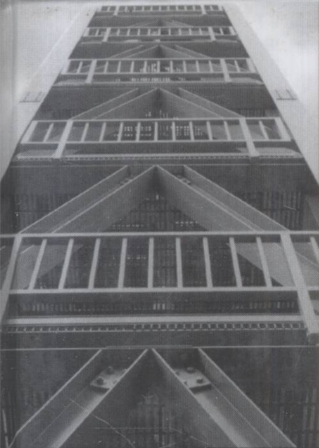
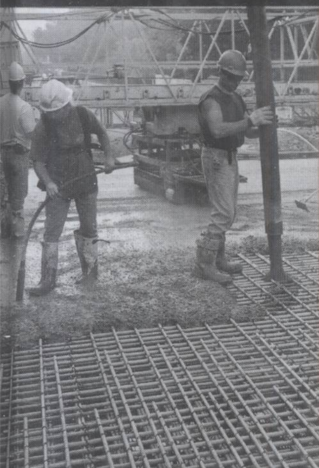
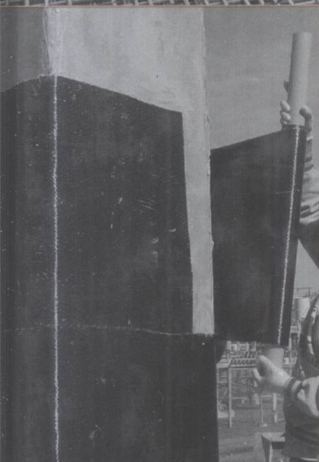
Composites for CONSTRUCTION

Structural Design with FRP Materials







LAWRENCE C. BANK

COMPOSITES FOR CONSTRUCTION:

Structural Design with FRP Materials

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COMPOSITES FOR CONSTRUCTION

PREFACE

Fiber-reinforced polymer (FRP) composite materials have developed into economically and structurally viable construction materials for buildings and bridges over the last 20 years. FRP composite materials used in structural engineering typically consist of glass, carbon, or aramid fibers encased in a matrix of epoxy, polyester, vinylester, or phenolic thermosetting resins that have fiber concentrations greater than 30% by volume. They have been used in structural engineering in a variety of forms: from structural profiles to internal reinforcing bars for concrete members to strips and sheets for external strengthening of concrete and other structures. Depending on the form of the FRP product used in structural engineering, the FRP material is supplied either as a ready-to-use structural component such as a wide-flange profile or a reinforcing bar, or it is supplied in its constituent forms as dry fiber and liquid polymer resin and formed and cured in situ to create a structural component. These two forms should be familiar to structural engineers, as they have analogs in conventional structural materials such as steel beams or steel reinforcing bars which are supplied in ready-to-use form from a steel mill, or portland cement concrete, which is supplied in the form of cement, aggregate, and water constituents and is formed in situ to create a structural element.

The purpose of *Composites for Construction* is to provide structural engineering students, educators, and professionals with a code-based text that gives detailed design procedures for FRP composites for civil engineering structures. The emphasis of the book is on the design of structural members and structural systems that use FRP composites as one or all of the structural materials in the structure. The emphasis of the book is not on the design of the FRP composite materials themselves, and the book provides only a brief review of topics related to constituent materials, micro- and macromechanics of composite materials, and manufacturing methods of composite materials. It is important to emphasize that this book is self-contained and that no prior knowledge of FRP composite materials is required to use the book and to learn how to design with FRP composites in structural engineering. Fiber-reinforced composite materials have been used for many decades in the aerospace, automotive, and the industrial and recreational products industries. Many excellent textbooks and reference books are available that cover the manufacturing, mechanics, and design of fiber composite materials. Nor does the book cover topics of structural analysis or structural mechanics, except where needed to explain design procedures or design philosophy.

Composites for Construction is intended primarily for use as a college-level text in civil and structural engineering curricula. It is intended for senior-level (fourth-year) undergraduate students in civil engineering programs or first-year graduate students in structural engineering programs and for their instructors. Users of the book will find that its form is similar to that of traditional structural engineering design textbooks used to teach subjects such as steel design, reinforced concrete design, and wood design. The book is intended to be covered in a one-semester three-credit lecture-style course on FRP composites in structural engineering. Alternatively, the book can be used to supplement course material in courses on reinforced concrete design, steel design, or wood design since many of the topics covered have parallels to analytical and design methods in these subjects and are logical extensions of the methods used in these subjects. When used for a stand-alone course in a civil or structural engineering program, it is expected that students will have had at least one course in structural analysis, one course in reinforced concrete design, and one course in structural steel design (or design of wood structures). If students have the appropriate background, the book can also be used in architectural engineering or in construction engineering curricula.

Composites for Construction is divided into four parts. The first part provides an introduction to FRP applications, products, and properties and to the methods of obtaining the characteristic properties of FRP materials for use in structural design. The second part covers the design of concrete structural members reinforced with FRP reinforcing bars. The third part covers the design of FRP strengthening systems such as strips, sheets, and fabrics for upgrading the strength and ductility of reinforced concrete structural members. The fourth part covers the design of trusses and frames made entirely of FRP structural profiles produced by the pultrusion process. From a mechanics point of view, the type of FRP material examined in the three design parts of the book increases in complexity from a one-dimensional FRP reinforcing bar to a two-dimensional thin FRP strip or plate to a three-dimensional thin-walled FRP profile section. As the geometric complexity of the FRP component increases, so does its anisotropy and hence so does the number of properties that need to be considered in the structural design.

The format for each of the three design parts of *Composites for Construction* is similar. It starts with a discussion of the design basis and material properties used for the specific application of the FRP material in the design considered in that part. This is followed by sections related to design of specific types of structural members and structural systems (such as beams and columns or trusses and frames) that are unique to the different types of FRP materials examined in each part. In each chapter, examples of the design of typical members and structures are provided in a step-by-step, annotated format that enables the reader to follow the design processes. Each chapter concludes with a set of recommended homework problems. Each design part of the book also discusses important construction- and constructability-related aspects of FRP composites in structures. FRP materials are generally new to structural designers, and most designers have not yet inculcated an intuitive understanding of their behavior as they have for traditional materials such as concrete, steel, and wood. It is therefore important to understand how FRP materials are erected or installed or applied in the field and how the construction process can influence the design process.

As noted, *Composites for Construction* is code-based, which means that it provides design procedures in accordance with published structural engineering design codes, guides, and specifications. The discussion of FRP reinforcing bars and FRP strengthening systems follows a load and resistance factor design basis and presents design procedures for FRP materials used in combination with reinforced concrete according to the most recent editions of the design guides published by the American Concrete Institute: ACI 440.1R-06, *Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*, and ACI 440.2R-02, *Guide for Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. The final part of the book provides design guidance for FRP profile sections according to a combination of recommendations of the ASCE *Structural Plastics Design Manual*, the *Eurocomp Design Code and Handbook*, the *AASHTO Specifications*, and manufacturer-published design guides. Procedures are provided for the structural designer on how to use this combination of codelike documents to design with FRP profiles.

When *Composites for Construction* is used as a textbook for a one-semester (15-week) course, the following allocation of time is recommended: Part One, three weeks; Part Two, four weeks; Part Three, four weeks; Part Four, four weeks. *Composites for Construction* is based on course notes developed by the author while teaching this course over a number of years at the University of Wisconsin–Madison and at Stanford University (while on sabbatical in 2003–2004). Based on the author's experience in teaching this course in recent years, a number of more advanced topics will need to be omitted, depending on the students' background, to be able to cover all the material in a one-semester course. This includes an in-depth treatment of micromechanics and lamination theory (in Chapter 3), FRP bars for bridge decks (in Chapter 5), load–deflection response in FRP-strengthened structures (in Chapter 9), FRP shear strengthening of columns (in Chapter 10), FRP confinement for ductility enhancement in columns (in Chapter 11), FRP profile beam-columns (Chapter 14), and combined FRP flexural–tension members (in Chapter 14). A midterm examination covering Parts One and Two and a final examination covering Parts Three and Four is recommended. In addition, individual or group design projects that run the length of the entire semester are recommended.

The imperial *inch–pound–second* system of units is used throughout the book, as these units are commonly used in U.S. design practice. SI (System International) and metric *cm–g–s* units are used occasionally where standard practice is to report material properties in these units (even in the United States). However, a complete SI version of the design examples and problems is not included at this time, in the interest of brevity.

Composites for Construction focuses on the mainstream application areas of FRP composites in structural engineering at the time of writing. Over the years there have been a number of other applications and uses of FRP composites in structural engineering. In many cases, code-based guidance has only recently been developed or is currently being developed for these applications. The applications include FRP tendons for internal or external prestressing of concrete; FRP stay cables for bridges or guy wires for towers; FRP grids, meshes, and gratings for reinforcing concrete; FRP stay-in-place forms for concrete beams, slabs, or columns; FRP strengthening of prestressed concrete structures; FRP strengthening of masonry structures; FRP strengthening of steel, aluminum, or timber structures; mechanically fastened FRP strengthening systems; FRP pretensioned sheets for strengthening; and FRP strengthening for blast loads on structures.

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LARRY BANK

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