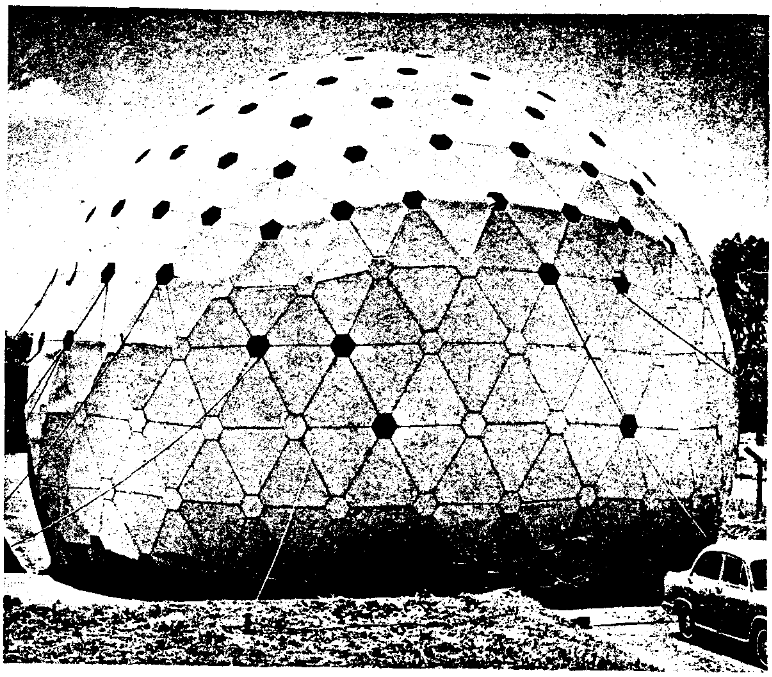


This 16·5 metre fibreglass reinforced plastic radome made at the National Aeronautical Laboratory, Bangalore, symbolises the strides India has made in composites technology — combining two or more different materials to produce something superior to the components. Here's an account of . . .

THE MANY USES OF COMPOSITES

S. RAMASESHAN

N. BALASUBRAMANIAN

Modern technology places severe demands on materials. The requirements are so self-contradictory that a single homogeneous material can hardly meet them. Hence materials have been combined to form composites. The combined properties are not only superior to the properties of the individual components but also to their sum. Frequently, composites are endowed with new properties which the constituents do not have. The idea of composites is not new but the technology has grown rapidly only in the last 15 years, so much so that composites have revolutionised the attitude to engineering design and have led to structures which are technically and aesthetically superior. Composite materials are being tailor-made today to obtain the required mechanical properties as well as the electrical, optical, thermal, magnetic and superconducting properties. And they have special significance in a world with depleting natural and energy resources.

Since the composites industry is science-based and labour-intensive, it is particularly suited to India. Through innovative uses, composites can play a significant role not only in aerospace but also in production machinery, boats, silos for grain storage, transportation, sports equipment and in a variety of general engineering applications.

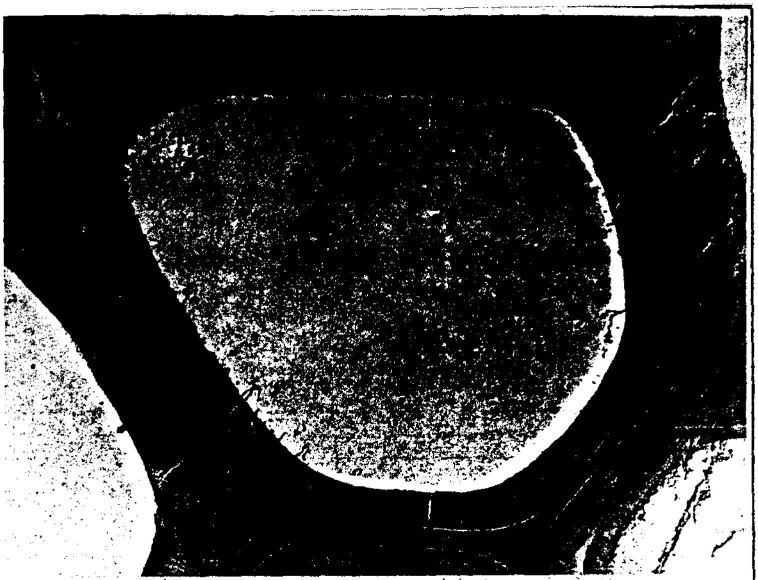
Composites can be defined in many ways. However, for the present discussion, we shall define them as a combination of two or more chemically distinct materials with a distinct interface separating them. Thus, they should be distinguished from *alloys*, in which the mixing of two or more components takes place at an atomic level, and there is no distinct interface between them. As an example of a composite material, we may consider a ductile matrix (resin or metal) reinforced by a stronger but brittle fibre. The reinforcement can also be in the form of particles, flakes or ribbons. The matrix is not only strengthened but made tougher or more fracture-resistant by the reinforcement.

There are many examples of composites in nature. Bone, for instance, is a composite of the mineral hydroxy apatite and the polymer collagen. Nature has evolved this composite structure over millennia. The bonding between the two is so good that bone is stronger not only than collagen but pure apatite itself. How is this possible? Hydroxy apatite is a strong brittle material. Small cracks can develop in any material under stress but they are dangerous in a brittle material. At the bottom of a crack the stress gets concentrated and causes the spreading of the crack. In the case of ductile materials, the high stresses at the tip of the crack are relieved because the material flows plastically under stress. Cracks in a brittle solid can be stopped if we provide weak interfaces. In bone a crack which occurs in the hydroxy apatite is ' stopped ' at the point where it meets the apatite-collagen interface. The small cracks are prevented from propagating. Thus, bone combines the ' stiffness ' of apatite with the crack-resistance of collagen, producing a composite material which is far superior to each of its components. Essentially similar considerations apply to many of the examples we will be considering in this article.

Consider another example: if a sharp notch is cut on the surface of a bamboo pole which is then bent, it does not snap. On the other hand, splinters are peeled off near the notch but no crack propagates into the material. In this case the weak interfaces along the fibre virtually disconnect the crack from the material on the other side of the fibre. In effect, the cellulose fibres act to ' deflect ' the cracks that start to propagate within the lignin matrix.

The above two examples indicate that the matrix and the reinforcing material can mutually act to prevent crack propagation in each other and to obtain high strengths. The properties of the composite depend, of course, on the properties of the reinforcement, of the matrix and of the interface between the two (see box on p. 14). (The bamboo is also protected from buckling by the cylindrical struts on the outside.)

Ancient civilisations had designed a number of composites purely from empirical considerations. The use of straws in bricks was known long ago in India. The presence of chopped straw prevents the propagation of



NATURE MADE THIS COMPOSITE

Wood is a composite of cellulose fibres in a matrix of lignin. This electron micrograph of a cross-section of aspen (enlarged 11,900 diametres) shows the lumen or cell cavity (pale central object) surrounded by the wall of a cellulosic cell (grey portion); the darkest material is lignin (Courtesy: *Scientific American*)

cracks developed when the wet clay dries rapidly in the Sun. The South American potters of Maya and Inca civilisations used plant fibres instead of straw. The Eskimos had to build their houses with ice, which is so brittle that cracks can run through the ice for kilometres. But it was common knowledge among these primitive people that if only they could put in some moss (two to four per cent) in water and freeze them together to form a composite, the ice could be converted into a new material which would not crack even if hammered. They also knew that the sea-ice, on account of the salt crystals dispersed in it, would not crack as easily as fresh water-ice would. The Mongolians used a laminated composite of horn, bone and wood to make bows. The Egyptians seem to have understood that the properties of wood can be improved by cutting it into thin veneers and gluing them together to form cross-plies. This results in plywood which minimises shrinkage and swelling when moisture is absorbed and also has good strength properties and resistance to splitting. The Samurai swords of Japan were laminated composites which combined different steels to achieve the desirable properties of (*a*) an exceptionally hard (martensitic) edge, (*b*) a tough, soft core, and (*c*) sides or covers of intermediate hardness. The swords were made by a laborious process in which all the constituents were hammered out, folded over and hammered out and welded again until a highly laminar structure was achieved. In the finished blade, there were thousands of layers of highly oriented fine-grained steel.

Fibres

The modern technology of composites has been made

Principles of reinforcement in composites

The principles of reinforcement in composites can be understood by a simple application of Hooke's law. When you load a bar, of, say, a metal, it gives way or stretches. According to Hooke's law, the bar of length *l* stretches by an amount Δl, which is proportional to load *L*, provided *L* is small.

$$\Delta l \propto L \quad \text{.......................} (1)$$

For the same load, bar of twice the length will extend by ($2\,\Delta l$). To get a number which is characteristic of the material and does not vary with the different shapes of the same material, we choose to use a ratio Δl to *l*, known as strain ε. Similarly, the ratio of load to the area of the bar, *A*, is independent of the size of the bar. This ratio is known as stress, σ. It is more useful to write Hooke's law in terms of stress and strain, as

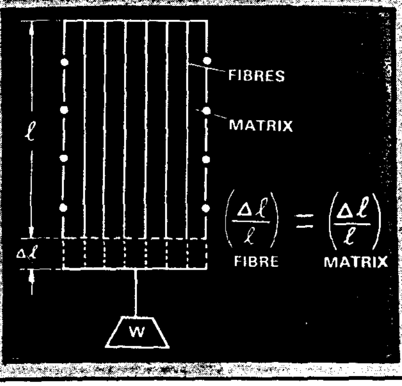
$$\sigma = E\,\varepsilon \quad \text{.......................} (2)$$

where the constant of proportionality *E* is the Young's modulus and is a property of the material. A material is very stiff or difficult to deform if its *E* value is high. We have so far considered the case of a homogeneous material. For the case of composites containing a matrix and a reinforcing phase, say, a fibre, the equations have to be modified.

In the case of ideal fibre composites, the matrix material is reinforced by fibres which are uniform, continuous and unidirectional. Such a composite is shown in Fig. 1. The fibres are gripped firmly by the matrix so that there is no slippage at the fibre matrix interface. Under these conditions, the total load L_c is shared by the fibre and the matrix.

$$L_c = L_m + L_f \quad \text{..............} (3)$$

Fig. 1



where *L* is the load and the subscripts *c,m,f* refer to the composite, matrix and fibre, respectively, in terms of stresses

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f \quad \text{.......} (4)$$

where *A* is the area. Since the fibres run throughout the length of the specimen, the areas can be replaced by volume fractions as follows:

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad \text{.......} (5)$$

The equation represents the rule of mixture for stresses. The 'no slippage' condition implies the matrix and fibre extend by equal amount when stressed. Hence the strains in the matrix, fibre and composite are all equal.

$$\varepsilon_c = \varepsilon_m = \varepsilon_f \quad \text{...............} (6)$$

As a consequence, equation (5) can now be rewritten to give the rule of mixture for moduli. Equation (4) also enables a comparison of loads carried by the fibre and the matrix when th matrix and the fibre are deformed elastically. Equation (6) can be rewritten in terms of stresses and moduli, *E* using Hooke's law,

$$\frac{\sigma_c}{E_c} = \frac{\sigma_m}{E_m} = \frac{\sigma_f}{E_f} \quad \text{...........} (7)$$

$$\text{or} \quad \frac{L_f}{L_m} = \frac{E_f}{E_m} \times \frac{V_f}{V_m} \quad \text{...........} (8)$$

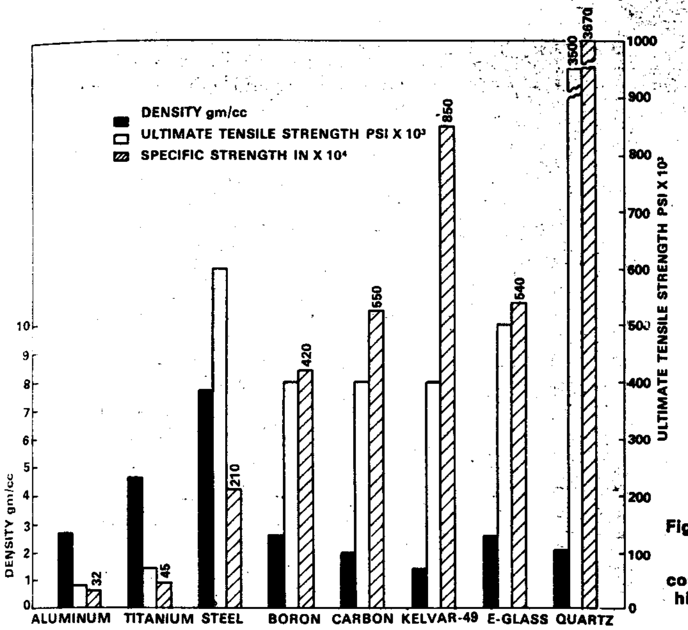


Fig. 2 Specific strength of fibres in comparison to high-strength alloys

possible by the development of high performance reinforcements, usually in the form of fibres. These fibres are put in a ductile matrix such as a resin or a metal.

Interestingly, the fibres available today are of materials that were considered brittle and unusable until recently. The properties of some of the fibres are shown in Figs. 2 and 3 along with the properties of high-strength alloys (combination of metals). We see that a quartz fibre which has one-fourth the weight of steel, is some 16 times stronger than the latter. But quartz fibres are difficult to grow and are very expensive. The glass fibre is probably the most widely used and is the only fibre available in India commercially. Glass fibres can be drawn from molten glasses of the appropriate composition. In the marble process, the refined glass is first made into marbles which are annealed and subsequently melted into an electrically heated fiberising element, referred to as a bushing. In the direct melt process, refined glass is fed directly into the bushing. Commercial bushings are made of platinum and contain thousands of orifices. Although glass fibre has high strength (500,000 pounds per square inch or 500,000 psi; 1 psi = 0·07 kg per cm^2), its use will always be restricted by its low stiffness (10 million psi).

The carbon (C) fibre is about six times as stiff (60 million psi). When C fibres were first available, they were so expensive that only aerospace applications could justify their use. Recent developments have changed the picture. Most frequently, C fibres are made by the controlled heating of organic fibres, similar to 'synthetic' fibres used in fabrics. High-quality fibres are produced beginning from polyacrylonitrile (PAN), though even rayon can be used. The cost of PAN-based C fibres is 32 dollars (Rs. 300) for a pound. (These are not yet available commercially in India.) Sometimes, C fibre is made using the acrylic fibre but the resulting fibre lacks the superior properties of PAN-based C. Recently, there have been improvements in methods of producing PAN itself which have led to a reduction in cost of about 30 per cent.

An alternate but cheaper route to C fibre starts with pitch as a raw material. The pitch is heat-treated to form a liquid crystal phase called mesopitch which is subsequently drawn into filaments at high temperatures. The idea is to freeze in the directional alignment of molecules found in the liquid crystal phase. The pitch-based C fibres were introduced by Union Carbide of USA last December under the trade name Type P and sell for \$20 (Rs. 180) per lb (454g). Today they lack the tensile strength of the PAN-based C but the strength of

Usually the fibres have modulii 10 times or more compared to the matrix. Hence, in a composite with 50 per cent volume fraction, the fibre carries a load 10 times or more than the matrix.

These ideas can be modified in a rather straightforward manner in a practical situation where the fibres are available only in short lengths or are broken and, therefore, discontinuous. Calculations show that if the length-to-diameter ratio or the aspect ratio of the fibre exceeds 10, the efficiency of load transfer from the weaker matrix to the stronger fibre is still around 98 per cent compared to the ideal case. The surface area of the fibre is so large that the load transfer at the interface is still very efficient even if the bonding is not perfect.

The maximum strength and modulus are realised in a composite along the direction of the fibre. Hence the properties of the composites can be varied by orienting the fibres appropriately. The properties of such a composite can be calculated using the rules of mixture and by taking into account corrections due to orientation dependence of fibre properties, stress concentrations at fibre ends, slippage at the fibre-matrix interface, etc. S. R. & N. B.

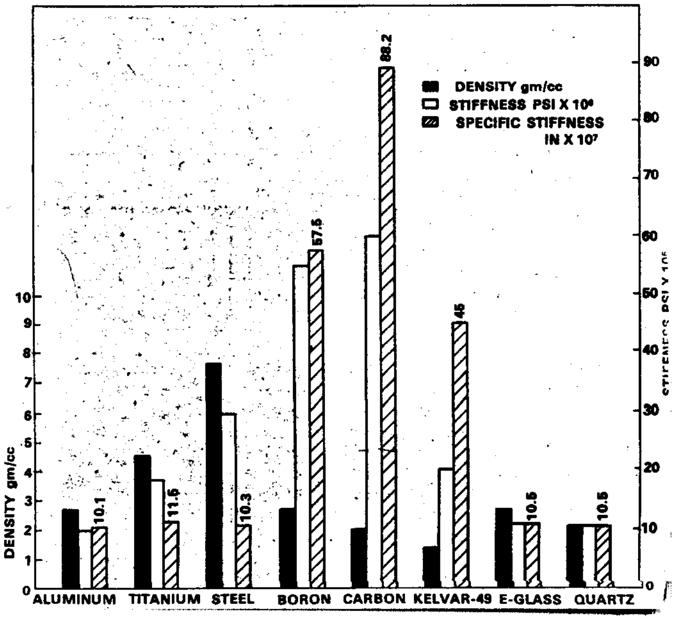


Fig. 3 Specific modulus of fibres

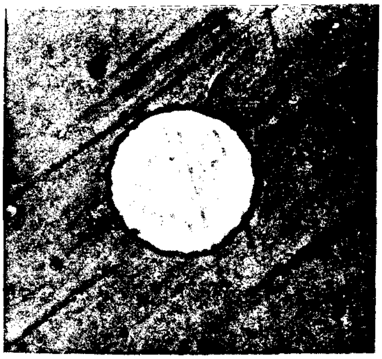


Fig. 4 Organic fibre in polyester matrix developed at NAL (diameter of the fibre 30μm)

the fibre is bound to improve in the near future. It is the pitch process which may help us realise the dream of a five dollar per pound carbon fibre. Until we get to this stage, the search for a cheaper fibre with properties intermediate between those of carbon and glass is justified.

The answer here may be the organic fibres. The best of them, Kevlar-49 developed by Du Pont, has the strength of glass fibres, twice the stiffness but half the density, and it sells for about five dollars a pound. An experimental organic fibre developed at the National Aeronautical Laboratory (NAL), Bangalore, is shown in Fig. 4. These fibres being organic have a better interface with plastics than do the inorganic fibres. Unlike glass fibres, they do not lose part of their strength while abrading against each other. Scanning electron microscopy shows that composites with organic fibres have an intrinsically low compressive strength. The difficulty is overcome by using them in hybrid composites with fibres which are strong in compression, such as glass or carbon.

While the main interest in the fibres mentioned above is in their mechanical properties, there are other fibres which are very useful because of their thermal properties like that of a high melting point and low conductivity (thermal insulation). An example is the high silica fibre (Nalsil) developed at NAL. The process takes advantage of the fact that E-glass fibres are available in the country. These contain 55 per cent silica and 45 per cent of other oxides which are removed by leaching with acids, which is quite an economical process. The high-silica fibre, when introduced into a phenolic matrix, gives a composite which is being used as ablative (heat-shielding) material in re-entry vehicles, although this may be replaced by carbon-carbon composites in some ablative applications. Fig. 5 indicates the thermal resistance of a Nalsil fabric. An oxyacetylene flame (1700°C) held at a distance of 2·5 cm can burn a hole in an E-glass fabric in less than two seconds; under similar conditions it takes 150 seconds to burn through the Nalsil fabric. This duration is adequate for re-entry applications.

A widespread application for Nalsil will be in the insulation of large furnaces resulting in energy savings. The fibre is light and, therefore, costs less to transport. It is possible to use graded insulation, that is, use a thin layer of alumina in the hot portion (temperature above 1000°C) near the furnace and use Nalsil for the major part of insulation.

Fabrication of composites

In making the final composite, of course, the fibres have to be situated in the matrix in the definite desired configuration. Some composites require the fibres to be placed parallel to each other, others require a random distribution. Some depend on a strong fibre matrix interface for their specific function, while weak bonding is important for other properties. Therefore, in each case, an appropriate method of introducing the proper fibres into the proper matrix must be found. There are a variety of such techniques (Fig. 6). Resins have been developed with the desirable properties such as (*a*) control of curing, hot or cold, (*b*) flexibility and viscosity which can be varied by adjustments in composition, and (*c*) storage for long periods until catalysts and accelerators are added. Some of them can be stored in a state of partial cure which makes it possible to pre-impregnate the fibre by resin and use the prepregs when required to make the products. These properties make a wide variety of fabrication methods possible.

Fig. 5 Heat resistance of Nalsil determined in a burn-through test

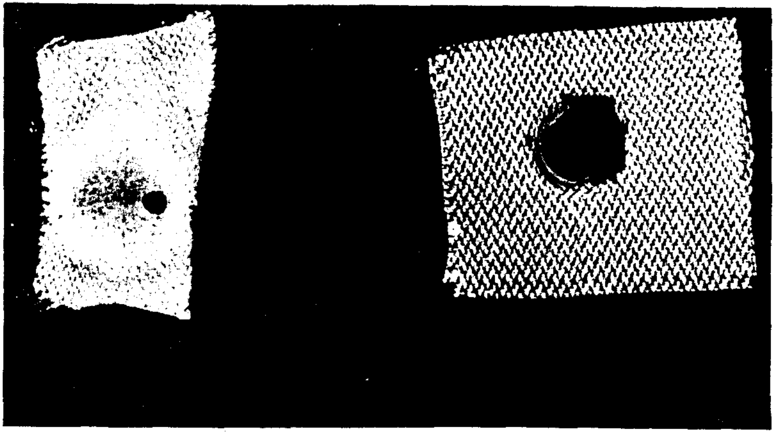
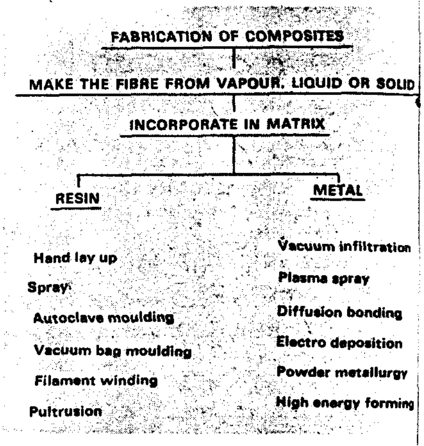


Fig. 6



The simplest process for making reinforced plastics is that of placing, manually, reinforcements (say, fibre-glass) and resins on a shaped mould (made of wood or plastics) and using squeezers or rollers to push in the resin and remove the air bubbles. Thickness is controlled by the number of layers of material placed against the moulds. Variations of this process include using heat to accelerate the cure or using a vacuum bag, pressure bag or autoclave to permit the application of pressure against the laminate to force out air (to reduce voids) and eliminate excess resin (to increase the glass-to-resin ratio). In the *spray-up process*, glass fibres are ejected into a resin stream and the mixture is directed at the mould. The *filament winding process* uses continuous strands and the product is in the shape of a surface of revolution. The strands are fed through a resin bath and wound on a suitably designed mandrel. Alternately, filaments coated with resin (prepregs) can be used. The winding machines are similar to lathes. The *pultrusion process* is analogous to extrusion in the case of metals. In this process, continuous

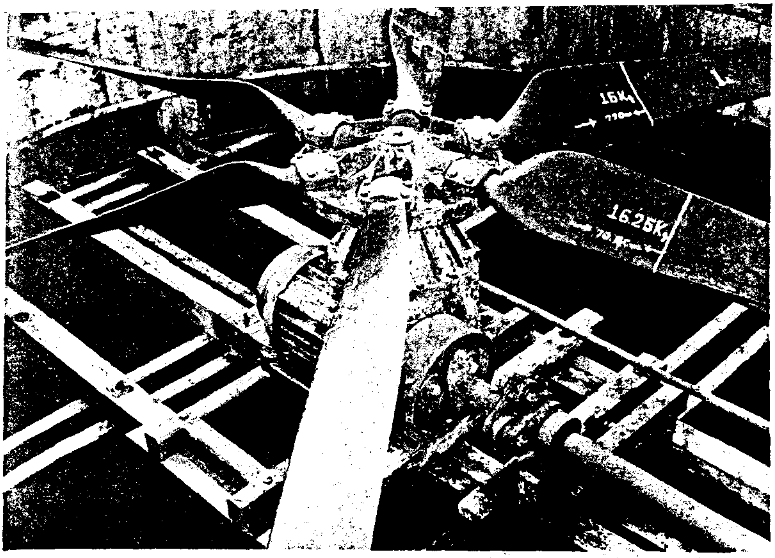


Fig. 7 FRP blades for cooling tower fan

reinforcements are fed through a resin bath and pulled through a die which determines the geometry and the resin content. A section of the die is heated to cure the composite.

Some of these methods have been employed at NAL to produce fibreglass reinforced plastic (FRP) components for various applications. A 16·5 metre radome (or a dome-shaped weather-resistant FRP covering for radar equipment) designed and built by NAL is shown on p. 13. FRP was chosen for this application since it is both transparent to radar waves and can meet the structural requirements. The structure has to withstand winds with speeds of 240 kph, erosion due to dust, corrosion due to salt in coastal areas, loads due to snow accumulating on the top, and solar radiation. The material has to undergo sufficient environmental testing before being selected for this application. The energy of chemical bonds in plastics is about the same as the energy of ultraviolet radiation from the Sun. Hence solar radiation can reduce the strength of plastics by breaking up the chemical bonds. Moisture can seep along the fibre, just as oil is sucked up by the wick of a lamp, and this would degrade the bond between the fibre and the plastic. Protective coatings can solve these materials problems. NAL now has the capability of designing and building radomes up to 30 metres in diameter with a radar transmission efficiency of 90 per cent.

We have developed more recently FRP tubes with controlled porosity. These can be used as a structural back-up support for the membranes used in desalination plants. Since these replace metallic tubes (stainless steel, for instance), which are more expensive and difficult to drill accurately, this development will lower the cost of desalination plants. We have also developed FRP containers for transportation of chemicals. In these applications, a good design is essential, since the structure must not only carry the weight, withstand splashing of acids, etc, but also must be able to resist failure for long periods. Expensive failures have occurred as a result of bad design and lack of non-destructive evaluation before the tank was loaded. The intrinsic advantages, however, are obvious, since the container is lightweight which means less energy is expended in transportation.

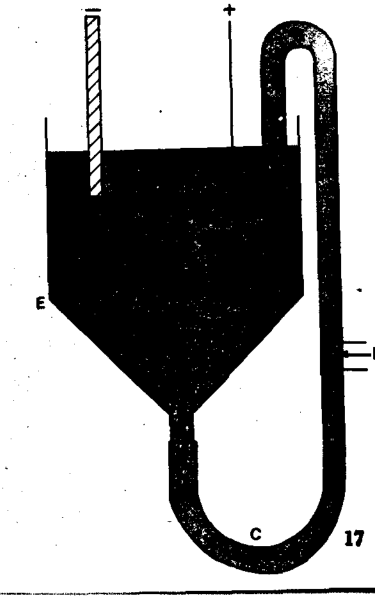
We have developed cooling tower fan blades — which are part of every major thermal power station — up to 7·5 metres in sweep. Fig. 7 shows a set of six FRP blades developed at NAL and installed at the cooling tower of the NAL wind tunnel centre. These blades consist of FRP skins and polyurethane foamed *in situ*. Their low weight compared to wood results in reduced power consumption. FRP can replace the traditionally used wood, which has the problem of warping, and aluminium, which corrodes easily when stressed. Other applications that have been developed at NAL include FRP insulating tubes and arc chambers for the electrical industry, and cyclone separators used in the chemical industry as dust collectors for separating corrosive mists from an air stream.

But resin matrix composites are not suitable for continuous use at temperatures above 250°C. For use at temperatures above this limit, metal matrix composites have been developed. Some methods of producing metallic composites are shown in Fig. 6. In the vacuum infiltration process, fibres aligned in a mould are infiltrated by the molten metal in a vacuum environment. This technique has been developed at NAL and applied to the preparation of composites of aluminium reinforced by stainless steel wires. This method will be used for the preparation of composites of tungsten fibres in a nickel matrix for use in aircraft gas turbine engines.

The method of *plasma spraying* used for boron-aluminium composites, for instance, employs a plasma torch which sprays matrix materials in the form of liquid droplets onto a rotating mandrel covered with aligned fibres. Composite tapes formed this way can be consolidated into structural parts by *diffusion bonding*. The diffusion bonding process of combining filaments with matrices such as aluminium and titanium involves the use of pressure and temperature. The matrix is in the form of foils, and fibres are laid on them in predetermined orientation and spacing. Alternate layers of metal foils and reinforcing fibres can be arranged to get the desired volume fractions. The whole assembly is then heated to develop bonding by diffusion.

Metallic composites can also be prepared by *electroforming*, that is, by electroplating the matrix on fibres wound on a mandrel or by codepositing the metal matrix and dispersed particles on to a substrate. The latter have applications as cutting tools. Electro-deposited composite coatings consisting of a metal matrix

Fig. 8 Apparatus for depositing particle dispersed metal composite coating. A — Top of the electrolyte; B — Connecting tube; C — Peristaltic pump; D — Inlet port; E — Cone shape vessel; F — Air sucking point



and co-deposited dispersed particles impart wear resistance, dry lubrication and creep resistance. Fig. 9 shows the cross-section of a composite of nickel reinforced by silicon carbide particles. The particles are seen to be distributed uniformly. Electroforming has the advantage of combining the fibre or particles with the matrix at low temperatures so that thermal degradation of the fibre or particles is avoided.

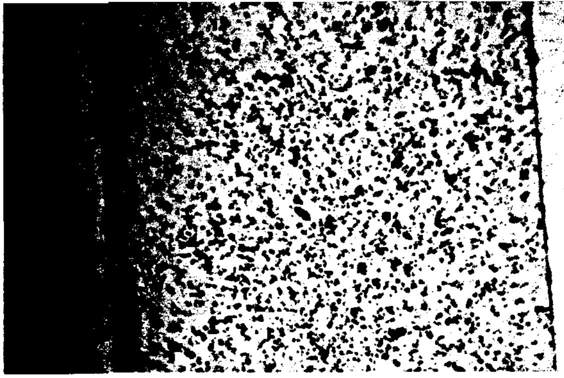


Fig. 9 Cross-section of a silicon carbide reinforced nickel composite (particle size is 2μm)

Composites have been produced by *powder metallurgy* techniques. The metal matrices in the form of powders are mixed with whiskers or chopped fibres. The combination is consolidated by pressing, sintering or hot isostatic pressing. In-situ fibering of second phase particles can also occur in a compact during hot pressing. These techniques are applicable to ceramics also. High-energy forming methods such as explosive forming and pneumatic impaction have also been used for making metallic composites.

A radically different method is the simultaneous growth of the reinforcing and matrix materials from a single melt. In *eutectic* solidification, two phases crystallise from the liquid. If the growth rates of the phases are compatible, one of the phases will crystallise out in the form of aligned fibres, the other forming the matrix. Nickel and cobalt alloys reinforced by tantalum carbide fibres have been obtained by unidirectional solidification and have properties superior to nickel base superalloys.

Inexpensive composites for less sophisticated uses

The spectacular development of high-performance fibres and composites should not obscure the fact that the principle of composites can be applied to several more common engineering materials, some of which are inexpensive and are readily available in India. Natural fibres such as sisal, ramie and jute have strengths exceeding 1,00,000 psi, and modulus of 10 million psi (similar to a high-strength aluminium alloy). However, they absorb moisture which causes swelling, increases weight and decreases mechanical properties such as tensile and creep strength. Moreover, they are vulnerable to attack by insects and fungi. These problems are overcome by incorporating them in a protective plastic matrix, impervious to moisture. However, an accidental crack in the matrix can expose the fibre. Therefore, development work to improve the moisture resistance of natural fibres is necessary. In the chemical structure of jute, oxygen and hydrogen atoms combine to form a group called the (OH) group. The presence of (OH) groups in jute is responsible for its moisture absorption. However, the complete removal of (OH) groups would make the structure of jute collapse. Hence, we have developed a chemical treatment which partially removes the (OH) groups, thus reducing the moisture absorption of jute by a factor of three. The strength, however, is reduced by only 15 per cent. The chemical treatment also prevents jute from absorbing resin *into* its tubular structure.

Ferrocement is a thin shell of concrete reinforced with wire mesh, with varying configurations and diameters of wire. It is different from reinforced concrete in that the wires can be bent more easily than the rods used in reinforced concrete. The fineness and dispersion of the steel mesh helps to prevent cracks from propagating. It is more impermeable to water than concrete. Thus, the difference between reinforced concrete and ferrocement (or ferroconcrete) illustrates the distinction between a mixture and a composite. In reinforced concrete, the reinforcing rods take up the tensile load but do not contribute to compressive strength and the concrete takes up the compressive load but does not contribute to tensile strength. In ferrocement, however, the fine wires are uniformly distributed and have large surface area so that the concrete which is weak in tension can transfer the load along the interface to the wire, and because of this *load transfer*, the composite behaves as though it

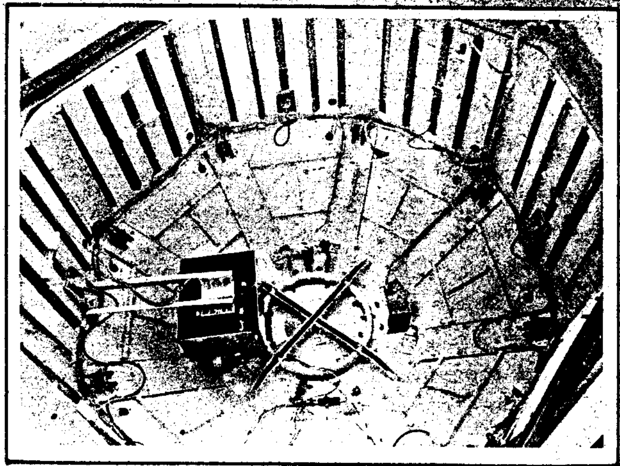
Composites with operator properties

The composites mainly discussed in this article have additive properties in the sense that the constituent phases contribute proportionally. There is a class of composites where the physical output of one phase operates as the input into the other phase. One example is a composite consisting of a piezomagnetic phase A and a piezoelectric phase B. (Piezoelectricity is the property by which a crystal develops electricity when we stress it, say, by bending it. Conversely, an electric pulse applied to the crystal will change its dimensions. A crystal is piezomagnetic, or magnetostrictive, if it develops a magnetic pulse when stressed or alternately changes dimensions when a magnetic field is applied to it.) In such a composite, the application of a magnetic pulse induces a change in the shape of *A*. Since *A* and *B* are bonded together, *B* is also strained and being piezoelectric consequently develops an electric pulse. Thus, a magnetic pulse is converted into an electric pulse by the composite. The composite is the unidirectionally solidified eutectic of barium titanate ($BaTiO_3$) which is the piezoelectric phase and the mixed nickel-iron oxide ($NiO\text{-}Fe_2O_3$) which is the piezomagnetic phase. Composites with operator properties can have entirely new properties or can give a known conversion but with a higher yield.

Composites for non-structural applications include superconducting cables. It is possible to combine strength with superconductivity when carbon fibres are coated with a superconducting compound. The coated fibres can be wound to form containers for plasma.

For optical applications, sodium fluoride-sodium chloride (NaF-NaCl) eutectics can be solidified unidirectionally so that NaF rods are parallel to the axis of the specimen grown. The composite then has image transmission properties similar to those of fibre optic materials. The spacing between the rods can be controlled by the conditions of solidification. In fact, the solidification in this system was studied under zero-gravity conditions in a space processing experiment and the inter-rod spacing was found to be more uniform compared to the eutectic composites solidified on Earth. The controlled eutectic can then act as a far-infrared transmitting medium for wavelengths longer than the inter-rod distance (typically 6 μm). Other examples of non-structural composites include aligned indium antimonide-nickel antimonide eutectics which are currently in use as magneto-resistive and infrared materials.

S. R. & N. B.



FRP nutation damper in Aryabhata

An exciting project of design and fabrication of a nutation damper for the first Indian satellite Aryabhata was undertaken jointly by the Indian Space Research Organisation (ISRO) and NAL. Aryabhata is a spinning satellite. A spinning satellite is stable only when it is spun about its axis of maximum moment of inertia. Due to various disturbances, the spin axis wobbles or " nutates ". Whenever this wobble (" nutation angle ") exceeds a specified limit (about 0·1°), the scientific data from the spacecraft become less reliable.

The nutation damper shown in the photograph is a circular *annular* ring with its cross-section in the shape of the letter ' D '. The ring is partially filled with a viscous fluid, say, silicone oil. Although the ring is symmetrical with respect to the spin axis, it is important that its plane does not pass through the centre of gravity of the spacecraft. If the spacecraft is spinning without nutation, the fluid is distributed uniformly inside the ring. When nutation starts and exceeds the specified limit, the liquid tends to flow to one side which leads to the decay in the nutation angle.

The nutation damper makes sure that the nutation angle never exceeds 0·1° at spin rates of 15 rpm or above. In order to meet such stringent specifications, the ring was made with considerable precision with respect to the outer and inner surfaces. The ring, 40 cm in diameter, was moulded using an accurately machined mandrel (a shaped rod around which FRP is formed) of a low-melting alloy (Woods metal). After moulding, the ring was immersed in boiling water. The mandrel melted and the molten metal flowed through two small holes. The hollow ring was then filled partially with silicone oil and the holes sealed. The nutation damper underwent trials in the laboratory and met all the foreseeable space requirements. It is now installed in Aryabhata, and has been performing satisfactorily.

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were a homogeneous material and is strong both in tension and compression.

Ferrocement technology is easily acquired and has a number of applications in developing countries: grain silos, storage tanks, boats, etc. If the boat size exceeds 10·5 metres, ferrocement boats are cheaper than those made of FRP, and lighter, too. These are obviously superior to wood which has the problem of warping. In these applications, a layer of FRP can be sprayed onto ferrocement, if necessary. In general, the replacement of wooden structure by composites is a welcome step towards the conservation of forests.

In composites which use cheaper fibres or natural fibres, the cost is controlled by the resin. Hence resins must be developed cheaply and from non-petrochemical sources. In our laboratory, lignin was isolated from coconut shells and the waste from paper industry. This lignin was allowed to react with formaldehyde in alkaline medium to give a resin which compares well in its properties with commercially available and more expensive phenolic resins.

India entered the age of composites a few years back with the development of the FRP technology for rocket nose cones, radomes, antennas and a variety of components for chemical, electrical and other engineering industries. More recently, a development effort supported by the United Nations Development Programme and the Department of Science and Technology aims at the development of newer fibres and composites in India. Six laboratories are participating in this project. For composites to be more widely used in India, the cost of the fibres and resins must be lowered and non-destructive evaluation procedures must be encouraged so that confidence in these new materials will be generated.

Composites technology has matured to a level where even with high material costs, the cost of composite *structures* is about 15 to 25 per cent less than those made of conventional materials. This is because much less material is required since the strength and stiffness are high. Another factor is the low wastage in forming operations, since hand and laser trimming are used. The ratio between the amount of raw material purchased and the amount that actually goes into the structure of the completed aeroplane (the buy-to-fly ratio) is 10 : 1 for conventional materials, whereas it is only 1·05 : 1 for composites. Today, in a high performance jet plane, about one per cent of the airframe is made of composites, but the percentage will increase markedly. A US Government study of Advanced Design Composite Aircraft (ADCA), a nearly all-composite aircraft, showed that the production costs would be lower by 21 per cent and fuel savings would be of the order of 30 per cent. It should be possible in India to construct a light all-composite aircraft as an inter-institutional study project. Even greater impact will be felt in this country when radical changes in our thinking about materials occur as a result of the appreciation of the science of composite materials.

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Recommend reading: **1.** Dubin, G. (Ed) 1969 *Handbook of Fibreglass Plastics.* Van Nostrand, New York. **2.** Kelly, A. 1972 *Strong Solids.* Clarendon Press, Oxford, UK. **3.** Broutman, L. J. and Krock, R. (Ed) 1974–76 *Advances in Composite Materials* (6 vols). Academic Press, New York.