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FIBROUS COMPOSITE MATERIALS

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Abstract

The mechanical properties of fibrous composite materials will be reviewed. Such materials are made, either in order to realise in practice the properties of the fibres, or else in order to increase the toughness of a matrix. The mechanical principles governing the interaction of fibre and matrix will be sketched and up to date examples of the properties of both types of composite given.

When I was first asked to give this talk I thought that I would put fibrous composite materials in the context of other composite materials.

The word composite was first used in engineering science for clipper ships which had wooden planks on iron frames and copper on the outside of the ship in order to counteract marine borings by organisms and barnacles in tropical waters.

You use in your every day life, as I do, paper, which is a composite; but there are many others, and I don′t want to talk about paper at all, partly because I don′t know anything about it. I am grateful to those one or two members of the audience who have taken me aside over coffee and told me some important things about paper in case, they said, I made a mistake.

When I first became interested in composite materials, I read some of Cox′s articles which I found quite unintelligible, and I expect some of you clever people in the audience can explain them to me.

I want to put fibrous composites in their engineering context. I want to show you some of the latest artefacts that have been made from them, and I want to show, if I can, the science behind those artefacts.

The latest is probably the newest aircraft in the armoury of the West, the AV8B, which is currently being made by the McDonnell-Douglas Corporation and British Aerospace. This aircraft has nearly a quarter of its weight in carbon fibres. Carbon fibres were only invented 15 years ago, so you can see that there has been a rapid progression to full-scale use. There is another aircraft, the Lear Fan 100, a civil aircraft which will be built in Northern Ireland, whose airframe is planned to be 80% in either carbon reinforced plastic or glass reinforced plastic. So this is another composite which is coming into use.

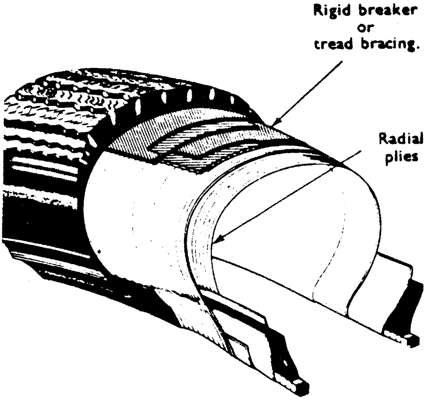
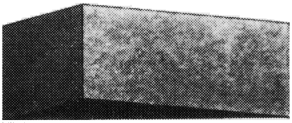


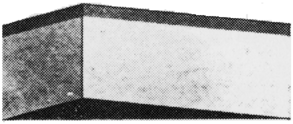
Fig 1—Cutaway section of a radial ply tyre

Apart from paper the other fibrous composite most people in the room use is the tyre. A tyre (figure 1) now consists of sets of fibres arranged as radially and diagonally interlaced plies. This replaces the older form which did not have the radial ply. I´ll return to that point in a minute. That is a fibrous composite, again, with which we are familiar. There are many types of composites, of course.

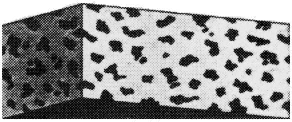
A composite really is a material in which the individual pieces are not recognisable to the naked eye so that we think of it as a homogeneous material. The use of fibre composites, at least in high-performance applications such as aerospace or tyres, stands side by side with particulate composites.



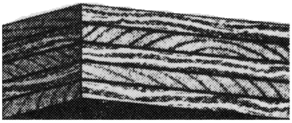
1 ALLOYING



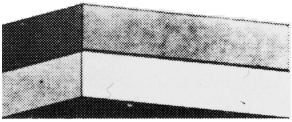
2 COATING



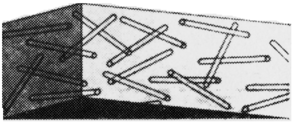
3 DISPERSION



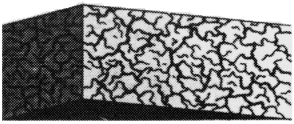
4 LAMINATING



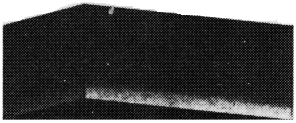
5 BONDING



6 FIBRE-REINFORCING



7 POWDER-COMPACTING



8 DIFFUSION

Fig 2

As I said, there are many types of composites and figure 2 summarises some of them: you can stick two materials together as in bonding: or you can coat one material on another: or you can disperse particles of one material in a matrix of another: there are composites where the pieces of one material form one continuous phase isolating pockets of the other one: or there are fibre reinforced composites like the one you are so familiar with: and at the bottom left-hand corner there is wood.

Let me give you a couple of examples of particulate composites.

Particulate composites are usually made to provide a special combination of properties, as in a bearing, or else because a material's properties are different in bulk from when it is in a particular geometric form: e.g. a fibre, a thin plate or film, or a particle small in all directions.

To give you some examples, very high coercive force magnets are made by taking individual magnetic domains and bonding them together. An individual magnetic domain is, in size, somewhere between 1,000 Ångström and a micron. To make a very highly coercive magnet you must take individual magnets and stick them together in some way. The newer dental cements, some of which you carry in your mouths, are made by taking small particles of glass and bonding them together. The reason for using small hard particles, as in the cutting tool which also consists of small hard particles, is that for brittle solids the breaking strength of the individual particle varies inversely with the square root of the size, so its strength rises as the size gets smaller. Therefore, to make a very efficient hard cutting tool you use small particles, about 5 microns long, of tungsten carbide.

It is not easy to make a compact containing more than 30 or 40% by volume of solid particles. For the cutting tool one seeks 80, 85 or 90% which is only possible by a very special method, namely solution. In this case we need to dissolve the tungsten carbide, so the matrix has to be cobalt, which conveniently does this. There is no other way of making that compact so dense.

Bearings are similar: in every bearing you seek a particular combination of properties. There must always be a very hard phase, in the case in figure 3, the roughly square looking particles, which do the supporting. There must also be a soft phase so that when bits of bearing material come off, they can be embedded. In bearings that work without lubrication (that distinguishes the right-hand one from the left-hand one in figure 3) you must always have a material which smears and forms a renewable surface against the other side of the rubbing journal. In this example it happens to be lead, and you must take care that there is no chemical reaction between the smearing phase and the other. Those are simple examples of composites, these ones, as I said, being non-fibrous. They are useful because a particular property is only demonstrated in a particular geometric form.

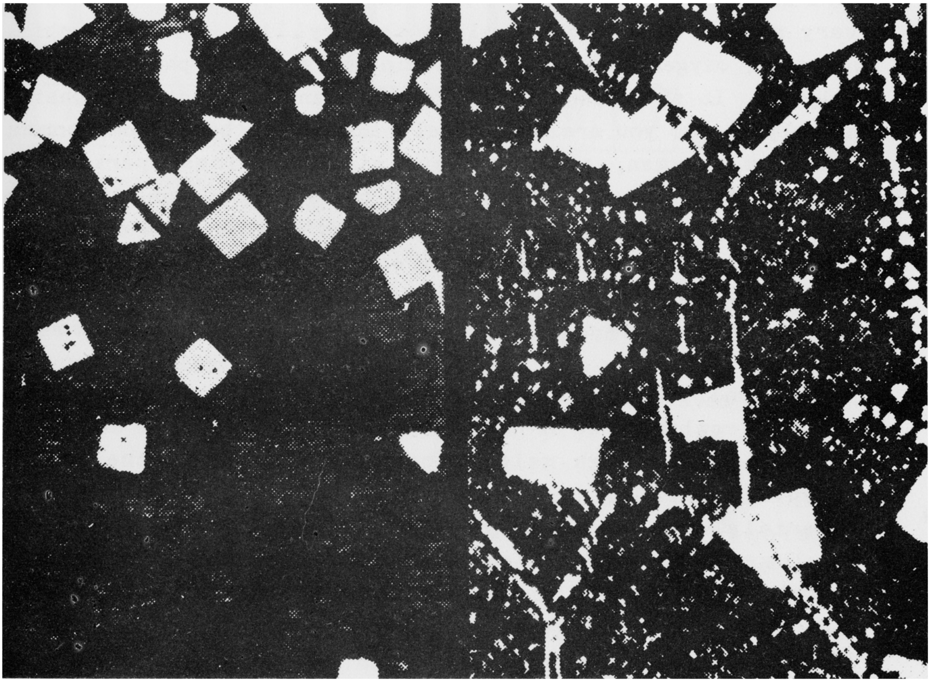


Fig 3

Now let's turn to fibrous composites.

Fibrous composites in aerospace and in high-performance engineering are of interest because they are strong, stiff and light and if they are to be strong, stiff and light they will be made only of certain selected chemical elements. Firstly I will show you what those chemical elements are, and then I shall explain why they have to be fibrous.

To make a very strong solid, you need the atoms closely bound together by strong covalent bonds: covalent bonds are necessary to prevent shear. The non-directional metallic bond is no use in resisting shear: you must have a strong covalent bond. Covalent bonds are formed only by elements early in the periodic table, and in order for the material to be solid there must be three or more covalent bonds. So you are limited if you want to design a very strong solid to the elements beryllium, boron, carbon, nitrogen, oxygen, and perhaps aluminium, silicon, phosphorus and sulphur. It so happens that phosphides and sulphides are easily hydrolysed, so you are effectively limited to beryllium, boron, nitrogen, oxygen, aluminium and silicon. These particular elements form three or more covalent bonds, and because they come early in the periodic table, they contain rather few nucleons. Because the covalent bond is directional, the packing of the atoms with respect to one another is not close-packed, so that the solid consists of light atoms held widely apart: hence the low density.

By considering the quantum mechanics of the covalent bond, you will realise that if the atomic potential well is deep, the material has a high melting point, and that if the atomic potential well is deep and rapidly curved at its base, the materials will have a high elastic modulus. A high elastic modulus combined with a high melting point implies a low thermal coefficient of expansion. All of these properties follow from a strong covalent bond, just two shared electrons. That means that ideal materials of great chemical stability, low thermal coefficient of expansion, and great stiffness will be made from the covalently bonded elements: they will also be light in weight and should, therefore, be ideal for aerospace and transport applications.

Figure 4 compares strength per unit weight, on the left-hand side, with stiffness per unit weight, on the right-hand side, for several materials. From this it is clear that the paramount materials are alumina, silicon carbide, boron, and graphite. It is also clear that things like nylon and glass can be relatively strong but not very stiff.

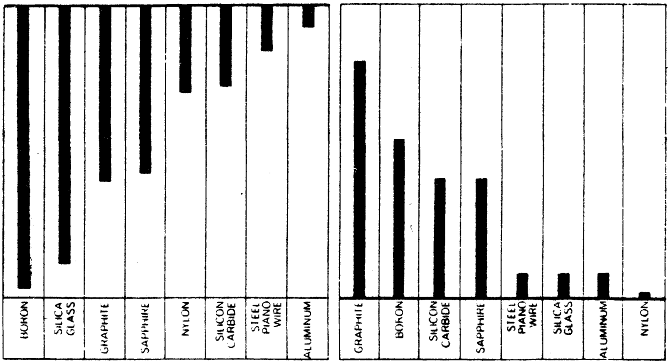


Fig 4—Strength and stiffness of various materials are compared. Strength (*left*) is represented as greatest free-hanging length; in the case of boron it is 189.4 miles. Stiffness (*right*) is represented on an arbitary scale indicating relative stiffness per unit weight.

Why is stiffness necessary? Stiffness is necessary because most engineering structures are not designed on strength, they are designed essentially on stiffness.

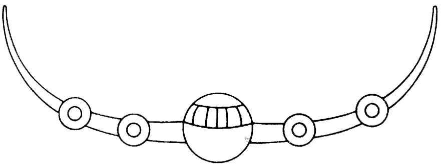


Fig 5

Figure 5 illustrates the well-known picture from Gordon's book that if you design the aeroplane wing out of fibre-glass with the requisite strength but which does not have the requisite stiffness, the wings would nearly meet above the pilot's head. That is the result of carrying out the design calculations solely on strength, and not considering stiffness.

So far I have explained that for strength and stiffness you must have a solid bound by covalent bonds, but I haven't told you why it has to be in fibrous form. That essentially follows from two reasons: firstly, the covalently bound materials are brittle: and secondly, they contain cracks. If the material is a glass, then, in addition, the surface needs protection. But if it is like graphite fibres or heavily drawn textile fibres it needs a microstructure in which the atomic planes are more or less aligned and with any cracks that there are, running in one particular direction. And the strength and stiffness will be developed in the direction of the atomic planes, regardless of whether or not there are defects present.

So, the argument runs, you need a fibre because any transverse crack will be limited in dimension by the diameter of the piece. A piece small in one dimension has a high strength. Its stiffness depends on the regularity of the atomic arrangement, and there of course the process of drawing, in the manufacture of both carbon fibres and all the textile fibres, leads to alignment in a particular direction, and hence to strength. Without going into niceties and discussing the strength and stiffness of, say, boron fibres, I shall just tell you that if you align your covalent molecules in one direction by a process of drawing, and you protect the surface, you will have a thing which is both strong and stiff. Practical considerations limit the diameters to some 10 microns or so.

At that stage you would say "if I put those together I could make a rope but as a rope has rather little transverse strength, why don′t I put them in a matrix?" and that is one set of arguments which will lead to a fibrous composite of boron or graphite or of `Kevlar′, which is a new, highly drawn polyparabenzamide, effectively benzene rings linked by CONH-groups, the polypeptide link. Those aligned and in a matrix, will give a material of high stiffness, high strength and low weight. Another way you can look at it though, is to look for materials which have high modulus and high yield strength.

Figure 6 shows that the ceramics and the carbides have high yield strength, and that graphite, magnesium oxide, aluminium oxide, glass and the ceramics have high modulus. But figure 7 shows that they have very little toughness. So if you want to use them you must make them tough in some way, and that of course is where the matrix comes in. You bind the fibres together in a way which provides toughness.

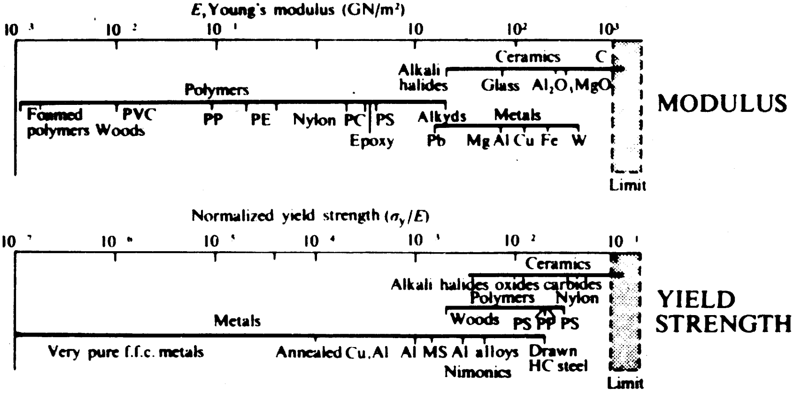

E, Young's modulus (GN/m²)
10^{-3}
10^{-2}
10^{-1}
10
10^2
10^3
Ceramics
C
Alkali halides
Glass
Al_2O_3
MgO
Polymers
Foamed polymers
PVC
Woods
PP
PE
Nylon
PC
PS
Epoxy
Alkyds
Metals
Pb
Mg
Al
Cu
Fe
W
Limit
MODULUS
Normalized yield strength (σ_y/E)
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Ceramics
Alkali halides oxides carbides
Polymers
Nylon
Woods
PS
PP
PS
Metals
Very pure f.f.c. metals
Annealed Cu, Al
Al
MS
Al alloys
Drawn HC steel
Nimonics
Limit
YIELD STRENGTH

Fig 6

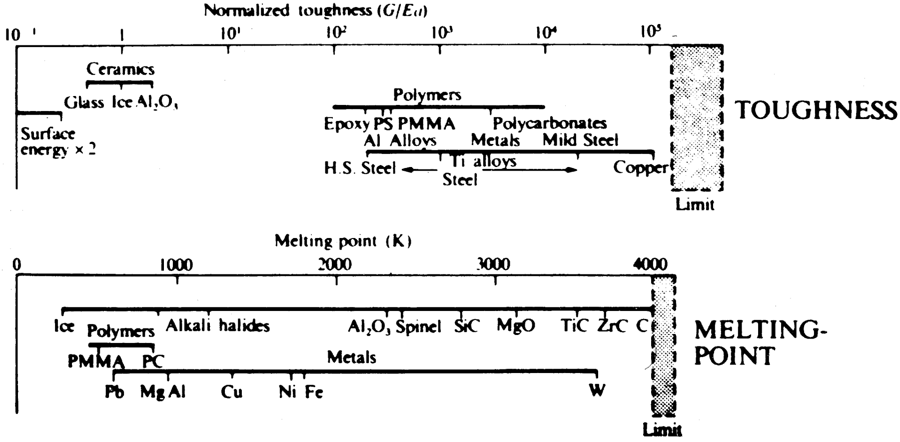

Normalized toughness (G/Ea)
10^{-1}
1
10^1
10^2
10^3
10^4
10^5
Ceramics
Glass
Ice
Al_2O_3
Surface energy × 2
Polymers
Epoxy
PS
PMMA
Polycarbonates
Al Alloys
Metals
Mild Steel
H.S. Steel
Ti alloys
Steel
Copper
Limit
TOUGHNESS
Melting point (K)
0
1000
2000
3000
4000
Ice
Polymers
Alkali halides
Al_2O_3
Spinel
SiC
MgO
TiC
ZrC
C
PMMA
PC
Metals
Pb
Mg
Al
Cu
Ni
Fe
W
Limit
MELTING-POINT

Fig 7

Figure 8 shows how by altering the matrix you can change the fracture style of a carbon fibre composite from very brittle to extremely fibrous-looking.

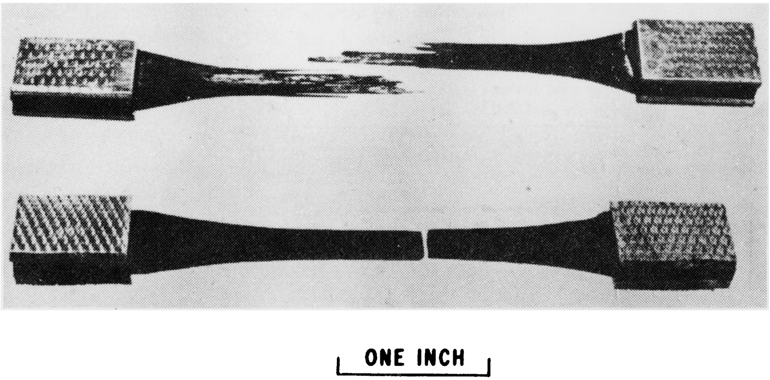


Fig 8

You can even make a material that fractures exactly like wood, even though there is none in it.

So far so good, but there is a penalty to be paid for putting the fibres into a matrix, namely, that the matrix dilutes the fibres. So we aim today to try to attain packing fractions of the fibres of 65%. When one does that one has to compare the properties of the fibrous composite with those of a homogeneous alternative material.

Figure 9 shows modulus divided by specific gravity and tensile strength divided by specific gravity, which are the ruling properties for the mechanical engineering of lightweight components, for various different fibre-matrix combinations. The glass, the Kevlar 49, and the high-strength graphite are all in resins suitable for aerospace purposes which happens to be epoxy, though for other applications it needn't be. The point I want to emphasise here is that these materials, showing values of their modulus:specific gravity ratio up in the hundreds, have much better stiffness per unit weight than the competitive materials, duraluminium, titanium, even beryllium. Their strengths too are greater but it is much more important that their stiffnesses be.

Material	Modulus / Specific Gravity				Tensile Strength / Specific Gravity			
	[0]		$[0/45/90/135]_s$		[0]		$[0/45/90/135]_s$	
	GPa	(Msi)	GPa	(Msi)	GPa	(Msi)	GPA	(Msi)
Steel (AISI 4340)	25	(3.7)	25	(3.7)	230	(33)	230	(33)
Aluminum (7075-T6)	25	(3.7)	25	(3.7)	180	(26)	180	(26)
Titanium (Ti-6Al-4V)	25	(3.7)	25	(3.7)	250	(36)	250	(36)
Beryllium	42	(6.2)	42	(6.2)	260	(38)	260	(38)
E Glass/Epoxy	21	(3.1)	11.2	(1.6)	490	(71)	260	(37)
S Glass/Epoxy	47	(4.0)	15	(2.2)	790	(115)	430	(62)
"Kevlar" 49/Epoxy	55	(7.9)	21	(3.0)	890	(129)	340	(49)
HS Graphite/Epoxy	92	(13.3)	35	(4.1)	780	(114)	300	(44)
HM Graphite/Epoxy	134	(19.5)	49	(7.1)	460	(67)	170	(24)
UHM Graphite/Epoxy	171	(25)	61	(8.8)	370	(53)	130	(19)
Boron/Epoxy	103	(15)	39	(5.7)	620	(90)	240	(34)

Fig 9

Such a material however is very weak in one direction and so the way it is used is not just as an aligned composite: you must attempt to give it some strength at right angles to the fibres.

Figure 10 illustrates strength against angle of the fibres for an uni-directional composite. You can see how fast it drops. If you cross-ply, make a laminate, then the strength falls off much less rapidly, such as is done in ply-wood, and, as I said earlier, in the modern tyre.

In applications such as the ones I am talking about, regularly-made arrays are much more valuable than random arrays because the packing in the individual laminations can be as high as 65 or 70%, though this again can give rise to certain difficulties.

If you imagine pulling a balanced-ply laminate containing two sets of fibres, each set at the same angle to the stress, you can imagine there will be a scissoring effect and an interlaminar shear will develop.

Nowadays, and in fact for the last few years, much of the design work in composites is concerned with the minimisation of these internal stresses.

This is of course very important.

What happens is that when a balanced-ply laminate of orthogonal fibre sets is stressed cracks develop in the fibres normal to the stress direction.

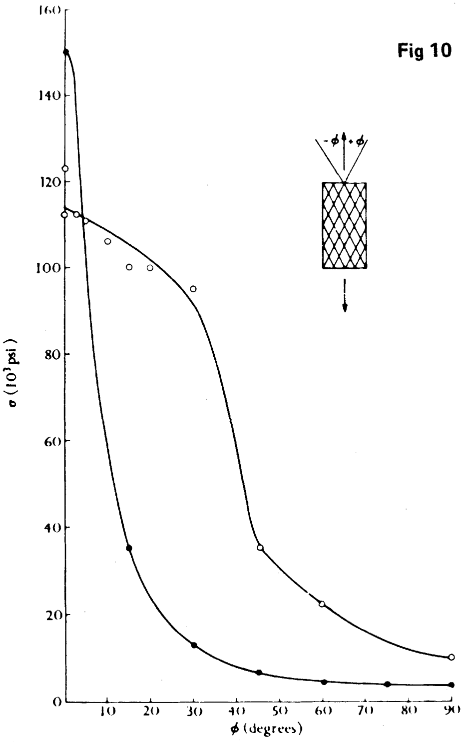


Fig 10

If the matrix material is transparent, the cracks can even be seen. Recent work, particularly that at the NPL, has shown that one can minimise the cracking by making the fibre laminate thinner. Figure 11 shows a case in which all properties are the same in the upper part as in the lower, the only difference being that in the lower part the laminates are much thinner, and you can see that there are no cracks. In the upper part, however, though the strain is the same, you can see cracks.

So far I have spoken about strength and stiffness, but there is another reason for putting carbon or other fibres into materials, and that is to prevent cracking. In angle-ply composites we have to take into account not only the properties parallel to the fibres but the transverse properties. Careful manipulation of the interaction between thermal expansion and elastic properties can give rise to some clever characteristics.

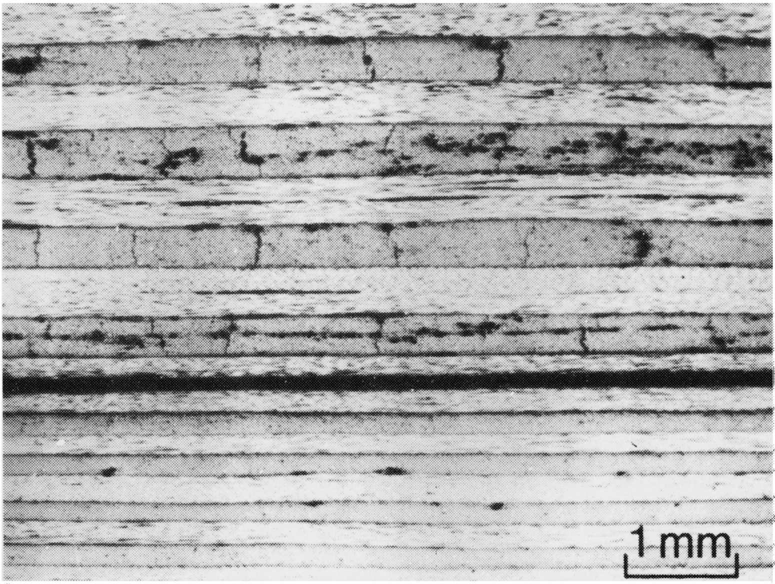


Fig 11

You can with proper design, for example, make materials with negative coefficients of thermal expansion. There are only very few materials that I know of that have negative coefficients of thermal expansion, eg silicon and graphite itself in certain directions, but by playing with composites, one can arrange that it occurs over diverse temperature ranges and in a number of situations.

The last reason for fibre re-inforcing very brittle matrices that I want to mention, is to stop cracks.

In figure 12 the picture is reversed and we use fibres in a material which is itself

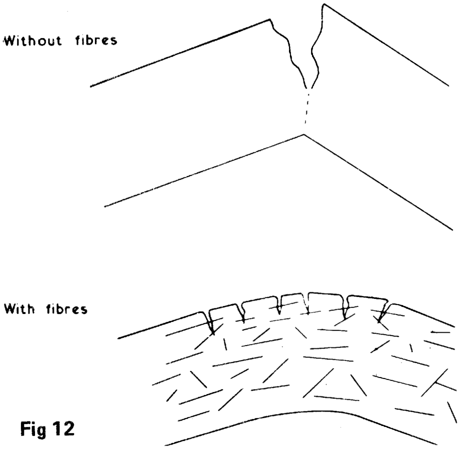


Fig 12

very brittle, unlike the matrix in a fibre-reinforced composite which must show some ductility. Here fibres are used to bridge cracks. If you think of a piece of cement and you crack it and bend it, the material will fail.

But if you put fibres into it the mechanical interaction between the fibres and the cracks ensure that the opening of the crack is limited by the presence of the fibres.

This is the basis of fibre-reinforced cement as opposed to reinforced concrete using large steel bars. Fibre-reinforced cement, which has been developed in the last 15 years, contains arrays of fibres in the brittle matrix. These fibres prevent the cracking with such efficacy that such cement can in fact be bent into knots by adding a sufficiently large volume loading of fibres. The fibres are there just to prevent the cracks running. Careful inspection of the surface would show a large number of cracks.

Composites are really rather like people. You use crack ups on a small scale to prevent catastrophe on a big one.

Thank you.