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Carbon fibre and fibre lamination in prosthetics and orthotics: some basic theory and practical advice for the practitioner

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Introduction

The first experiments with carbon fibre (CF) in prosthetics and orthotics were probably made by Mr. Nigel Ring, Chailey Craft School and Heritage, Sussex, England, around 1966.

This was in the very early days of CF technology, just a couple of years after the introduction of the very expensive stretched high modulus fibre. It was a very promising new technology, but it turned out, that there were some very expensive lessons to be learned by the high tech industry, before the new material could be safely used in product development. The most famous of these lessons is probably the one when the first use of carbon fibre in jet engine turbine blades failed after the production had started, with disastrous economical consequences for the company.

Mr. Ring tried to make light, stiff torso sockets for upper limb amelics, and soon after Dr. David Simpson, Edinburgh, the author and maybe some others followed. The results were interesting but the costs were prohibitive and it must be confessed, that we did not use the fibres very intelligently at the time.

In 1972 Mr. Bengt Östberg at our Een & Holmgren Uppsala branch tried to reinforce aluminium braces with carbon fibre prepreg after final adjustment of the brace. The aluminium was then used as a core in the final product. The results were excellent, but the manufacturing technique, including the use of a large and heavy autoclave, was too impractical for use in prosthetic and orthotic service.

In the late 1970s Mr. Össur Kristinsson, Iceland, invited us to join him in the development of his new trans-femoral socket concept, the flexible socket. A key component in this concept is a very stiff upright, and for this he suggested the use of CF. Since then the author has maintained a very productive contact with Mr. Kristinsson, although many others have provided very important inputs to our development and to our education programmes.

We can now look back at more than a quarter of a century playing around with CF and more than a decade routinely using it in prostheses, orthoses, corsets and orthopaedic footwear, and we are far from the only ones. CF is now widely used in prosthetics and orthotics and many allied industries, pioneered by Blatchford, UK, (prosthetic components) and Proteor, France (orthotic components) have introduced CF products and applications, one of the most recent ones the very interesting Icelandic Masterstep foot. Many of these products are beautiful examples of good professionalism in

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development and high quality production, while some of them bear evidence, that the developers did not know what they were doing, or that they hoped, that the customers would not know what they are buying. "If there is CF, it must be high tech and good!" The author has seen products where a black matrix has been used to give the impression that there is carbon fibre in it.

We have given many courses to our own Een & Holmgren/LIC staff, and we have been invited to give courses all over the world on fibre mechanics, CF and lamination since 1981. This activity has been very stimulating, although it has been a surprise, that there was such a need for improved understanding of basic fibre mechanics and lamination procedures There is no doubt, that the introduction of the expensive CF has stimulated us to improve our act and do much better also with GF (glass fibre) and other less expensive fibres.

This paper briefly summarises the classroom content of these courses and emphasises mechanical aspects. It includes basic engineering analyses, experience gained by the author and others, and recommendations and (printed) information from suppliers and manufacturers such as Union Carbide, Thoray and Exel. Complicated chemical and mathematical analyses have been purposely avoided because that is just not the way to communicate with the intended target group: the advanced, interested and demanding practitioners amongst prosthetists, orthotists and orthopaedic technicians.

The designer is strongly recommended to study the subject more closely in textbooks on fibre mechanics. Most designers are used to working with isotropic materials like metals, and this is a completely different game. Fibre composites are anisotropic (different properties in different directions), and strength and stiffness are much more dependent upon the manufacturing process.

In high tech applications in space and aeronautical engineering, the performance to weight ratio is very important, and thus high costs for calculating and testing the design and refining the manufacturing procedures are accepted even if the gain may appear to be small. In mass production and in less critical applications, such as fishing rods, ski poles, sailing masts, guitar necks etc., a marginal improvement of the performance is usually not very important. Thus the costs spent for optimising the product are modest, while efforts are spent on rationalising the manufacturing. Some years ago the author approached different manufacturers asking for cost estimations for manufacturing components for prosthetic systems. It turned out, that the high tech industries, specialised in space and defence technologies, were 6-10 times more expensive at maybe 10-15% better performance compared to what the other category of companies could offer. The other companies gave us, satisfying more limited demands, 5-8 times more for the dollar, if you prefer to put it that way.

In prosthetics and orthotics we see a lot of manufacturing of individual objects, using hand lay-up, vacuum membrane moulding and other techniques where the tooling costs are low. It is the author's view that in this category of design and manufacturing extremely good results and high quality products are within reach with only a basic understanding of fibre mechanics, let us call it "guided common sense", and this is what this presentation is about.

There are several problems when introducing CF, and also glass fibre (GF) although it is much less expensive, in prosthetics and orthotics. One is that the basic rules of materials distribution are not fully appreciated. The difference between stiffness and strength is sometimes not understood (CF is not significantly stronger than GF, 0 to some 40% only, but it is about three times stiffer). Many find it difficult to understand, that the fibres cannot be permanently deformed, and consequently the shape of a fibre dominated composite cannot, with exceptions to be discussed later, be adjusted after curing if full strength is expected.

Maybe one reason for misunderstandings is the confusing concept of reinforced plastic (RP). We do not reinforce the plastic. We use the plastic as a matrix to hold the fibres in such a position, so that they can do as much as possible of the job. It would be more correct, maybe, to say "matrixed fibres", but "fibre composite" is an excellent name.

A composite material is a material consisting of more than one component. In this context it consists of fibres to provide strength and stiffness, a matrix to bond the fibres in order to utilise their properties and, sometimes, a core to distribute the material in an optional way.

Due to limited understanding of moment of inertia many professionals in prosthetics and orthotics believe, that CF can just be added to the lamination, and if the results were not sufficient, the quality of the available CF is blamed. This misunderstanding is very common, and also in medicine there is a tendency to be trapped by "materials voodoo". It is believed, that new materials will, in a miraculous way, solve old problems. The use of materials and the utilisation of materials properties are based on engineering science with a long tradition, and maybe this science should more frequently be applied properly before miracles are asked for.

One early mistake was that layers of CF were sometimes mixed in between layers of GF in the lamination. We studied the result of such a lamination during the early development of the flexible socket (now called the ISNY socket or the Scandinavian Flexible Socket) (Fig. 1). The weight bearing structure is a medial beam, subject to a bending moment. Strength is no problem, but if the beam bends (i.e. is not stiff enough), there will be problems when the lateral wall of the flexible socket collapses, and also other stresses may occur and cause problems.

A bending moment was applied (a force acting with a lever arm of 60mm) and the deflection of the beam was measured (Fig. 2). It turned out, as expected, that a properly laminated CF beam with straight, continuous fibres was 3 times stiffer than a correctly made GF structure. But this GF structure was some 5 times stiffer than the CF-GF-mix, where no efforts had been spent on straightening the fibres or orienting them in the correct direction (Fig. 3). The conclusion is that excellent results are possible if GF is correctly used while very

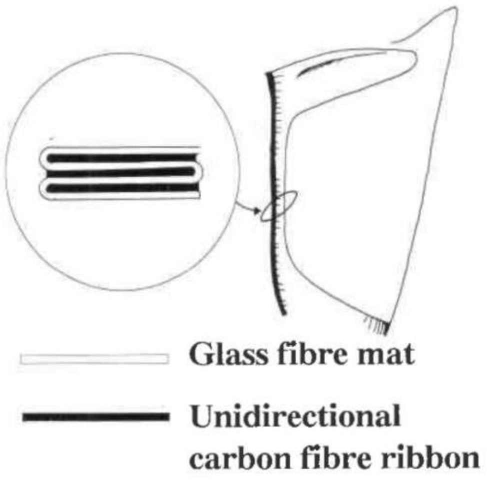

Fig. 1. Mixed layers in early flexible socket lamination.

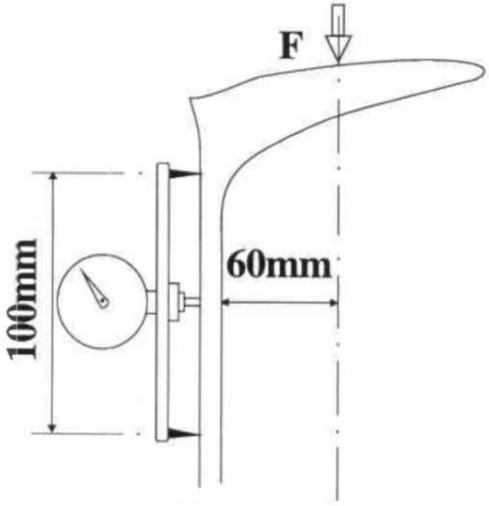

Fig. 2. Arrangement for measuring deflection.

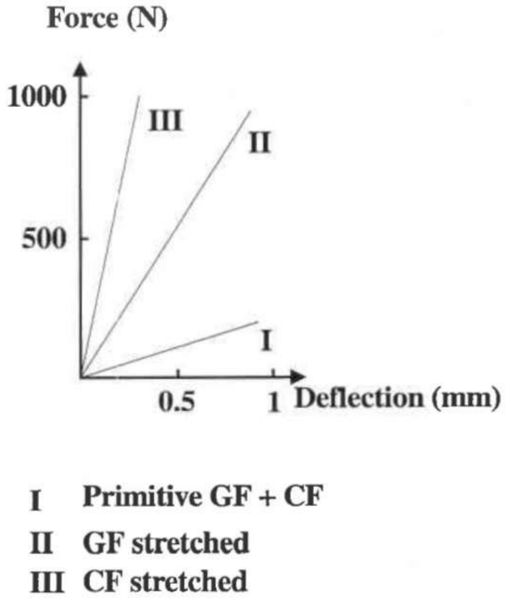

Fig. 3. Deflection of medial upright.

bad results at very high costs are likely to appear when using CF improperly. A CF fibre composite will not be much stronger, but it will be three times stiffer and some 10-20% lighter than a GF one.

At the time of this experiment, 1980-81, our annual CF consumption in Stockholm and Uppsala was about USD 200,000, most of it wasted, obviously. Our fibre mechanics and lamination education programme was one of our best investments ever!

Stress, strain and Hooke's law

Although mathematical calculations will be avoided as much as possible in this paper, it is necessary to agree upon some definitions and principles and share frames of reference. This is why I take the liberty of hooking up on the wall some elementary aspects of strength of materials.

The *tensile stress (σ)* is the pulling or pushing force divided by the cross-section area, or the force per unit of cross-section area (assuming that the stress is uniform across the section).

The *strain (ε)* is the relative deformation, i.e. the elongation or shortening divided by the length where the cross-section area is not changed.

When there is stress there is strain, or, when there is strain, there is stress. If the material returns to its original dimensions when the load is removed, there is elasticity, and if the stress is proportional to the strain, there is linear elasticity, and the material follows *Hooke's law*. Proportionality means that the stress can be calculated by multiplying the strain by a constant. This constant or stress to strain ratio is called *modulus of elasticity* or *Young's modulus (E)*. The higher the modulus of elasticity, the stiffer the material, and the less strain at a given stress (or more stress at a given strain).

It may be confusing, but the lower the modulus, the more elastic the material.

Hooke's law states that: $\sigma = E \times \varepsilon$

The material is elastic if no deformation remains when the stress is relieved. If there is remaining deformation, the stress must have exceeded the yield point into the plastic range. This is what happens when a metal rod is permanently bent (Fig. 4).

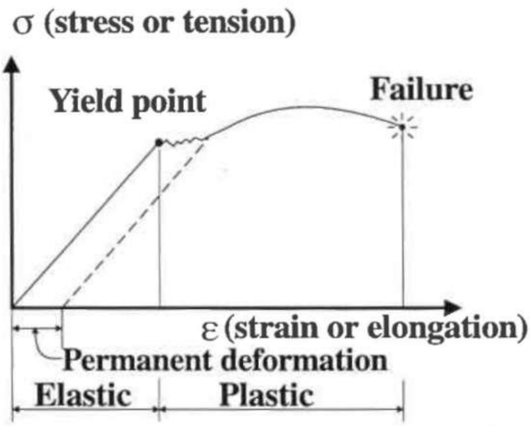

Fig. 4. Stress versus strain in steel.

The principles are basically the same for shear. There are shear stresses and shear elasticity modules, related to angular deformations. For further information see any elementary textbook on strength of materials.

Basic principles of handling bending and torsion

Fibre composites are frequently used in structures subject to bending. Bending is a balance or equilibrium between an external bending moment on the structure and an internal resisting moment in the structure. (A bending moment, of course, is a force combined with a lever arm).

If a beam is subject to bending (Fig. 5), it is stretched along the top face and compressed along the bottom face. Navier's principle tells us that the strains are proportional to the distance from the neutral line (NL), and so are the stresses if Young's modulus is not changed

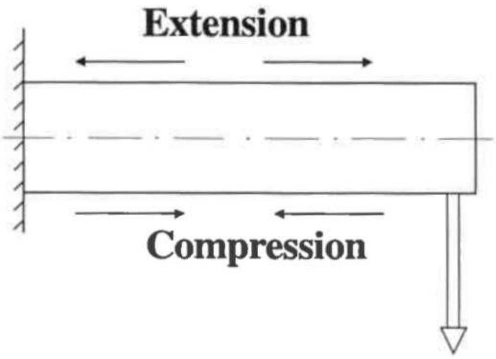

Fig. 5. Extension and compression when bending a beam.

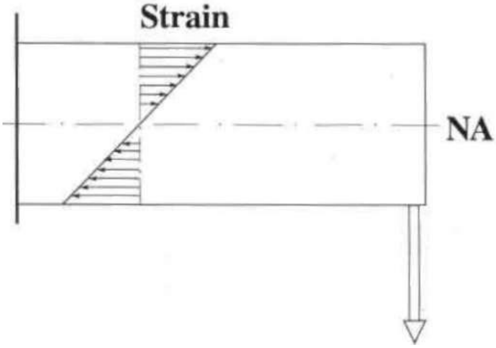

Fig. 6. Navier's principle: the strain is proportional to the distance from the neutral axis.

(Fig. 6). Hence the internal balancing contribution to the strength from each increment of the cross-section is proportional to its distance from the neutral line. The contribution to the stiffness is proportional to the square of this distance. In the neutral line, there is no compression or extension, and hence there is no point in putting strong and expensive material there, a common habit in prosthetics and orthotics. On the contrary, from the view point of costs and weight, the material should be moved as far away as possible from the neutral axis. And consequently, the further the fibres are away from the neutral axis the more effectively they are used.

The I-beam, made from steel, is a classical example of this (Fig. 7). It is available in many standardised sizes, and it has been used in bridges, buildings, cranes etc. for many, many years. The distance between the flanges is secured by a thin wall, called the web. The web also handles the shear flow (see later).

By moving away the material or the fibres from the neutral axis. the *moment of inertia* is increased without increasing the amount of material, and the moment of inertia expresses the ability to resist bending.

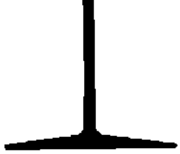

Fig. 7. The I-beam.

Fig. 8. Sandwich.

An alternative possibility to increase the moment of inertia is to build up a sandwich structure, where the thin wall is replaced by a light and/or cheap *core* (Fig 8).

The principle for moment of inertia also applies for torsion. A tube of slightly larger diameter does the same job with less material than a solid rod (Fig. 9).

Torsion is, however, not "pulling and pushing", but shear or shear flow in the cross-section perpendicular to the radius about the neutral axis. The shear flow must be *closed*, and if it has to find its way close to the neutral axis, most of the effect is lost. Thus the I-beam does not serve well against torsion. For this purpose the winner is a cylindrical tube. Also a sandwich used for torsion has to be modified, so that the face of the sandwich (with continuous shear resisting fibres. see later) closes the cross-section (Fig. 10).

Fibre mechanics – the art of using strings

The fibres are extremely thin, and

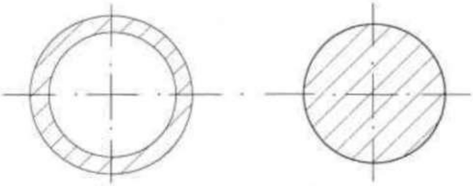

Fig. 9. Rod and tube.

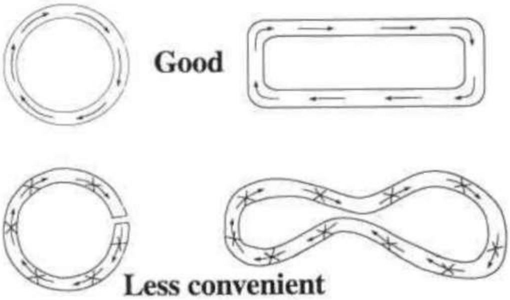

Fig. 10. Closed and open shear flow.

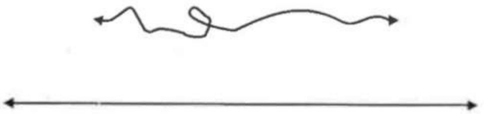

Fig. 11. Relaxed and stretched rope (or fibre).

consequently do not resist bending or twisting. However, they do resist pulling tension. They work like strings or ropes. If rope is laid out as in (Fig. 11) and pulled at both ends, it must be straightened out before it resists or takes the load. *All fibre data is related to continuous, straight fibres, parallel to the stress.*

If the rope is surrounded by some other material, like plastic, it is more difficult to straighten out. But under these circumstances the resistance is provided by the plastic material and not by the rope until of course, the rope is straight. In composite terms, the composite of rope and plastic, or fibre and matrix, is *matrix dominated* until the fibres are straight. When matrix dominated, the strength and the stiffness of the composite is determined by the matrix, and the fibres are more or less wasted.

Metals are usually *isotropic* i.e. they exhibit the same strength properties in all directions, and this is what most design engineers are trained to deal with. Fibre composites are *anisotropic*, i.e. stronger and/or stiffer in one direction than in another. This is a cultural shock for many designers, who are more or less lost when the strength properties are different in different directions. In some directions they are *fibre dominated* and strong, because the fibres take the load. In others they are *matrix dominated* and weak, because the matrix takes the load. But most of the time they are *partially fibre dominated* (Fig. 12).

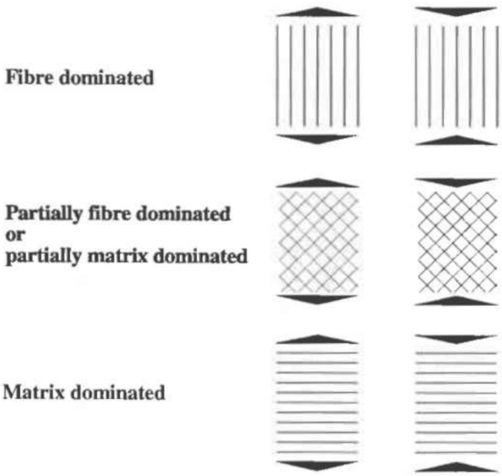

Fig. 12. Fibre domination and matrix domination.

The art of optimising fibre composites in a structure is the art of orienting and securing the fibres. In high tech applications this art is complicated, and there are still questions to be answered. It is, however, possible to obtain very good results, if some simple rules are obeyed.

There are two basic kinds of stresses to be considered:

- pulling/pushing (or stretching/compressing);
- shear.

Pulling/pushing

Pulling/pushing is the most important kind of stress when bending, at least in isotropic materials. Also fibre composite strength to bending is built up by material as far as possible from the neutral axis, to be pulled above it and to be compressed below it.

Pulling is no problem, but how about longitudinally compressing a string? We have all seen that when bending a tube with thin walls, it has a tendency to break in a buckling mode, far before tensile failure is reached (Fig. 13). Buckling is a stability problem, and is handled by structional stiffness or by support. The situation is improved if the wall is made thicker, or if the tube is filled with some material, that supports the wall and prevents it from buckling. If this is the case, most materials are as strong in compression as they are in tension. This is also true for our fibres (except for Kevlar). But if the fibres are not straight when the longitudinal compression starts, buckling has already been initiated. But if everything is right, fibres can handle longitudinal compression stress.

Shear

Shear not only occurs when there are external

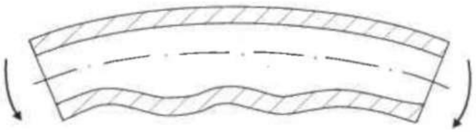

Fig. 13. Buckling.

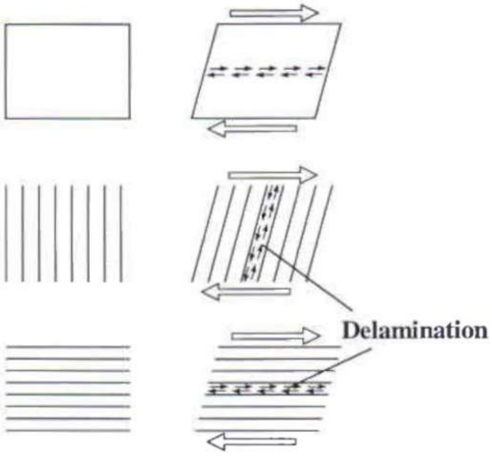

Fig. 14. Shear in matrix domination.

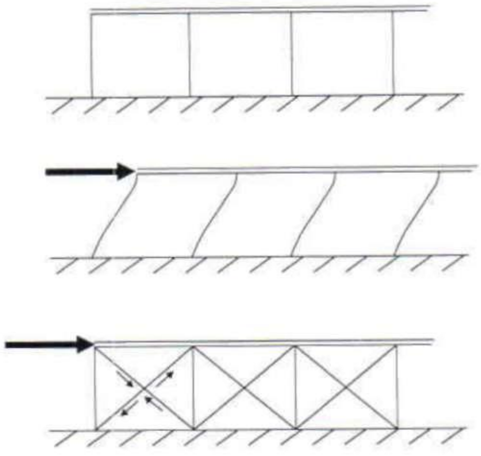

Fig. 15. The fence method.

shearing loads such as in torsion. There is usually (not in "pure" bending) internal shear when there is bending (see later). There are actually, if you penetrate the subject much deeper, stresses and strains due to pushing or pulling and due to shear in all the three dimensions, when there is a load. If the material will not resist shear, the other tensions will be the same everywhere and in all directions in the material, and the material behaves as a fluid obeying the laws of hydromechanics. Fibre composite mechanics has a little of hydromechanics too in its more advanced aspects, because plasticity of the matrix includes a tendency to relax shear stresses and redistribute (and "equalise") the load distribution. So there is partially hydromechanics, a lot of solid body mechanics and the complicating element of anisotropy. No surprise then, that it is sometimes confusing and that it may be difficult to interpret experiences.

Back to our more practical approach! If the above fibre configurations are used, the result will be delamination due to the matrix domination mode (Fig. 14). The shear forces cause the matrix between the layers of fibre to fail or delaminate. When such delaminations occur, careless manufacturing is often blamed, although it would probably be more reasonable to draw the conclusion that the shear strength of the matrix was not sufficient.

But this is only if matrix domination has to be accepted. The fibre dominated solution to this problem is the same as when reinforcing a fence (Fig. 15). We orient the fibres in such a way, that shear is transferred to extension and compression of fibres and not borne by the matrix. It is the same as in framework construction where bending moments in the beams are not accepted.

Laminates

In fibre composite language, fibre orientation is defined by angles (Fig. 16). A lay-up may consist of 0° (zero degrees, i.e. parallel to the "main" force) fibres to handle basic stresses from bending, 90° fibres to handle perpendicular, delaminating stresses and 45° fibres to handle shear. These different angles are usually (for obvious reasons) not woven together. They are added on top of each other, layer after layer, and this is actually the process of lamination. A work instruction, telling

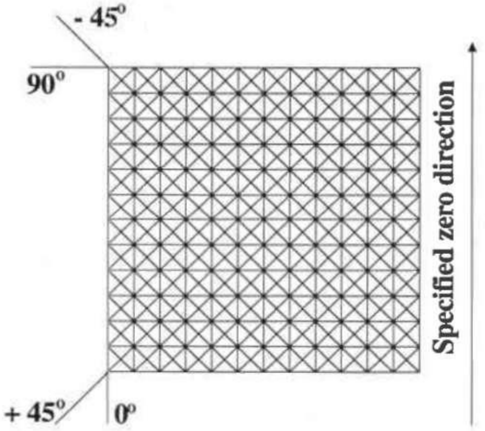

Fig. 16. Fibre orientation in laminates.

the orientation of each layer, may look like this:

1x +45°
1x -45°
1x +45°
1x -45°
5x 0°
2x 90°
core
2x 90°
5x 0°
1x -45°
1x +45°
1x -45°
1x +45°

This is a symmetrical sandwich, and the above instruction tells the operator how to orient the fibres.

Each layer is called a lamell, and the total result of several lamells is called a laminate or, in a sandwich structure, a face. Weaves, sheets, rowings, prepegs etc. used for this purpose will not be reviewed or discussed here except for two comments:

1. In prosthetics and orthotics "angulated weave" tubing has become very popular to handle shear. When the tubing is stretched out over a small cross-section the angle of the fibres is small, close to 0°. As the cross-section increases, the length of the tubing decreases and the fibre angle increases. If the extremes are avoided, the angle kept to say between 30° and 60°, this is a very elegant solution, also providing a closed loop for the shear flow at torsion.
2. There are weaves available where the carbon fibres are looped. The author has so far not heard a satisfying explanation of the reason for using expensive CF instead of GF when the composite is going to become matrix dominated anyhow!

Holes

Holes are very dangerous in laminates and should, if possible, be avoided. Unfortunately this is not always possible. Holes interrupt the continuity of the fibres, not only where the hole is, but also at a long distance from the hole (Fig. 17). The interrupted fibres can take care of load only where the load has been transferred to them by matrix shear from other adjacent fibres. As a result, there is a risk of delamination due to shear stress in the matrix not only at the hole, but also very far from it. How about letting the fibres pass outside the holes? (Fig. 18). Sorry, but when the load is applied, there is a tendency to straighten out the fibres resulting in perpendicular stresses in the matrix, and again there is a risk for delamination. Winding fibres around the holes does not help either. Firstly it just moves the problem to outside the winding, and secondly the radius would probably be smaller than the fibres would tolerate.

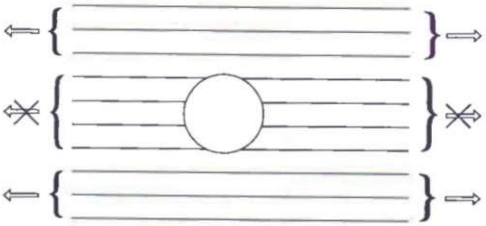
Fig. 17. Drilled holes.

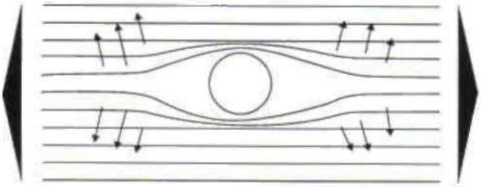
Fig. 18. Fibres passing outside holes

Holes in a continuous fibre composite always result in high shear stress, partial matrix domination and risk of delamination.

Permanent, plastic deformation

The reason why a metal rod can be permanently bent is that the material becomes plastic when the stress exceeds the yield stress. This property of

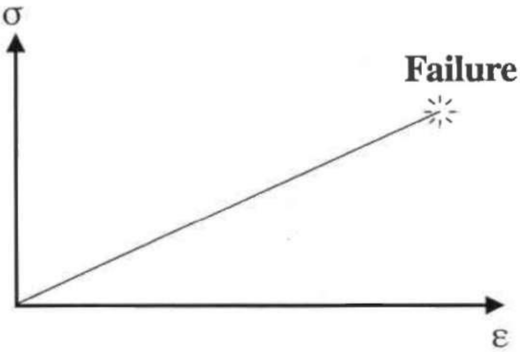

Fig. 19. Stress versus strain in GF and CF (no plastic range).

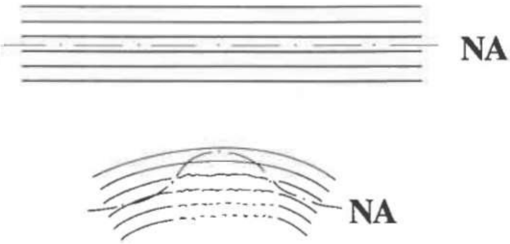

Fig. 20. Fibre collapse at buckling.

steel and other metals allows us to adjust for instance an orthotic upright. Neither glass fibres nor carbon fibres have any yielding properties. They do not deform permanently due to load (except for GF when heated to high temperatures). They deform elastically until they fail (Fig. 19).

Consequently a GF or a CF structure *cannot* be corrected or modified plastically after curing, at least not if the fibres are continuous. Also when heat is used and the matrix is thermoplastic, the compressed fibres lose their support, buckle and collapse (Fig 20). When they collapse they no longer contribute to the fibrous cross-section and the neutral axis moves towards the opposite face. We have nicely converted our fibre dominated composite to a matrix dominated one, and wasted our expensive fibres. If our composite still serves the expected purpose, there was no need for the fibres in the first place. A 100% fibre dominated GF or CF composite is, however, virtually not sensitive to fatigue. The matrix material may be much more sensitive to fatigue, and if there are no fibres to limit the extension due to loads, the structure may break after too short a time in use. Plastic deformation of a rod, with maintained fibre domination is possible only if the fibres can "slide" relative to each other and remain stretched in the correct orientation. This is possible if the total length of the rod is heated, and if the angle between the ends of the rod is kept unchanged (Fig. 21).

The above is an endless source for discussion and misunderstanding. The author has seen several demonstrations, where manufacturers have proudly introduced thermoformable carbon fibre sheets. But looking through a strong magnifying glass at the side where the fibres have been compressed has so far always given evidence, that many of the fibres have terminated their useful careers.

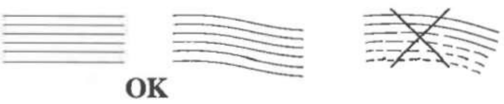

Fig. 21. Plastic deformation with thermoplastic matrix.

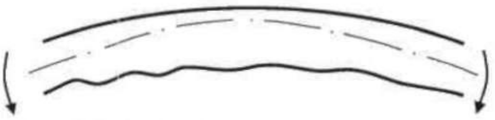

Fig. 22. Buckling of compressed face.

In sandwich design

When subject to bending the compressed face has a tendency to buckle (Fig. 22). Buckling is, mechanically, a *stability* problem, with very small forces required to initiate it. The main task of the core, besides maintaining the moment of inertia, is to support the face so that buckling is never initiated. For this purpose, the core does not have to be very strong, but it has to be *stiff* and well bonded to the face. Consequently, and for more than one reason, the use of a spongy core may not be very clever.

If a composite beam is curved, and subject to bending as in Figure 23, there will be a tendency to straighten out the convex face and further bend the concave face (b). If the core is not able to resist the stress thus developed between the faces, there will be a compression and a structural collapse and a loss of moment of inertia, thus, the structure will become weaker.

If the beam is being bent the opposite way, the opposite will happen, and we are likely to see a delamination due to the perpendicular stresses pulling the faces apart. In this case also the demands upon the bonding between the core and the faces increase.

In both the above cases the core needs to be strong enough to handle compression or extension. Perpendicular (90°) lamination may help, also if there is no sandwich structure, but a "homogeneous" lamination (Fig. 24).

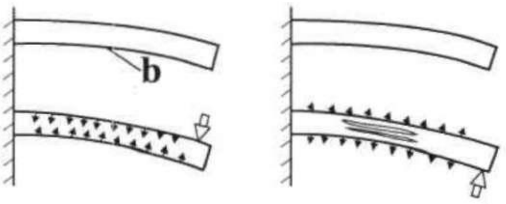

Fig. 23. Bending of curved beam.

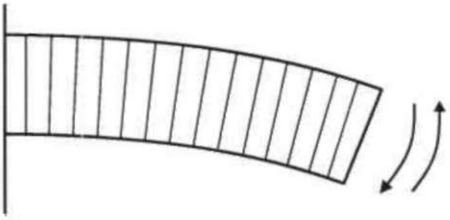

Fig. 24. 90° (perpendicular) lamination.

The "rule of thumb" is *that composite beams should be made straight if possible.* A change of the geometry may give a local bending moment, which stresses the matrix and may cause delamination in a homogeneous laminate as well as in a sandwich structure.

Let us look at a beam, consisting of two planks (Fig. 25). One is on top of the other, and they are not bonded to each other. When the beam or "beam-pack" is bent, the compressed side of each of the two parts will become shorter, and the stretched sides will become longer. As a result, it will look like the lower one is sticking out past the upper one. This does not happen in a solid beam because shear stresses prevent it. The shear stresses due to bending are zero at the upper and the lower end points of the cross-section, and they have their highest value on the neutral axis (Fig. 26). (Shear stresses due to bending do not appear when there is "pure" bending with constant bending moment along the beam).

In isotropic materials, like steel, the shear stresses due to bending can usually be neglected (exception: very short beams where, as a rule of thumb, the height of the beam is more than 1/5 of the length). In composite structures and sandwich structures, these shear stresses have a tendency to cause delamination or fracture of the bonding between the faces and the core or of the matrix between the fibres. They stress the matrix and, if the matrix is sensitive to fatigue, delamination and failure may occur with limited use. The simplest solution is to use a high quality matrix and bonding and of course a core material that can handle shear flows.

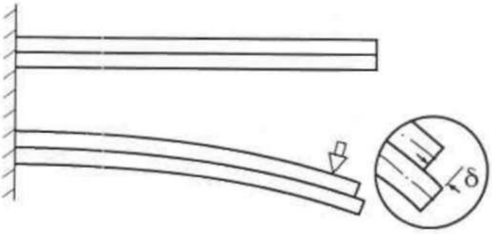

Fig. 25. "Beam pack".

Fig. 26. Shear due to bending.

The structure is converted to a fibre dominated one, at least at the edges, by adding a 45° (30° – 60°) lamination between the faces (Fig. 27). It may also, in a partially fibre dominated way, substitute for 90° lamination as shown in Figure 24.

This lamination will take over the shear load in its vicinity, but further away its influence fades out. If it is repeated at certain intervals by putting in webs, you have a "multi-box" less dependent upon matrix shear strength, but also much more expensive.

Bending of fibres

Due to the high modulus (stiffness) of CF high stresses are developed when bending the fibres. This is why special attention is required in forming and handling. To avoid fracturing CF the bend radius should be as large as practical. If the fibres are forced to conform over a sharp edge, breakage is likely to occur.

Rule of thumb: avoid bend radii of less than 40mm (1.5") for CF, the more critical the higher the modulus.

Composites

Fibre composite design calls for knowledge of the production methods. The properties of the composite depend on how it is made. *Pultrusion* stretches the fibres longitudinally, while *filament winding* stretches them tangentially. Hand lay-up often leaves the fibres loose.

Data that is available on the properties of long fibre composites is, as said before, related to well stretched, parallel, continuous fibres, where the force is parallel to the fibres. Thus, the fibres

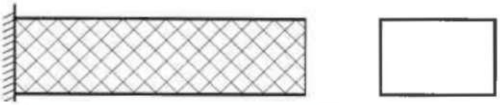

Fig. 27. Fibre orientation for handling shear due to bending.

determine the strength as well as the stiffness of the composite. If the force is perpendicular to the fibres, the matrix determines the strength, and the stiffness is determined by the fibres and the matrix. Short fibre composites approach the properties of perpendicularly loaded long fibres, i.e. significantly less fibre domination for strength than for stiffness.

How is it that a fibre composite can be matrix dominated regarding strength and partially fibre dominated concerning stiffness in the very same direction?

Look at the matrix dominated orientation in Figure 12. The fibre to matrix ratio does not matter. Also if there is 90% fibre, the fibres never bridge the force flow. The composite is 100% matrix dominated concerning strength. But if the fibres are much stiffer than the matrix, which they are, they will act as a stiffening filler. Then the composite is partially fibre dominated as far as stiffness is concerned, be it that we are no longer talking about loads along the fibres.

In reinforced concrete the reinforcing steel bars may be pre-stressed. There is a tension in the bars before external load is applied. It would be wrong to say that the fibres in plastics are pre-stressed the same way. The thermal shrinking of the matrix during setting may actually *compress* the fibres and the yielding of the matrix after setting relaxes the stresses. As a matter of fact, CFs may have a negative thermal expansion coefficient, which means that they shrink when heated during setting, and expand again when cooling to normal temperature.

It is important that the matrix tolerates a longer elongation to failure than the fibres with a considerable margin. If this is not the case, the properties paid for of the fibres cannot be fully utilised as matrix failure ruins the laminate before the fibres take the full load.

As the purpose of the matrix is first of all to create working conditions for the fibres, it is obvious that the fibre content should be high. When using autoclave, pultrusion or filament winding processes, 65% fibre by volume is the highest value for long fibre composites except for extreme requirements, when 70% may be reached, It is however, possible to exceed 50% by more primitive methods. It deserves attention, that the quality of laminations performed in limb fitting shops, using a combination of vacuum membrane moulding combined with manual removal of excess matrix, is sometimes so high that the composite industries are unable to offer competitive solutions!

For short fibres 15-30% fibres by volume is normal.

If cylindrical fibres are ideally distributed and pressed together, the space between them represents about 9% of the volume, and the fibres about 91%. There is, however, no reason to try to exceed 65-70%, because then there is a risk that the matrix may not be able to cover the surface of the fibres completely, resulting in inferior bonding.

There is no point in copying conventional metal structures or designs and making them from fibre composites. It is often said that the key to composite design economy and success is *integration of functions* or *integrated design.* It is not the purpose to emphasise on design philosophies here, so let us avoid it by suggesting that as much as possible is integrated in large modules and units instead of assembling a lot of very specialised small components. Specialised components are bolts, hinges, bearings etc.. It is not only the anisotropy that causes problems. Bolting, riveting, press fits etc. do not behave as in metals, very much because they rely upon pre-stresses possible, because the metals are used in their elastic range. The plastic matrix materials may not offer such assistance for a longer period of time.

One further reason that makes integrated design attractive is that fibre composites can be formed to shape without waste of material due to machining.

It may be reasonable at this point to draw the conclusion, that investing in "materials substitution" projects, where fibre composite components or modules are supposed to replace conventional metal ones may not necessarily be a very sensible approach.

Prepregs

A prepreg is a tape or a fabric with unidirectional fibres, impregnated by a thermosetting resin, usually an epoxy resin, to serve as matrix.

The resin is partially cured to a "tacky" state (B-state). The resin is finally cured by heating under pressure when the intended structure has been formed.

Narrow tapes are used when the shape is more complicated, while large sheets are used for bending in one plane (aircraft wings etc.).

Fibres

The basic requirements for fibres in the composite are:

- higher tensile strengths than the matrix, as the load is supposed to be carried by the fibres;
- higher modulus of elasticity than the matrix, which is a condition (Hooke's law), that the fibres take the load;
- less tension to failure than the matrix, to avoid the matrix failing before the fibre strength is fully utilised;
- good adhesion to the matrix;
- good chemical resistance to the matrix.

The fibres are usually divided into three classes:

- low modulus fibres. E<5000 MPa (synthetic and cellulose);
- medium modulus fibres. E=5,000-150,000 MPa (glass and synthetic);
- high modulus fibres. E>150,000 MPa (synthetic, whiskers, carbon, boron).

Types of fibre are:

glass - good strength, low cost;
Kevlar - toughness, poor compression properties and thus less convenient for structural designs;
carbon - stiffness, strength, good shock absorbing and friction properties, low weight.

CF fibre is brittle. CF composites have no yielding behaviour, and tolerance to impact is low. This tolerance can be improved by mixing in some 30% by volume of Kevlar, glass fibre or synthetic fibre for protection.

CF has good electrical and thermal conductivity. Electrostatic painting is possible. The heat dissipation is low.

It should be noted, that some high modulus CFs exhibit zero or even a negative thermal expansion coefficient

When comparing the relative merits of CFs and GFs in practical applications, the following may serve as a "rule of thumb" summary:

- in a fibre dominated composite, the strength will be about the same, but a CF composite will be about three times stiffer than a GF composite.

If there are 50% fibres, the CF composite will be about 10-15% lighter. The strains and consequently the stresses in the matrix will be about 1/3 when using CF.

The fibres can be long or short. Short fibres cost less and fabrication costs are lower in mass production.

Graphite is by definition a three dimensional crystallographic structure, which is not present in commercially available fibres. The term "carbon fibre" is technically correct. "Graphite fibre" is not. There is no such thing, and it is unfortunate that the term has ever been introduced.

The early development of CF may be summarised as follows:

- carbonised cotton 1879 (Edison)
- carbonised Rayon (terribly expensive) late 1950's (Courtauld and Union Carbide)
- stretched high modulus fibre 1965 PAN (polyacrylonitrile) based fibre (expensive) 1969;
- high modulus fibre from petroleum pitch (great promise for cost-effective industrial applications. High modulus per dollar);
- continuous pitch fibre 1976.

CF is mainly made by carbonising polyacrylonitrile fibres at high temperatures. The tensile strength and the modulus of elasticity can be adjusted by varying the end temperature in the final stage of the process.

Kevlar is a marvellous fibre when energy has to be absorbed. This is why it is used in bullet-proof vests, in sails and in other similar, tough applications. The author has never had any reasons to work with it, but would be delighted to pass on an advice given by several very experienced US experts many years ago: "The best way to use Kevlar in structural designs is to avoid it! It is so full of surprises for the developer that the development costs become disastrous!"

The main reason for the problems is probably the poor compression tolerance of the Kevlar fibre.

The fibres are very thin, typically 6-9 microns diameter for CF and 12 microns for Kevlar.

Coupling agent

After pulling, the fibre is usually treated with a surface coating, sometimes called sizing, to make it anti-static and to protect against wear and fracture etc. during the continued handling (spinning, weaving etc.). Sometimes the sizing has to be removed (by burning) before the fibre is laminated, but often it serves as a coupling agent to improve the bonding to the matrix. The quality of this bonding determines the quality of the strength properties and the resistance to damp environment of the composite. Different coatings are used for different fibres and sometimes for different matrices. The most common coupling agents for glass fibres are silanes. Vinyl silanes are used for polyester. Metacrylic based silane with polyester results in a transparent composite.

Amino silanes are used with Epoxy and phenols.

The sizing on carbon fibres is usually low molecular epoxy, not completely hardened.

Warning: the above sizing on carbon fibre is usually aggressive to your skin, and should be handled like working with epoxy resins. Use long gloves to avoid skin contact.

Mixing fibres

Sometimes CF is used in prosthetic and orthotic applications with the intention to locally increase the strength or the stiffness in a hand lay-up GF composite. As it is difficult to stretch the fibres, the gain is often minimal.

There is more to it, however. This may be visualised by looking at an example where the idea is that a laminate is supposed to be stronger if some GF is replaced by CF. This is a common idea. But it is not necessarily a good one, and some simple calculations may explain why, at the same time as they demonstrate how the available data can be used. Hopefully the departure from explaining without mathematical analysis will be excused.

The manufacturers information sheets tell us:

Fibre	σ(failure) (MPa)	E (GPa)
Glass	3,400 (or 3,400 N/mm^2)	70 (or 70,000 N/mm^2)
Carbon	2,600 (or 2,600 N/mm^2)	210 (or 210,000 N/mm^2)

Hooke's law says: $\sigma = E \times \varepsilon$, or, the higher the modulus the faster the stress develops as the material is stretched.

Hence for the GF the extension before the fibres break is 3,400/70,000 = 0.049, which is about 5%.

For the CF we get 2,600/210,000 = 0.0124, which is about, 1.2% extension before all the fibres break.

If we have a rod with a GF cross-section of 100mm^2, the fibres will break at a total load of 3,400 x 100 = 340,000 N. The equal amount of CF will carry only 260,000 N, which is less, but not very much less. But what happens if we replace 20% (by volume) of the GF with CF?

We know that all the CFs break at 1.2% extension, and as there are 20mm^2 of them the load they carry when they break is 2,600 x 20 = 52,000 N. The extension of the GFs is the same, 1.2%, at this point is 0.012, and hence the stress is 70,000 x 0.012 = 840 N/mm^2 in a cross-section of 80 mm^2. Hence the GFs carry 67,200 N when the CFs give up. The total load is at that moment 67,200 + 52,000 = 119,200 N. When the CFs have given up, the 80mm^2 of GFs are left to make the best of the situation, and they give up of course at a total load of 80 x 3,400 = 272,000 N.

The above is illustrated in Figure 28, but the bottom line is, that by replacing 20% of the GF with CF, we actually *sacrificed* 20% of the strength. The situation would have been even worse, if 50% of the GFs were replaced by CF.

There are hybrids, though, where GFs and CFs are said to work together in such a way, that they break simultaneously. One explanation to this is that the GFs and the CFs are stretched differently in the manufacturing process.

Rule of thumb: mixing of different fibres is pointless if the interaction between the fibres is not carefully taken into account.

Matrices

The main roles of the matrix are:

- stabilise the fibres and keep them in place;
- distribute and transfer loads between the fibres;
- transfer loads at partial or total matrix domination, notably shear loads;
- protect the fibres against the surrounding environment.

The matrix may be thermosetting or thermoplastic.

Thermosetting matrices include epoxy, vinyl ester, polyester, polyurethane, acrylic etc.

Thermoplastic matrices include nylon, polyethylene, petroleum pitch etc., but also metals like titanium and magnesium are used.

If the fibres are supposed to transmit the loads, the fibres must fracture before the matrix. If not, the fibres cannot be utilised to the limit of their strength. Hence the matrix must have a longer elongation (strain) to fracture.

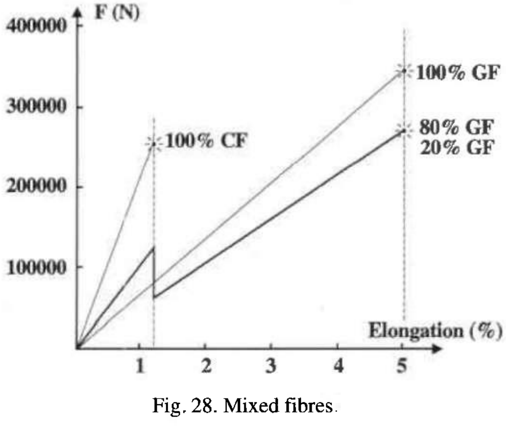

Fig. 28. Mixed fibres.

It is not correct to say, that the bond between the fibres and the matrix should always be as strong as possible. Too strong a bond may give a fibre cleavage failure mode and to weak a bond a delamination failure mode. There is an optimal bond for maximum tensile strength in a composite.

The different coefficients of thermal expansion of fibre and matrix will develop internal tensions when heating and cooling, also when there is no external load. When tensions due to external loads are added to these internal pre-tensions, we may too soon reach the tolerance level and get failure at less external load than we had expected. We may actually get cracks in the matrix before any external load is applied.

The first critical moment is actually during the exothermic setting process when laminating with a thermosetting matrix. If the internal stresses are eliminated at peak temperature during the setting, stresses will be developed during cooling, the greater, the more difference between the expansion coefficients. The thermal expansion of the fibres can usually be neglected. Hence it boils down to a requirement, that the thermal expansion coefficient of the matrix should be as small as possible. Different sources report different figures, but it is hopefully possible to agree that polyester expands about 10 times more than epoxy, and acrylic expands 10-30 times more than epoxy per unit temperature change.

This is one of several reasons why epoxy is the technically superior matrix material. Other reasons are that it is best for wetting, protection and fatigue. For the most advanced high tech CF applications epoxy is more or less the one and only serious alternative. But it is also the most expensive, and it is very aggressive to the skin before hardening.

The chemical resistance of epoxy depends on the hardening system. It is generally good, but amine cured epoxy has poor resistance to acids. Anhydride cured ones neither resist strong alkalis nor organic solvents. There is a wide range of epoxy resins and hardeners available, and there is a lot to gain by selecting them carefully to satisfy the requirements.

In mass production, at pultrusion and filament winding, epoxy is sometimes substituted by vinyl ester (CF sailing masts, ski poles etc.) with very good results due to its excellent resistance to weather and chemical stresses combined with good mechanical properties.

But GF with polyester is excellent for many applications. In optimised (integrated) design it made possible a weight reduction from 8 to 2 pounds of a rear wheel suspension element of a Volvo truck. The springs of the Corvette sports car are GF with polyester matrix.

It should be noted, that shrinking during manufacture using polyesters as well as vinyl esters, can be significantly reduced by using additives.

Acrylic is an interesting compromise. The reason why it is used in prosthetics and orthotics, also for CF, is probably that it has a successful tradition there for use with the other fibres. It was early discovered, that it had to be modified by thinning to be able to wet sufficiently for use with CF, and we witnessed the birth of "carbon acrylic". It may be an ideal matrix to work with in prosthetic and orthotic shop conditions, but it is certainly not the best way to utilise CF. Acrylics are actually very seldom, if ever, mentioned in the composite literature.

During the past decade a lot of interesting development has been going on in the area of fibre composites with thermoplastic matrices, but so far no simple method to add the matrix to the continuous, long fibres has been introduced. Such laminates are commercially available, and if the user knows what he is doing, they can be very useful. Sometimes the matrix is "semi-thermoplastic". If epoxy is used, it may be possible to soften it by heating and deform it permanently once or twice. This property expires, however, when the cross-linking starts (see below).

Unfortunately, however, it is frequently believed, that if the matrix is thermoplastic, the composite is also thermoplastic. This is, as discussed above, not true, at least not if the composite is supposed to maintain its strength properties after deformation.

It is very different with short fibre composites. Nylon with short GF or CF has become very successful, also in prosthetic and orthotic applications. These composites also exhibit a true, but limited thermoplastic behaviour.

Matrix strength

As indicated above, the most sought after strength in the matrix is shear strength. This is very much because it is sometimes more or less impossible to avoid matrix domination for shear stresses due to bending.

It is frequently suggested, that the matrix should be "post-cured" after hardening by heating to about 80° Celsius for a couple of hours. Many thermosetting materials give a better final result if heated to a much higher temperature. Some materials should actually be heated up to softening (for carbon acrylic 180°C) to enable them to develop full intramolecular strength by *cross-linking*. Tests reported by Hexel of France show that considerable permanent improvement of the shear strength in their epoxy bond for car body panels is possible by cross-linking by 150°C postcuring.

Core

The main roles of the core in a sandwich structure are:

- to secure the geometry of the cross-section, i.e. the moment of inertia;
- to support the compressed fibres to prevent them from buckling;
- to resist shear stresses due to bending.

The demands upon the core material vary, according to the specific conditions at hand. Some requirements are general, though:

- good bonding to the matrix in the faces;
- sufficient stiffness to keep the faces in place and prevent them from buckling.

Specific requirements, related to the conditions include:

- strength, especially shear and compression;
- low cost;
- light weight,
- thermal resistance;
- chemical resistance;
- water resistance;
- UV resistance;
- flexibility.

Foams and honeycombs are frequently used for lightweight cores. Also felt can be used, provided that it is saturated by the matrix resin during manufacture.

In the ISNY version of the Scandinavian Flexible Socket GF is used for core, with the same matrix as for the faces. This is, of course, an excellent solution, if weight is not very critical.

In our early development of CF orthoses an Omega-shaped profile was used to maintain the cross-section. Unfortunately, the profile had a tendency to collapse at bending. It worked like a corrugation and, as the shear flow was not closed, it could not handle torsion either (Fig. 29).

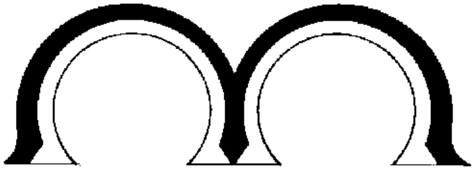

Fig. 29. Omega profile.

To facilitate easy shaping of the core now used for our CF orthoses, we initially cut slits in the edges of the core (Fig. 30). It turned out, that during the lamination, the fibres were bent over the incisions by the external pressure (or the internal vacuum). We actually initiated buckling and slight matrix domination. This was enough to reduce strength as well as fatigue resistance.

We have come across a procedure, recommended by a supplier, where no core is used. Furthermore, a woven CF mat is used, where the fibres are not straight (commented on above). It is shown as "X" in Figure 31.

It is probably not unfair to say, that this is an example of waste of expensive material.

Figure 31 shows results of comparing some different core concepts in the apparatus shown in Figure 2. The PI kit for manufacturing medial upright and brim for an ISNY socket (distributed by PI Medical Co. in Sweden) was developed by two of our skilled technicians after having received fibre mechanics education equivalent to the content of this article. The core is made from ABS.

Fatigue and lifetime

CFs and GFs resist fatigue loads very well. Some sources indicate that the fibres themselves

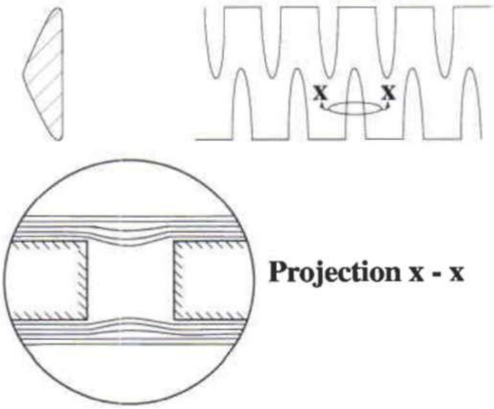

Fig. 30. Slits in core.

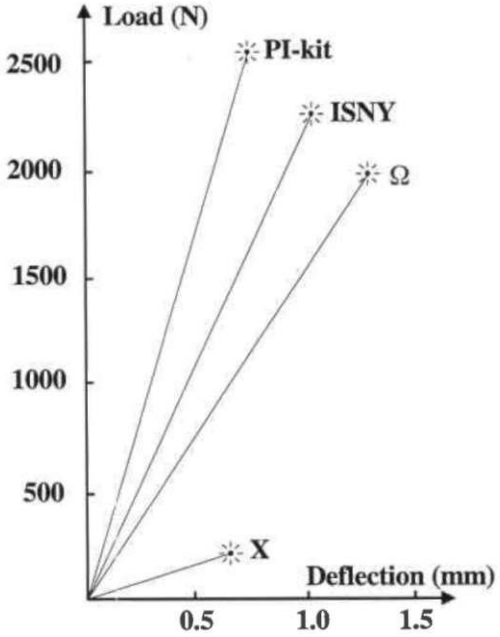

Fig. 31. Deflection with different core designs.

are not at all sensitive to fatigue. The problem is not the fibres but the matrix. Although there may be 100% fibre domination, there is always strain, and consequently also stress in the matrix. Thus the composite is of course sensitive to fatigue also if only the matrix is sensitive to fatigue, and some matrices are. As CF is three times stiffer than GF, CF composites offer better fatigue properties than GF composites because the matrix is about three times less strained.

A rule of thumb is, that for CF epoxy composites fatigue can be neglected if all fibres are parallel to the load (100% fibre domination). In less "pure" fibre orientation, with a mix of angles, at least 40% of the calculated static load can be tolerated as fatigue load (tolerated for 10,000,000 cycles). This is much better than steel, which is much better than aluminium alloys.

If designed properly, however, GF polyester makes for excellent springs with a long lifetime.

It is absolutely reasonable to state, that one of the distinct advantages of well made fibre composites is that they offer excellent fatigue resistance.

But there is a cloud in the sky. The strength of some matrixes, including the highly praised epoxy, decreases by ageing, and hence there may all of a sudden be a failure. This is not fatigue in the classical sense, but it definitely restricts the lifetime.

The fatigue limit is, by the way, in the classical sense defined as the highest stress accepted by the material for an eternal amount of times. In engineering it has been agreed, that for testing 10 million times represent sufficiently well an eternal amount of times. Repeated loads under the fatigue limit do not consume lifetime, whilst loads above it reduce the lifetime. This is not generally true, however. It is all right for steel, but aluminium and aluminium alloys have no fatigue limit. Every time they are stressed, a fraction of the lifetime is consumed. This is a reason why the author has never trusted aluminium components in prosthetics and orthotics, and it is a problem that aircraft designers are very well aware of. Hence, with reservation for ageing, fibre composites may be much more attractive than aluminium alloys as far as fatigue is concerned.

Fatigue in fibre composites usually presents itself as delamination, and tends to start at holes and edges (where the shear stresses in the matrix are highest). Dynamic loading before use to about 80% of maximum load is a common treatment to improve the static and the dynamic strength.

Kevlar is sensitive to UV light and some glass fibres are sensitive to water. Hence a good seal is necessary, especially if the composite is cut across the fibres, to avoid capillary penetration of substances and rapid deterioration. Better wetting and adhesion improve long time strength and fatigue resistance, which is an argument for the use of epoxy.

Electrocorrosion may reduce the lifetime of screws, rivets and metal embedments in CF composites. Stainless steel or titanium are strongly recommended.

Lifetime tests

Industries as well as authorities frequently perform lifetime tests, applying a certain load to a certain amount of cycles. Most of these tests are accelerated i.e. they are run at such high frequencies, that the "lifetime" behaviour can be tested in days or weeks. Accelerated tests of fibre composites do no usually provide true information. When testing a prosthetic foot, the author got much better lifetime, if the frequency was reduced and the tested object was allowed to rest overnight.

This is a subject that should be closer looked into, to avoid obsolete or inadequate test procedures preventing a very promising development.

Safety

CF irritates in much the same way as GF. Furthermore, the risk of skin contact with not completely hardened epoxy sizing before lamination must always be avoided (see above). Skin irritation from such materials through pockets in trousers have been reported. Use work gloves, protective clothing, eye protection and fume extractor. Wash clothes used at CF or GF work separately.

Horror stories have been told about risks. One is that fibres, that find their way to the lungs, will stay there and occupy more and more space. Doctors have ensured, that there is no way that they will get there. The author prefers to trust nobody and be careful and use protection.

It has been suspected, that certain similarities between the CF molecules and the asbestos molecules give reasons to believe, that there may be similar risks. Experts have stated, that this must be a misunderstanding and that there is no documentation of such risks. Evaluating this conflicting information is beyond the author's competence.

There is, however, a lot of documentation of the inertness of carbon, and the author has had pieces of carbon in his body for 45 years without the slightest irritation or tendency to rejection.

Initially it was recommended that electrical equipment operating in the vicinity of CF composite fabrication should be protected against possible intrusion and consequent short circuit. Broken pieces of CF and CF dust produced when grinding, during lay-up etc. are light and it was said that they were easily airborne and could fly long distances. It has been suggested recently, that this risk has been overestimated. It may be overestimated, but it is probably very expensive if it happens.

Use of fume extraction is strongly recommended whenever handling and working with carbon fibres. Some industries use water to catch particles during grinding, cutting etc..

The risk and the protection measures when using epoxy, polyester, acrylic etc. are well known in prosthetic and orthotic practice and do not need to be discussed here.

How do GF and CF compare?

There are many ways to compare, depending on priorities of course, but one way or another comparisons unfortunately usually boil down to expense comparisons instead of final economy considerations.

As said above, it is easy to waste a lot of money by using CF more or less as a filler. GF is a much cheaper filler. In more advanced applications, professionally used, GF may also be as good as CF at a much lower cost.

When comparing fibre composites to metals like steel and aluminium, the costs for tooling and for manufacturing must be taken into account, and a high raw materials cost may very well occasionally be balanced out by a low manufacturing cost.

Technically, the most interesting comparison is very often the performance to weight ratio. Using

Table 1. Stiffness, strength and density (data from Exel: Designer's Handbook).

Fibres	Density (Kg/m^3)	E (N/mm^2)	E/dens.	σ (N/mm^2)	σ/dens.
E-glass	2,540	70,000	27.6	1,500	0.59
S-glass	2,500	85,000	34.0	2,100	0.84
CF-high strength	1,800	230,000	128	3,500 – 8,000	1.95 – 4.45
CF-high modulus	1,800	400,000	222	2,100 – 6,000	1.17 – 3.33
Boron	2,630	400,000	152	2,100 – 4,100	0.80 – 1.56
Kevlar	1,450	150,000	103	3,700	2.55
SIC$_4$ (Whiskers)	2,200	500,000	227	7,000	3.18
Polyurethane	1,100	70,000	63.6	1,500	1.36
Metals					
Aluminium	2,700	70,000	25.9	230 – 700	0.085 – 0.26
Steel	7,900	210,000	26.6	500 – 2,200	0.063 – 0.28

typical values with no reference to any specific products, Table 1 compares some fibres and aluminium and steel with reference to strength and stiffness, visualising the excellent performance available from fibre composites. The reader is advised to update himself concerning currently available products.

If fatigue strength is taken into account, the fibre composites come out even better.

But again, and this may serve as a short summary, *the product has to be designed for the material, and the manufacturing process is part of the design.*

Literature

This is not supposed to be a reference list, but rather a suggestion to literature for further penetration of the subject.

- Langley, M. (1973) Carbon fibres in engineering.- London: McGraw Hill.

This book, with contributions by several most distinguished authors, is for many engineers the basic textbook on the subject. It is unfortunately out of print, but it is available at engineering libraries. Other excellent books, frequently referred to, are:

- American Society for Testing of Materials. Composite materials:
  - Testing and design, 1969
  - Fatigue of composite materials, 1975
  - Fracture mechanics of composites, 1975.
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Some manufacturers and suppliers supply good and sometimes excellent information material. Practitioners, like orthopaedic technicians, may find such material adequate in the development of a sufficient understanding of applied fibre mechanics and lamination technology. But it is important to make sure that such material is updated, as the supply of products referred to (specific fibres, weaves, prepregs etc.) may have been discontinued.

Good examples of such manufacturers' information are:

- Designer's Handbook
  EXEL Oy, INDUSTRIAL COMPOSITES, Helsinki, Finland.

- THORNEL Product Information, Amoco Performance Products Inc., USA.

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