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Popular Science & Technology Series

composite materials

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Popular Science & Technology (PST) series is published by DESIDOC to promote knowledge and understanding of the applications of science and technology in Defence among Defence personnel, students and the general public. Since the aim is to create awareness of current developments in frontier areas of science and technology among these groups, the presentation of material in the PST publications is lucid and generally in non-technical language. The text is supported by illustrations. Each issue of PST is devoted to a particular topic of current interest. PST is a half-yearly publication.

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Composite Materials

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Foreword

The PST series brought out by DESIDOC (DRDO) aims at overviews on scientific and technical topics of Defence interest in simple language to create an awareness of the subject among readers and to inculcate the spirit of scientific temper. The main emphasis has been on applications of Science and Technology in Defence R&D.

We all know that the 20th centuary has witnessed revolutions in a number of fields like computer, radar, space, missiles, etc. but the most interesting changes have taken place in the area of composite materials.

Composite materials have been extensively used all over the world in almost all industries such as aerospace, automobile and transportation, marine, chemical/electrical/mechanical/civil engineering, building construction, electronics & telecommunication. Defence is one of the major users of composite materials, particularly for rockets/missiles and other ordnances. As the production/manufacture of composite materials and fabrication of products from them is a labour-oriented technology, composite materials are more interesting and appropriate to a country like India.

In this issue, Dr JP Agrawal, one of my colleagues in ERDL, has made an effort to present an overview on science and technology of composite materials including their applications in various industries.

It is hoped that this monograph would stimulate the interest and curiosity of a wide range of readers on the subject.

(Dr. Haridwar Singh)
Director, ERDL
Pune

7.12.1990

Preface

The invention and subsequent growth of composite materials has brought a revolution in the world over the last three decades. The composite materials industry has grown at a phenomenal rate and has given birth to a wide range of new materials with fresh applications leading to an increase in their demand. These materials are finding applications in almost all walks of life. Aerospace, defence, automotive, chemical, electronics & telecommunication and building industries being the major beneficiaries of their tremendous growth.

The Indian Society for Composite Materials (ISCM) was established in 1982 and its major objective is to popularise usage of composite materials and disseminate the latest developments in this field. I happen to be the Joint Secretary of ISCM and therefore, decided to write an article on composite materials during my assignment with the St-Etienne University, France. In my opinion, it would be a befitting contribution to the ISCM. I sincerely hope to disseminate the information on composite materials, in a layman's language with the help of this publication.

This book gives an overview on science & technology of composite materials including their applications in various industries. The plan of presentation is given under contents.

The entire material in this publication is based on published literature which is not less than an ocean to a common man, and I have tried to condense the same in the best possible way. It is not possible to thank all writers/researchers individually whose books/research papers I must have consulted, but I express my thanks to all whosoever contributed to the cause of composite materials in any way.

JP Agrawal

To The Memory
of
MY FATHER-IN-LAW
LATE SHRI D P RASTOGI

Acknowledgements

This monograph was written during my assignment with the St-Etienne University, France where I was invited under the Indo-French Scientific & Technical Cooperation Exchange Programme. I, therefore, express my sincere thanks to the French Government, Prof JM Vergnaud, Research Adviser and authorities of St-Etienne University for providing library facilities.

I am grateful to Director, ERDL, ERDL management, Scientific Adviser, Defence Research & Development and DRDO management for granting me study leave without which it would not have been possible for me to go to France.

In the last but not the least, I would like to express my gratitude to Dr Haridwar Singh, Director, ERDL for writing the Foreword.

Contents

1

Materials Then and Now

Ever wondered at the small changes that keep taking place around us in all spheres of life? How new materials are slowly replacing the conventional materials and thus altering our way of life? They are to be found in all spheres—starting from clothing and furnitures to high-tech items like missiles.

You would perhaps be aware that in your grandparents' *time everything from cigarettes to supari* used to be packed in 'tins' or cylindrical metal containers. Not any longer; now even shampoos come in attractive polythene pouches.

Similarly, the houses in olden days used to be brick and mortar affairs with lots of wood used for rafters, beams, doors and windows. Having realised the disastrous effect decreasing number of trees has on ecology, people have turned to other, newer building materials as substitutes for precious wood.

The cooking utensils of yesteryears used to be of brass or copper. These have been replaced by hindalium and stainless steel. Housewives invariably use shining, colourful plastic containers to store cooking ingredients these days and not empty, rusted milk-food containers used by their mothers.

Fighter aeroplanes and computers were gigantic affairs to begin with; but are now sleek yet more powerful than their predecessors.

The list is endless. Rubber tyres replacing wooden wheels; bright nylon or polyester dress materials becoming more popular than cotton; tennis rackets made of lighter materials being preferred over the old, heavy wooden ones; and so on.

In general, life has improved tremendously, thanks to mankind's progress in science and technology. This has made possible to have newer and better materials for applications in all walks of life. These materials have the advantages of the older materials eliminating the disadvantages.

Most of man's inventions have come about because of his needs. At first he used only the materials which surrounded him in nature. Wood and stone for tools and animal skin for clothing. Then he learnt to weave natural fibres like cotton and silk to make cloth. Slowly he discovered the use of iron and copper to make hunting implements.

Later, he learnt to use fire to make pots and pans from clay and to mix metals like copper and tin to produce the alloy bronze. In this way he began to make new materials that are not found readily in nature. Another synthetic material that was first made in early times was glass, a compound of silica and soda ash.

Man's scientific understanding has greatly increased in the last two centuries, which have witnessed a revolution in technology. Scientists have discovered how to make special synthetic materials like plastics.

The word *plastic* is derived from the Greek word 'plastikos', meaning 'fit for moulding'. It is quite a fitting word as plastics can be fabricated into rigid, tough, corrosion-resistant objects.

Plastics can be inorganic or organic, natural or synthetic. But increasingly, the word has come to denote synthetic organic plastics, essentially *polymers*. These polymers, meaning many (poly) parts (meros) are composed of giant molecules or units called *monomers*. Each monomer is composed essentially of carbon and hydrogen. Sometimes, they may contain other elements like oxygen, nitrogen, chlorine, silicon, etc. Most polymers are immensely long chains; sometimes *linear*, sometimes *branched*. This is possible because carbon atoms can combine very easily with one another and with many other kinds of atoms. They have the ability to form strong bonds in long chains.

Most of the developments in plastics took place as a result of man's search to replace wood, cement and other materials with newer ones having better properties. Celluloid, first made from cellulose and camphor was developed in a bid to find good billiard balls! Some developments were as a result of military needs during World War II.

The first synthetic plastic, bakelite, was invented by L H Baekeland in 1906 by reacting phenol and formaldehyde. *Polyvinyl chloride* (PVC) and related polymers were first manufactured in the late 1920's. Polystyrene, lucite and plexiglass (acrylic) were invented in the 1930's.

Many plastics are made from other plastics; for example Acrilan, Orlon, and Dynel are made from styrene. Some other plastics are nylon, polyethylene, teflon, etc.

Polymers are produced by complicated chemical processes but they involve basically two types of chemical reaction—addition polymerization and condensation polymerization. In the former, the individual monomers add to one another directly, without change in composition. In the latter, two or more monomers react to form a chain eliminating a small part of themselves, usually water.

Plastics are generally classified as *thermoplastics* and *thermoset* plastics. Thermoplastics melt or soften when heated, and thus can be reprocessed, whereas the thermoset plastics remain hard after formation. At high temperatures, they do not melt, but decompose.

With the invention of plastics, man started using this material to replace the conventional ones. Metals though tough have inherent drawbacks like heavy weight and loss of strength due to corrosion. However, many plastics though versatile are not strong or stiff enough as such for use in sophisticated applications.

Of late, scientists have started mixing materials with different properties in a new way so as to make new materials which have the good properties of the constituent materials, without having the inherent weaknesses or disadvantages of the individual materials. These new materials are called *composite materials.*

What exactly are these composite materials ? How are they manufactured? Are there any naturally occurring composite materials? In what fields are they employed? Will the products made of composite materials be affordable enough for the common man? What other revolutions are likely to take place in this field in the years to come? We shall try to answer these questions in the following chapters.

2

Composite Materials—What are They

DEFINITION

A composite material is made by combining two or more dissimilar materials. They are combined in such a way that the resulting *composite material* or *composite* possesses superior properties which are not obtainable with a single constituent material. So, in technical terms, we can define a composite as 'a multiphase material from a combination of materials, differing in composition or form, which remain bonded together, but retain their identities and properties, without going into any chemical reactions.'

The components do not dissolve or completely merge. They maintain an interface between each other and act in concert to provide improved, specific or synergistic characteristics not obtainable by any of the original components acting singly.

Bone is a simple example of a natural composite material having the best properties of its constituents. Bone must be strong and rigid; yet flexible enough to resist breaking under normal use. These requiste properties are contributed by its components. A mature bone is made up of two basic kinds of materials—organic and inorganic. The organic component, consisting mostly of proteins, carbohydrates and fats, makes it pliable and gives the required softness. The inorganic component, made up of calcium phosphate, gives it the required strength and rigidity.

The most common synthetic composite material is glass fibre reinforced plastics (GRP) which is made out of plastics and glass fibre. The individual components have altogether different properties to that of the composite material, GRP. Plastics are light, durable, have excellent corrosion resistance and can be easily moulded to any complex shape. But they are not fit for load-bearing applications because of lack of sufficient strength, stiffness and dimensional stability. Glass fibre, on the other hand, possesses very high strength and is sufficiently stiff and durable. Like plastics, it also cannot be used for load-bearing applications because of its brittleness and fibrous structure. But when both these are combined in the correct proportions and a particular glass fibre arrangement, we obtain GRP which has the improved mechanical and other properties suitable for load-bearing applications.

CLASSIFICATION

Composite materials may be broadly classified into natural and synthetic composite materials. Figure 1 schematically shows the classification of composite materials.

Synthetic composite materials are generally prepared by taking the ingredients/constituents separately and physically combining them by diffe-

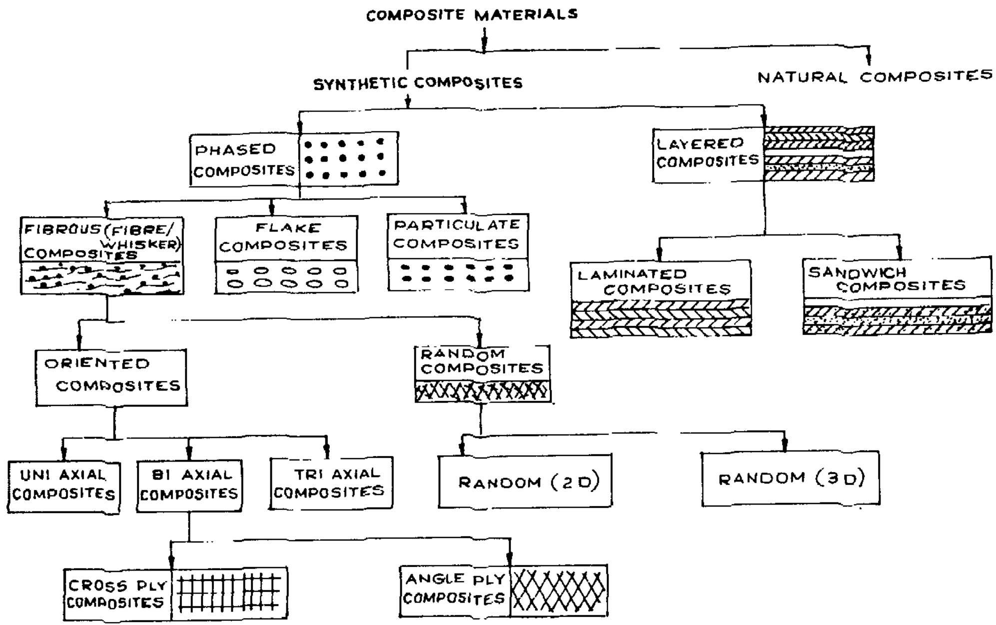

Fig. 1 Classification of composite materials

rent techniques and random/oriented arrangement of fibres. Two ingredients may be composed together as (i) layered composition in which layers of ingredient materials are bonded to one another, and (ii) phase composition in which one ingredient is inserted into the other ingredient. The phase that receives the insert in the phase composition is the continuous phase and is called *matrix*. The purpose of adding the insert is generally to improve the mechanical properties of the matrix or to make it cost-effective. If the insert is added to improve the mechanical properties, it is called *reinforcement* but if added to make it cost-effective or to change a property other than mechanical properties, it is called a *filler.*

Matrix

Matrix is also known as binder material. It (i) provides shape to the composite material, (ii) makes the composite material generally resistant to adverse environments and (iii) protects reinforcement material from adverse environments. The materials which constitute matrix of composite materials are plastics, metals, ceramics and rubber.

(i) *Plastics matrix:* Plastics matrix based composite materials constitute more than 95 per cent of composite materials in use today. Both thermosets as well as thermoplastics are used as matrix materials. As thermosets mostly exist in liquid state before cross-linking, it is very convenient to combine reinforcements in the required proportion, shape the product and cure it into solid. Thermoplastics, on the other hand, have to be heated and liquified for adding inserts.

(ii) *Metal matrix*: Metals can also be reinforced with high strength fibres in order to improve the strength and stiffness (Young's modulus). However, it reduces elongation and toughness. Boron reinforced aluminium is very popular for aircraft applications.

(iii) *Ceramic and other brittle matrix*: Ceramic, carbon and glass are widely used for this purpose. The introduction of fibres into ceramics improves tensile strength and toughness. Similarly, carbon/glass reinforced with carbon fibres have better toughness.

(iv) *Rubber matrix*: Rubber is highly elastic and incorporation of fibre or particulate filler enhances rigidity of rubbers. Carbon black, cotton, nylon and steel fibres are widely used for this purpose.

Reinforcement

It is the reinforcement material which basically gives strength, stiffness and other mechanical properties to the composite material. It is generally in the form of fibres, whiskers, filaments and includes glass fibre, carbon fibre, Kevlar fibre, boron filament/fibre, asbestos fibre, etc. On the other hand, fillers are in the form of flakes or fine particles.

HISTORICAL DEVELOPMENT

Composite materials have been in use since biblical times when chopped straw was added to brick to make building materials. The modern composite materials age began with the introduction of particulate or fibrous reinforcement material into thermoset phenolics in the early 1900s. Glass fibre was commercially produced for the first time in the USA in 1937. The first GRP was made in 1942. Since then, there has been tremendous development in terms of new reinforcement materials, matrix materials and production methods. Fibre reinforced plastics (FRP), particulary glass fibre reinforced plastics are meeting the demanding techno-economic requirements of various industries as can be seen from Fig. 2.

Much of the early impetus to the development of composite materials (FRPs, GRPs) was on account of the needs of military aircraft during World War II.

The USA is the major consumer of composite materials. In 1984, 11 million kg of composite materials were produced worldwide and US consumption was around 60 per cent of the total.

Just as mankind has moved from the stone age to the composite age, so have composites evolved from the chopped straw bricks of primitive times to today's sophisticated ceramic matrix composites and metal matrix composites. There has been an extraordinary explosion in composites usage, research and applications. Now composites find unusual and exotic applications such as in stealth aircraft and as superconductive composites. Composites are one of the fastest growing industries and continue to demonstrate a marked impact on the materials world.

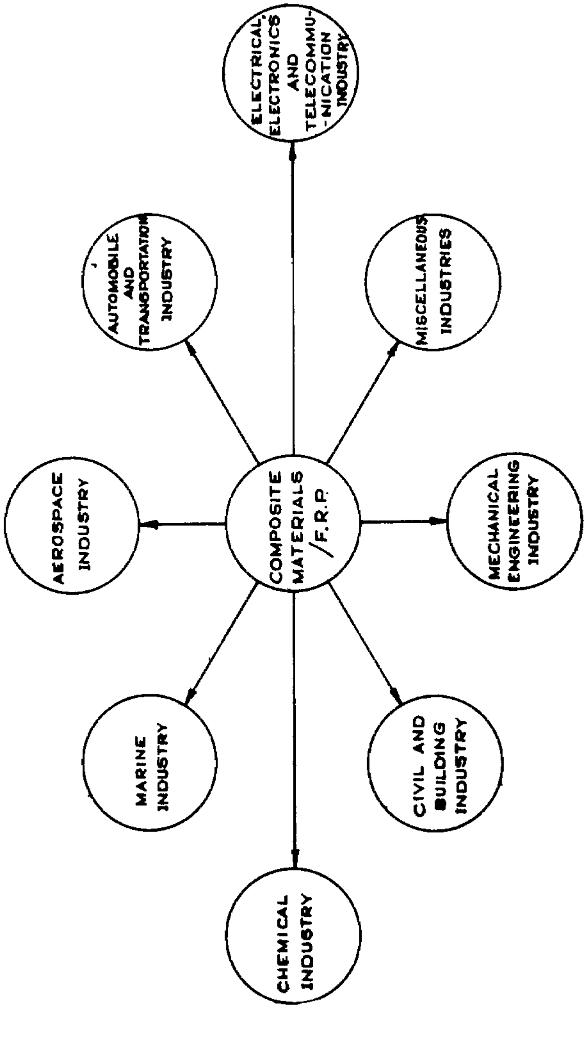

Fig. 2 FRP application tree

SIGNIFICANCE

Composite materials are generally costlier as compared to conventional materials but still their use is becoming increasingly popular because of their undermentioned properties.

Lightness: The strength-to-weight ratio is high in composite materials as compared to conventional materials and therefore, they require less energy for moving them around. As a result, weight reduction contributes to fuel economy in transportation by road, rail, sea or air. This property is regarded as a boon in the age of shortage of energy.

High specific properties: Composite materials possess better strength, stiffness and less weight and thus, their use for fabrication of structural parts of an aircraft or automobile provides an additional advantage. Specific strength and modulus of composite materials are superior than metals and therefore, they are preferred to conventional metals.

Design and processing flexibility: Composite materials offer a wide design flexibility and products may be fabricated by adopting simple hand lay-up or by using very sophisticated numerically controlled machines.

Cost effectiveness: Products from composite materials can be easily moulded into any complex shape, and steps like machining, drilling, cutting, etc. are altogether eliminated; thus making production cost-effective and efficient.

Functional superiority: Composite materials possess better properties and functional advantages. Thus their products are corrosion resistant, good electrical insulators, anti-magnetic and therefore, are suitable for chemical equipment, transformer tubes and mine sweepers respectively.

Durability: Composite materials are more durable under adverse environmental conditions and at the same time, require less maintenance. As a result, they work out to be cheaper over a longer life-span in spite of their higher initial costs. Also, the very low maintenance cost offsets the initial high cost.

Thus, it can be seen that these improved composite materials have a combination of stringent requirements such as higher strength, higher modulus, less weight, easy formability, low expansion, etc. We can have a combination of contradictory properties. In a nutshell, the significance of composite and advanced composite materials lies in the vast opportunities offered by them, which were undreamt of until a few years ago.

The following chapters describe the raw materials used in the making of composites, production techniques, finishing operations and quality control methods for composite materials.

3

Constituents of Composite Materials

As we saw in the previous chapter, composite materials are made from constituents which can be grouped as (i) matrix/binders, (ii) reinforcements and/or (iii) fillers, additives and auxiliary chemicals. Now we will describe in more detail the various kinds of these raw materials.

BINDER MATERIALS OR MATRIX

Plastic Matrix

The matrix or binder materials employed for fabrication of composite materials are usually polymers commonly called resins. As stated in the earlier chapter, polymers (plastics) are of two types—thermosetting and thermoplastics. The *most commonly used thermosetting polymers are* phenol-furfural, urea-formaldehyde, melamine-formaldehyde, epoxy, unsaturated polyesters and silicones. The most common thermoplastic polymers are cellulose nitrate, low density polyethylene (LDPE), high density polyethylene (HDPE), polyamides, polyvinyl alcohol and polyisobutylene.

Unsaturated Polyesters

Unsaturated polyesters can claim to be among the first of the many synthetic resins which are now the basis of the composite materials industry. These are formed by condensation of polyhydric alcohols and polybasic acids (one of them must contain non-aromatic unsaturation) and it is cross-linked with a polymerizable monomer such as styrene monomer. The monomer becomes a part of the catalyst and cobalt naphthenate accelerator.

Depending upon the requirements, combination of acids and glycols are chosen for manufacture of a polyester.

Glycols: Ethylene glycol, diethylene glycol, propylene glycol, polyethylene glycol, etc.

Acids: Phthalic acid (general purpose), isophthalic acid (superior strength, toughness, weathering characteristics, heat and chemical resistance), adipic and sebacic acids (flexibility), tetrachloro/bromophthalic anhydride (flame retardancy), chlorendic/HED acid (flame retardancy), maleic anhydride (most widely used and available at low cost), fumaric acid, mono/dichloro maleic anhydride (flame retardancy).

Monomers: Styrene (most widely used because of low cost, availability, better curing and weathering characteristics and compatibility), diallylphthalate (for imparting toughness and outstanding electrical and heat resistance and dimensional properties).

An inhibitor is added to the resin to avoid premature gelling during storage at room temperature. The most commonly used inhibitor is hydroquinone (0.01-0.02 per cent of the weight of the resin). However, a number of other inhibitors—inorganic substances (sulphur, copper, nitrates), aromatic nitro compounds (DNT, TNT and picric acid) and amines (aniline, phenylenediamine) may also be used for this purpose.

Many catalysts and accelerators are commercially available for curing of polyesters. The use of catalyst is mainly dictated by the processing temperatures.

Benzoyl peroxide paste	— Elevated (70°C) temperature
Lauroyl peroxide	— Medium temperature
Methylethyl Ketone (MEK) peroxide	— Room temperature

Accelerators are also added to polyester resins to speed up free radical formation by peroxides. Cobalt naphthenate is generally used with MEK peroxide and benzoyl peroxide to facilitate free radical formation to initiate polymerization.

General purpose polyester (GPP) resins are the cheapest resins suitable for varied applications in FRP. Propylene glycol is used for low cost polyester resins which give good physical and chemical properties. Vinyl ester is also coming into usage in India and its advantage is high temperature resistance and better resistance to alkaline conditions. Polyester resins are used extensively in hand lay-up, SMC and DMC moulding.

Epoxy Resins

These have terminal epoxy groups and are made by condensation of epichlorohydrin and bisphenol-A. The polymerization/ cross-linking of epoxy resins is initiated on adding primary/ secondary/tertiary amines, amides, anhydrides, etc.

Epoxy resins are regarded as compounds which contain more than one epoxy group, capable of being converted to cured (thermoset) form with the help of hardeners/curing agents. Most of the commercially available epoxy resins are formed by the reaction of Bisphenol-A (Diphenylol propane, DPP) and epichlorohydrin in the alkaline medium.

Novolac epoxy resins are also commercially available now. The main features of these resins are that they maintain their properties at high temperatures and possess high heat deflection temperature (HDT) and high glass transition temperature (T_g). The presence of a phenolic backbone provides short-term thermal stability coupled with chemical versatility of epoxide group and also it has led to their manifold newer applications.

The following characteristics of epoxy resins induce interest in users for their application.

- Ability to be cured rapidly or slowly
- Ability to be processed by a variety of techniques
- Ability to accept a wide range of fillers and pigments
- Absence of volatile matter during cure
- Excellent adhesion on almost all substrates
- Excellent toughness

- Excellent chemical properties
- Good electrical properties
- Low shrinkage and therefore, better dimensional stability

Vinyl Ester

The vinyl ester resins, originally pioneered by Dow fifteen years ago under the name Derakane, are a compromise between epoxies and polyesters and are essentially epoxy resins specially fitted with reactive end-groups to enable them to cure (cross link) in much the same way as polyesters. This gives them the chemical resistance, toughness, ductility and price structure reminiscent of epoxies, together with the fabrication convenience of polyesters.

These are superior to other resins in respect of excellent heat resistance, wetting characteristics for glass fibres, toughness, extremely good chemical resistance to reagents and retention of mechanical properties at elevated temperatures. These resins are also curable with X-ray and gamma rays.

Phenolics

Phenolic resins are the third most important composite binders. Recognition of the need for the fire resistance and low smoke evolution has recently given fresh impetus to phenol-formaldehyde resins. Since the resin liberates water during polymerization, it is not as easy to handle as polyesters or epoxies which are totally convertible into polymers. Glass fabric-phenolic composites (laminates) provide an optimum design for applications in underground train panels, where smoke is particularly undesirable and as heat shields in high perforemance cars (around turbochargers and catalytic converters). Also, they stand to win much of the market for secondary structures in aircraft (as cabin interior furnishing, cargo area linings, etc.).

The prepolymer which is a viscous liquid is made by reacting phenol and formaldehyde in the presence of acid/alkali and is capable of further cross-linking on heating. Polymerization takes place due to addition condensation on heating. Phenolics are invariably blended with fillers, fibres, etc. and curing is done *in situ* using heat in the mould. Phenolics are not softened by the application of heat but eventually char and burn if the temperature is high enough. These are practically insoluble in common solvents but decompose on treatment with hot alkalies and concentrated oxidizing acids.

Urea/melamine may be used in place of phenol and results in urea/melamine-formaldehyde resins. The melamine-based resins are superior in respect of hardness, heat and impact resistance but their cost makes them unattractive.

Silicones

Silicone is the name given to a group of polymers that have a skeleton structure of alternate silicon and oxygen atoms with various organic groups attached to silicon atom. Silicones, the first of the inorganic polymers, are a combination of Si-O- linkages that can be classified into two major groups—rigid and elastomeric. The -O-Si-O- linkages in silicones provide heat resistance while the -C-H-linkages enable the practical working characteristics of polymer. The laminating and coating silicones are in the rigid group. Their mechanical properties are poor which can be improved by the addition of fillers. Generally silicone resins are in the form of solvent diluted fluids that are characterised by heat stability, water resistance, weathering oxidation resistance and outstanding electrical properties. The outstanding electrical properties of silicone-fibre glass laminates coupled with retention of mechanical properties at elevated temperatures, have made this type of composite standard for radomes for supersonic vehicles.

Polycarbonates

These are polyesters derived form carbonic acid. These are usually prepared by the reaction of diaryl carbonate with diols or by condensing phosgene ($COCl_2$) directly with diols. The main features of these thermoplastics are high impact strength, heat resistance and dimensional stability. They possess a combination of properties which make them suitable replacements for light metals such as zinc and aluminium. These are not indigenously available at present and are too costly.

Polyacetals

The first of the family is polyformaldehyde (trade name DELRIN). The term acetal refers to an oxygen atom which joins the repeating units of the structure in an ether rather than ester type of link. These are also made from acetaldehyde or mixtures of formaldehyde and acetaldehyde. These are extremely rigid without being brittle and retain the properties at elevated temperatures. In order to increase thermal and chemical resistance, terminal groups are converted to esters/ethers. As they pack closely, they provide a high degree of stiffness, toughness and chemical resistance.

Polyacetals are hard and rigid materials with good impact strength, electrical properties and high softening point. Similar to polycarbonates, these are excellent substitutes for many light metals. Polyacetals have a smooth and hard surface with a low coefficient of friction and are resistant to organic solvents but are attacked by strong acids.

These are also not indigenously available and too costly like polycarbonates.

Polyimides

This polymer has been known for many years with most of the research originating in Du Pont Laboratories, USA. Polyimides have now reached commercial fruition after many years of research into processing techniques. They were patented in 1959 and produced commercially as coatings and films in 1961. The synthesis is a two-step process in which the water molecules are liberated only in the last step. Thus, a dianhydride and diamine react readily to yield a polymeric acid which on heating evolves two moles of water per polymer unit to give polyimide.

At present, polyimides are the best commercially available structural adhesives with long-time ageing capabilities and have the added advantage of lower costs than aromatic heterocyclic polymers.

Poly (Amide-Imides)

The polyimide structure was modified by the incorporation of amide linkages in search for improved processibility. This resulted in easier processing but also caused an undesirable loss in strength retention at elevated temperatures. These polymers possess definite merit where performance is important at somewhat lower temperatures. This polymer is synthesised from an aromatic diamine and trimellitic acid chloride-anhydride.

Polyimides possess superior properties and are now well recognized as materials for extreme environments. The polyimide and copolyimide resins with various inorganic and organic reinforcements are now widely used for aerospace, defence, nuclear and other similar applications demanding high reliability.

Phenoxies

Phenoxy resins are strong, very hard and tough. The toughness is being retained by these materials upto –60° C. Chemical resistance to acids, alkalies and aliphatic hydrocarbons is excellent but poor to aromatic hydrocarbons and esters. An outstanding characteristic of phenoxies is their good adhesion to metals, wood, glass, papers and many plastics and this adhesion is water resistant.

A number of binder materials or matrices are available for the fabrication/production of composite materials. However, polyester and epoxy resins are still extensively used for FRP fabrication and it will not be an exaggeration of fact if it is stated that these two resins constitute about 95 per cent share of the total matrix systems employed for FRP.

Slight impact damage is not easily detected with thermoset composites. This is a disadvantage of thermosets as compared to thermoplastics behaviour. Thermoset resins can be made tougher by formulation tricks such as adding a small quantity of dispersed rubber. Careful control of the dispersed phase particle size distribution is essential. Even so, the toughness does not equal that of the best thermoplastics. Another threat to thermosets, more distant perhaps, is posed by the new geopolymers—essentially alumino-silicates which can be processed at 20-80°C and after a short cure are stable to about 120°C. They can be reinforced with heat stable silicon carbide fibres to form impressive materials.

The commercially available thermoplastics are polyethylene, polypropylene, polystyrene, polymethylmethacrylate (PMMA), nylon, polytetrafluoroethylene (PTFE), polyvinylchloride (PVC), polyvinyl acetate, etc. The well known copolymers and terpolymers for this purpose are styrene-butadiene, styrene-acrylonitrile, butadiene-acrylonitrile, vinyl chloride-vinylidine chloride, ethylene-vinyl acetate, acrylonitrile-butadiene-styrene (ABS), acrylic acid acrylonitrile-butadiene (AAB), etc.

Many innovative polymers have been produced and mention may be made here of only a few—

polybenzimidazoles, polyphenylquinolines, phthalocyanine, polyphenylene sulphide (PPS), polyether etherketone (ICI's PEEK), polyimides and polyether suphones (3M's Astral 360 or Union Carbide's Udel).

REINFORCEMENT

There are a number of reinforcement materials and the selection is done depending upon the properties to be imparted to the end product. Major fibres used as reinforcement materials are mentioned hereunder.

Glass

Glass for reinforcement is available in several forms like fibres, rovings, chopped strands, yarn and mats (Fig.3). A particular form is chosen depending on the moulding methods and properties to be imparted to end products.

(i) *Glass fibres*: There are a number of grades available for reinforcement purposes and common grades are E-glass fibre (major glass fibre for composite materials and imparts high level electrical resistivity, surface resistivity and possesses good fibre forming characteristics), A-glass fibre (cost-effective grade for general purpose but easily attacked by moisture due to high alkali content), C-glass fibre (imparts higher acid resistant properties than E), S-glass fibre (retains strength at elevated temperatures in addition to elastic moduli than E), Z- glass fibre (produces excellent corrosion resistance to alkaline solution and used mainly for cement products),

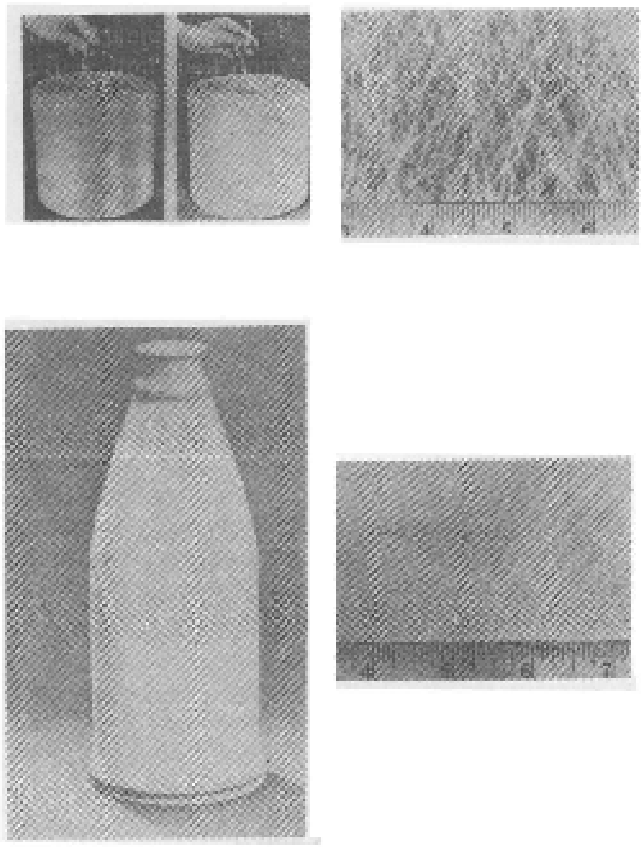

Fig. 3 Several forms of glass reinforcement
(a) roving, (b) chopped strand mat, (c) yarn and (d) fabric

M-glass fibre (possesses high Young's modulus and is used mainly for structural applications where stiffness is more important than strength) and D-glass fibre (possesses low dielectric constant and dielectric loss values and is ideally suited for high performance electronic applications).

(ii) *Continuous strands and rovings*: Rovings, essentially obtained from continuous strands, are mainly used for filament wound products such as rocket motor casings, pressure bottles, tanks and automobile parts, etc. The chopped rovings when combined with a polyester resin, designed to thicken (not to harden until it is heated), give rise to pre-impregnated materials—sheet moulding compound (SMC) if in the sheet form or dough moulding compound (DMC) if in the form of bulk material.

(iii) *Chopped strands*: Glass strands which are chopped to short length (~3 to 10 mm) are used in making DMC by incorporating into a polyester resin (whose polymerization is arretsted in the gel state) and for reinforcement of thermoplastics.

(iv) *Yarn*: These are analogus to other textile fibres and are used for weaving glass cloth or heavy cords for tyres of different vehicles.

(v) *Mat*: These are made by holding together glass fibre strands (length ~20-50 mm) with the help of a resin.

Glass fibre is the cheapest and the most commonly used reinforcement material and more than 95 per cent FRP are made by using glass fibre. Glass fibre based composite materials are not suitable for very high performance applications and therefore, carbon, boron, Kevlar fibres are used for this purpose. The composite materials based on these fibres are known as *advanced composite materials* and possess higher Young's modulus and better stiffness characteristics. However, their exhorbitant cost makes them unattractive for general applications.

Carbon Fibres

Glass fibres suffer from low elastic stiffness (of course, possess excellent strength characteristics) and limited char strength (relatively low melting point) for ablative applications. This necessitated the use of carbon fibres in place of glass fibres for ablative and structural applications. These are produced from certain precursors—polyacrylonitrile (PAN) fibre and viscose rayon fibre. The work on manufacture of carbon fibre from jute and pitch which are abundantly available in India has also been reported recently. M/s HERCULES, USA is a well known manufacturer of carbon fibres. Carbon fibres have strength and modulus vastly superior to glass fibres. Although they are at present much more costly, they will undoubtedly lead to further development of composite materials for more exciting applications. In view of their superior heat stability, carbon fibres can be used for reinforcing ceramics, metals, and plastics, giving engineers and technologists a completely new range of materials.

Boron Fibres

Boron fibres possess low density, high tensile strength, moduli and are extremely hard and are therefore, highly suitable for aerospace applications. These are manufactured by melt spinning, electrolysis and chemical vapour decomposition processes; the last one being most satisfactory. The high strength, high stiffness and buckling resistance are considered prime prerequisites for aircraft applications and in view of this combination of properties, boron composites possess greatest potential in the aircraft industry despite their high costs.

Kevlar (Aramid) Fibres

Kevlar fibres are known as high performance fibres and became commercially available in 1972. These fibres offer advantages over glass fibres in respect of strength-to-weight ratio coupled with excellent impact resistance.

Du Pont manufactures commercially two grades of Kevlar, i.e., Kevlar 29 and Kevlar 49 at their Richmond, USA plant and their annual production is 22 million kg. They have recently started their plant at Maydown, Northern Ireland and its capacity is expected to be approximately 7.0 million kg per year. Kevlar 29 is more suitable where high impact is of primary importance whereas Kevlar 49 is used for aerospace applications (ceiling panels and other interior parts of Lockheed L-1001 aircraft). Kevlar fibres are available as yarns, rovings, and woven fabrics. Hybrid laminates of carbon/Kevlar 49 fibres-epoxy matrix possess higher impact resistance than either fibre alone. Dutch firm, Akzo also manufactures Twaron aramid fibres.

Whiskers

The growing demand of the aerospace industry for materials having *greater specific strength and impulse* led to the development of near perfect crystals of silicon carbide, silicon nitride and aluminium oxide (sapphire) which are known as whiskers and have much greater tensile strength and modulus than even the best fibres. Whiskers have high strength because they are essentially perfect crystals, have large ratios of length to cross-section which does not allow defects (defects weaken longer crystals) to occur. They posses a combination of the best properties of glass and boron. They are still not available commercially and are manufactured on pilot plant scale only. They retain their strength properties to a better extent at elevated temperatures which is due to the absence of imperfections responsible for slip.

Natural Fibres

These include inorganic fibres like asbestos fibres and organic fibres like jute, coir, sisal, etc.

Asbestos Fibres

Asbestos is available in several forms—loose fibres, non-woven mats, woven fabrics, long and medium length fibre felts, rovings, papers, yarns and bulk fibres. Among asbestos fibres, Chrysotile ($3Mg.2SiO_2.2H_2O$) fibres account for the major applications. Asbestos fibres impart resistance *against heat, flame, chemicals* and moisture. The resins employed for this reinforcement are phenolics (most common), silicones, polyesters (mainly DAP modified and triallyl cyanurate modified), melamine and epoxy.

Asbestos Reinforced Plastics (ARPs) offer the advantages of high erosion and ablation resistance, excellent retention of strength at elevated temperatures, relatively low cost, good chemical and water resistance, low thermal diffusitivity, high modulus of elasticity and good machinability. Asbestos reinforcement provides a strong bond between the resin and the fibre which is partly attributed to the excellent wettability of the asbestos reinforcement. Strong structure panels can be fabricated from long fibre asbestos products. These panels have exceptionally high modulus of elasticity. ARPs, especially phenolic resin impregnated ones, have excellent char characteristics and are valuable in the high temperature ablation field. ARPs are used to manufacture many parts for missiles, aircraft, rockets and space vehicles.

The bond between resin and glass fibres is not very strong and is improved by combining asbestos fibres with glass fibres and therefore, mechanical properties of GRPs may be improved by exploiting this concept. This also makes GRP structures cost-effective.

Synthetic Organic Fibres

Until recently there were very few synthetic fibres available. Today the picture has changed and the composite industry now has several groups of organic fibres, notably polyethylene terephthalate (PET) and high density polyethylene (HDPE) along with an interesting variety of development materials. Compect PET introduced several years ago, is finding use as an impact improver to replace glass in thermoset systems. Another fibre is HDPE which is an ultra high strength fibre. Unfortunately, both fibres have temperature limits.

The fibres of the future are ultra high molecular weight and ultra oriented polymers based on PE, PP and PVA (polyvinyl alcohol) as well as rigid rod and flexible coil polymers. Liquid crystal polymers will also eventually be available in fibre form. Aramid fibres have a tremendous potential because of their outstanding wear resistance, resistance to high temperature and oxidation. They also have stiffness comparable to high modulus graphite fibres and strength. Polybutylene terephthalate (PBT) has the best combination of properties of any organic fibres on a specific modulus and specific strength basis. However, its compressive strength is about the same as aramids and 50- 70 per cent less than that of graphite.

The work on development of polydiacetylene fibres, ceramic fibres, new generation of organic fibres such as polybenzoxazoles and polybenzothiazoles, etc. and composites based on them, is in progress and the day is not far when these materials will be commercially available for use.

FILLERS, ADDITIVES AND AUXILIARY CHEMICALS

The term 'fillers' is very broad and consists of a very wide range of materials. These are invariably used in reasonably large loadings (above 15 per cent). Fillers are usually added to reduce cost, to improve processing properties and mechanical/electrical/ physical properties. The term additives describes those materials usually added to matrix. The additives are usually added to improve some specific properties—surface, optical, thermal, environmental—and they are added in smaller loadings (less than 10 per cent). Auxiliary chemicals do not get involved in polymeric reactions of matrix, do not form a part of composition of FRP product but assist production of FRP in many other ways. They are mould releasing agents (silicone grease), solvents (acetone, toluene, trichloroethylene, etc.) and protectives.

Fillers

These should be inert and their presence in a polymeric matrix should not affect the processing and polymerization. The classification of fillers is shown in Table I.

The selection of fillers is governed by chemical constitution, physical characteristics, availablility, price and finally on the property to be imparted to the end product.

Additives

The additives are classified according to their specific function rather than chemical basis. They are grouped as

(i) Processing additives — Processing stabilizers and aids, lubricants (internal and external), etc.

Table I: Classification of fibres

FILLERS

Organic		Inorganic	
Fibrous	Non-Fibrous	Fibrous	Non-Fibrous
Cotton seed hulls Sisal Wood flour Purified wood cellulose	Carbon black (gives better packing with coarser Fillers) Graphic (provides head stability, lubricity and electrical conductivity) Walnut shell flour (provides good, smooth and lustrous finish) Coconut shell flour (provides better electrical properties and good impact strength).	Asbestor Fibre Glass Fibre	Silica (extremely inert & heat stable and provides good electrical properties) Talc (reinforcing filler & products exhibit higher stiffness & creep resistance at ambient and elevated temperatures). Mica (provides high dielectric strength, low power factor & high dielectric constant). Clay (controls flow properties & provides more uniform composites). Calcium silicate (improves compounding characteristics in conjunction with clay for working BMC). Calcium carbonate (low cost, non-toxic, odourless and offers low shrinkage characteristics). Antomony trioxide (provides flame retardancy). Alumina trihydrate (provides flame retardancy in addition to low smoke emission).

(ii) Surface property modifiers — Thixotropic agents, anti-static agents anti-wear additives, adhesion promoters, etc

(iii) Optical property modifiers — Pigments and dyes, nucleating agents, etc.

(iv) Anti-ageing additives — Antioxidants, UV stabilizers and fungicides, etc.

The factors like compatibility, migration, health hazards, side effects, etc. are also taken into account while going for selection of an additive.

METAL MATRIX COMPOSITES

Metal Matrix Composites (MMCs) are of interest today because they offer opportunities to tailor a material with a combination of properties unavailable in a single material, i.e., combining the very high tensile strength and modulus of elasticity of various types of fibres with low density of a metal such as aluminium, titanium or magnesium to obtain a composite material with a higher strength-to-density or modulus-to-density ratio than a single known material. They are also of interest because of the improvement in fatigue resistance. The silicon carbide particulates whiskers-aluminium composites (aluminium reinforced with silicon carbide particulates/whiskers) have important features like high modulus, high abrasion resistance, low thermal expansion and low production cost.

Metal matrix composites are one of the strongest candidates for use as structural materials in many demanding environments as replacements to existing super alloys. Their use as structural components can greatly increase service temperature and improve specific mechanical properties. Boron-aluminium composite (aluminium reinforced with boron) is lighter than aluminium, possesses the strength and stiffness of steel and is the only material which has been fully qualified for flight-critical aircraft structures like those in the space shuttle Orbiter. Graphite-aluminium/titanium composites (graphite reinforced aluminium titanium composites) are used for applications where thermal stability is the major criterion. Reinforced copper is another metal matrix composite which is very interesting for applications in the fields of missiles, ordnance, electronics and space. In most of the advanced countries, steel is being replaced with reinforced copper in Gatling gun. This saves considerable weight and permits rapid sluing of the gun for improved efficiency. These are also likely to be used in the Light Combat Aircraft (LCA) which is under development in India

CERAMIC MATRIX COMPOSITES

The development of ceramic matrix composites (CMCs) by incorporation of naturally occurring ceramic particles/refractory particles like clay, zircon, ZrO_2, TiO_2, mica, graphite, coconut shell char powder, flyash and glass powder in aluminium/aluminium alloy matrix has brought to the horizon a new class of composites and is getting popular all over the world in recent years.

ARTUFF ceramic composites are the first commercially available ceramic composites manufactured form a high-purity aluminium oxide matrix reinforced with silicon carbide whiskers. These are characterised by extreme hardness, excellent machinability, design and performance predictability.

These materials are regarded as versatile materials for broad-based applications under the most severe operating conditions. Typical applications in industry are deep draw tooling, seal rings, valves and seats, pump components and extrusion dies—areas which require the ultimate resistance to wear erosion from abrasion and the ability to withstand thermal or chemical attack. It is reported that a ceramic matrix composite valve in a high-pressure slurry pump increases the pump's service life 45 times over the stainless steel valve.

4

Production Technology

The primary structural parameters that influence the properties of composite materials are (i) types of fibre and their length (ii) fibre packing and orientation (iii) kind of matrix (iv) ratio of fibre to matrix and (v) processing method employed.

It is well established that a higher fibre to matrix ratio gives better mechanical properties. Also, the geometrical arrangement of fibre within the matrix is equally important in order to impart stiffness and strength in all directions.

There are basically two approaches for processing of composite materials.

- Taking the ingredients separately and combining them appropriately at the time of fabrication.
- Making a semi-processed mixture of fibre and matrix such as moulding compounds (SMC, DMC, BMC, etc.) and prepregs. This method is generally useds for bulk production. Figure 4 schematically presents the various processing methods for fabrication of products out of composite materials.

MOULDING

Moulding can be done in two ways, i.e., open-mould

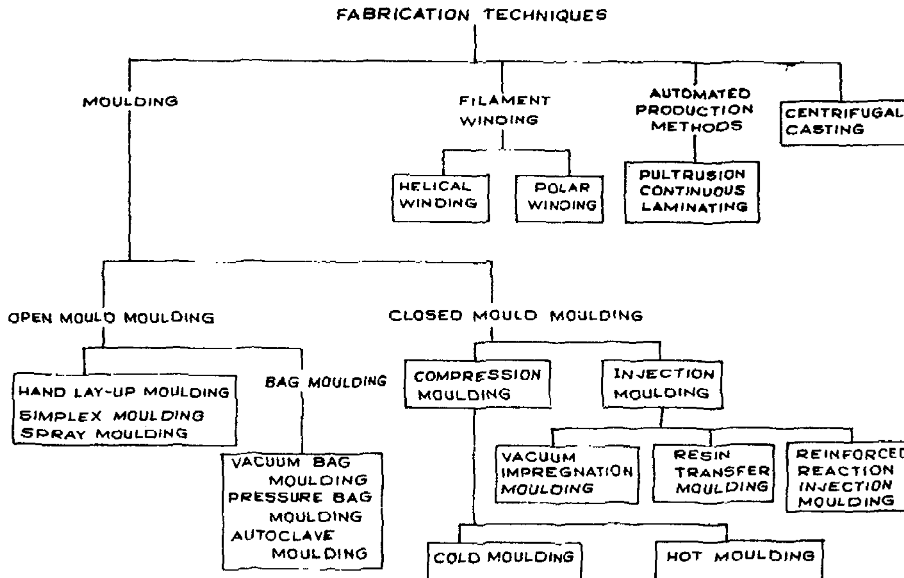

Fig. 4. Processing techniques of composite materials

moulding and closed-mould moulding or matched die moulding.

Open-Mould Moulding

Open-mould moulding is a term used for a number of methods. The simplest is hand lay-up moulding. In this, the resins and reinforcement are deposited in a mould by hand/hand tools. This is also known as 'contact moulding' as resin is in contact with air. Polyester, epoxy and phenolic resins are widely used in this method.

In this technique, laminate thickness is not decided by the number of layers but by the time of spraying.

In open-mould moulding where pressure is a must in view of other considerations, the following methods are preferred and depending on the method of application of pressure, these are termed as 'vacuum bag moulding', 'pressure bag moulding' and 'autoclave moulding'. In these methods, mould made out of plastics or FRP are used since applied pressure is not high.

Closed-Mould Moulding

This is one of the widely used techniques and includes compression moulding and injection moulding.

In compression moulding, a predetermined weight of moulding charge is placed in a heated mould cavity, mould is closed and pressure is applied by means of a press (4-column upward/downward moving platen, direct acting hydraulic press). The press and mould are kept closed until the charge becomes rigid enough to maintain its given shape. As soon as the curing cycle is over, pressure is released, mould is opened and the product is removed. One of preforms, reinforced moulding products, i.e., DMC, BMC or SMC, prepregs and wet lay-up, is used as the mould charge depending upon the size, shape and properties of finished products. The mould temperature depends on the resin which is used and the general range is

Polyester	:	80-150°C
Epoxy	:	145-200°C
Silicone	:	150-190°C

In injection moulding, at least one component is injected into the mould cavity. This method consists of 'vacuum impregnation moulding', 'resin transfer moulding' and 'reinforced reaction injection moulding'.

Pressure is invariably used in 'closed mould moulding' whereas pressure is not generally used in 'open mould moulding' except for very important aerospace and electrical applications by means of vacuum bag, pressure bag or autoclave (pressures are of low magnitude). As regards difference in terms of applications, 'open-mould moulding' is used for fairly large components whereas 'closed-mould moulding' is suitable for bulk production of small sized components.

Filament Winding Technique (FWT)

The moulding methods are suitable for fabrication of complex shapes but, in general, do not impart very high strength. This is due to the fact that the proportion of fibre (source of impact strength) is not very high and also, it is randomly oriented. These limitations are overcome by FWT.

This involves winding of continuous filaments under controlled tension drawn from a spool mounted on a tension controlled device through a resin onto a rotating mandrel by a feeding point. The relative motion between feeding point and mandrel are such that filaments are put along the predetermined path on the mandrel surface and there is no gap between two adjacent windings. The number of windings are decided depending upon the thickness required and the mandrel is removed after curing at room temperature or elevated temperature.

Fibres are normally oriented in the direction of principal stresses or some other angle to them so that the stresses developed are balanced and higher structural strengths are imparted to composites. Filament winding is the most ideal fabrication process where filament strength is fully utilised due to proper orientation of fibres and also, products are void-free with high fibre content. Further, filament wound pipes withstand higher pressures as compared to moulded/centrifugally cast pipes. However, there are some limitations of this process—(i) interlaminar shear strength is low, (ii) filament wound structures have less ultimate bearing strength than conventional laminates and are more rigid and less ductile.

Depending upon the requirements, a particular type of winding is selected. The main methods for FRP fabrication may be classified as helical winding, polar winding and special purpose winding.

Continuous On-line and Automated Production Techniques

The above methods for production of composite materials are either labour intensive or semi-automatic.

India is a developing country and FRPs are generally manufactured by manual manufacturing techniques or semi-mechanised techniques. However, fully automated techniques have also been developed in order to meet higher production output. These are pultrusion process, continuous production of corrugated and flat sheet, continuous production of filament wound pipes and centrifugal casting of pipes. Pultrusion process is used for making thin long rods of diameter upto 250 mm; thin walled pipes of upto 250 mm outer diameter; and structural sections like flats, angles, tiles, channels, etc.

Polyesters account for 90 per cent of pultrusion binders and epoxies for the remainder. As regards reinforcement, fibre glass in the form of mat, cloth and roving is the principal material. However, parallel-oriented roving is the major ingredient for rods.

FINISHING OPERATIONS AND REPAIRS

Composite material products made/fabricated by various moulding/winding processes are usually rough and not good looking and therefore, require machining and finishing. This also enables to maintain correct dimensional tolerances as per specifications. Sometimes, these products get damaged and require reliable repairing before they are put back into operation. These operations are similar to operations for metals but with more precautions.

Machining and Finishing

The complex shaped products, if produced with the help of moulds and dies involving large expenditure, become very expensive. In order to restrict expenditure on moulds and dies, it is preferred to give shapes by machining. An account of machining operations for supplementing various moulding operations is given in Table II.

Table II: Machining operations for various types of moulding

Processing Method	Purpose of Machine	Type of Machining
Compression, injection and transfer moulding	Deflashing, Degating	Cutting off, filling
Laminating	Cutting sheets to drilling sizes	Cutting off,
Winding	Uniform and finished outside diameter and slots	Turning and milling
Pultrusion	Cut length of pultrudate	Cutting off

In addition, finishing operations also include 'cutting and sawing', 'turning', 'milling, 'drilling', 'threading and tapping', 'shearing and punching' and 'joining' operations. These are usually done by following corresponding metal working technique. While undertaking these operations, utmost care is taken to avoid damage and coolants are always recommended as FRPs are poor conductors of heat.

Damages and Repairs

The most frequent damage to components fabricated out of composite materials is due to impact and it is generally localized around the point of impact. This can be repaired without much difficulty.

In case of a hair crack, it is enlarged into a V-shaped groove (Fig. 5) with the help of a file, deep down to gel coat and the main laminate beneath is exposed. It is now cleaned to make it free from dust and dried. A composition based on general polyester and filled with chopped strands or woven roving mats as reinforcement, is filled into the V-shaped groove, slightly in excess and is allowed to cure. The repaired surface is now rubbed with 320 wet-and-dry abrasive carefully. It is finally painted to match the finished colour of the product.

QUALITY CONTROL

Matrix (resin) and reinforcement (fibre) constitute major raw materials and therefore, in order to maintain quality and ensure reproducibility of end product, testing of raw materials as well as finished products is undertaken. The testing of raw materials involves testing of resin and reinforcement material (fibre) as well.

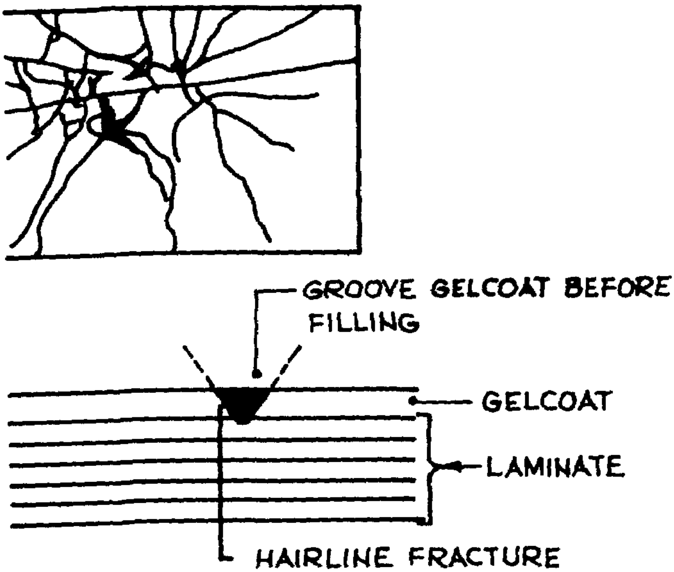

Fig. 5 Repair of hairline fracture in composite material

Testing of Composite Materials

The testing of composite materials involves their testing for many properties and these have been put together broadly under (i) mechanical properties (ii) thermal properties (iii) optical properties (iv) chemical and environmental properties. Standard specifications in terms of IS, BS, ASTM or Federal specifications are well known for determining these properties and therefore details are being not given here. The precautions to be taken at the time of their testing and acceptance criteria for these materials are also appended in these standards.

The composite materials are not generally tested for all the properties but major thrust is given to the properties which are important from the end-use point of view.

5

Advanced Composite Materials

In composite materials the reinforcement, which is usually a fibre or filament of high strength, is the primary load carrying element and the matrix, which serves the purpose of binder, is the load transfer medium for the reinforcement fibres.

Glass fibre is most commonly used for FRP fabrication. Carbon fibre, Kevlar fibre, alumina fibre, boron filament, polydiacetylene fibre and whisker, etc. have recently been developed and if these fibres/filaments/whiskers are used as reinforcement, the strength and other properties of FRP increase manifold. Such composite materials are known as *advanced composite materials* or *advanced composites*. These composites have higher Young's modulus and better stiffness characteristics than those based on glass fibre. Similar to the composite materials, epoxies, phenolics, silicones and polyimides, binder resins are widely used for advanced composite materials. Different grades and types of fibres and so the resins, are available. By a proper permutation and combination, it is possible to design an advanced composite material of desired characteristics. By selecting flame retardant resins, advanced composite material can also be made ablative.

The market activity of advanced composite materials (ACMs) is concentrated mainly in three areas: aerospace/aircraft; recreational; and industrial.

Automobiles and other miscellaneous applications constitute a relatively modest market. Major market activities of advanced composite materials for 1985 are shown in Fig. 6. It appears that the demand for

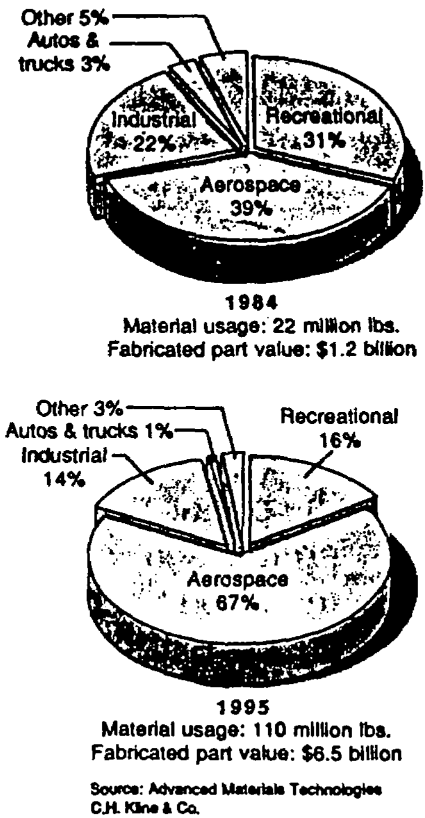

Fig. 6 Comparative chart showing use of ACM in industry

ACMs will grow by over 15 per cent annually during the next decade. At present, the United States' consumption represents about 60 per cent of the total.

Advanced ablative composite materials are used in re-entry vehicles for space explorations and also for fabrication of motor/launch tubes for rockets/missiles/launch vehicles, pressure gas storage vessels and nozzles in different rockets/space vehicles. Epoxy- graphite is most widely used for structural applications (wings and tail sections, pressure vessels and seat rails) in F 18 and AV-8B aircraft. This also finds extensive structural applications in Boeing 757 and 767 ailerons, elevators, rudders and spoilers, etc. Graphite-Kevlar-epoxy hybrid advanced composite materials are extensively used for wing/body fairings, landing gear doors and trailing-edge panels.

The year 1987 was a very remarkable year in the history of ACMs when STARSHIP I, all- composite business aircraft, was produced at Maythcon Company's Beech Aircraft subsidiary and went for certification trials near Witchita, Kansas. The aircraft's advanced design and composite construction provided high strength, lighter weight and less drag. The aircraft undertaking trials are shown in Fig.7.

Future military aircraft are likely to use 40-50 per cent advanced composite materials and therefore, will be lighter with improved performance and will be considerably more fuel-efficient. All-composite motor blades of Swiss Super Puma helicopter (Fig. 8) are fabricated using hybrid glass/carbon/ aramid prepregs and possess unlimited life, immunity to corrosion and impact, fail-safe performance, de-icing capability and

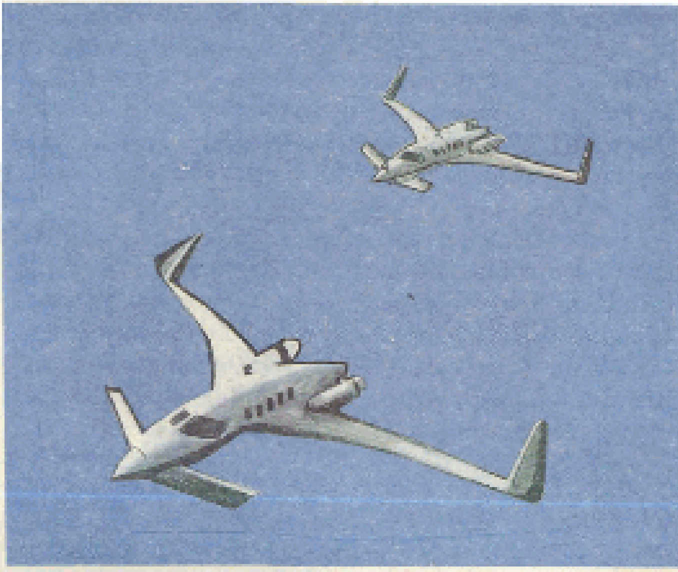

Fig. 7 All-composite starship I business aircraft produced by a subsidiary of Maythcon Company

Fig. 8 All-composite rotor blades in the Swiss Super Puma helicopter

reduced maintenance costs. Also, various helicopter manufacturers are making serious attempts to develop an all-composite design for the entire helicopter. Construction is under way on the Navy's first all-FRP minesweeper hunter, the largest FRP structure built so far in the United States.

Applications in the second largest market for advanced composite materials include a variety of products and utilize a variety of material systems. Tennis-racket frames and golfclub shafts are available with carbon-fibre reinforcement as are fishing rods with glass, carbon and boron fibres and canoes with aramid reinforcement. A modern ski

Fig. 9 Modern skis made of carbon-epoxy ACM

(Fig.9) made of carbon fibre-epoxy ACM, is light yet strong enough to support massive stresses—bending, twisting, shock, impact and long term fatigue, cycling under extremes of temperature and humidity, etc. Similarly, racing yachts are made in Switzerland entirely (hull, decks, bulkheads and furnishings) from woven aramid fabric-epoxy ACM.

Advanced composite materials based on carbon fibres are becoming very popular in orthopaedic surgery. High density polyethylene (HDPE)-polyester composites are being looked at for medical implants such as the lining of knee joints and hip sockets as well as for sealing. ACMs are also used for centrifuge rotors, X-ray tables, computer-printer daisy wheels, corrosion-resistant pipes and sucker rods, etc. However, in automotive industries applications for gears, bearings, leaf springs, truck drive shafts, etc. are pretty much limited.

6

Applications of Composite Materials

As we have already seen, composite materials possess a unique combination of properties such as

- High strength to weight ratio, i.e., lightness in weight
- Better toughness, fatigue and stiffness
- Functional superiority, i.e., better corrosion, weathering and fire resistance, electrical insulation and anti-friction properties
- Translucency (transmission ~ 85%)
- Ease of fabrication or versatility of fabrication methods
- Better durability and low maintenance cost

This has stimulated tremendous interest for using composite materials in various industries. Their applications range from a simple wash basin to high-tech applications such as in space shuttles. A detailed account of their applications, industry-wise, is given in this chapter.

AEROSPACE INDUSTRY

Composite materials are used in aircraft for primary (radomes and dielectric panels) and secondary (doors, ring tips, ducts and fairings) structures.

Radome (Fig.10) is a protective covering capable of transmitting electromagnetic signals with less distortion and loss. The most important requirements for a radome are uniform electrical thickness and wavelength identical to the radar equipment with which it is to be used. Large sized FRP radomes have recently been developed by Defence Research and Development Laboratory, Hyderabad for the first time in India. The materials used for wall construction are E-glass rovings and epoxy resin because of their good electrical as well as mechanical properties. The technique adopted is polar winding. The glass rovings-epoxy composites are extensively used for 'nose-radomes', 'rotodomes', and 'aerial window'. With the availability of boron filaments, these are preferred for radome fabrication in foreign countries as these composites have been reported to be significantly more efficient than their metal and glass-epoxy composites counterparts. Although use of composites for radomes are best known, the wide use of composite materials (FRP/GRP) in aircraft is for ducting—aircraft ventilation ducting, protective ducting (for electrical cables run), air conditioning systems, etc. The material of construction is polyester-glass/asbestos composites using tape winding either on a lathe (for straight runs) or by hand for more complex structures (Fig.11).

A large variety of secondary structures (fairing, electrical distribution panels, propeller spinners, tank platings, furnishings, etc.) are made by wet lay-up of polyester-glass cloth composites. Furnishings have not received the publicity of radomes and ducting but composites are popular for the furnishings of the aircraft passenger cabin. The secondary components

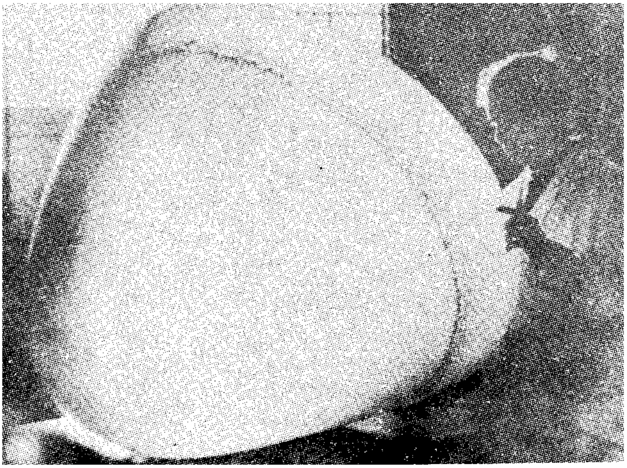

Fig. 10 Fluted core radome for Britannia aircraft

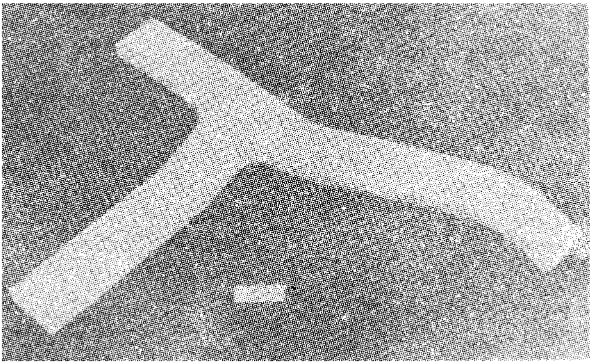

Fig. 11 Flexible polyurethane glass cloth duct

fabricated from boron-epoxy composites are also available in foreign countries. However, cost is always an important factor affecting their widespread use for this purpose.

MIRAGE 2000 elevons, radiobay doors, fins, rudders , etc. are reported to be made of carbon or hybrid boron and carbon-epoxy composites and a weight reduction of the order of 25 per cent similar to radomes is claimed.

The use of composite materials in the aerospace vehicles is plentiful and in many applications, it is the only functional material. Most reentry heat shields for missiles (Jupiter, Altas, Titan, Polaris, Minuteman, etc.), and spacecraft (Mercury, Appolo, etc.) are made of glass-phenolic or asbestos-phenolic composites. The heat shield of warhead of the first Indian Intermediate Range Ballistic Missile (IRBM), AGNI, which was launched in May 1989 is made of carbon fibre-phenolic composite which protects it from temperature rise to about ~ 3000° C.

Glass/Kevlar-polyester/epoxy composites are extensively used by the rocket industry in the manufacture of motors/cases (Fig.12) which act as propellant confinement vessels . Rocket motors made of glass fibre-epoxy composites work successfully as upper stage motors of two-stage air launch missiles. Graphite epoxy composites for rocket motors offer significant advantages—higher velocity, greater range and altitude, greater strength and stiffness over the glass fibre-epoxy motors and demonstrate 17.7 per cent weight savings. The reduction in weight of rocket motor implies increase in the weight of propellant

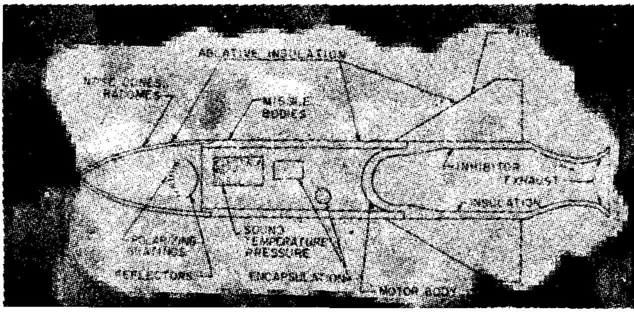

Fig. 12 Composite missile

which results in increase in the range or payload. This is considered to be of strategic importance from the military angle. The third and fourth stage motors of SLV-3 were made of Kevlar-epoxy composites using Filament Winding Technique. Similarly, the third stage motor of AGNI was also fabricated from Kevlar-epoxy composites. The development work on launch tubes for Indian Multi-Barrel Rocket System (MBRS-PINAKA, surface-to- surface rocket with ~ 45 km range) using glass fibre/rovings- epoxy composites is in advanced stage. Further, the use of carbon-carbon composites/graphite cloth-phenolic composites for nozzles and exit cones, ceramic composites as jet vanes for gas flow orientation in tactical rockets, silicon carbide composites for ramjet chambers, etc. is becoming more and more preferable because of the unique combination of properties of composites.

Asbestos-polyester/phenolic composites find extensive application for nosecone and insulation of blast tubes. The blast tube of Target Missile developed by Aeronautical Development Establishment, Bangalore (propulsion system by ERDL, Pune) is insulated by asbestos reinforced polyester. Similarly, blast tube of an anti-tank missile, NAG (under development in DRDO) is lined with refrasil cloth impregnated with resin.

AUTOMOBILE AND TRANSPORTATION INDUSTRY

The potential for increasing fuel economy by reducing the vehicle's weight has stimulated tremendous interest for composite materials in automobile and transportation industry. As a result, industrially developed countries like Japan are extensively using graphite dispersed aluminium composites for automobile parts where friction is involved. The applications of composite materials in railways and road transports are well established all over the world including India.

Railways

In European countries, the main structural interest for composite materials is the construction of non-metallic tank wagons and small trackside buildings. Typical non- or semi- structural uses of glass fibre-polyester composites are—end wall sections of diesel railcars and locomotives, doors, various ducts, rectifier trays, floors in toilet compartments, corridor ceiling panels, etc. Refrigerated containers (made from GRP and PU foam sandwich held in a metal frame) are used by British, French, Italian, Dutch and

German railways for transporting sensitive chemicals. The important advantages of these materials are the absence of metallic containers (which serve as thermal paths) and freedom from corrosion combined with ease of cleaning.

The British Railways use GRP rodstock (coated with butyl rubber) as underbridge tunnel and section insulators on the 25 KV overhead power system. The use of glass fibre/cloth-polyester composites for roof light sheeting for station canopies and passenger shelters is also widespread because of substantial reduction in maintenance.

The Netherlands Railways uses GRPs extensively for the production of gearcases on motor coaches of multiple train sets. Another application of composite materials (GRP with a surface containing carborundum) is toilet floor units. The German Federal Railways and Italian State Railways also use similar item as one-piece moulding and tank wagons or compartmented tank wagons (tank made from a sandwich structure of GRP and rigid PVC foam) for the conveyance of wine, milk, fruit juices and fuel. The reduction in weight is around 25 per cent. The French National Railways also use GRP containers for the transportation of milk and GRP tanks lined with either PVC or polyester for conveyance of chemicals. The containers are designed for easy transfer on and off. Similarly, the Hungarian Railways transport hydrochloric acid in GRP lined tanks. The Sweden railways use a sandwich structure (two GRP skins with a core of rigid PVC) for roof panels, toilet floors, seat shells, etc. (Fig.13).

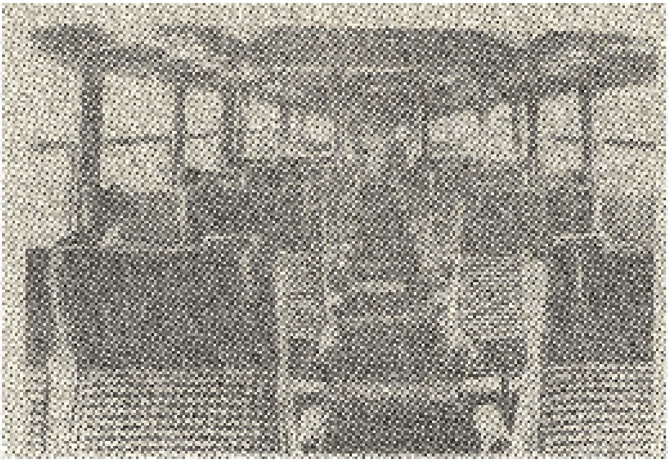

Fig. 13 Cold moulded seat shells fitted in a coach

Most of the European railways also use GRP trackside boxes and cupboard extensively to house switchgears and signalling equipment. Thus GRPs are making useful technical and economic contributions to the railways and these materials will undoubtedly be used increasingly in future.

Road Transport

Glass fibre-polyester/epoxy composites are the usual materials for the production of three-wheeled vehicles for invalids, commercial vehicles (cabs and trucks), car bodies (Fig. 14), sporting cars, buses, ambulances, caravans, mobile shops, etc. in foreign countries. GRP is also used in motor cycle and scooter industry mainly due to weight saving and the need to obtain an inexpensive weather-resistant streamlined fairings. The hood, doors and rear end of Peugeot car (model 205) are fabricated from hybrid

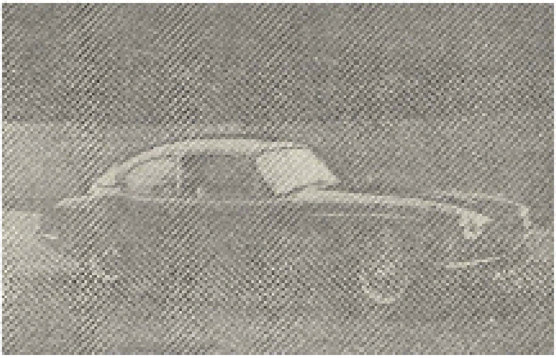

Fig. 14 World's first car made of GRP

aramid and carbon fibre-epoxy composites (Fig.15). In India also, bodies of Maruti cars are made of GRP. The construction of refrigerated and non-refrigerated truck bodies as well as tanks for transportation of milk, beer, fruit juices, wines and many other chemical products by road is done from GRP in European countries.

M/s Peugeot, France's leading car manufacturer has recently started manufacture of bicycles from composite materials (Fig. 16) on a commercial scale. The frames of these bicycles are made of glass/carbon-epoxy composites. These weigh 30 per cent less but are eight per cent stiffer than the conventional alloy material. Similarly, the bumpers, automotive wheels and auto parts are made from GRP. The drive shafts are made from carbon fibres-polyester/epoxy composites and brake liners and clutch facings from asbestos reinforced plastics.

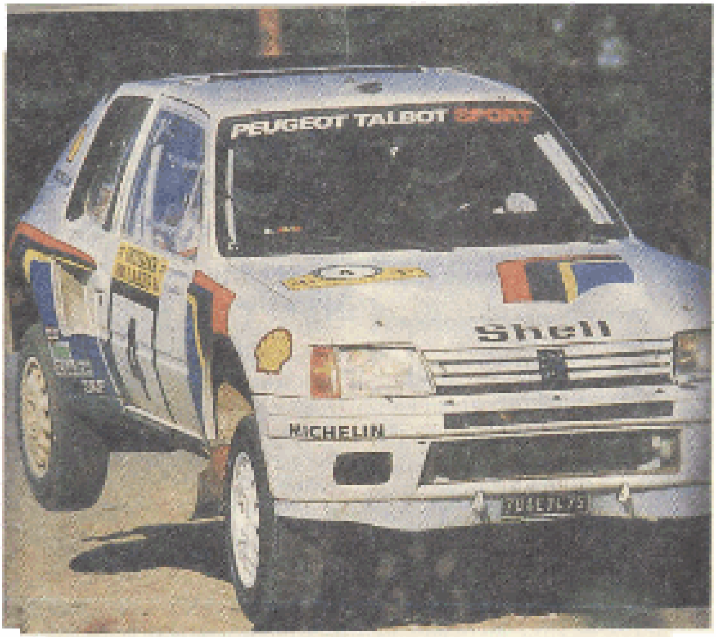

Fig. 15 Peugeot car (model 205) fabricated from aramid and carbon fibre-epoxy composite

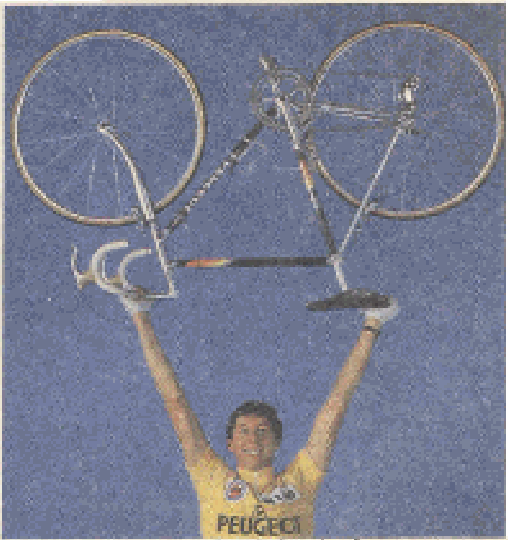

Fig. 16 Bicycle frame made of glass/carbon-epoxy composite

The National Engineering Laboratory, Scotland has developed FRP suspension arm for motor cars in 1989. It is better than the conventionally made arm in respect of noise level, suspension, alignment and toughness (Fig.17).

MARINE INDUSTRY

Composite materials have been used in a wide variety of structural and non-sturctural marine applications almost from the time of their introduction as commercial materials and their use for such applications is constantly growing. The material, generally, for this purpose is glass fibre-polyester/epoxy composites (GRP). The following applications illustrate the versatility and wide applicability otf GRPs as marine structural and non-structural materials.

Boat Construction

The most important application of GRPs is for the construction of both civilian and military boats (Fig.18). The dome fabrication on submarines (Fig.19) from composite materials is said to be advantageous in many respects. The construction of floats and buoys is also being done from GRP (Fig.20). Phenolic composites are widely used for fishing boats.

Outer Hull Structures and Protective Coatings

GRP outer hull structures are installed on deep diving vehicles in foreign countries. Composite materials also find applications as coatings to protect

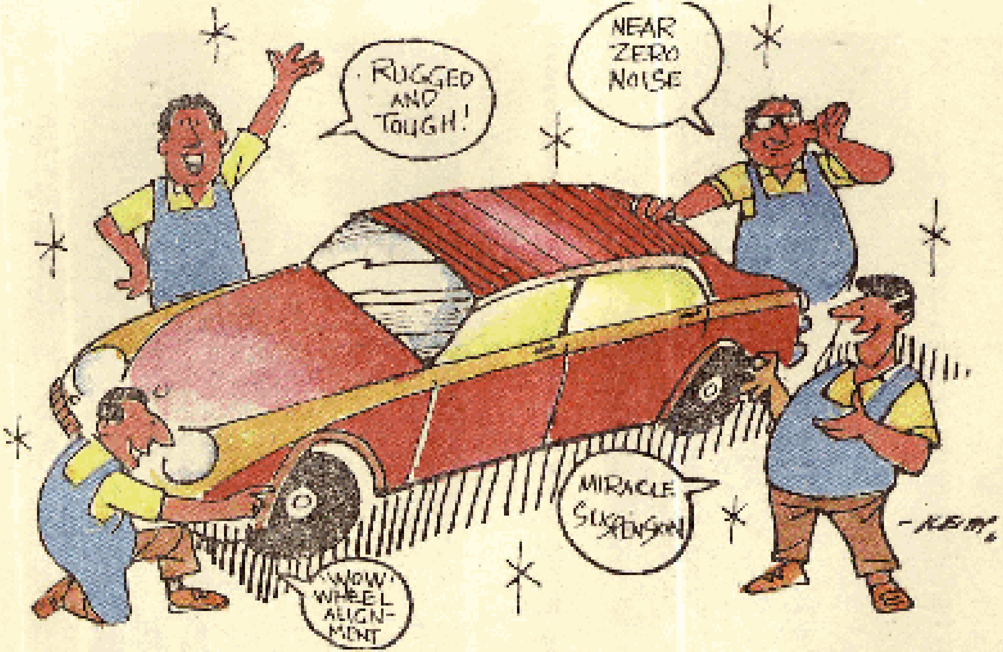

Fig. 17 FRP suspension arm for cars

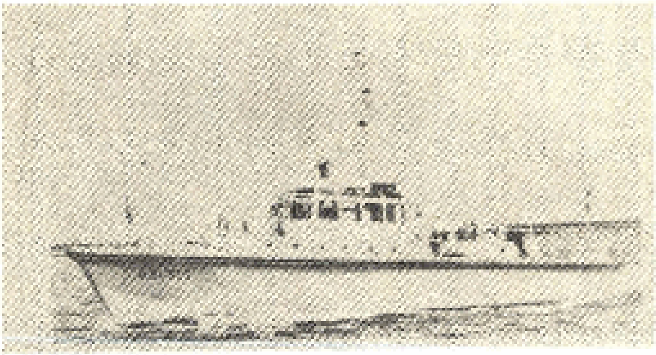

Fig. 18 Pilot boat of Netherlands made of composite material

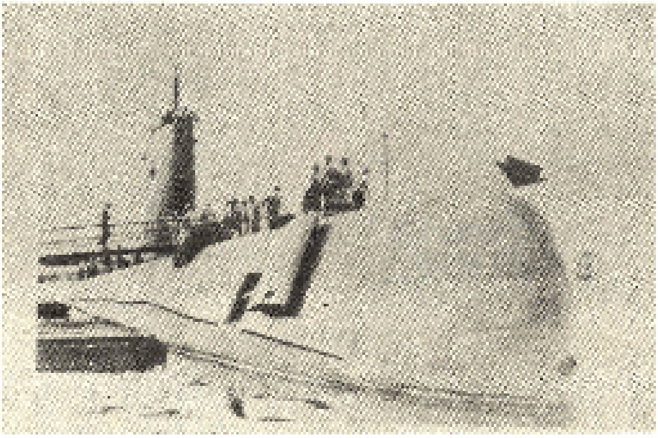

Fig. 19 Composite material sonar dome on submarine

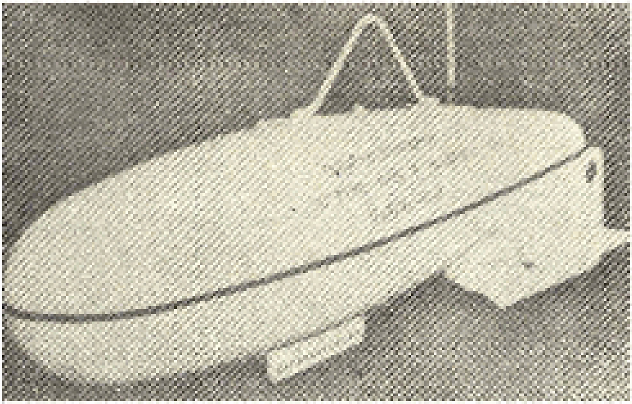

Fig. 20 Mine sweep float

substrate material from degradation.

Fairings

GRP fairings are used in naval craft to fair the water flow around discontinuities, to minimise turbulance and provide good hydrodynamic shape for optimum performance.

Shipboard Structures

Shipboard structures such as tanks for storage of both fuel and water are extensively used in shipboard applications. Deckhouses (Fig. 21) made of glass-polyester composites are also in use to withstand severe shock loading and perform well in comparison with an aluminium counterpart.

CHEMICAL ENGINEERING INDUSTRY

Composite materials are used as construction

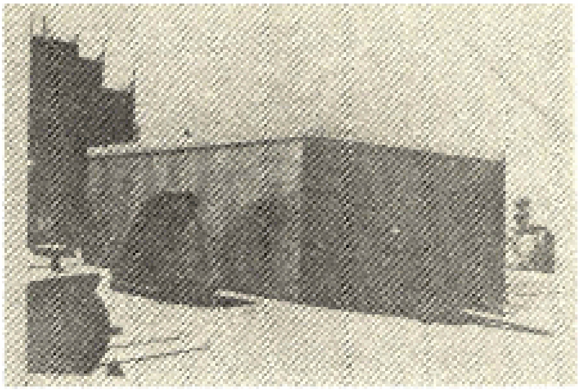

Fig. 21 Destroyer deckhouse

materials for tanks and vessels, pipes, tubes, ducts, chimney stacks and protective lining for them.

Tanks and Vessels

These are fabricated in two ways:

- Completely monolith tanks and vessels (small and moderate sizes)
- Separate sections bolted together to form tanks and vessels (large sizes)

Storage tanks with capacity of around 340 kilolitres, process vessels of 2/3 m diameter working under full vacuum or internal pressures, pipelines of lengths measuring in kilometers and working under extremely arduous chemical, pressure and external loadings (soil or tial), underground storage tanks, concrete tanks, pressure and gravity discharge vessels, mixer impellers, fans, pump bodies, filter plates and condenser water box made of composite materials are in service in the UK. India has also made a beginning for such applications on a small scale. Figures 22-24 depict these applications.

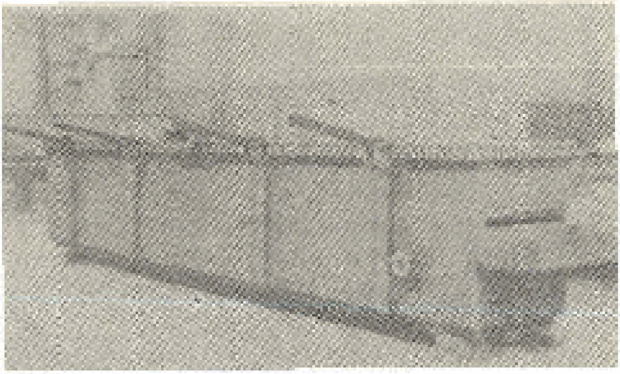

Fig. 22 Decanting tank made of glass-polyester composite

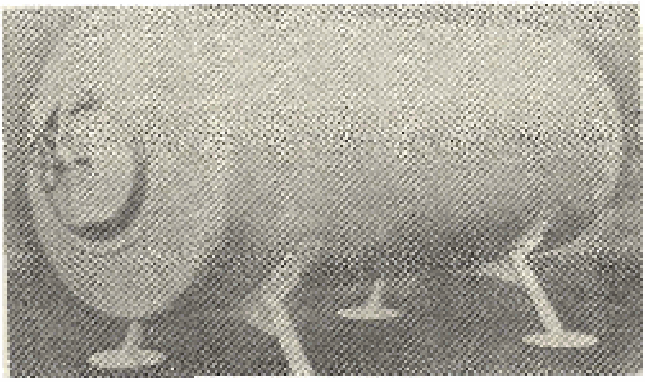

Fig. 23 Cylindrical tank made of glass-polyester composite

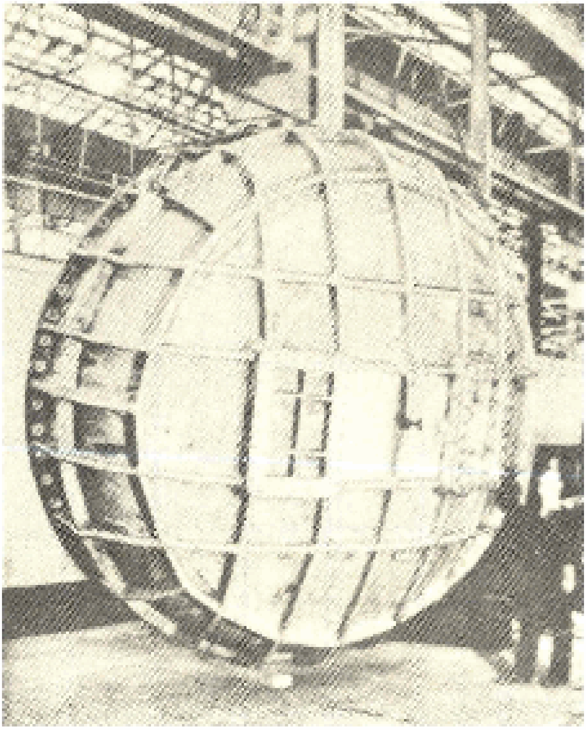

Fig. 24 Condenser water box for power station plant

Chimney stacks over 900 m high; pipes for acid effluent systems (Fig.25), ducts (Fig.26), chlorination plants, dyestuff plants and in the oil industry, for cooling waterlines and oil cooler bodies are being made of glass fabric-epoxy/polyester composites because of their high mechanical strength coupled with lightness, high resistance to a wide variety of chemicals and ease of fabrication.

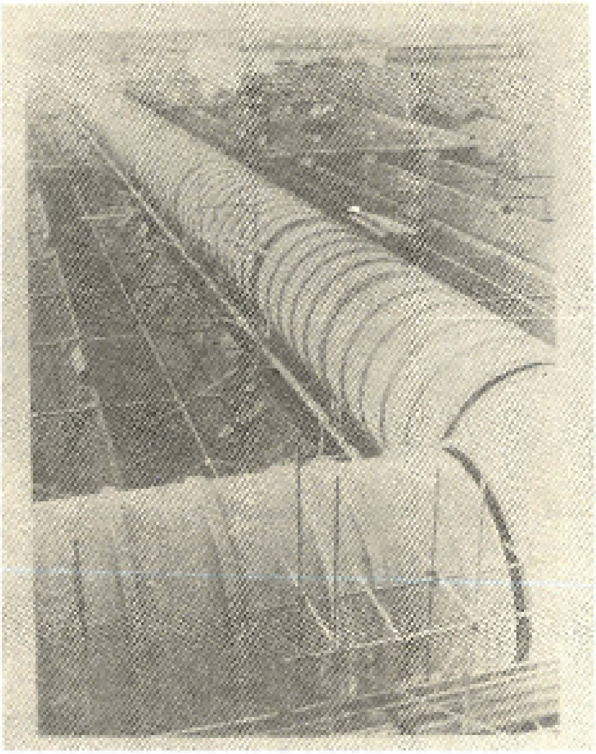

Fig. 25 4.1 m × 250 m long polypropylene lined glass-resin composite fume extraction system

Polyfluorochloroethylene-glass fibre composites are used as lining of tanks and vessels, protective surfacing to laboratory bench tops, chemical plant floors, conveyor belting, moulds, etc.

These composites use polyesters (isophthalics, bisphenols and modified version of these resins) and glass reinforcement in the form of rovings, chopped strand, woven rovings and fabrics. Sometimes,

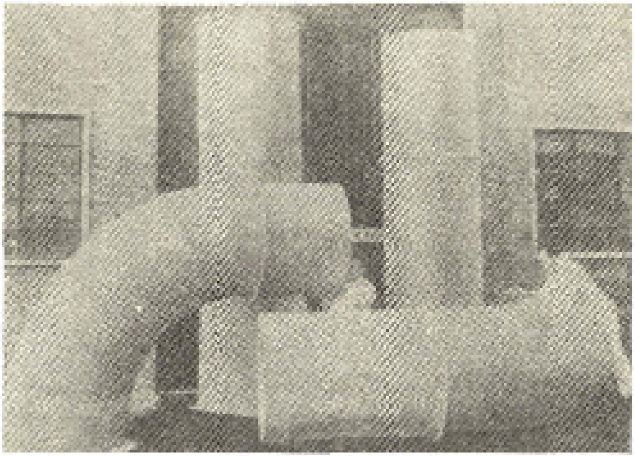

Fig. 26 Large diameter duct made from glass-polyester composite

thermoplastic (especially PVC and polypropylene) liners are frequently used in conjuction with glass/resin for strength purposes.

MECHANICAL ENGINEERING INDUSTRY

There has been a great upsurge in the development of particle reinforcement composites (particulate composites) which have wide range of properties and applications depending on the nature of the reinforcing particles. The manufacture of particulate composites is generally being done by Liquid Metallurgy Technique (LMT) where second phase particles are introduced into the molten first phase followed by castings of particulate composites.

The aluminium-graphite/coconut shell char/mica composites find extensive use as engine pistons, piston liners, bearings, babbit bearings, sliding contacts, seals, etc. because their use reduces friction. The use of aluminium-ceramic composites not only imparts anti-friction properties but also improves wear resistance. Therefore, these composites find applications where anti-friction properties coupled with wear resistance is the requirement. Aluminium-zirconium/alumina composites are used for applications where abrasion resistance is of prime importance such as in shafts. Aluminium-glass composites, on the other hand, are of great potential for structural applications in the form of rods, channels and angles. The bearings made of phosphor bronze in the roll necks of steel and non-ferrous mills are being fabricated from a cheaper material, i.e., cotton-phenolic composites. India is considered as one of the pioneers in the field of particulate composites using LMT and these composites, as a result, have a bright future in India.

CIVIL AND BUILDING INDUSTRY

Polymer impregnated concretes (asbestos reinforced composites) find extensive applications in USA, USSR, Japan and European countries for sewer pipes, tunnel lining, mine supports, manholes, coarse building panels, boards, pavement patching, strengthening of bridge and also in offshore structures. Polymer concretes have been used in India for strengthening of various dams like Koyna and Bhandardara in Maharashtra, Idukki and Cheruthani in Kerala, Bhadra in Karnataka and Hirakud in Orissa.

The jute/sisal/hybrid jute and glass-polyester/epoxy/phenolic composites are used for low cost house/civil structures (Fig.27). These compositres are of special significance for countries like India where natural fibres are available in abundance. On the other hand, GRP load-bearing panels are used for this purpose in European countries as well as in American countries (Fig.28). Sometimes GRP cladded panels are also used for house/building construction. (Fig. 29,30).

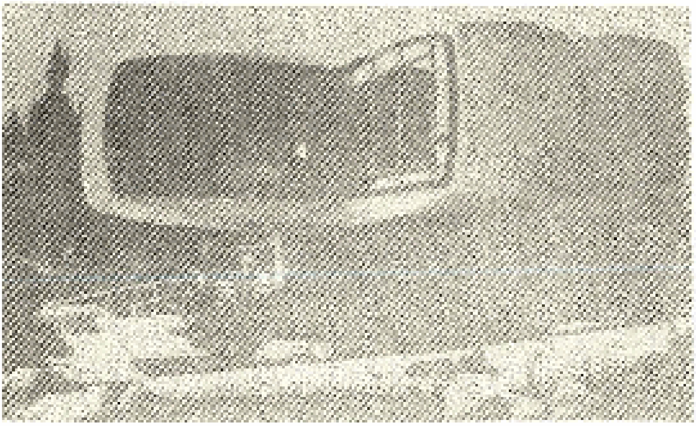

Fig. 27 The house of tomorrow made of glass reinforced polyester resin

GRPs are also used for the fabrication of roof light sheets (Fig.31), corrugated sheets and sectional buildings. Roof light sheets are used for roof and vertical lighting of factories, warehouses, railway stations and swimming pools. Translucent GRPs are most suitable for 6 domelights on industrial, commercial 6 and public buildings. Ordinary corrugated sheets are used for partitions in industrial and commercial buildings while decorative ones are used for hotels and places of entertainment. The

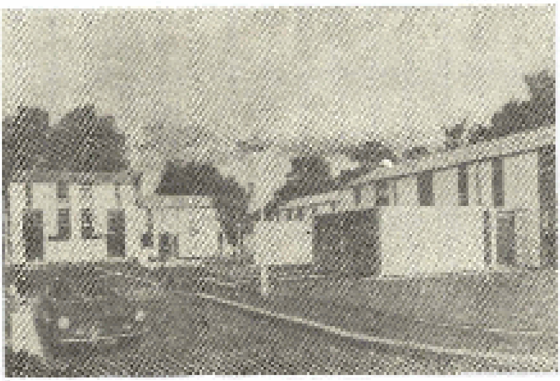

Fig. 28 Three-storeyed dwellings constructed from GRP load-bearing panels

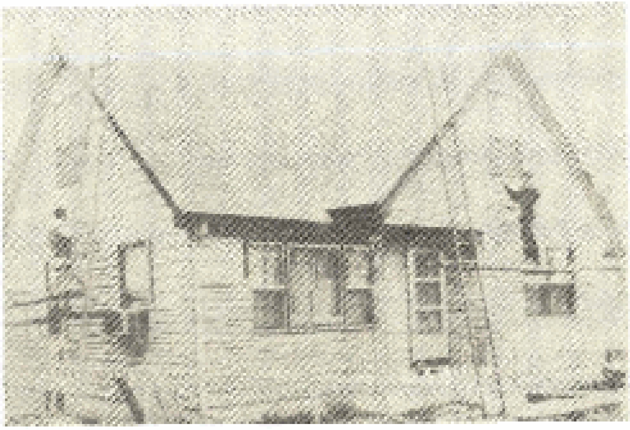

Fig. 29 Cladding external walls with terox imitation stone facing made from glass-polyester panels

sectional buildings are particularly suitable on sites where access is limited or where the ground cannot support traditional structures without excessive

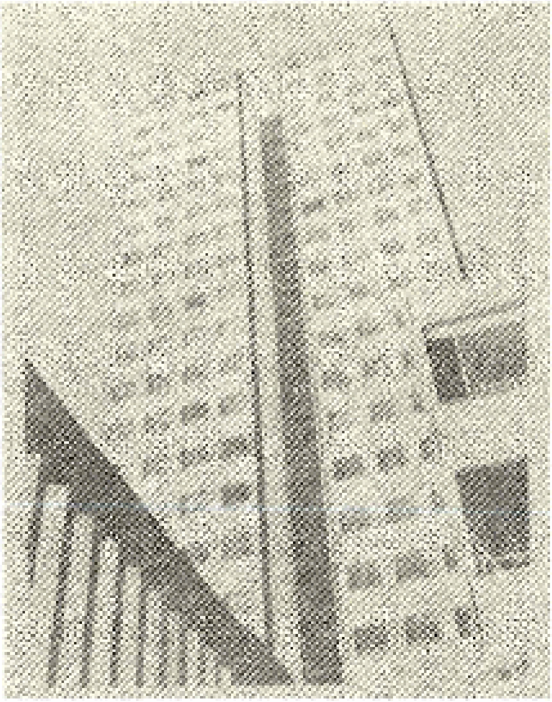

Fig. 30 22-storey GLC dwellings clad with GRP skinned panels

costly foundations. Light railway trackside relay rooms, living accommodation, laboratories at Antarctic bases, light-house towers, desert accommodation, weekend chalets, bathroom units, tanks and cisterns, window frames, etc. are some examples. Other uses of GRPs include construction of road links, lamp columns, garage doors, transmission poles, porch roofs and canopies.

The shelters on oil-drilling sites use GRP filled with

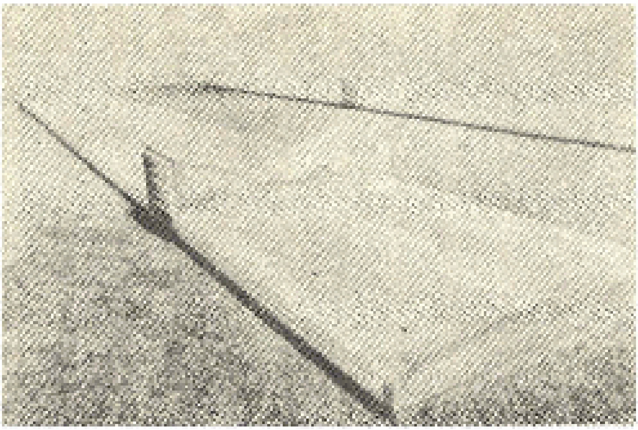

Fig. 31 GRP roof lights

expanded PVC for various components such as doors and door frames.

ELECTRICAL, ELECTRONICS AND TELECOMMUNICATION INDUSTRY

The principal application of glass fibre-epoxy/polyester composites/laminates in this industry is for printed circuit boards (PCBs), electrical insulation boards, connectors and cable insulators. Asbestos fibre-epoxy/polyester composites are also used for electrical motor cases, housing for auto-heaters and air conditioners, lamp sockets, switchboards, underground conduits and valves. The composites of latest origin, Kevlar/carbon fibre-epoxy composites, find extensive applications in fabrication of structural components for aerospace and electronic applications. Fibre glass-polyester/epoxy composites are the preferred materials (over wood and aluminium) for construction of masts (Fig.32) and spars

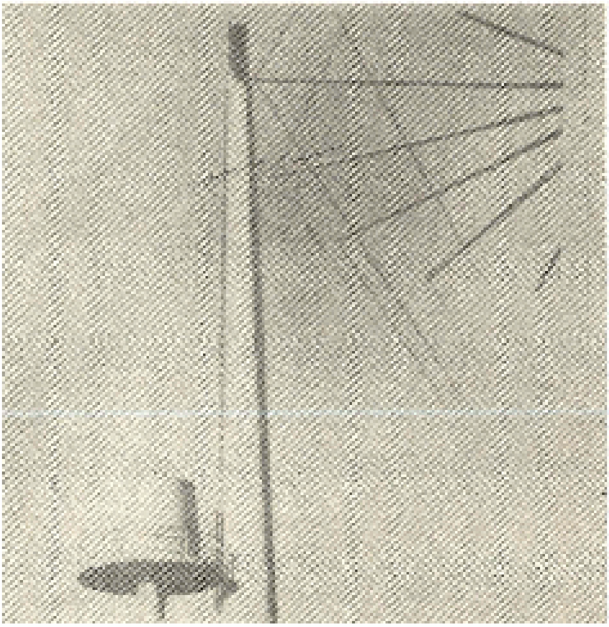

Fig. 38 FRP mast for ship communication

because of light weight, durability and superior performance.

MISCELLANEOUS INDUSTRIES

We have so far discussed the applications of composite materials in various industries. In addition, there are several applications which could not be included under above mentioned industries. They are listed here.

The scenario as regards to the use of composite materials in America and European countries has undergone tremendous change in recent years. Many designers are turning to these materials as a means of producing furniture which is considered better than the ones made from conventional or traditional materials. Chairs (Fig.33) and seats for home, school, bus and railway are invariably manufactured from composite materials. In India also, Indian Airlines has made a beginning in this direction and one can find chairs made of GRP at most of the airports. The corrosion resistance of GRP is attracting attention of domestic appliance manufacturers. Articles such as washing machines, plumbing fixtures (bath tubes, wash basins and sinks), etc. are regularly manufactured using GRP composite materials. These materials are also used for making structural parts for TV sets, radios and portable record players (glass reinforced polystyrene).

Another area of interest is surgery. Development of composites is considered a boon in medical sciences and has given to mankind a new direction in the treatment of joint diseases. Biocompatible composites (*water emulsifiable epoxy reinforced with carbon* fibre) are considered better materials for orthopaedic surgery and are used as bone substitutes. Implants and prostheses are readily available, not only for hip joints but also for knee, shoulder and other joints. The advantages of using these materials for this purpose are their better fatigue life than stainless steel and reduction in the rigidity of bone- plate system. Artificial limbs are produced in USA and surgical splints are currently in use in UK. Further, moulded cosntainers made of glass-nylon composite are available for a tissue processor used in cancer

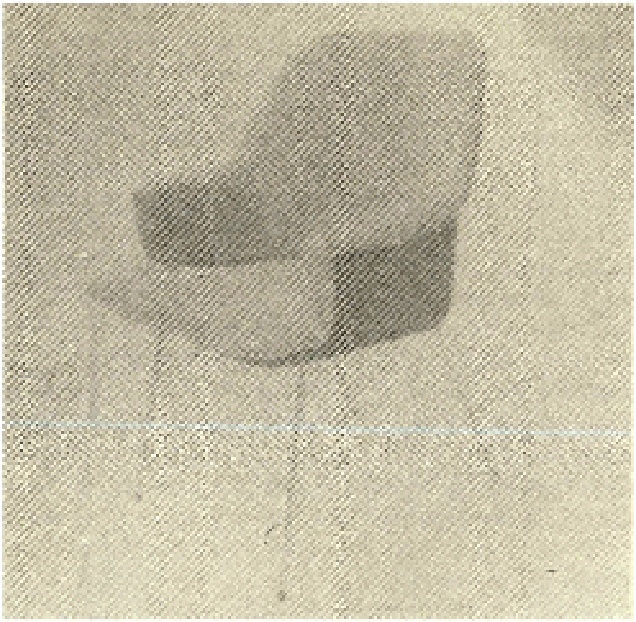

Fig. 33 Upholstered chair with *glass-polyester* shell

diognosis. Similar to the applications of composite materials (glass-polyester composites) for domestic furnitures, beds made of metal frames and GRP base find extensive use in hospitals in foreign countries.

Composite materials also find applications in a big way in sports goods where their superior properties compensate for any additional cost. Fishing rods are being made from glass- phenolic/ polyester composite tubing which are claimed to maintain their srtaightness for a long time. Tennis racket frames (Fig.34), golf-club shafts, modern skis, racing yachts, etc. are being fabricated from advanced composite

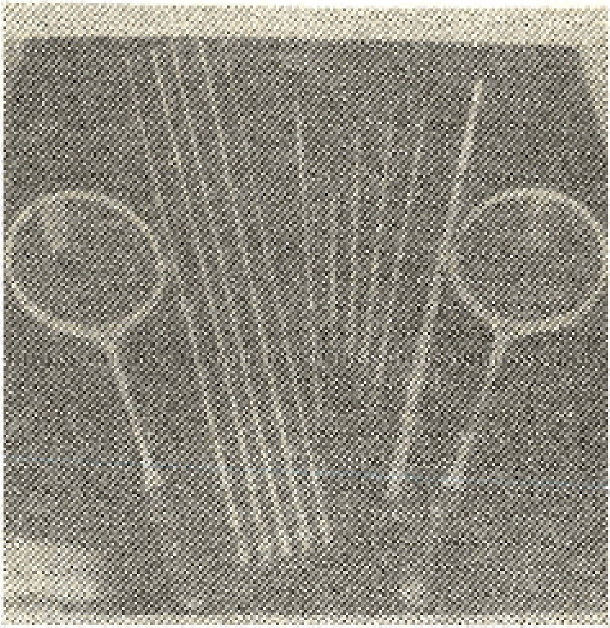

Fig. 34 Tennis racket frames and car aerials made from ACM

materials. India, being an agricultural country has tremendous potential for application of composite materials in horticulture. GRP tanks are used on tractors for spraying insecticide on crops and fruit trees in advanced countries.

Jute-epoxy/polyester/phenolic composites are being used for fabrication of silos for grain storage, household utility goods. Glass/sisal-epoxy/polyester composites are used for helmets (Fig.35), post-box (Fig.36) and consumer goods—wall hangings, table mats, handbags, purses, etc. Because of their better insulating properties, asbestos-epoxy/polyester

Fig. 35 Helmet made from glass-sisal-polyester/epoxy composite

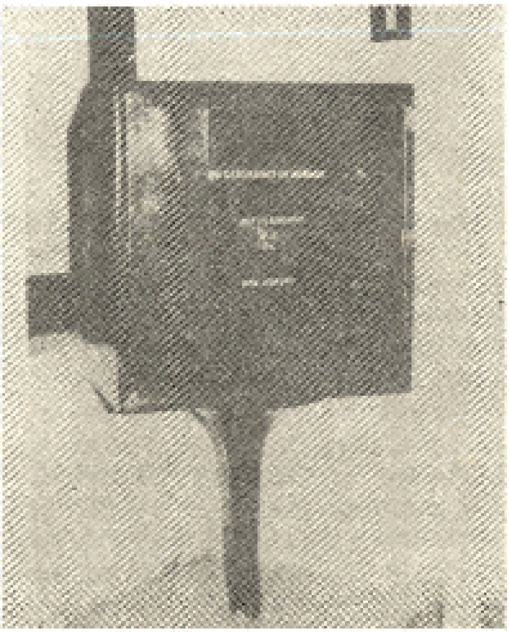

Fig. 36 Postbox made from glass sisal-polyester/epoxy composite

composites are extensively used for cooking utensil handles. GRPs also find applications as machine guards.

The production of mannequins (Fig.37) from glass fibre-polyester/synthetic rubber composites is a boon to the fashion garments business all over the world. The business, which currently accounts for a $ 2 billion turnover in Europe alone is gradually making its presence felt in India also. Indian shops are now discovering the latest trends in mannequins as an effective means to show off the high-fashion garments flooding the stores. These mannequins are slowly edging out heavy clay ones. They are washable, can be dismantled easily, and are very light as compared to their clay counterparts.

DEFENCE INDUSTRY

The application of composite materials described under various industries earlier are equally useful in Defence as well. In addition, there are some specific applications which exist exclusively in Defence.

In modern warfare, the combat soldiers, their support equipment, vehicles and other military hardwares require personnel and ballistic armour systems for protection against a variety of enemy threats—bullets, projectiles, fragments, rockets and missiles.

It implies that the lightest personnel and ballistic armours providing maxium protection against ballistic threats are of strategic importance. The lightness of composite materials coupled with their

Fig. 37 Mannequins made of glass-polyester composite

high strength is considered the main criteria for their application for this purpose. Glass/nylon 66 fibres/other woven fabrics-epoxy composites are used for making flexible armours particularly body armours. With the advent of ultra-high modulus and high tenacity yarns/fibres such as aramids (Kevlar 29), their composites offer better ballistic protection. Compared with glass fibre-polyester composites, Kevlar-polyester armours generally have 15-45 per cent higher ballistic resistance at 15-25 per cent lower weight against a typical small arms ammunition. Hybrid composites, i.e., containing more than one type of fibre in a composite, hybrid Kevlar and graphite (improved compressive strength) and hybrid Kevlar and glass (improved stiffness) are also used for some ballistic protection.

Besides personnel protection, ballistic resistant armours are also widely used for protection of aircraft, armoured vehicles, etc. prone to attack by high velocity armour piercing projectiles where a very high degree of ballistic protection is essential. For such applications, armours made of extremely hard ceramics as outer facings backed with high-strength metal alloys and composite materials are used. GILLFAB 1160 (woven Kevlar rovings-vinyl ester composites), a high performance and light weight composite is used for ballistic armours for protection in military equipment and navy vessels.

Defence Metallurgical Research Laboratory, Hyderabad has developed Kanchan armour which provides more ballistic protection to Vijayanta tank and MBT Arjun against diverse threats. The ballistic protection provided by Kanchan armour is better than any standard monolithic aluminium alloy armour in current use.

Explosives Research & Development Laboratory, Pune has recently developed Filament Winding Technique and Inhibitor Sleeve Technology for inhibition of composite propellants which are being used for various rockets/missiles (PINAKA rocket, PECHORA and TRISHUL missile, etc.) under development in DRDO. These techniques are based on the concept of FRP fabrication which possess high strength-to-weight ratio. The use of these techniques reduces the dead weight of inhibitor resulting in increase in weight of propellant leading to increase in range or payload of rocket/missile and is considered of strategic importance from military point of view.

7

Prospects and Relevance of Composite Materials to India

Composite materials industry took off in India around 1970 when M/s Fibreglass Pilkington Limited set up their glass factory in Bombay. We have now some more companies making fibre glass. GRP was introduced in India after the setting up of a glass factory in Bombay, but today there exists a sound industrial infrastructure within the country. FRP manufacturing technology is poised for a rapid growth. We have the capacity of manufacturing 20,000-25,000 tonnes of FRP per annum in India today but the real production is less than 10,000 tonnes per annum. However, it is expected that the growth of FRP industry will enhance maniforld in the years to come with the popularization of their applications in various walks of life.

Composite materials are being increasingly used for structural, non-structural and engineering materials in industrial applications all over the world including India. The way their use is becoming popular in India and elsewhere shows that composite materials have become an integral and essential class of materials for modern technological developments. The glass fibre-epoxy based composite material was used for fabrication of third and fourth stage motors of SLV and in Indian Intermediate Range Ballistic Missile (IRBM) Agni. However, popularization of these materials is linked with their cost in a developing country like India and if we are able to bring down their cost, their use for various applications will be tremendously enhanced.

The Department of Science and Technology and Council of Scientific and Industrial Research have already recognized the great importance and potential of these materials and are giving due importance to the development of FRP technology in all its facets in India. The setting up of the FRP Centre at the Indian Institute of Technology, Madras reveals the sincerity and concern of the technology in this country. The Govt. of India has also recently started Advanced Composites Centre at DRDL, Hyderabad for catering to the needs of various composites in fabrication of missiles under development in DRDO. GRP and its technology have already been recognized as an important area listed under the National Science & Technology Plan. Further work on development of glass fibre and carbon fibre, which is strategic for advanced composites, is in progress in different laboratories scattered all over India. In order to make FRP cost-effective, work on various aspects pertaining to the use of indigenous fibres like jute, sisal, coir, etc. which are abundantly available in India as reinforcement, is being done at Regional Research Laboratory, Bhopal, Regional Research Laboratory, Trivandrum and Indian Institute of Technology, Kharagpur. Similarly, development work on resin from indigenously available non-edible oils (neem oil, etc.) is also in progress in an attempt to bring down their cost.

To finish on an optimistic note, let us hope that the steps taken by all concerned, i.e., Government of India, industries, research laboratories and users in this direction would open a new era for enhanced usage of composite materials as a substitute.

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Glossary

Ablative material	: A material which absorbs heat (while part of it is being consumed by heat) through a decomposition process (pyrolysis) which takes place near the surface exposed to the heat.
Accelerator	: A material which, when mixed with a catalyzed resin, will speedup the chemical reaction; either in polymerizing of resins or vulcanization of rubbers. Also known as *promoter*.
Bag moulding	: A technique in which the consolidation of the material in the mould is effected by the application of fluid pressure through a flexible membrane.
Binder	: The resin or cementing constituent of a plastic compound which holds the other components together; the agent applied to glass mat or preforms to bond the fibres prior to laminating or moulding.
BMC	: Bulk moulding compound.
Buckling	: Crimping of the fibres in a composite material, often occuring in glass-reinforced thremosets due to resin shrinkage during cure.
Catalyst	: A substance which changes the rate of chemical reaction with-

out itself undergoing permanent change in its composition; a substance which markedly speeds up the cure of a compound when added in minor quantity as compared to the amounts of primary reactants. (See hardener, inhibitor, promoter and curing agent).

Centrifugal casting : A high production technique for cylindrical composites, such as pipe, in which chopped strand mat is positioned inside a hollow mandrel designed to be heated and rotated as resin is added and cured.

Contact moulding : A process for moulding reinforced plastics in which reinforcement and resin are placed on a mould, cure is either at room temperature using a catalyst-promoter system or by heat in an oven and no additional pressure is used.

Curing agent : A catalytic or reactive agent which when added to a resin causes polymerization; synonymous with hardener.

Curing time : The period of time during which a part is subjected to heat or pressure, or both, to cure the resin; interval of time between the instant of cessation of relative movement between the moving parts of a mould and the instant that pressure is released. (Further cure may take place after removal of the assembly from the conditions of heat/pressure).

Cure : To change the properties of a resin by chemical reaction, which may be condensation or addition; usually accomplished by the action of either heat or catalyst, or both, and with or without pressure.

DMC : Dough moulding compound.

Elasticity : That property of plastic materials by virtue of which they tend to recover their original size and shape after deformation.

Exotherm : The liberation or evolution of heat during the curing of a plastic product.

Fatigue : The failure or decay of mechanical properties after repeated applications of stress. (Fatigue tests give information on the ability of a material to resist the development of cracks which eventually bring about failure as a result of a large number of cycles).

Fibre : Relatively short length of very small cross-section of various materials. Can be made by chopping filaments. Also *filament, thread, bristle.*

Filament	: Individual glass fibre of indefinite length, usually as pulled from a stream of molten glass flowing through a thin hole. In the operation, a number are gathered together to make a strand or end of roving or yarn.
Filament winding	: A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape or other) either previously impregnated with a matrix material or impregnated during the winding are placed over a rotating and removable form or mandrel in a previously prescribed way to meet certain stress conditions. Generally the shape is a surface of revolution and may or may not include end closure. When the right number of layers are applied the wound form is cured and the mandrel removed.
Flame retardants	: Certain chemicals which are used to reduce or eliminate a resins's tendency to burn. (For polyethylene and similar resins, chemicals such as antimony trioxide and chlorinated paraffins are useful).
Flammability	: Measure of the extent to which a material will support combustion.

FRP : Fibrous (glass) reinforced plastic; a general term covering any type of plastic reinforced cloths, mat, strands, or any other form of fibrous martial.

Gelation time : That interval of time, in connection with the use of synthetic thermosetting resins, extending from the introduction of a catalyst into a liquid adhesive system until the interval of gel formation.

Gel coat : A resin applied to the surface of a mould and gelled prior to lay-up. (The gel coat becomes an integral part of the finished laminate, and is usually used to improve surface appearance, etc.).

Hand layup : The process of placing (and working) successive plies of reinforcing material or resin-impregnated reinforcement in position on a mould by hand.

Hardener : A substance or mixture added to plastic composition to promote or control the curing action by taking part in it. Also, a substance added to control the degree of hardness of the cured film (See catalyst)

Impact strength : The ability of a material to withstand shock loading; the work done in fracturing a test specimen in a specified manner under shock loading.

Inhibitor	: A substance which retards a chemical reaction; used in certain types of monomers and resins to prolong storage life.
Insulator	: A material of such low electrical conductivity that the flow of current through it can usually be neglected. Similarly, a material of low thermal conductivity.
Interlaminar shear strength	: The maximum shear stress existing between layers of a laminated material.
Mandrel	: The core around which paper-, fabric-, or resin- impregnated glass is wound to form pipes, tubes, or vessels; in extrusion, the central finger of a pipe or tubing die.
Monomer	: A simple molecule which is capable of reacting with like or unlike molecules to form a polymer; the smallest repeating structure of a polymer for addition polymers, this represents the original unpolymerized compound
Moulding	: The shaping of a plastic composition within or on a mould, normally accomplished under heat and pressure; sometimes used to denote the finished part.
Polar Winding	: A winding in which the filament path passes tangent to the polar

opening at one end of the chamber and tangent to the opposite side of the polar opening at the other end. A one circuit pattern is inherent in the system.

Polymer : A high-molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the *mer*; for example, polyethylene, rubber, cellulose. Some polymers are elastomers, some are plastics. When two or more monomers are involved, the product in called a copolymer.

Polymerization : A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called *copolymerization*, or *hetero-polymerization*. (See condensation polymerization).

Preform : A preshaped fibrous reinforcement formed by distribution of chopped fibres by air, water floatation, or vacuum over a surface of a perforated screen to the approximate contour and thickness desired in the finished part. Also, a preshaped fibrous reinforcement of mat or cloth formed to desired shape on a mandrel or mock-up prior to being placed in a mould press. Also, a compact *pill* formed by compressing premixed material to facilitate handling and control of uniformity of charges for mould loading.

Prepreg : Ready-to-mould material in sheet form which may be cloth, mat, or paper impregnated with resin and stored for use. The resin is partially cured to a 'B' stage and supplied to the fabricator who lays up the finished shape and completes the cure with heat and pressure.

Pressure bag moulding : A process for moulding reinforced plastics, in which a tailored flexible bag is placed over the contact layup on the mould, sealed and clamped in place. Fluid pressure, usually compressed air is placed against the bag and the part is cured.

Pultrusion : Reversed 'extrusion' of resin impregnated roving in the manufacture of rods, tubes and structural shapes of a permanent cross-section. The roving, after passing through the resin dip tank, is drawn through a die to form the desired cross-section.

Reinforcement	: A strong inert material bounded into a plastic to improve its strength, stiffness, and impact resistance. Reinforcements are usually long fibres of glass, asbestos, sisal, cotton, etc. in woven or nonwoven form. To be effective, the reinforcing material must form a strong adhesive bond with the resin. *Reinforcement* should not be used synonymously with filler.
Roving (filament winding)	: The term roving used to designate a collection of bundles of continuous filaments either as untwisted strands or as twisted yarns. Rovings may be lightly twisted, but for filament winding they are generally wound as bands or tapes with as little twist as possible. Glass rovings are predominantly used in filament winding.
Self-extinguishing resin	: A resin formulation which will burn in the presence of a flame but will extinguish itself within a specified time after the flame is removed.
Shear	: An action or stress resulting from applied forces which causes or tends to cause two continuous parts or a body to slide relative to each other in a direction parallel to their plane of contact.

SMC : Sheet-moulding compound.

Transfer moulding : Method of moulding thermosetting materials, in which the plastic is first softened by heating and pressure in a transfer chamber, and then forced by high pressure through suitable sprues, runners and gates into the closed mould for final curing.

Vacuum bag moulding : A process for moulding reinforced plastics in which a sheet of flexible transparent material is placed over the lay-up on the mould and sealed. A vacuum is applied between the sheet and the lay-up. The entrapped air is mechanically worked out of the lay-up and removed by the vacuum, and the part is cured. Also *bag moulding.*

The Book

Composite materials, being lighter in weight and generally resistant to heat and corrosion, are fast replacing the conventional materials in many fields of application. With the advent of carbon, graphite and boron fibres, advanced composite materials have proved to be specially useful in sophisticated *items like missiles and spacecraft.*

This book describes the various aspects of composite materials in a lucid, elegant and comprehensible manner, ably supported by tables, charts and photographs. The book covers the historical landmarks in the growth of composite materials, their constituents, production technology, advanced composite materials (ACMs), applications in various industries and relevance of composite materials *to India and their prospects.* There is also a glossary of technical terms used in the book.

The Author

Dr J P Agrawal, Deputy Director, Explosive Research & *Development Laboratory, Pune, has a Ph.D.* in explosives. *He* is actively involved in the Integrated Guided Missiles Development Programme (IGMDP) of Govt. of India and was given 'Cash Award' for his significant contribution. He is the Joint Secretary of the Indian Society of Composite Materials. Besides, he is associated with other research institutes in different capacities.

Dr. Agrawal has published more than 50 research papers, reports, and popular articles in various national and international journals. He also has patents to his credit.