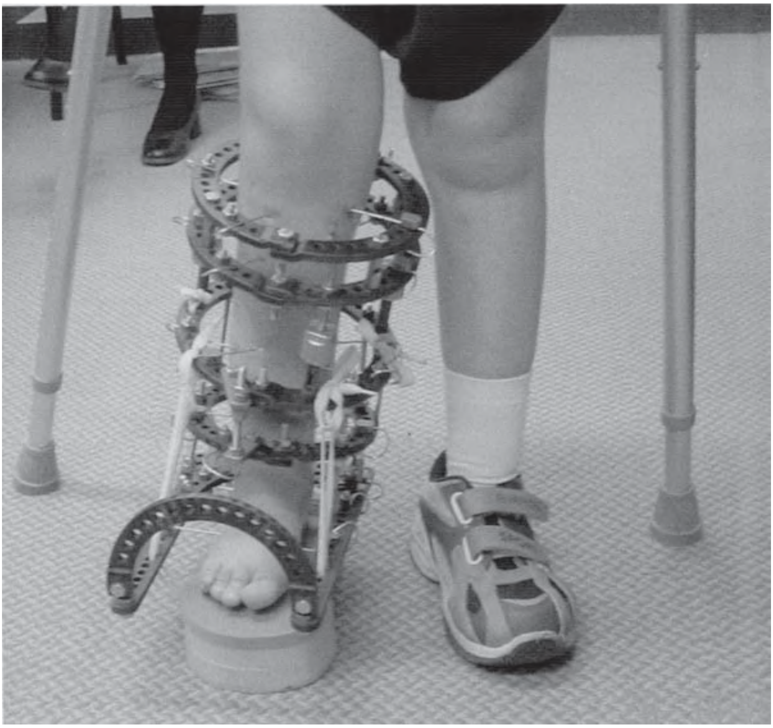
Carbon hip prostheses have also been developed, which, being of composite, provide the potential to have controlled stiffness and stress distribution in the femur. This could result in significant property improvements over prostheses developed from conventional metal working methods, so that patterns of stress closer to those in the natural situation develop. This gives better regeneration of bone and reduces the potential for loosening. However, long-term success has yet to be proven, and such prostheses are not yet on free sale to surgeons.

External fixation devices made from iron were developed from horseshoes in Russia, now known as the Ilizarov ring fixator for fractures. The materials



13.5 Prototype carbon embroidered bone plate.

used have been developed and carbon is used with the main advantage of weight reduction and radio lucency (Fig. 13.6). They are not widely used, however, and many surgeons prefer to stay with steel devices, often on grounds of cost.



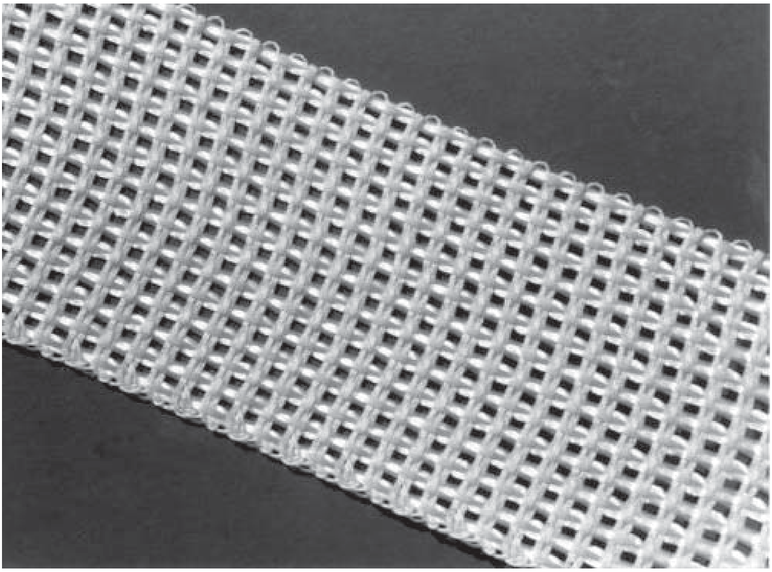
13.6 Illzarov ring fixators.

13.4 General application

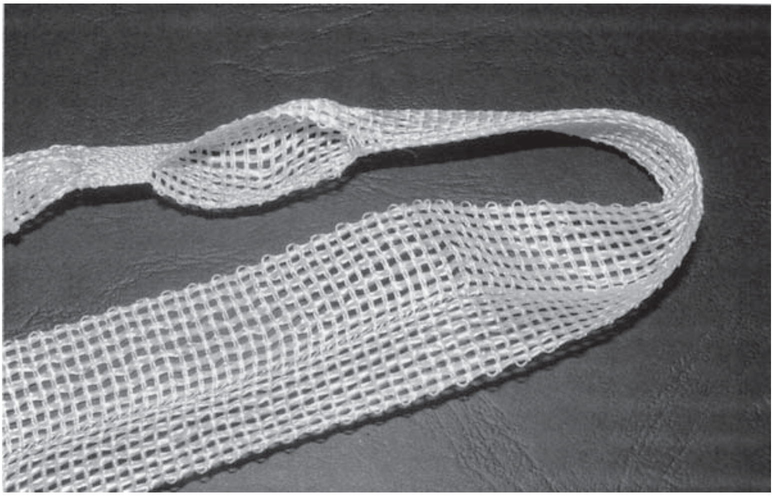
There is potential for textile reinforced composites to be used in very many general applications within the medical industry, in common with many other areas described elsewhere in this book. For example, fabric reinforced printed circuit boards have applications in all walks of life including medical equipment. Specific applications include those requiring a low attenuation of radiation, in particular X-rays. With the increased use of minimally invasive surgical techniques requiring monitoring by X-ray during surgical operation, thin, non-metallic operating tables are useful in helping to reduce the radiation dose that is received by the patient and scattered to those working in the theatre. Carbon fibre operating tables have particular value in this area: they can be thin, yet retain the necessary rigidity. When covered with foam and a waterproof cover, a carbon fibre-based operating table will have all the performance characteristics needed.

13.5 Living composites

A number of textile materials can be used to reinforced natural tissues, as well as replace them. Textile surgical implants, such as suture threads, have been in use for many generations and over the past 40 years there has been extensive use of polyester woven and knitted tubes in the replacement of arteries. More recently, however, textile structures have been developed that will act as a scaffold for natural tissue re-growth, the textile remaining within the body for the rest of the patient's life and forming a living textile reinforced composite. One example is the Leeds–Keio artificial ligament for the replacement of the anterior cruciate ligament of the knee. The textile structure of this device is a mock-leno weave (Fig. 13.7) formed into a complex pocketed integrally woven tube (Fig. 13.8). During the operative procedure a bone plug is removed from a biomechanically appropriate site on both the tibia and the femur before a bone tunnel is drilled through the centre of the joint in the optimum position to join the two bone plug sites. The pocketed tubular woven fabric is threaded through the bone tunnel and the bone plug inserted within the pocket at one end of the textile structure. The ligament device is pulled tight through the bone tunnels and the second bone plug placed within a pocket formed at the other end of the artificial ligament.



13.7 Mock leno woven tape.



13.8 The woven pocket tape used in the Leeds–Keio artificial ligament.

Post-operatively, the bone will grow between the bone plug of both the femur and the tibial bones to lock the textile structure in place. Along the rest of the length of the polyester device natural tissue ingrowth will occur. As the knee is flexed and loaded, the tissue eventually orients itself and a natural composite of ligamentous connective tissue reinforced by polyester fibre is formed in a true tissue/textile composite material.

14

Textile composites in sports products

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14.1 Introduction

Conventional composite materials generally consist of a reinforcing textile structure and a surrounding matrix with other mechanical properties. By combining two or more materials, the best properties of each material are combined. The reinforcing fibres can supply strength and stiffness in any wanted direction, while the (generally polymer-based) matrix protects the mostly brittle fibres against shocks and chemical agents. Whether or not mechanical stresses and strains are efficiently transmitted between fibres and matrix depends on the adhesion between the both of them. Using (physico-) chemically compatible components is thus necessary when designing a composite. Fibre/matrix compatibility is enhanced by applying sizings on the fibres, thus avoiding delamination between fibres and matrix.

The use of textile composites in sports gear is relatively new. In the earlier days, other materials were used. Calfee and Kelly[1] report that natural materials (e.g. wood) were initially used because of their good shock absorption, but these had many drawbacks. According to these authors – together with Jenkins[2] and Axtell *et al.*[3] – their anisotropic nature results in low perpendicular strength, and their large variation in properties and high moisture absorption result in unwanted deformations.

In the 1970s light-weight metals such as aluminium and titanium became popular[2]. These provided higher stiffness and a significant reduction in weight[1,2]. However, since aluminium has no fatigue stress limit, even small stresses contribute to fatigue[1]. Combined with its great flexibility, this led to overbuilt designs[1]. Other drawbacks include its high shock transmittance (resulting in, e.g., tennis elbow) and inherent isotropic nature, which leaves no freedom to meet mechanical demands in different directions (as opposed to composites)[1].

Later on, glass/epoxy composites, followed by carbon/epoxy and others, replaced metals[2]. These anisotropic materials allowed the 'insertion' of (mechanical) properties at certain places where extra strength is required[1, 2].

Miracle and Donaldson[4], Spry[5] and Mattheij *et al.*[6] mention that, by changing the amount, direction and type of reinforcement, one may vary properties along a certain cross-section, resulting in an optimal combination between performance and low weight. According to Jenkins[2], Spencer[7] and Chou *et al.*[8] composites provide higher specific stiffness, fatigue performance and shock damping than metals.

One of the latest developments is the combination of composites with other materials. Composite or metal baseball bats, for example, cause excessive ball speed (injuries), while a combination of wood with E-glass (or graphite) fibre reinforced composite results in an optimal combination of ball speed control and shock absorbance[3, 4]. Other good examples are modern skis that combine composites with metal and natural (and other) materials. Depending upon the desired properties, a combination of materials is made in such a way that optimal properties are achieved. According to Murphy[9], the combination of composites with other materials (e.g. in metal–composite combinations) can also be interesting given that when composites do fail, they generally fail spectacularly.

The usefulness of composites in sports gear depends upon the intended end-use. Some applications require good shock (and thus energy) absorption, while others require a minimal energy loss in order to generate high speeds. Most of the time, a balance between several more or less contradictory requirements has to be sought. The eventual properties of the product depend upon the materials used, the design and the production technology. The effects of changes in these factors, as well as resulting property changes, are discussed below, together with numerous examples.

14.2 Materials

14.2.1 Reinforcing fibres

Fibreglass is the most classical reinforcement. Its specific stiffness equals that of steel and it is more flexible and tougher than carbon[4, 5]. Its use in sporting applications however, is – according to Spencer[7] and Jacoby[10] – limited because of its poor fatigue performance and high vibration transmittance.

Carbon is five times stiffer than glass, but lighter than aluminium[5]. Together with its good fatigue resistance this results, for example, in light and strong bicycle frames[4, 7]. Carbon's vibration transmittance might be a drawback in some applications[10]. Graphite is even stiffer than carbon but also more brittle[4]. Its shock resistance makes it ideal for skis, bicycle frames and tennis rackets.

The 'sweet spot' transmits minimal vibrations when hit, and exists in equipment such as tennis rackets. Miracle[4] and Goode Snow Skis[11] report that the use of graphite broadens this spot, resulting in more 'forgiving equipment', ideal for inexperienced players and for avoiding injuries (such as tennis elbow).

Kevlar is a poly-aromatic amide that provides light-weight tensile strength and toughness, combined with good vibration damping and impact resistance[4, 10]. It is used in skis and also in many types of protective gear[4]. Boron is much stronger than carbon. Compression properties are especially good[4]. Combining carbon (tensile stiffness) and boron (compressive stiffness) results in a synergistic effect, i.e. the overall stiffness is better than could be predicted based on individual strengths[1]. Boron can, for example, be used as longitudinal reinforcement in golf clubs[4]. Celanese[12] produces light-weight Vectran® liquid crystalline polymer (LCP) fibres that are as strong as boron fibres. Their stiffness, however, is comparable to that of glass fibres. Their impact and shock resistance are outstanding, which leads to many possible uses, such as in golf clubs, bicycle wheels and tennis rackets.

Shock damping and fatigue resistance can further be increased by using poly(ethylene) (PE) fibres. A possible example is a carbon/PE reinforced bicycle[4]. Further weight reduction is also possible by using ultra-high modulus fibres. Such carbon and graphite fibres can be obtained by stripping off the outer fibre layer, leaving the stronger core[1, 13]. This list of possible fibres is by no means exhaustive.

14.2.2 Resins

Generally resins provide good vibration damping (far better than metal)[1]. Conventional thermoset resins (such as polyester and epoxy) are often combined with epoxy and rubber modifiers that lower vibration transmission[2]. One must, however, make sure that vibrations are not completely eliminated since the player needs 'information' from the impact in order to play a ball well.

Unsaturated polyesters are the most commonly used in the composites industry because of their good mechanical and chemical properties, in combination with their relative cheapness. They are mostly combined with conventional glass fibre reinforcement. Epoxies, on the other hand, are more expensive but provide better wetting out of the fibres. Their strength and corrosion resistance is better than those of polyester resins, and they are mostly used in combination with high-performance reinforcements (carbon, graphite, etc.) or with high glass contents. Vinyl esters have properties that lie between those of polyesters and epoxies. When considering sporting goods, epoxy is generally used as a matrix material because cost is not a major issue. Epoxy furthermore provides better adhesion and consequently has better resistance to harsh conditions such as water or moisture in general.

Thermoplastic resins offer very high toughness and durability. Compared with thermoset resins they have a higher damage tolerance, are 100% tougher, and are 600% more resistant to cracks and invisible damage. This makes them ideal for use in heavy-duty equipment such as (nylon/carbon) hockey sticks[14].

The following example illustrates the importance of the matrix. Vibration and shock transmission is higher in conventional carbon/epoxy tennis rackets than in those with a polyurethane-modified epoxy matrix, and certainly than in those with a thermoplastic polyamide-6 matrix. The latter absorbs more moisture but this only further reduces vibrations[8].

14.3 Design

14.3.1 General

In general, using different fibre angles (reinforcement shapes), different plies or thicknesses, different (combinations of) materials, etc., may all contribute to the eventual resulting properties[1]. But special techniques that are not specifically composite related, such as microbearings or overall shape modifications, may be also used to obtain the same effect[13].

14.3.2 Reinforcement shapes

Only a few examples of reinforcement shapes are discussed here. Braided reinforcements combine multidirectional reinforcement with an automated process, high uniformity, few seams and overlap, and good draping characteristics[3, 4]. Reinforcement angle and thickness can be greatly varied, resulting in products such as baseball bats that can appropriately be reinforced near the area of maximum stress, namely the handle[3]. Use of braids also reduces torsion – compared with unidirectional reinforcement – such as in ski ‘torsion boxes’ (see further on) or prepreg carbon braids in tennis rackets[4, 7].

Weaves have lower draping characteristics, and overlaps are often necessary to enable smooth load transfer between different plies. They may, for example, be used (as 0/90° weaves stacked at ±45°) in combination with unidirectional reinforcement in order to produce tennis rackets with high shear strength and stiffness (torque reduction)[2, 8].

The ‘tailored fibre placement’ (TFC) concept is worth mentioning. Fibre preforms with stress-aligned fibre orientations can be made, based on the embroidery technique that is also used for decorating purposes. This technique is suitable for lightweight parts with a complicated stress course, such as bicycle frames and brake boosters[6]. Completely unidirectional reinforcements can also be used. These result in excellent flexural and tensile stiffness and strength, but very limited torsion resistance. Generally, several forms of reinforcement are combined in order to obtain the desired combination of flexural, tensile and torsional properties.

14.3.3 Materials

It is important to choose a material according to the desired effect. Stiffer materials such as glass, carbon, graphite and aramide are needed when one, for example, wants to achieve high speeds. If not, some of the energy that has been put into the system may be lost in deformations. A good example is the outside of skates.

Less stiff materials, on the other hand, are needed when some or more degree of deformation is wanted in order to absorb shocks. Good examples include protection equipment, but also the inside of skates. The latter can, for example, be made from heat-mouldable foams mixed with carbon fibres. When the boots are preheated, one is expected to step in and the interior of the skate is consequently remoulded in order to fit perfectly to the feet[10].

14.3.4 Material partition and positioning

Differences in reinforcement and resin placement enable a shift in the centre of gravity. The ends of kayaks, for example, may contain more (light) PE than the rest of the boat, enabling the kayak to move more easily over the waves. Other examples include ski poles, bats and golf clubs; where shifting the centre of gravity can provide more speed and better equilibrum[4]. Pole vaults are another possible example. They are made stiffer at the butt end using a mixture of carbon and fibreglass in order to obtain optimal properties[5].

Combination with other non-composite materials may consist of using foams or honeycomb structures in order to reduce weight and increase (flexural) strength, e.g. closed cell foam is used between two layers of fibreglass in boating, while polyurethane (PUR) honeycombs or foams are used in the core of ski ‘torsion boxes’ (see Fig. 14.2 on page 454[4, 5]). Quaresimin *et al*.[15] mention the use of epoxy foam in between layers of carbon/epoxy for the production of bicycle cranks. Using lighter foam hardly affects the specific properties of the end-product.

Damping rubber or thermoplastics, on the other hand, may be used for vibration damping in tennis rackets. The ‘ISIS’ (impact shock isolation system) in tennis rackets, for example, consists of a separated graphite handle that is reconnected using graphite rods encased in PUR elastomer or thermoplastic (e.g. nylon) resin[13].

Overall, design features may also be effective in reducing torque. Stiffening both sides of the throat area and cross-bar with titanium/graphite in tennis rackets, for example, instead of using braided reinforcements will also reduce torque[13].

14.3.5 Some special features

Many features (not specifically related to composites) are possible, but only a few examples are given here. The insertion of thousands of microbearings in tennis rackets allows the racket to store energy as it swings backwards. This energy is released as the ball is hit, adding kinetic energy and thus speed to the ball. The increase of ball speed is combined with a reduction in shocks and vibrations[13]. Inclusion of piezoelectric materials, for example in skiing, is a possible future application. Its principle is the conversion of mechanical energy to electrical energy that is consequently dissipated, thus reducing vibrations[2].

14.4 Production technology

14.4.1 Continuous processes

Continuous processes are only suitable for (quasi) continuous cross-sections. Pultrusion, for example, is a relatively cheap way of producing profiles with a high level of unidirectional reinforcement. It involves pulling a profile through a heated die where it cures. Multidirectional reinforcement (mats), however, may also be inserted to provide transverse strength. Possible applications are ski poles and parts of carbon/nylon bicycle wheels[4, 7]. Suominen[16] and Spencer[7] also mention combinations with other techniques such as (filament-, co- or pull) winding or roll wrap. The latter enables the production of hollow shapes by working around a round mandrel. Using this combination of techniques leads to a combination of flexural and torsional resistance. Continuous processes result in low property variations and possible examples include golf clubs and fishing gear[4, 5, 7]. The latter can be produced as a combination of continuous carbon fibres that are spirally wound (torque resistance and transverse strength), unidirectional longitudinal glass fibres (vibraton transmittance) and longitudinal carbon fibres (flexural strength)[5].

14.4.2 Discontinuous processes

Discontinuous processes are generally slow and expensive, but they are necessary when cross-sections vary. Most sporting goods have complex shapes, thus necessitating the use of discontinuous processes. Tennis rackets may be made by resin transfer moulding or compression moulding (with internal bladder), while a special technique such as balloon moulding (that does not require rigid tools) may be suitable for baseball bats[3, 7]. Carbon/epoxy bicycles and carbon/glass/aramid surf paddles are generally integrally moulded[4, 17]. Again, many other examples are possible: the number of possible techniques is virtually unlimited.

14.5 Applications

Several examples are given here. As will be demonstrated, different applications require different combinations of materials, design features and production processes.

14.5.1 Pole vault

In pole vaulting, the early use of bamboo poles and of the aluminium poles in the 1960s have long gone. These poles have been replaced with carbon fibre composites. Froes[18] states that the ideal pole should be light and highly flexible but also stiff and torsion-resistant, and that energy loss should be minimal. Nowadays, a typical pole consists of three reinforcement layers. The outer layer contains epoxy reinforced with unidirectional carbon fibres, which provide high stiffness for low weight and good fatigue resistance, and return a maximum of energy. The intermediate and inner layers respectively consist of glass fibre webbing and wound glass filaments in an epoxy matrix, thus increasing the torsion resistance. The amount of glass and carbon can be varied in such a way that the pole is much stiffer at the butt end[5]. According to Bjerklie[19], the pole may thus be custom built to the vaulter's weight, take-off speed and hold technique.

14.5.2 Fishing gear

Fishing gear is somewhat similar in construction but requirements are different. Unidirectional carbon fibres provide flexural strength, while unidirectional glass fibres provide the necessary vibration transmittance. Torque (torsion) resistance and transverse strength is obtained through continuous carbon fibres that are spirally wound[5].

14.5.3 Bicycles

Bicycles have greatly evolved in the past few decades. The two major advances are in the frame and wheels. Aiming at minimal frame bending combined with minimal weight, carbon fibre composites are the materials of choice if there is no concern over cost. A light-weight race bicycle (used by professionals) with a carbon reinforced frame, front fork and seat post is shown in Fig. 14.1. In addition, frames have recently been produced from magnesium, aluminium, titanium and metal–matrix composites. Hybrid frames such as carbon fibre reinforced composites combined with titanium have also been produced[18]. Carbon has a relatively high vibration transmittance but good fatigue resistance, while the resin matrix has low vibration transmittance (good shock absorption), and titanium – as a metal – low fatigue resistance.

14.1 Lightweight race bicycle made of composite parts (courtesy: Giant, http://www.giant-bicycles.com)

Combining these materials may result in combining high fatigue resistance with increased shock absorption, while the overall weight remains low.

When going off-road, shock absorption becomes very important. Appropriately designed wheels can absorb a significant part of these shocks. Glass fibre reinforced nylon wheels have been produced to this end. Using a thermoplastic matrix such as nylon (polyamide) results in better shock absorption[4, 18]. Disc wheels (i.e. without the traditional spokes) made of aluminium alloys and carbon fibre reinforced composites have been developed for reasons of aerodynamics[18]. However, when crosswinds occur, these wheels make the bicycle difficult to control and so they become no longer beneficial in these conditions. A compromise might be a three- or five-spoke wheel, which besides making the bicycle more controllable, also cuts drag (by flattening the few remaining thin blades that slice through the air)[19]. Depending upon the track and weather conditions, other materials and designs may be necessary in order to obtain the best results.

14.5.4 Golf

Golf clubs are nowadays lighter, longer and have a bigger head (with equal mass) than before. The net results are greater club head speeds – because of the long arc – and straighter shots (because of the bigger sweet spot). The club shaft may be constructed from graphite reinforced epoxy – and even boron fibres may be used[14] – while the oversized hollow head is made of titanium[9, 18]. Changing material partitioning may also be helpful in shifting the centre of gravity, thus providing more speed[4]. These modern technologies result in an equalising effect (less gifted players perform much better owing to the reduced skill needed for playing golf), and change the game. This is why the US Golf Association has imposed a limit on the club head volume, as well as on the COR or 'coefficient of restitution'. This is the ratio of the speed of a ball before and after hitting the club and has been set at a maximum of 83%[9].

14.5.5 Baseball/softball

Aluminium baseball bats have recently been banned in the major American leagues because they resulted in excessive ball speeds, which led to more injuries upon impact, but also because they altered the game itself as the field became too small. However, after the ban in baseball, new double-walled aluminium and titanium softball bats were made. These provided a bigger sweet spot, combined with a greater ball velocity[18]. These lightweight metal bats, however, acted as 'equalisers': they turned average hitters into spectacular ones. Again, this type of bat was banned for security reasons and now a limit is set to what is called the BPF or 'bat performance factor'. For a conventional wooden bat, the BPF is set to 1.0. An aluminium bat that returns 10% more energy to the ball than the wooden one receives a BPF of 1.1 and bats that exceed 1.2 BPF are considered illegal. Designers have responded to these restrictions by making new types of bats, e.g. hybrid constructions with carbon fibre reinforced composite and honeycomb aluminium in a double-wall design[9]. The former provides strength and stiffness but is thought to reduce ball speed compared with aluminium, while the latter provides a weight reduction combined with increased flexural stiffness. Speed control is also possible by adjusting the partitioning of materials (e.g. reinforcing fibres), thus affecting the position of the centre of gravity[4]. This is an example of how composites may also be used for security and fair play reasons, instead of only for conventional design reasons (speed, vibration damping, weight, etc.).

14.5.6 Tennis

Tennis rackets have evolved from wooden and metal frames (the latter were introduced in the late 1960s) to the modern ones, which are made of monolithic metals, metal–matrix composites and carbon fibre reinforced composites. The goal in designing these modern rackets ranges from efficiency increase – i.e. accelerating the ball across the net – to damping the dangerous vibrations that can lead to tennis elbow. Accordingly, many types of rackets are possible. Increasing the rackets' sweet spot, which depends upon the stiffness of the frame and the size and shape of the racket handle and head, can reduce vibrations. Modern technologies have enabled the production of relatively large but still mechanically stable rackets, so the International Tennis Federation has now imposed a limit on the size of the racket[18]. An example of such a banned racket is a type that used elongated strings in order to create a larger sweet spot and generate more power and spin for less effort[9].

The use of carbon fibre reinforced composite frames results in high stiffness and corresponding efficiency. To reduce the high-frequency vibrations upon impact, racket handles may be constructed by wrapping multiple fibre reinforced layers around a soft core of injected PUR or a honeycomb construction[18]. An alternative way of damping vibrations may consist of using a separated graphite handle and reconnecting it by using graphite rods encased in PUR elastomer or a thermoplastic resin such as nylon[13].

A state-of-the art racket may, for example, be based on a urethane core, graphite fibres and – to a lesser extent – Kevlar fibres. The graphite provides strength and stiffness, and also prevents twisting of the racket head upon impact outside the sweet spot. The Kevlar fibres lead to additional strength and durability, and furthermore contribute to damping vibrations[18]. Using weaves of these materials and stacking them at ±45° (or braided reinforcement[13]), in combination with unidirectional reinforcement, results in rackets with high stiffness and high resistance to twisting[2, 8]. These state-of-the art rackets are lighter and stiffer, can be swung faster and give balls more rebound. Because of these high available speeds, modern tennis has shifted in favour of the fast servers[9]. A possible solution might lie in imposing energy-related limits as in golf and baseball.

Reduced torsion in tennis rackets may also be achieved by changing overall design features. Stiffening both sides of the throat area and cross-bar with titanium/graphite, for example, may eliminate the need for using braided fabrics in the frame. Other, not necessarily composite-related, design changes include the insertion of microbearings. These store energy, thus resulting in higher ball speeds (efficiency) combined with shock reduction[13].

Depending on the player level and his or her requirements a whole range of rackets is being made, using countless combinations of materials, material shapes, design features, etc. This explains the great variations in racket types.

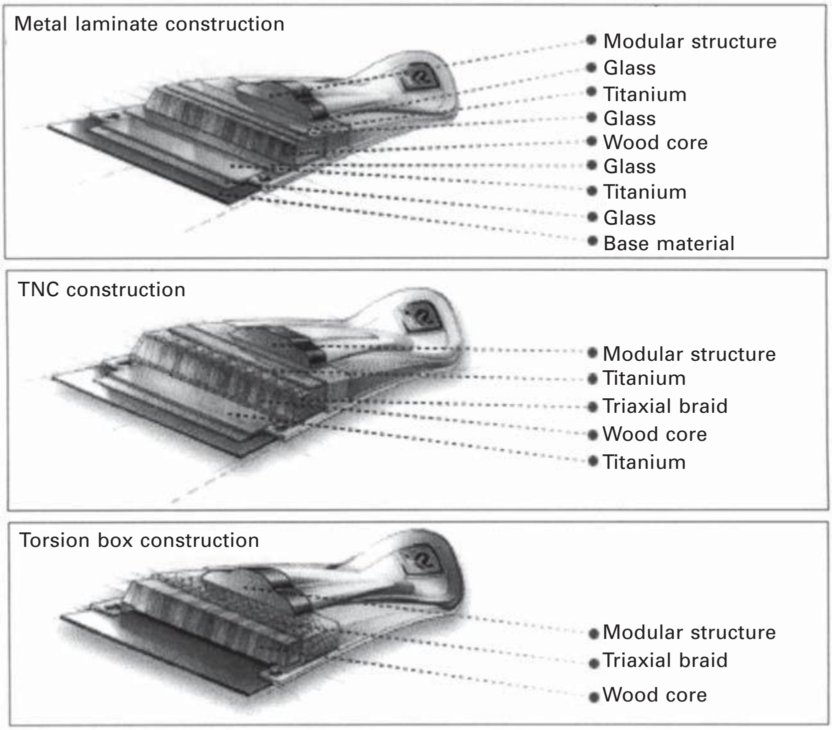
14.5.7 Kayaks

Competition kayaks were once made of mahogany veneers but are now constructed of a combination of carbon fibre cloth, Kevlar and epoxy resins. This stiff design minimises the amount of energy wasted in flexing as the hull passes through the water, thus making this energy available for upholding the maximum possible speed. Weight reduction is also remarkable, although competition kayaks are now subjected to minimum weight requirements. Because of this, other parts such as foot brakes and seat supports are now being made of fibre reinforced composites in order to further reduce the overall weight[19]. Again, changing material partition may also improve the products' qualities: by introducing more – light – PE in the ends than in the rest of the hull, the kayak will more easily move over the waves[4]. Paddles were once made of solid poplar but are now also made of composite materials. Changing the paddle shape into what is called a spoon-shaped 'wing' paddle has further improved propulsion efficiency, although new paddling techniques are required[19]. This is again an example of how new technologies can change a sport.

14.5.8 Skis and snowboards

Figure 14.2 gives an idea of the possible build up of a K2 ski[20]. In fact, the same principle is also valid for water skis and snowboards. In the centre of the construction one can find the core. Aström[21] and others report that this flexible and lightweight part may be made of (PUR) foam, wood/foam composite or wood, or be simply empty[4, 10, 22]. Note the use of natural materials. Sometimes channels are introduced into the core in order to further reduce weight and increase flexibility[10, 23].

The core is wrapped with a composite material, resulting in the 'torsion box'. This torsion box is contoured to give the right amount of flex and



14.2 Possible ski constructions (courtesy: K2 Skis[20]).

spring and – especially – to eliminate twist[24]. This wrapping may consist of glass/carbon/epoxy prepreg (reinforced in different angles) or triaxial braids, for example three layers of pre-impregnated fibreglass[4, 10, 20, 22]. The latter may also be wet-rapped but this known to cause more mistakes. *Design News* magazine[25] reports that wrappings consisting of co-extruded acrylonitrile-butadiene-styrene (ABS)/fibreglass sheet, rubber and fillers may also be used.

This central section is then sandwiched between a top and precision-milled base layer(s). Unreinforced thermoplastics are generally used as base layer[21]. Moulding (and other) techniques are used for the construction of both layers. Multilayered skis may furthermore consist of sheets of glass/epoxy or reinforcing fibres such as carbon (strong, fatigue resistant), Kevlar (impact resistant), graphite (vibration resistant), titanium or others[10, 21]. On top of this construction, a secondary core is possible. This secondary core is based upon modular technology and works both as a suspension system as well as a mass damper[20].

Different styles of snowboards depending upon the snow type are now available. Deep, powdered snow requires more flexibe boards, while icier terrain requires stiffer boards. Because of their laminated construction, the boards in question require an epoxy adhesive that will keep the layers in place through all types of terrain. This adhesive provides excellent wet-out of the fibreglass and other reinforcing layers, resulting in good fatigue and thermal resistance. Increasing the amount of epoxy without changing the amount of glass fibre results in stiffer boards, which perform better on icier terrain. The bindings can be made of nylon-based composites. This thermoplastic matrix provides good impact resistance, even in sub-zero temperatures[25].

14.5.9 Ice hockey

Ice hockey is an application where shock resistance is of major importance. Heavy-duty equipment such as hockey sticks can be made of nylon/carbon composite. The thermoplastic matrix provides toughness, durability and shock resistance. Hockey skates may also be a combination of thermoplastic matrices and stiff fibres. The outside of these skates may be reinforced with stiff fibres such as glass, carbon, graphite or Kevlar. The stiffer the fibres used, the less energy will be wasted on deformations[10]. A heel stabiliser wedge made of an engineering thermoplastic elastomer, on the other hand, may improve the skater's efficiency by allowing more forward flexing than traditional skates while providing lateral and tendon support[25]. The inside of skates can be made from heat-mouldable foams mixed with carbon fibres. The boots are preheated and the user puts them on; the interior of the skate is consequently remoulded in order to fit the feet perfectly[10].

14.6 Conclusion

Considering the given examples, one can easily see that a virtually limitless number of material combinations are possible. Composite materials, but also other materials, are used for sports gear in order to obtain an optimal combination of properties for each possible application. By furthermore optimising design and production techniques, one may obtain a product that is suited for any possible combination of applications, conditions and player experience. Modern technologies also allow for the production of custom-built items.

In some sports these improvements have led to serious changes in the game itself, the required skill to play the game, security issues, etc. As a reaction to these technological changes, many sporting federations have imposed limits on sporting goods. Inserting composite materials into sporting goods has proved to be very useful – not only in improving overall performance – but also in controlling every possible property, thus leading to safer and fairer sporting. The future of composite materials in sporting goods probably consists of combining them with other materials, thus using the best properties of each constituent, and obtaining products that are suited for any given requirement.

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14.8 References

1. Calfee C. and Kelly D., 'Technical White Paper – Bicycle Frame Materials Comparison with a Focus on Carbon Fiber Construction Methods', Calfeedesign, http://www.calfeedesign.com/calfee_TWP.pdf, 2002, 1–13.
2. Jenkins M.J., 'Good vibrations – materials swing into action', *Materials World*, 2000 **8**(6) 11–13.
3. Axtell J.T., Smith L.V. and Shenoy M.M., 'Effect of composite reinforcement on the durability of wood baseball bats', *32nd International SAMPE Technical Conference*, Boston, SAMPE Publishing, 2000.
4. Miracle D.B. and Donaldson S.L., *ASM Handbook – Volume 21 Composites*, Ohio, ASM International, 2001.
5. Spry W.J., (1998), 'Sports and Recreational Equipment', in Dostal C.A., *Engineered Materials Handbook – Volume 1: Composites*, Ohio, ASM International, 845–847.
6. Mattheij P., Gliesche K. and Feltin D., 'Tailored fiber placement – mechanical properties and application', *J. Reinf. Plast. Comp.*, 1998 **17**(9) 774–786.
7. Spencer B.E., (1998), 'Composites in the sporting goods industry', in Peters S. T., *Handbook of Composites*, London, Chapman & Hall, 1044–1052.
8. Chou P.J.C., Ding D. and Chen W.-H., 'Damping of moisute-absorbed composite rackes', *J. Reinf. Plast. Comp.*, 2000 **19**(11) 848–862.

9. Murphy M., 'Blast off!', *Popular Science*, 2002 (June issue, via http://www.popsci.com).
10. Jacoby M., 'Olympic science', *CENEAR*, 2002 **80**(5) 29–32.
11. 'Goode Snow Skis – Technology Overview', http://www.goode.com/sstech.html, 2003.
12. Celanese Acetate L.L.C., 'Vectran – Grasp the World of Tomorrow, Engineering Data' http://www/vectran.net, 2003.
13. Tennis Warehouse Recquet Technology Glossary, http://www.tennis-warehouse.com, 2003.
14. 'Falcon Sports Senior Hockey Sticks', http://falconsports.com/Products/Senior.html, 2003.
15. Quaresimin M., Meneghetti G. and Verardo F., 'Design and optimisation an RTM composite bicycle crank', *J. Reinf. Plast. Comp.*, 2001 **20**(2) 129–146.
16. Suominen M., 'High performance carbon fiber pultrusion profiles for the future', *10th European Conference on Composite Materials*, Brugge, 2002.
17. 'AT Paddles – Bentshaft Whitewater and Touring Paddles, AT2 series', http://www.atpaddle.com, 2003.
18. Froes F.H., 'Is the use of advanced materials in sports equipment unethical?', *J. Minerals, Metals Materials Soc.*, 1997 **49**(2) 15–19.
19. Bjerklie D., 'High-Tech Olympians', *Technol. Rev.*, 1993 (January) 22–30.
20. 'K2 Skis', http://www.k2skis.com/skis/technology.asp, 2002.
21. Aström B.T., *Manufacturing of Polymer Composites*, London, Chapman & Hall, 1997.
22. 'Evolution Factory Tour', http://www.evoski.com/factory_tour.html, 2002.
23. 'The Dynamic Ski Technology: Hyper Carbon, Texalium …', http://www.skidynamic.com, 2003.
24. 'Surflight Hawaii Composite Controlled-Flex Technology', http://www.surflight.com/tech.html, 2003.
25. 'Plastics create a winter sports wonderland', *Design News*, 1995 (20).