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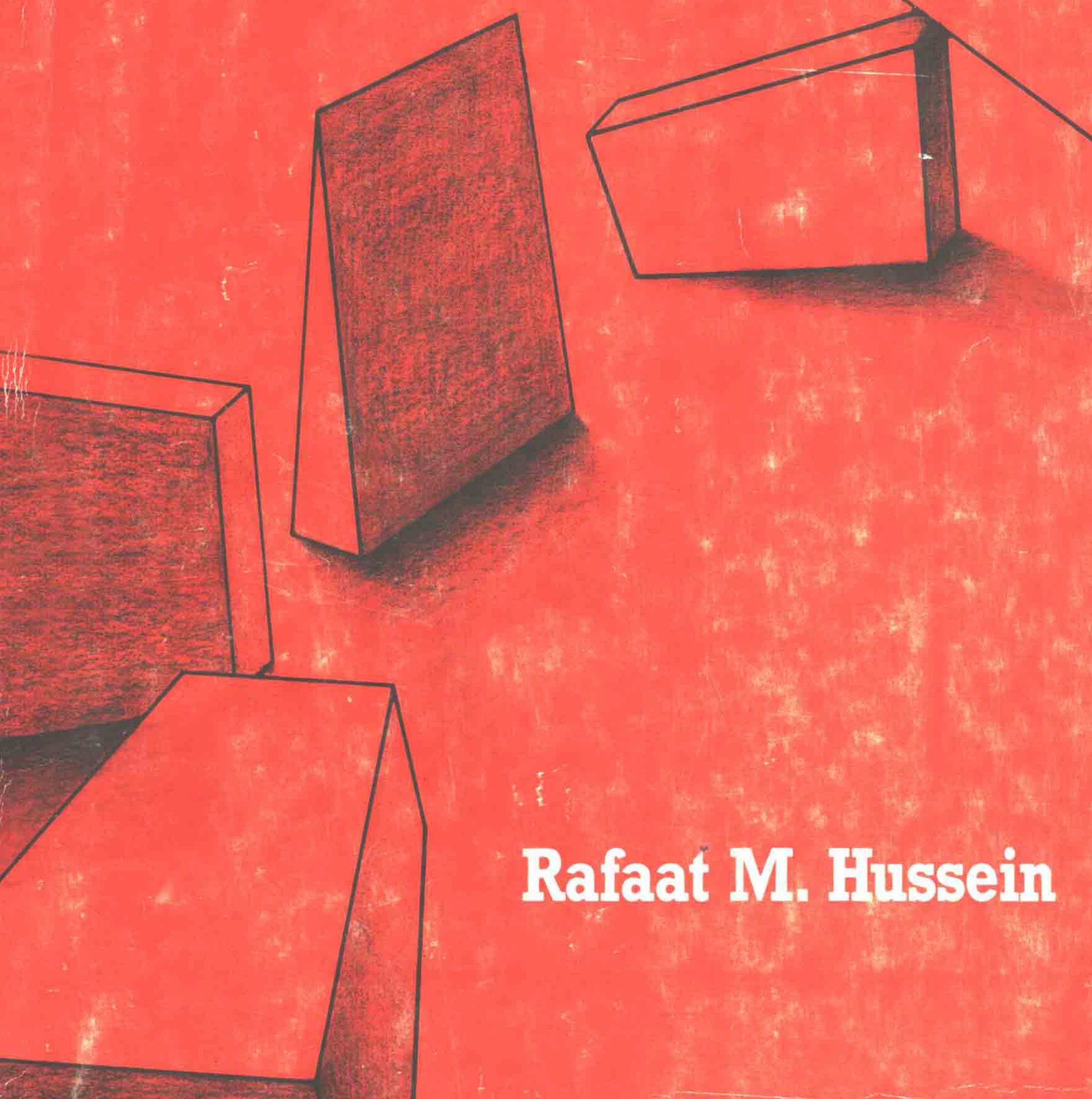
ANALYSIS AND DESIGN



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PREFACE

This book presents principles and methods for the analysis and design of composite construction and shows how these theories may be used in practical design problems.

Construction with composite materials has been extensively used in the aerospace industry, and its application in building is rapidly increasing. This great interest in composite materials is explained by the following quote from Dietz [Composite Engineering Laminates, MIT Press]: "Demands on materials imposed by today's advanced technologies have become so diverse and severe that they often cannot be met by simple single-component materials acting alone. It is frequently necessary to combine several materials into a composite to which each constituent not only contributes its share, but whose combined action transcends the sum of the individual properties, and provides new performance unattainable by the constituents acting alone. Space vehicles, heat shields, rocket propellants, deep submergence vessels, buildings, vehicles for water and land transport, aircraft, pressure tanks, and many others impose requirements that are best met, and in many instances met only by composite materials."

The concept of composite structures is not new. A piece of laminated wood stored at the Metropolitan Museum of Art, New York, was found at Thebes and shown to belong to the Eighteenth Dynasty (about 1500 B.C.). On its bottom are five pieces glued and laminated to a heavier piece, which is made of glued veneer. Another example is the ancient sarcophagus of wood veneers laminated to a heavier wood substrate and now in the Boston Museum of Fine Arts. The subtle principles of a composite system were understood intuitively and empirically and are now the subject of major research. Sandwich construction is also characterized by the use of two layers of strong material, called "faces," between which a thick layer of a light-weight and comparatively weak core is sandwiched. Such composite construction has found many applications in the aerospace and building industries. It is used in the construction of helicopter rotor blades, helicopter flooring, aircraft wings, deck panels, fire walls, access doors, and baggage racks. Movable objects, like tank trailers that transport bulk milk and fruit juices, ladders for use in telephone line service, and truck trailer panels and doors, are being built using composite sandwich panels. Architects are recognizing the fact that the composite concept is well suited for curtain wall applications. In addition, it is employed widely in structural walls, roofs, and floorings for house trailers, small boat hulls, shipboard doors and bulkheads, table tops, and furniture. Folding plate roofs can also be built using composite panels. One-story homes, motels and similar buildings have been successfully built with composite panels. As an example, a motel and a restaurant were fabricated in

Canada and shipped for erection in the Caribbean Islands. Another example is the widespread use of composite panels in the southern United States, and in northern Canada, and in Europe. In multi-story buildings, composite panels have a place in the total system up to perhaps four floors, but only two-story buildings have been built.

Answers to many problems related to structural systems may be found in composite construction, which offers several advantages. Virtues related to environmental requirements may include structural integrity, durable finishes, weather-tightness, dimensional stability, sound or microwave absorption. From the point of view of structural performance, composite construction is an efficient structural design due to the great stiffness achieved by different geometrical arrangements of the most highly stressed elements. Other advantages of composite construction may include high strength-to-weight ratios, increased fatigue life, endurance, low moisture permeability, electrical insulation, color processability, reduced shop labor, simplified materials handling, and potentially lower costs to the house manufacturer and for transportation.

Although many types of composite structures have been invented, developed, tested, and marketed for use in the construction trade, there exist no design codes or specifications to assist designers. Thus, a designer must determine on his own to criteria for selection and design which are most appropriate for his particular application. Normally, he may gain valuable assistance from the wealth of information accumulated since the beginning of the Second World War. However, in the final analysis he makes his own determination of the suitability of a specific design for a particular application under investigation, together with, in many cases, a prototype test program to verify the adequacy of the design developed. For composite construction, because of the wide variety of available options for configuration, types of materials, and different fabrication processes, it is vital that the designer carefully establish his desired functional and performance requirements as accurately and in as much quantified detail as possible. A substantial part of the process involves the determination of the structural response and the proportioning of the elements which make up the component.

This book is aimed at assisting the designer to fully understand the different structural aspects of composites, to select suitable materials and structural design criteria, and to analyze the effects of loads and restraints. The book presents the state-of-the-art in this field. Its objective is to provide simplified formulas and design aids related to composite structures. Mathematical derivations are in a form suitable for this objective. Methods of analysis and basic assumptions underlying each theory are discussed. Particular attention has also been paid to provide the complex mathematical results in a practical, simple, exact form suitable for design offices. Parameters have been chosen in the formulas in such a way as to arrive at convenient forms, tables, and graphs. Extensive references have been presented at the end of each chapter. The results of the author's experience during the past decade have been included. Because the structural applications of composites are numerous, the implementation of all theories is devoted to laminated composites, which covers a broad spectrum in this field. It is felt that the book can easily be followed by persons not already familiar with its subject, including senior undergraduate, graduate students, and practicing engineers. A background in strength of materials and the fundamentals of structural analysis is sufficient to comprehend the theories presented.

This book is a result of the excitement and challenge that the author experienced in working in the field of composites. I would like to extend very special thanks to Professor Paul Cheremisinoff, from the New Jersey Institute of Technology for his continuous encouragement throughout all aspects of writing. My sincere gratitude goes also to Mrs. Charmine S. for her outstanding job in typing the manuscript.

Finally, truly unbounded thanks are due to my wife and son for their love and patience over the years, which made the writing of this book a reality.

RAFAAT M. HUSSEIN

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Composites in Construction

1.1 INTRODUCTION

There is growing interest in the development and applications of composite construction. Composite action, for example, is based on the concept of combining dissimilar materials to form a composite fulfilling specific design requirements.

A three-layer laminated panel, as a special form of composite actions, is characterized by the use of two thin layers of strong material, denoted as faces, between which a thick layer of lightwieght and comparatively weak core is sandwiched as shown in Fig. (1). In a structural panel of this type, the faces resist bending moments and in plane compressive or shear forces. The shear forces normal to the plane of the panel are resisted by the core, which also stabilizes the faces against buckling (Fig. (2)). This type of construction is efficient structurally due to the large stiffness achieved by spacing apart the most highly stressed elements, namely, the faces. The basic principle is much the same as that of an I-beam.

1.2 COMPOSITE LAMINATED PANELS IN CONSTRUCTION

Answers to many problems related to construction may be found in composite laminated panels which offer several advantages. Panel virtues related to environmental requirements may include structural integrity, durable finishes, weather-tightness, dimensional stability, sound or microwave absorption. From the point of view of structural performance, a composite laminated construction is an efficient structural design due to the large stiffness achieved. Other advantages may include high strength-to-weight ratios, increased fatigue life, endurance, low moisture permeability, electrical insulation, color processability, reduced shop labor, and potentially lower costs to the house manufacture and transportation.

As with any other component, there are some factors to be considered. When the core or facing materials may lead to corrosion problems, special pretreatments are required. No foam is fireproof, but many of them can be made nonflammable. Polyester laminated panels were tested, both painted and unpainted, by the Forest Products Laboratory, and it was found that the unpainted panels deteriorated the most in three year's weathering; the edgewise compressive strength reduced by 40 percent and the flexural strength by 30 percent. Painting the other polyester panels reduced the loss in edgewise compressive strength to 22 percent, but the reduction in flexural strength was still 30 percent. Similar effects on panel strengths were observed due to the effect of moisture contents. Although several advantages can be attributed to most plastic foams, their resistance to chemical agents should be considered in the manufacturing process.

1.3 MATERIAL REQUIREMENTS

A laminated composite panel in building systems should combine the features stated before. Constituents contribute to achieve these features as well as fulfilling the basic principle of this type of construction. A list of the required properties of each layer in a laminated composite panel is presented in Table 1.

Table 1

REQUIRED PROPERTIES

Panel	Skin	Core	Bonding	Frame	Connections
·Strength	·Strength	·Strength	·Strength	·Strength	·Cheap
·Rigidity	·Resistance to local damage	·Rigidity	·High peel	·Rigidity	·Simple
·Repairability	·Weather resistance	·Impermeability	·Strength	·Insulation	·Structural
·Durability	·Nonrotting	·Nonrotting	·Durability	·Repairability	·Weather-tight
·No loss of strength up to high temperature	·Fire resistance	·Fire resistance	·Low creep	·Weather resistance	
·Minimum weight	·Impermeability	·Sound Absorption	·No loss of strength up to high temperature	·Sound absorption	
·Fatigue	·Durability	·Insulation	·Fatigue		
·Vibration	·Reflective	·Durability	·Long life		
	·Sound absorbing	·Minimum weight	·Suitable for varied materials		
		·Incombustible	·Adhesion maintenance during contact with moisture or water		
		·Can accept adhesion	·Chemical stability regarding both faces and core		

1.4 PANEL MATERIALS

A laminated composite panel development provides the opportunity of not favoring any one material, but rather employing most of the available materials. Therefore, a desired design requirement can be achieved by more than alternatives of material combinations.

Some of the materials that have been or might be used are listed in Table 2.

Table 2

MATERIALS FOR LAMINATED PANELS

Faces	Core	Bonding	Frame	Connections
·Plywood ·Gypsum board ·High pressure laminates ·Painted steel sheet ·Stainless steel sheet ·Asbestos	·Kraft paper honeycomb ·Balsa wood ·Light weight concrete	·Latex ·Neoprene base contact cement ·Epoxy resins	·Timber ·Steel ·Aluminum	·Nails ·Screws ·Bolts ·Locking devices ·Cover strip

1.5 POLYMERS IN COMPOSITE PANELS

Combining several materials into one composite unit is not a new idea. The principles of a laminated system were understood intuitively and by experience by ancients. Spaced fibers were developed by a Frenchman named Dulcan in 1820. During World War II, demands on efficient use of labor and materials imposed by the aircraft industry resulted in promoting the use of laminted panels with plywood faces and honeycomb cores. However, by today's advanced technologies, new materials, most of which are polymers, were developed and this resulted in an impact on the area of laminated construction.

Laminated panels may be made entirely of plastics or a combination of plastic with other materials. For example, the core may be made of rigid foams and skins of aluminum. A list of other plastics for use in laminated panels is given in Table 3.

Table 3

POLYMERS FOR LAMINATED PANELS

Faces	Core	Bonding	
·Phenolic-Asbestos Laminates	·Fibre Glass	·Latex	·Phenlic-neoprene
·Epoxy-Glass Cloth Laminates	·Expanded Polystyrene	·Neoprene base contact cement	·Phenolic-vinyl
·Polyester-Glass Fiber Laminates	·Expanded Polyurethane	·Alkyd	·Polyacrylonitrile
·PVC	·Expanded PVC	·Acrylate	·Polamide
·PMMA	·Acrylonitrile styrene	·Caselin	·Polyethylene
·Laminated wood-plastic	·Cellulose Acetate	·Cellulose-nitrate	·Polyimide
·FRP	·Epoxy	·Cellulose-vinyl	·Polyvinyl-acetate
·Polyamide (nylon)	·Methylmethacrylate styrene	·Epoxy	·Polyvinyl-butyral
·Plastic Clad Plywood	·Phenolic	·Epoxy-novalac	·Resorcinol-phenol formaldehyde
	·Polyethylene	·Epoxy-phenolic	·Silicone
	·Polypropylene	·Epoxy-polyamide	·Vinyl buyralphenolic
	·Polystyrene	·Epoxy-polysulfide	·Vinyl Copolymers
	·Polyvinyl Chloride	·Epoxy-silicone	·Urea formaldehyde
	·Silicone	·Melamine-formaldehyde	·Urethane
	·Urea Formaldehyde	·Phenolic	
	·Urethane	·Phenolic-butadience acrylonitrile	

The behavior of a laminated panel depends on its constitutents, its geometry, and the applied technology in the manufacturing process. The virtues of some polymers for the use in such panels will be discussed next.

1.5.1 SURFACE FIBERS

Among the synthetic materials often used for the outer fibers of composite panels are:

Poly (vinyl chloride) - PVC - and vinyl chloride copolymers
Poly (methyl methacrylate) - PMMA
Laminated wood-plastic
Fibre-reinforced plastics - FRP

POLY (Vinyl Chloride):

Unplasticized PVC is a hard horny material, insoluble in most solvents and not easily softened. If it is mixed while hot with certain plasticizers, it forms a rubbery material.

PVC has a tendency to liberate hydrochloric acid, particularly at temperatures approaching the upper limit of serviceability. To prevent this reaction stabilization with acid neutralizers or absorbers is necessary. PVC is nonflammable, moistureresistant, odorless, tasteless, and offers exceptional resistance against a great number of corrosive media.

Advances in rigid PVC formulation and in processing equipment design have made available a new dimension in building panels to the building industry. PVC elements lend themselves admirably to use for roofing, siding, various shelter and enclosure structures, and for interior panelling; in fact, they have already caused some revolutionary changes in building concepts.

Rigid PVC panels have some outstanding advantages, as follows: attractive appearance, weatherability, lightweight, corrosion and fire resistance, easy to clean and easy to install. New rigid PVC-resistant to higher temperature - contains clorinated PVC; these plastics may be used at temperatures up to 100°C.

Copolymerization of vinyl chloride with other vinyl monomers leads to some products with improved properties.

POLY (Methyl Methacrylate):

This is a clear, colorless, transparent plastic with a high softening point, good impact strength and weatherability. Sheets of PMMA are commonly made by extrusion.

The resistance of PMMA to outdoor exposure is outstanding and it is markedly superior to other thermoplastics. It has a low water absorption and the abrasion resistance is roughly comparable with that of aluminum. Like other polymers, PMMA is thermally insulating.

In sheet form, PMMA and other acrylic polymers can be softened at high temperatures and formed (usually vacuum formed) into practically any desired three-dimensional shape.

These polymers have excellent transparency (total luminous transmission up to 93%), while polystyrenes in their initial stage rarely exceed 88% - 90%. Due to the latter characteristics, PMMA have been used for many lighting and glazing applications.

PLASTIC CLAD PLYWOOD:

The properties of this well-known and proved product are essentially those of solid wood except that the cross-piles greatly increase strength and stability in the cross-grain direction at the expense of some reduction in the grain direction.

Plastic clad plywood touches almost all of us. This laminate is the familiar work surface of the kitchen and many restaurant tables. Again, the advantages of the plywood and light weight are enhanced for the specific use, by the hardness, decorative quality and wear resistance of the plastic outer layer.

COMPOSITES:

Composite materials are being applied in increasing amounts for essentially the same reasons as for other applications; namely, they provide properties and behavior not attainable in single-phase materials, or they provide these features more efficiently, or at lower cost, or both.

The type of composite materials or composite structures principally found in building are:

Fibrous: Fibres embedded in a continuous matrix laminar;

Layers of materials blended together and possible interpenetrated by a building material particulate;

Particles embedded in a continuous matrix.

Composites have three outstanding advantages: ease of fabrication, high fracture energy, and potential low cost. The latter is particularly true for glass-reinforced resins, glass being by far the most common fibre used in resin-matrix composites. Added advantages of the resin-matrix composites often include the low density, low electrical and thermal conductivity, transluscence aesthetic, color effects, and corrosion resistance. The resin-matrix composites are highly formable, and their fracture energy is enormous. Table 4 illustrates the unusual fracture energy possibilities of resin-matrix composites.

Mechanical properties of a composite depend primarily on the type of fibres, their quantity in the laminate and their direction. The type of fibre, that is, its tension strength and its modulus, determine these properties in the finished laminate and the percentage value of these fibres is directly proportional to the tensile strength and to the modulus. These are short-fibre-reinforcements such as wollastonite, asbestos, or continuous filament reinforcements such as glassfibre, basalt fibres, high modulus organic fibres, aluminum oxide and other ceramic filaments, metal filaments.

The more important fibrous materials for advanced composites are compared in Table 5.

Table 4

FRACTURE ENERGY

Material	Energy to Propagate a Crack J/cm^2
Glass	0.061
Epoxy resin	0.61
Metal	183.00
Glass-reinforced epoxy	
Parallel fibre	3.1
Perpendicular	430.00

Table 5

PROPERTIES OF THE MORE COMMON FIBRES USED IN REINFORCED PLASTICS

Material	Tensil Strength (N/cm^2 x 10^3)	Modulus (N/cm^2 x 10^6)	Density (g/cm^3)
E glass	345	7.2	2.55
S glass	450	8.6	2.5
PRD-49-III	275	13	1.45
Boron	275-310	38-41	2.4
Carbon	103-310	69-62	1.4-1.9
Steel Wire	206-512	20	7.7-7.8

There are several glass formulations that have been used as fibres in polymeric composites, these include A, C, D, E, M, and S glass. In terms of advanced composites, E and S glass are not the most important. E glass, of low alkali oxide content (composition given in Table 6), has become the most widely used formulation for both textile and industrial applications.

Between fibre and matrix (resin), there is an interfacial bond (a coupling agent) whose function seems to prevent the complete adhesion of the fibre to resin so that relative motion is possible.

The cracks, instead of penetrating through the matrix and directly through the fibres, are deflected along the length of the fibres.

Table 6

FORMULATION OF E GLASS

Constituent	Content (%)
Silicon dioxide	52-56
Calcium oxide	16-25
Aluminum oxide	12-16
Boron oxide	8-13
Sodium and potassium oxides	0-1
Magnesium oxide	0-6

The most common coupling agents for glass are the organosilanes and the chrome complexes; the last are cheaper and preferred in a great number of applications.

The availability of a wide variety of manufacturing techniques has undoubtedly been an important factor in the steady growth of the reinforced plastics industry, and it is very likely that it will exert considerable influence on the progress of advanced fibrous composites and laminated panels.

Table 7 shows the relative efficiencies of various forms of fibrous reinforcements: the superiority demonstrated by the continuous-oriented fibre structures is apparent.

It has already been pointed out that the properties of a fibrous composite depend upon the characteristics of fibres, matrix and coupling agent. Several polymeric matrices are used and may be divided into: thermosets and thermoplastics. Sometimes, polyblends are used.

Cross-linked polyesters, phenol-formaldehyde, melamine-formaldehyde resins, epoxide and silicone polymers are among the most common in the thermosetting field.