The Behavior of Structures Composed of Composite Materials

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For a list of related mechanics titles, see final pages.

The Behavior of Structures Composed of Composite Materials

Second Edition

by

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To my beautiful wife, Midge, for providing the wonderful environment, love, patience and encouragement to complete this text - JRV

In loving memory of Nina, and also to my wonderful children, Sandy and Steve - RLS

Preface to the Corrected Second Edition

Since the introduction of the second printing, a number of exciting advances has taken place within the materials community. Historically, we have accepted the inherent properties of materials as given for any specified material; that is, metals, polymers, ceramics and so on. Introduction of composite materials technology has allowed researchers to consider multi-constituent systems resulting in properties that can be superior to each of the constituents independently. Now we are on the cusp of a new era in materials technology which can be coined as the engineered materials revolution. That is, we are now developing the capacity to tailor a material to perform a specific or representative set of functions from the basic atomic level. This technical development allows for the potential design of microsystems with nano-components. The advent of this technology offers a number of creative future applications in advancing miniaturized systems including structural nano-electronic devices, circuits, and computers as but a few examples. These advances are based upon the extraordinary properties of carbon nanotubes including a Young's modulus approaching that of diamond. These properties are ideal for reinforced composites, and this third edition provides the student or researcher with the necessary tools to advance the state of the art in structural design of new and potentially exciting multifunctional, self-repairing, self-duplicating, nano-structural materials.

Preface to the Second Edition

The purpose of this text is to educate the engineering reader in the various aspects of mechanics for using composite materials in the design and analysis of composite structures and products.

In Chapter 1, the text acquaints the reader with the description of a composite material, and its constituents. Then, methods by which to manufacture composite materials are discussed, followed by a description of the uses of composite materials early in the twenty-first century.

Chapter 2 provides the fundamentals of anisotropic elasticity, and the methods to characterize and mathematically describe composite laminae and laminates which are the "building blocks" of composite structures. Also discussed are thermal, hygrothermal, high strain rate and piezoelectric considerations in modern composites.

Chapter 3 then deals exclusively with the static and dynamic response of composite plates and panels subjected to a variety of mechanical and environmental loads in great detail. This includes stresses, deformations, buckling loads, natural frequencies and response to blast loads. Chapter 4 analogously treats a special case of the above, namely beams, columns and rods.

In Chapter 5, cylindrical composite shells are discussed, both in determining the stresses and deformations due to static loads, but in treating the buckling of these shells under various loads and their combinations. The peculiar behavior of shells, (such as the bending boundary layer) compared to plates and beams is discussed in detail.

Because so many practical structural problems are too difficult or complex to obtain analytical solutions, Chapter 6 provides in-depth knowledge of attacking real life structural design problems using energy principles and variational methods. Thus, the engineer can always obtain a solution to a problem.

Chapter 7 provides various strength and failure theories widely used today, and their comparison. Chapter 8 provides suggested ways to analyze and design adhesive bonded joints and mechanically fastened joints.

Chapter 9 has been added to provide a needed introduction to composite design philosophy.

Appendix 1 provides a discussion of micromechanics basics; Appendix 2 lists all or most of the test standards for polymer matrix composite and Appendix 3 lists the mechanical properties of many composite in use today.

At the end of each chapter are numerous problems, which can be useful as homework problems or modified for examination problems. Professors may contact the authors for solutions to these problems.

Appreciation is hereby expressed to James T. Arters, an engineering student at the University of Delaware, who meticulously typed the text through its evolution. His accuracy, stamina and diligence are greatly appreciated. Appreciation is also expressed to Dr. Gregg Schoeppner for his contributions to Chapter 1 and the Appendices, and to Ms. Jill O'Donnell for her manuscript reading.

Jack R. Vinson
Robert L. Sierakowski

Preface to the First Edition

While currently available tests dealing with the subject of high performance composite materials touch upon a spectra of topics such as mechanical metallurgy, physical metallurgy, micromechanics and macromechanics of such systems, it is the specific purpose of this text to examine elements of the mechanics of structural components composed of composite materials. This text is intended for use in training engineers in this new technology and rational thought processes necessary to develop a better understanding of the behavior of such material systems for use as structural components. The concepts are further exploited in terms of the structural format and development to which the book is dedicated. To this end the development progresses systematically by first introducing the notion and concepts of what these new material classes are, the fabrication processes involved and their unique features relative to conventional monolithic materials. Such introductory remarks, while far too short in texts of this type, appear necessary as a precursor for engineers to develop a better understanding for design purposes of both the threshold limits to which the properties of such systems can be pushed a swell as the practical limitations on their manufacture.

Following these introductory remarks, an in-depth discussion of the important differences between composites and conventional monolithic material types is discussed in terms of developing the concepts associated with directional material properties. That is, the ideas of anisotropic elasticity for initially homogeneous bodies in the phenomenological sense are described and presented. The use of such analytical tools is then presented through exemplification of selected problems for a number of classical type problems of various geometric shapes including plane stress, plane strain and the bending of a simply supported beam.

These ideas are carried forward and developed for continuous fiber composites in Chapter Two which discusses both single ply laminae and multi-ply laminate theory. This is then followed by a series of chapters, each of which deals with functional aspect of structural design in which the basic building blocks of a structural system are made. That is, plates and panels; beams, columns and rods; and cylindrical and spherical shells are each discussed within the framework of their potential use in a functional environment. Thus the traditional topics of conventional monolithic (isotropic) material structural elements such as structures subjected to static loads, thermal and other environmental loads, structural instability and vibratory response are included along with chapters on energy methods and failure theories of composite materials.

Energy methods have been included to present a tool for solving difficult problems of various types encountered in practice. Indeed, in many instances closed form solutions are not possible and approximate solutions must be sought. Energy methods thus provide both an alternative for the formulation of such problems plus a means of generating approximate solutions.

The chapter on failure theories is a generic presentation in the senses that any and/or all of the above structural components consisting of various multi-ply construction can fail when subjected to a sufficiently large loading combination. It is emphasized that the failure of composites is a complicated, changing issue because of the diverse ways in which such structural systems can fail due both to the geometric ply arrangement of the components, complicated load paths, and the diversity of failure mechanisms which can be activated. Therefore, this chapter should serve in a global sense at best as a guide to the prediction of structural integrity, while more common and acceptable phenomenological failure theories are being developed.

Finally, a chapter on joining is included to discuss to some detail the two methods by which composite material structural components can be joined: namely, adhesive bonding and mechanical fastening. Again, the material presented is an introduction to the subject which is rapidly changing and developing.

At the end of each chapter are several problems, characteristic of the material covered which can be used. Some answers are given in an appendix.

Knowing that nothing is perfect, the authors welcome any notification of errors and ambiguities, and if addresses are provided, authors will forward errata sheets periodically.

Appreciation is hereby expressed to many students at the University of Delaware, University of Florida, Ohio State University, The Ballistics Research Laboratory, and the Argentine Air Force who have helped directly or indirectly in refining, improving and correcting the text, as well as working various problems and examples. In addition appreciation is expressed to Dr. W.J. Renton, Vought Corporation, who has used portions of the text at the University of Texas-Arlington, and made suggestions and corrections.

Jack R. Vinson
Robert L. Sierakowski

Contents

CHAPTER 1

INTRODUCTION TO COMPOSITE MATERIALS

1.1 General History

The combining of materials to form a new material system with enhanced material properties is well documented in history. For example, the ancient Israelite workers during their tenure under the Pharaohs incorporated chopped straw in bricks as a means of enhancing their structural integrity (see Exodus 5). The Japanese Samurai warriors were known to use laminated metals in the forging of their swords to obtain desirable material properties. More recently, in the 20^{th} century civil engineers placed steel rebars in cement and aggregate to make a well-known composite material, i.e., reinforced concrete. One could say that the modern era of composite materials began with fiberglass polymer matrix composites about the time of World War II.

In order to introduce the reader to the subject matter of new high-performance composite materials it is necessary to begin by defining precisely what constitutes such a class of materials. Furthermore, one must also define the level or scale of material characterization to adequately describe such systems for discussion. This is done with the understanding that any definition and classification scheme introduced is somewhat arbitrary.

For introductory purposes, many workers in the field of composites use a somewhat loose description for defining a composite material as simply being the combination of two or more materials formed to obtain some useful new material or specific material property. In some cases the addition of the words microscopic and macroscopic are added to describe the level of material characterization.

The definition posed above is to a large extent broad-based, in that it encompasses any number of material systems for which different levels of characterization must be used to specify the system and for which different analytical tools may be necessary for modeling purposes. As a simplistic example of the definition used above we can consider a beam consisting of clad copper and titanium material elements used in a switching strip. Such a composite system can be considered at the macroscopic level as providing enhanced temperature-dependent material behavior due to the mismatch in coefficients of thermal expansion between the copper and titanium metallic elements. This material system, while consisting of two dissimilar materials and falling within the realm of satisfying the definition of a composite material would not be acceptable as being representative of modern definitions of composites for current applications in the aerospace, automotive and other technical areas. A representative list of journals dealing with composite materials is given in Section 1.9.

1.2 Composite Material Description

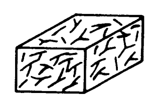
In order that agreement may be reached at the outset on a suitable modern day definition for advanced composite materials a structural classification according to the use of the following typical constituent elements is tabulated below.

STRUCTURAL LEVELS
(I) BASIC/ELEMENTAL Single molecules, crystal cells
(II) MICROSTRUCTURAL Crystals, Phases, Compounds
(III) MACROSTRUCTURAL Matrices, Particles, Fibers

Of the structural types cited above, Type (III), or the Macrostructural type is the most important for further discussion herein. Continuing with this, next consider a further classification within the structural framework adopted. A classification of combinations of materials is described and shown in Table 1.1.

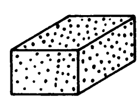
TABLE 1.1. Classification of Composite Materials

Fiber. Either continuous (long or chopped whiskers) suspended in a matrix material



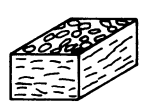
Fiber Composite

Particulate. Composed of particles suspended in a matrix material.



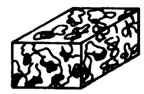
Particulate Composite

Flake. Composed of flakes which have large ratios of platform area to thickness and are suspended in a matrix material.



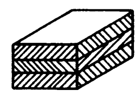
Flake Composite

Filled/Skeletal. Composed of a continuous skeletal matrix filled by a second material.



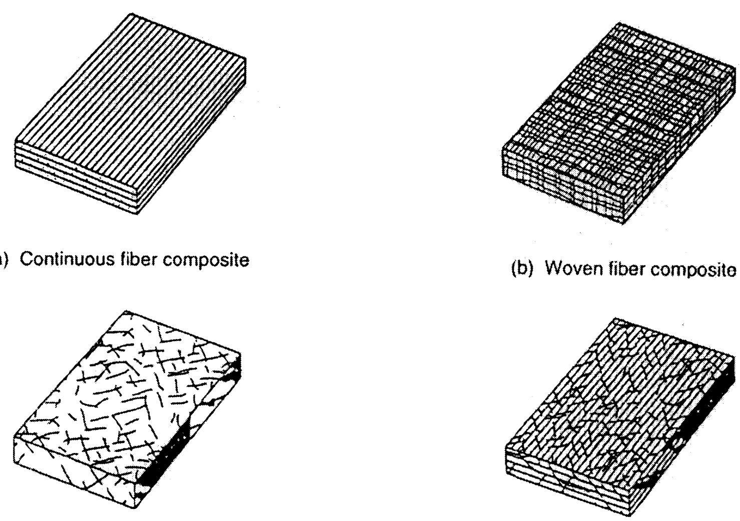
Filled Composite

Laminar. Composed of layers (lamina) bonded together by a matrix material.



Laminar Composite

The fiber composite classification in Table 1.1 can be further structured for identification by noting the direction and placement of fibers. This results in Figure 1.1 for classification of fiber-reinforced composite types.



(a) Continuous fiber composite

(b) Woven fiber composite

(c) Chopped fiber composite

(d) Hybrid composites

FIGURE 1.1. Types of Fiber-Reinforced Composites

A further classification of the woven composite configurations, shown in (b) above, is illustrated in the geometric architectures shown below in Figure 1.2.

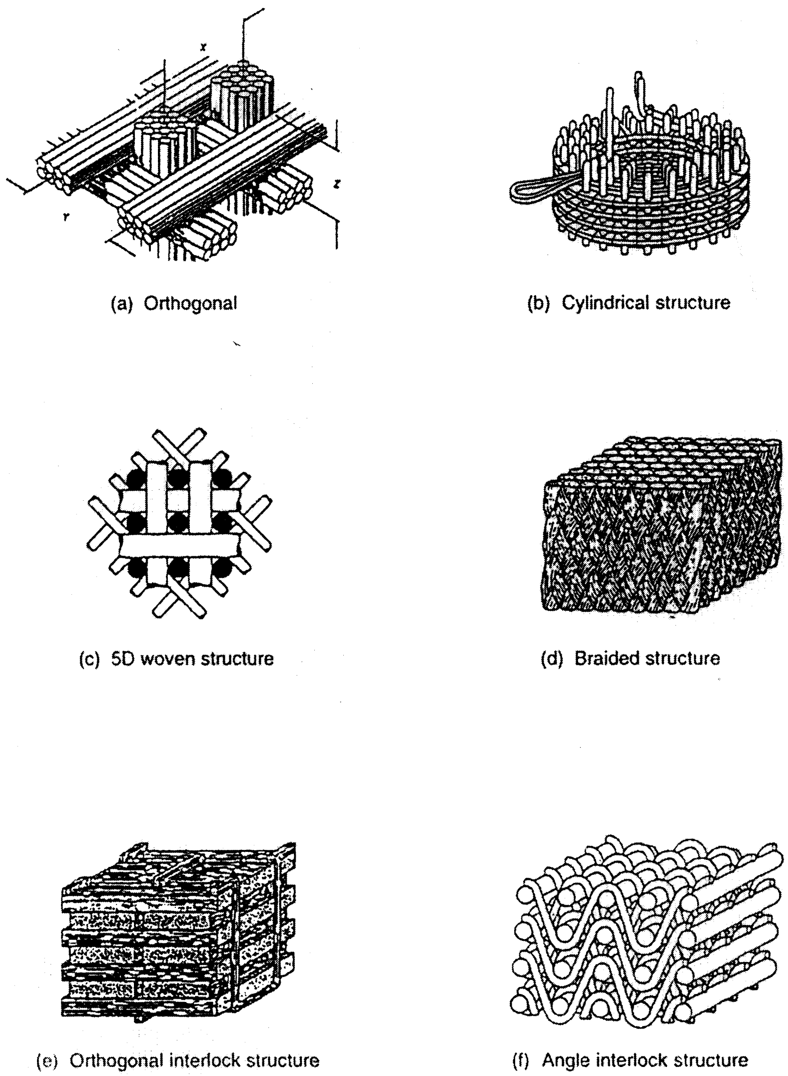


FIGURE 1.2. Types of Woven Fiber-Reinforced Composites

Of the composite material types described in Table 1.1, fiber composites have received considerable attention in recent years due to the development of advanced fiber types such as glass, Kevlar and graphite, which have moduli in excess of 3×10^6 psi/20 GPa. The incorporation of these fiber types into suitable binders/matrices, which may be metals, non-metals or ceramics, leads to a synergism in which the new material possesses unique properties compared to the properties of either of the constituent elements. The acceleration of this material's revolution is depicted in Figure 1.3, which shows the state a maturity of various materials and, in particular, the status of composite materials.

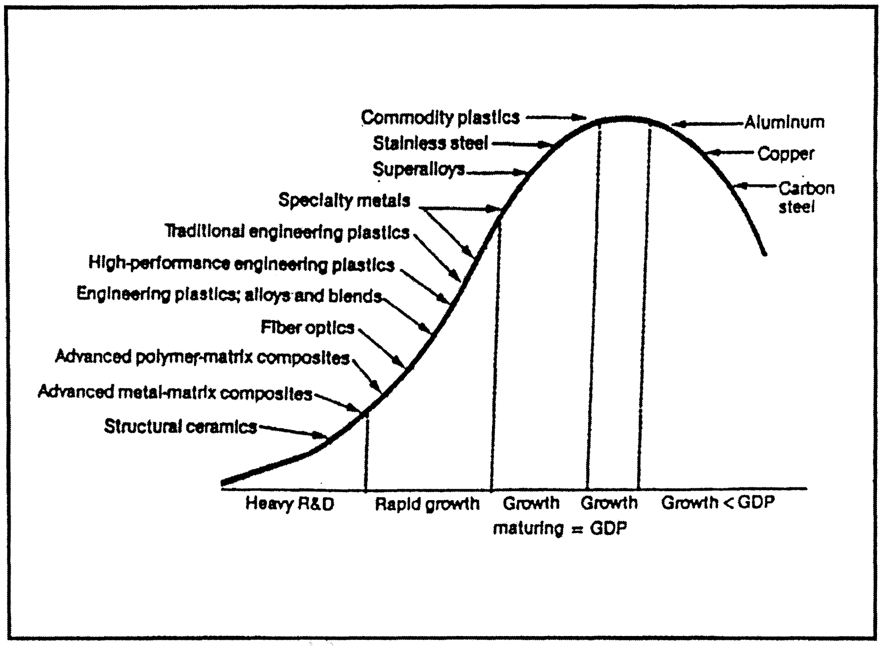


FIGURE 1.3. State of Materials Maturity

This leads to a definition of a composite material, which has been defined in ASTM D 3878-95c as:

"Composite Material. A substance consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents."

As previously discussed, the way in which the constituents of a composite material are engineered is critical to the performance of the material system. Composites consisting of fibers embedded in a suitable matrix (binder) material can consist of several configurations dependent upon whether the embedded fibers are continuous or discontinuous. The configurations are:

- Discontinuous, fiber-reinforced composite – A composite material which consists of chopped fibers or whiskers embedded within a matrix material.
- Fabric reinforced composite – A composite material in which the embedded fiber assembly consists of a fabric, which may be woven, knitted or braided.
- Fiber-reinforced composite – A composite material which consists of embedded continuous/discontinuous fibers in a matrix material.

- Filamentary composite – A composite material reinforced by continuous fibers embedded in a matrix material.

- Unidirectional fiber-reinforced composite – A composite material in which all the embedded fibers are all aligned in a single direction.

1.3 Types of Composite Materials

The important types of advanced composites can be depicted in the pie chart shown in Figure 1.4 below, which describes the five principal types of advanced composite material in wide use.

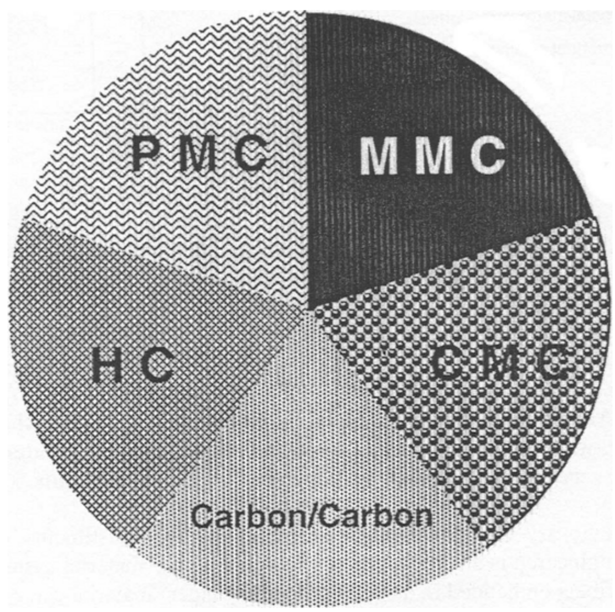


FIGURE 1.4. Principal Composite Materials

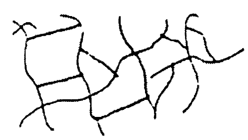
The composite types cited in Figure 1.4 include Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC), Ceramic Matrix Composites (CMC), Carbon-Carbon (CC) and Hybrids consisting of a combination of the previously mentioned matrices and/or fibers.

In composite materials in 2001, glass fibers are the most used, and electrical or E-glass fibers account for more than 90% of all glass fibers used. S-glass fibers comprise the other 10% and are typically forty to seventy percent stronger than E-glass. Also, S-2 glass fibers were developed in the 1960's for military applications.

The other two fiber types most often used in composite materials today are carbon and aramid (Kevlar) fibers.

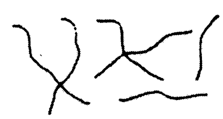
As to matrix materials by far the most often used are polymeric resins. Metal and ceramic matrix materials are used only for special applications. The polymeric resins fall into two categories: thermosets and thermoplastics. Thermoset resins become cross-linked during cure and the result is a final rigid configuration. Thermoplastic resins are processed at higher temperatures and remain plastic, can be reheated and can be reshaped. However, the majority of polymeric resins used in composites in 2001 are thermosets.

- Thermosets – This matrix can be characterized by having polymer chains that become highly cross-linked during cure. Once it is cured, it is in a final rigid configuration and there is nothing that will change it (short of a failure of the matrix). These matrices are advantageous for high temperature applications of composites.



Among the most often used thermoset resins are unsaturated polyester, halogenated polyester, vinylester, epoxy, phenolic, polyurethane and polybutadiene.

- Thermoplastics – This matrix can be characterized by having polymer chains that are not cross-linked. It can be remolded to a new shape when heated to approximately the same temperature at which it was cured. When using these matrices, the operating temperature should be kept below the cure temperature.



Among the thermoplastic resins the most often used include polyethylene, polystyrene, polypropylene, acryonitride-butadiene styrene (ABS), acetal, polycarbonate (PC), polyvinyl chloride (PVC), polysulfone (PSF), polyphenylene sulfide (PPS) and nylon (semi-crystalline polymide).

1.4 Constituent Properties

The mechanical properties of a composite material are determined by the properties of the constituent materials. As a starting point, the basic properties of commonly used constituents in composite material construction are discussed.

1.4.1 MATRIX PROPERTIES

The matrix represents the binding material of the composite, which supports and protects the fibers. It also provides a mechanism for the transfer of loads in the event of fiber breakage. Typically, the matrix has a lower density, stiffness and strength than the fibers. The response characteristics for polymeric matrix materials are usually viscoelastic or viscoplastic and therefore the matrix is affected by time, temperature and moisture. Indeed, the stress-strain response of polymeric matrices is influenced by all these factors. A summary tabulation of the properties of typical polymeric matrices is included in Table 1.2 below, and Table 1.3 provides properties of some structural matrix materials.

TABLE 1.2. Typical Matrix Properties

Material	Density (kg/m^3)	E_t (GPa)	E_c (GPa)	σ_t (MPa)	σ_c (MPa)	ν	α ($10^{-6}/^\circ C$)
Polyester	1200-1400	2.5-4.0	---	45-90	100-250	0.37-0.40	100-200
Epoxy	1100-1350	3.0-5.5	---	40-100	100-200	0.38-0.40	45-65
NARMCO 2387 (epoxy)	1210	3.38	3.86	29	158	---	---
PVC	1400	2.8	---	58	---	---	50
Nylon	1140	2.8	---	70	---	---	100
Polyethelene	960	1.2	---	32	---	---	120

In Table 1.2, E_T and E_C are the tensile and compressive moduli of elasticity respectively, σ_T and σ_C are the ultimate strengths, ν is the Poisson's ratio and α is the coefficient of thermal expansion.

TABLE 1.3. Typical Structural Matrix Resins

Resin	Tensile Strength (MPa)	Tensile Modulus (GPa)	T_g (K) *
Thermosets			
Epoxy (TSMDA)	103.4	4.1	463
Bismaleimide	82.7	4.1	547
Polyimide	137.9	4.8	630
Thermoplastics			
Polyhenylene sulfide	65.5	4.3	366 (555 mp)
Polyetheretherketone	70.3	1.1	400

*Glass Transition Temperature

1.4.2 FIBER PROPERTIES

Reinforcement of the matrix, to provide the majority of the strength and stiffness of a composite is accomplished by the fibers, which carry the majority of the loading and which inherently have superior properties to the bulk fiber material. The fiber can be of one of the following types:

- Organic
- Metallic
- Synthetic
- Mineral

Fibers, as used for reinforcement, can also be classified according to their geometrical properties. For reinforcement in a composite, characteristic fiber dimensions are seen below:

	Fibers	Whiskers
Length	5 mm	1 mm
	(.20) inches	(.04 inches)
	$> 100 \times$ dia.	$10 \times$ dia.
Cross Sectional Area	1.975×10^{-3} mm^2	
	$(3.6 \times 10 \, in^2)$	
Diameter	.25 mm	
	(.01 inches)	

A typical demand curve for carbon fibers is shown in Figure 1.5 [1]*.

* Numbers in brackets refer to references at the end of the Chapter.

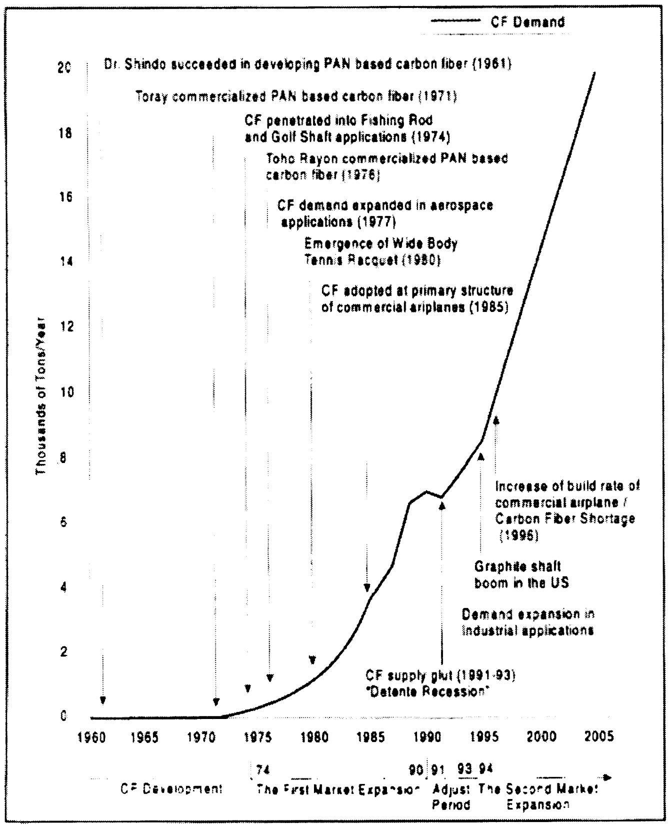


FIGURE 1.5. Demand for Carbon Fiber 1971-2005

1.5 Composite Manufacturing, Fabrication and Processing

Composite fabrication can be considered to be related to three basic manufacturing techniques shown in Table 1.4.

TABLE 1.4. Basic Manufacturing Techniques

Process	Description	Limitations
Laminating	Material, usually in form of reinforcing cloth, paper, foil, metal, wood, glass fiber, plastic, etc., preimpregnated or coated with thermoset resin (sometimes a thermoplastic) is molded under pressure greater than 6895 kPa into sheet, rod, tube or other simple shapes. Excellent dimensional stability of finished product; very economical in large production of parts.	High tool and die costs. Limited to simple shapes and cross section profiles.
Pultrusion	This process is similar to profile extrusion, however, it does not provide flexibility and uniformity of product control, and automation. Used for continuous production of simple shapes (rods, tubes and angles) principally incorporating fiberglass or other reinforcement. High output possible.	Close tolerance control requires diligence. Unidirectional strength usually the rule
Filament winding	Excellent strength-to-weight ratio. Continuous, reinforced filaments, usually glass, in the form of roving are saturated with resin and machine wound onto mandrels having shape of desired finished part. Once winding is completed, part and mandrel are cured; mandrel can then be removed through porthole at end of wound part. High strength reinforcements can be oriented precisely in direction where strength is required. Good uniformity of resin distribution in finished part; mainly circular objects such as pressure bottles, pipes and rocket cases.	Limited to shapes of positive curvature; openings and holes can reduce strength if not properly designed into molding operations.

Comparisons of various composite manufacturing processes are shown in Table 1.5(a) and (b).

TABLE 1.5(a). Comparison of FRP Composite Manufacturing Processes, Production Factors (adapted from Wittman and Shook, 1982)

Manufacturing Process	Equipment Costs	Rate of Production	Part Strength	Operator Skill Required	Part complexity	Reproducibility	Possible Fibre Forms (R-Random/C-Continuous)
Hand Lay-up	L	L	L	H	H	L	R,C
Spray-up	M	M	L	H	H	L	R
Tape Lay-up (Manual)	L	L	---	H	N	L	C
Tape Lay-up (Automated)	H	H	---	L	M	H	C
Vacuum Bag Moulding (Wet Lay-up)	L	M	M	H	H	L	R,C
Autoclave Moulding (Tape Lay-up)	H	M	H	M	M	H	C
Filament Winding	M	M	H	L	L	H	C
Pultrusion	H	H	H	L	L	H	C
Compression Moulding	H	H	*	M	H	H	R,C
Resin Transfer Moulding	M	M	*	M	H	H	R,C
Reaction Injection Moulding	M	H	*	M	H	H	R,C
Injecting Moulding	H	H	L	H	H	H	R
Stitched/Thermoform Preforms	M	H	M	M	M	H	R,C
Random Fibre Preforms	M	L	L	H	H	L	R
3-D Woven/Braided Preforms	H	M	H	L	H	H	C

Legend: H – high
M – medium
L – low

TABLE 1.5(b). Comparison of FRP Composite Manufacturing Processes, Materials (Rosato and Rosato 1990)

	Thermosets					Thermoplastics									
	Polyester	Polyester SMC	Polyester BMC	Epoxy	Polyurethane	Acetal	Nylon 6	Nylon 6/6	Polycarbonate	Polypropylene	Polyphenylene Sulfide	ABS	Polyphenylene Oxide	Polystyrene	Polyester
Injection Moulding	*		*	*	*	*	*	*	*	*	*	*	*	*	*
Hand Lay-up	*			*											
Spray-up	*			*											
Compression Moulding	*	*	*	*	*										
Preform Moulding	*			*											
Filament Winding	*			*											
Pultrusion	*			*											
Resin Transfer Moulding	*			*											
Reinforced Reaction Injection Moulding	*			*	*		*								

1.5.1 COMPRESSION MOLDING

For most high-volume fiber reinforced polymer matrix (FRP) composite parts compression molding is the primary choice. The high-pressure molding process produces high-strength, complex parts of a variety of sizes. Matched molds are mounted in a hydraulic or mechanical molding press. A weighed charge of bulk or sheet molding compound or a preform is placed in the open mold, along with a measured charge of resin. The heated mold halves are closed, and pressure is applied. Molding time, depending on part size and thickness, ranges from about one to five minutes. Inserts and attachments can be molded in. Compression-molded composites are characterized by good mechanical and chemical properties, superior color and excellent surface finish. Trimming and finishing costs are minimal. See Figure 1.6.

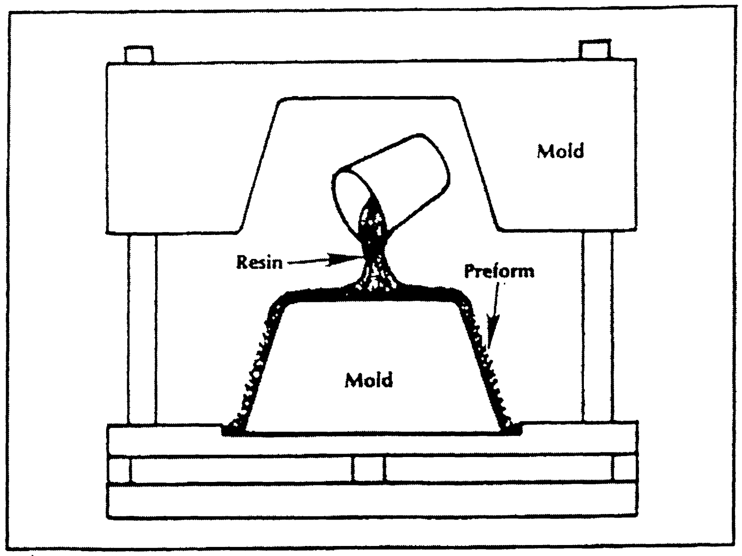


FIGURE 1.6. Compression Molding

1.5.2 RESIN TRANSFER MOLDING (RTM)

Suitable for medium-volume production of rather large FRP components, resin transfer molding is usually considered an intermediate process between the relatively slow spray-up and the faster compression-molding methods, which require higher tooling costs. RTM parts, like compression-molded parts, have two finished surfaces, but molded parts require trimming. Gel coats may be used. Abrate [2] provides an overall view of resin flow in fiber preforms.

Reinforcement mat or woven roving is placed in the bottom half of the mold, which is then closed and clamped. Catalyzed, low-viscosity resin is pumped in under pressure, displacing the air and venting it at the edges, until the mold is filled. Molds for this low-pressure system are usually made from reinforced plastics.

Vacuum-Assisted Resin Transfer Molding (VARTM): after the composite material is entered into the mold, and the part is vacuum bagged, a vacuum of ≥ to 14 psi and cure temperature of less than 350° F is applied. The vacuum compacts the composite and helps the resin wet out the preformed composite part. See Figure 1.7.

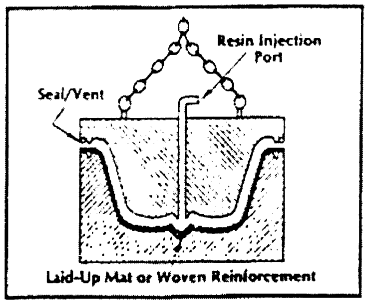


FIGURE 1.7. Resin Transfer Molding (RTM)

1.5.3 INJECTION MOLDING

Reinforced thermoset molding compounds can be injection molded, Figure 1.8, in equipment similar to that commonly used for thermoplastic resins. The principal difference lies in the temperatures maintained in various areas of the system. With thermoplastics, the injection screw and chamber are maintained at a relatively high temperature, and the die is cooled so the molded part sets up. In contrast, for a thermoset FRP, the screw and chamber are cooled so that the resin does not cross-link and gel, and the die is heated so it does cross-link and cure.

Injection molding offers high-speed production and low direct labor costs. Combined with the excellent mechanical properties available from long fibered BMC, the result is a capability for high volumes of complex parts with properties comparable to those of compression or transfer molded parts.

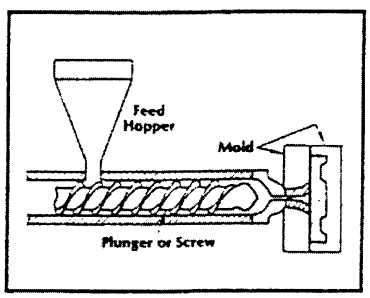


FIGURE 1.8. Injection Molding

1.5.4 COLD PRESS MOLDING

Cold press molding does not use external heat to effect part cure because the compound cures at room temperature, aided by the self-generated exothermic heat. Cold molding is an economical press-molding method, providing two finished surfaces on parts made, for manufacturing intermediate volumes of products using a low-pressure cure and inexpensive molds of plaster or glass reinforced plastic. These molds do not have sharp edges, so trimming after molding is required.

Preform or mat reinforcement is placed on the lower mold half and a resin/filler mixture is added. The mold is closed under moderate pressure or 20 to 50 psi, and the FRP part cures. Cold molding is suited mainly for relatively simple shapes, without ribs or bosses.

1.5.5 STRUCTURAL REACTION INJECTION MOLDING (SRIM)

Structural reaction injection molding shown in Figure 1.9, is suitable for medium-to-high volume composite parts requiring superior strength with no loss in toughness or flexibility. The SRIM process also produces parts with high impact resistance and lower weight, and is excellent for larger part sizes.

Like injection molding, resin is injected into a closed mold. However, the SRIM process utilizes a directed-fiber preform or reinforcing mat, which is placed into the mold prior to closure, resulting in even distribution of glass and uniform mechanical properties.

SRIM parts offer two finished surfaces, but the polyurethane systems typically used do not provide a Class A surface finish and are generally considered unsuitable for applications where cosmetics are important. For structural application, however, the low temperature and pressure characteristics of SRIM lead to lower equipment and manufacturing costs compared to similar processes.

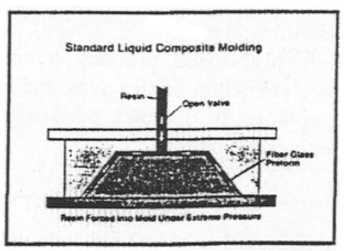


FIGURE 1.9. Structural Reaction Injection Molding (SRIM)

1.5.6 HAND LAY-UP

The simplest and oldest of the fabrication processes for FRP composites, hand lay-up, is a labor-intensive method suited especially for low-volume production of large components such as boat hulls and associated parts. See Figure 1.10.

A pigmented gel coat is first sprayed onto the mold for a high-quality surface finish. When the gel coat has become tacky, glass reinforcing mat and/or woven roving is placed on the mold, and resin is poured, brushed or sprayed on. Manual rolling then removes entrapped air, densifies the composite and thoroughly wets the reinforcement with the resin. Additional layers of mat or woven roving and resin are added for thickness. Curing is initiated by a catalyst or accelerator in the resin system, which hardens the composite without external heat.

Hand lay-up offers low-cost tooling, simple processing and a wide range of part size potential. Design changes are made easily. Parts have one finished surface and require trimming.