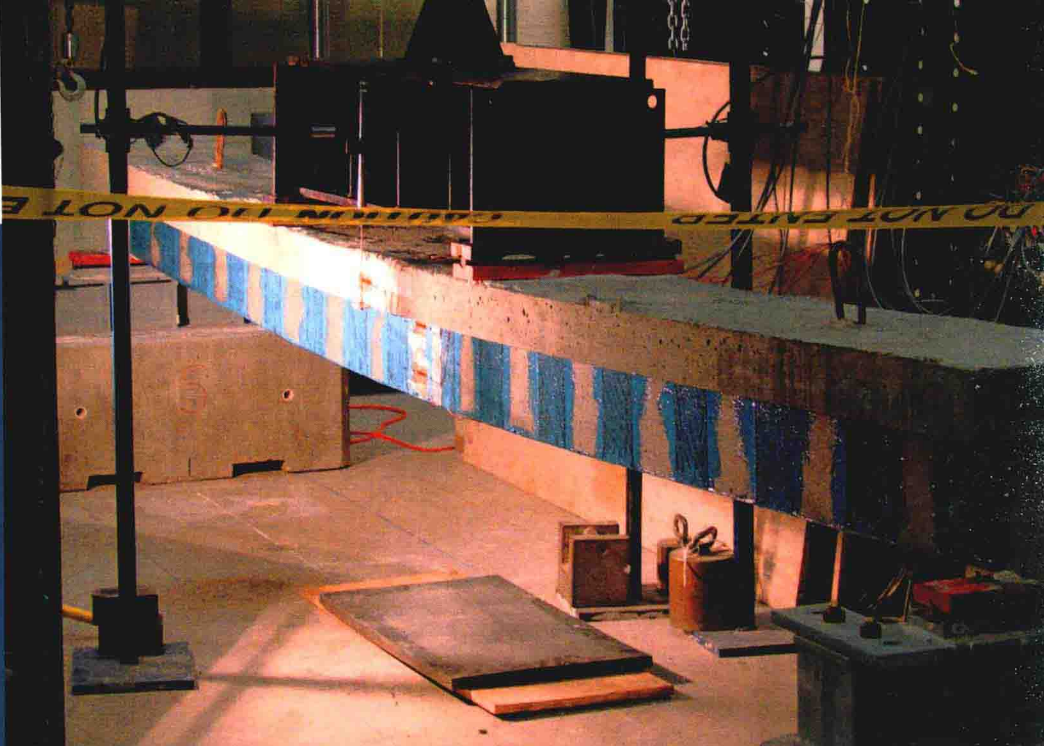
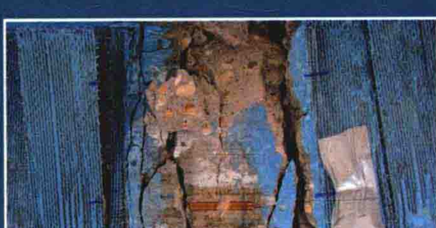


Strengthening Design of Reinforced Concrete with FRP




Hayder A. Rasheed

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Strengthening Design of Reinforced Concrete with FRP

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Composite Materials: Analysis and Design

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Dedication

To the memory of my
late father Abdul Sattar Rasheed
To my caring mother Ghania

Series Preface

Half a century after their commercial introduction, composite materials are of widespread use in many industries. Applications such as aerospace, windmill blades, highway bridge retrofit, and many more require designs that assure safe and reliable operation for 20 years or more. Using composite materials, virtually any property, such as stiffness, strength, thermal conductivity, and fire resistance, can be tailored to the user's needs by selecting the constituent materials, their proportion and geometrical arrangement, and so on. In other words, the engineer is able to design the material concurrently with the structure. Also, modes of failure are much more complex in composites than in classical materials. Such demands for performance, safety, and reliability require that engineers consider a variety of phenomena during the design. Therefore, the aim of the *Composite Materials: Design and Analysis* book series is to bring to the design engineer a collection of works written by experts on every aspect of composite materials that is relevant to their design.

The variety and sophistication of material systems and processing techniques have grown exponentially in response to an ever-increasing number and type of applications. Given the variety of composite materials available as well as their continuous change and improvement, understanding of composite materials is by no means complete. Therefore, this book series serves not only the practicing engineer, but also the researcher and student who are looking to advance the state of the art in understanding material and structural response and developing new engineering tools for modeling and predicting such responses.

Thus, the series is focused on bringing to the public existing and developing knowledge about the material–property relationships, processing–property relationships, and structural response of composite materials and structures. The series scope includes analytical, experimental, and numerical methods that have a clear impact on the design of composite structures.

Preface

The idea of writing this book emerged from a lack of detailed textbook treatments on strengthening design of reinforced concrete members with fiber-reinforced polymer (FRP) despite the large volume of research literature and practical applications that have been contributed since 1987. Even though two attempts to use glass-fiber-reinforced polymer (GFRP) to strengthen concrete members were made in Europe and the United States in the 1950s and 1960s, the technique wasn't successfully applied until 1987, when Ur Meier first strengthened concrete beams with carbon-fiber-reinforced-polymer (CFRP) laminates.

Knowledge in the area of FRP strengthening has matured, culminating with the introduction of specific design guidelines in Canada (ISIS Canada 2001), Europe (FIB Task Group 9.3 2001), and the United States (ACI 440.2R-02), the latter of which was significantly improved after six years in 2008 (ACI 440.2R-08). Today's structural engineer is entitled to a detailed textbook that establishes the art and science of strengthening design of reinforced concrete with FRP beyond the abstract nature of design guidelines. ACI 440.2R-08 provides better guidance than what is typically provided in codes of practice through its "design example" sections. Nevertheless, a textbook that treats the subject of FRP strengthening design with more depth is really needed to introduce it to the civil engineering curriculum.

This textbook has evolved from thorough class notes established to teach a graduate course on "strengthening design of reinforced concrete members with FRP" in spring of 2012 at Kansas State University. The course was widely attended by 18 on-campus senior level, master's level, and doctoral students as well as five distance-education students comprised of practicing engineers pursuing an MS degree. The course included four sets of detailed homework assignments, two term exams, and a research and development project for individuals or teams of two students, depending on the project scope and deliverables, evaluated through project proposals.

Even though the course covered a wide range of topics—from material characterization, flexural strengthening of beams and slabs, shear strengthening of beams, and confinement strengthening of columns, in addition to installation and inspection of FRP as externally bonded (EB) or near-surface-mounted (NSM) composite systems to concrete members—FRP anchorage, FRP strengthening in torsion, and FRP strengthening of prestressed members were left out of the scope of this first book edition. However, it is the intention of the author to add these and other topics to subsequent editions to allow for more selective treatments or more advanced courses to be offered based on this textbook.

The author would like to acknowledge his former graduate student Mr. Augustine F. Wuertz, who helped type a major part of the manuscript while at Kansas State

University. The author would also like to acknowledge Tamara Robinson for editing several chapters of this book as well as the Office of Research and Graduate Programs in the College of Engineering at Kansas State University for providing this editing service. The author would also like to thank Kansas State University for supporting his sabbatical leave during which this book was finalized.

Hayder A. Rasheed
Manhattan, Kansas, USA
Spring 2014

About the Author

Hayder A. Rasheed is professor of civil engineering at Kansas State University. Since 2013, he has held the title of the Thomas and Connie Paulson Outstanding Civil Engineering Faculty Award. Professor Rasheed received his BS degree and his MS degree in civil engineering majoring in structures from the University of Baghdad, Iraq in 1987 and 1990 respectively. In 1996, he received his PhD in civil engineering majoring in structures with a minor in engineering mechanics from the University of Texas at Austin. Professor Rasheed has four years of design and consulting experience in bridges, buildings, water storage facilities, and offshore structures. He spent three-and-a-half years as assistant professor of civil engineering and construction at Bradley University before moving to Kansas State in 2001. Between 2001 and 2013, he moved up the ranks at Kansas State. Since 2010, he has been a fellow of ASCE and a registered professional engineer in the state of Wisconsin since 1998. He authored and co-authored three books and more than 50 refereed journal publications. He developed a number of advanced engineering software packages. He also served as associate editor for the *ASCE Journal of Engineering Mechanics.* He is currently serving on the editorial board of the *International Journal of Structural Stability and Dynamics* and the *Open Journal of Composite Materials.*

Contents

1 Introduction

1.1 ADVANCEMENTS IN COMPOSITES

Fiber-reinforced polymer (FRP) composites are relatively new compared to conventional construction materials. These composites are manufactured by combining small-diameter fibers with polymeric matrix at a microscopic level to produce a synergistic material. FRP composites have been considered in aerospace applications since the mid-1950s, when they were used in rocket motor casings (Ouellete, Hoa, and Sankar 1986). Because of their light weight and design versatility, they have since entered structural systems in aerospace, automotive, marine, offshore drilling, and civil engineering applications, in addition to sporting goods such as skiing equipment, commercial boats, golf clubs, and tennis rackets (Jones 1975; Gibson 1994; ACI 440R-96 1996).

Typical structural elements made of advanced composites in fighter aircraft include horizontal and vertical stabilizers, flaps, wing skins, and various control surfaces, totaling weight savings of 20% (Gibson 1994). Other important structural elements are helicopter rotor blades. As for the use of advanced composites in commercial aircraft, they enter into the manufacturing of up to 30% of the external surface area (Gibson 1994). However, currently they are only conservatively used in secondary structures in large aircraft.

Advanced composites are used in a variety of additional industries as well. Structural systems constructed of graphite/epoxy composites in space shuttles include cargo bay doors and the solid rocket booster motor case (Gibson 1994). Typical structural elements made of composites in the automotive industry include leaf springs, body panels, and drive shafts (Gibson 1994). Typical pultruded structural shapes are used in lightweight industrial building construction to offer corrosion and electrical/thermal insulation advantages. Another use of advanced composites in civil engineering applications is in the building of lightweight, all-composite, honeycomb-core decks for rapid replacement of short-span bridges (Kalny, Peterman, and Ramirez 2004). Glass FRP (GFRP) reinforcing bars were produced using a pultrusion process created by Marshall Vega Corporation for use with polymer-based concrete in the late 1960s (ACI 440R-96), and these bars continue to improve in their characteristics, such as the addition of helically wound GFRP deformations for enhanced bonding to concrete.

1.2 INFRASTRUCTURE UPGRADE

The transportation infrastructure in the United States and worldwide is aging due to material deterioration and capacity limitations. Since complete rebuilding of such infrastructure requires a huge financial commitment, alternatives of prioritized strengthening and repair need to be implemented. One of the earliest techniques for repair and strengthening of concrete members, dating back to the mid-1970s, involved the use of epoxy-bonded external steel plates (Dussek 1980). However, in the mid-1980s, durability studies revealed that corrosion of external steel plates is a restrictive factor for widespread usage of this technique in external exposure (Van Gemert and Van den Bosch 1985).

A revolutionary advancement in the technique of external strengthening occurred when Meier replaced external steel plates with external carbon FRP (CFRP) plates in 1987. FRP is resistant to corrosion and has high strength-to-weight and high stiffness-to-weight ratios that provide efficient designs and ease of construction. FRP also has excellent fatigue characteristics and is electromagnetically inert. Accordingly, it is a viable replacement to steel in external strengthening applications. Since 1987, research in FRP strengthening techniques has developed an extensive volume of literature proving the effectiveness of the application. The ACI 440 Committee on Fiber Reinforced Polymer Reinforcement has twice reported on state-of-the-art advancements (ACI 440R-96; ACI 440R-07 2007). The same committee has produced two design documents for FRP externally bonded systems for strengthening applications (ACI 440.2R-02; ACI 440.2R-08 2008). The technology has matured to the point that it can be introduced to the structural engineering curriculum through the development of courses and textbooks.

1.3 BEHAVIOR OF STRENGTHENED REINFORCED CONCRETE BEAMS IN FLEXURE

Shallow beams are typically strengthened in flexure by externally bonding FRP plates or sheets on the tension face or soffit of the member, as shown in Figure 1.1. The fibers are oriented along the beam axis in the state-of-the-art application.

FIGURE 1.1 Strengthening the soffit of inverted reinforced concrete beam with CFRP.

Full composite action between the beam and FRP is usually assumed. However, this perfect bond typically depends on the shear stiffness of the interface adhesive (Rasheed and Pervaiz 2002). Most resin adhesives yield excellent bond characteristics with concrete and FRP, leading to perfect composite action. On the other hand, some resin adhesives have low lap shear stiffness, leading to bond slip between FRP and the concrete beam, thus reducing the composite action (Rasheed and Saadatmanesh 2002; Pervaiz and Ehsani 1990). With full composite action, glass FRP (GFRP) and aramid FRP (AFRP) do not increase the initial stiffness of the beam due to their relatively low modulus along the fiber direction. On the other hand, carbon FRP (CFRP) slightly increases the initial stiffness of the beam due to its high modulus along the fiber direction. Accordingly, this application is not used to stiffen the beams; instead, it is used to strengthen the beam due to the high strength of FRP materials available in practice, as shown in Figure 1.2.

Flexural failure modes may be classified as

1. FRP rupture failure after yielding of primary steel reinforcement. This failure mode typically takes place in lightly reinforced, lightly strengthened sections (Arduini, Tommaso, and Nanni [1997], Beam B2).
2. Concrete crushing failure after yielding of primary steel reinforcement. This failure mode typically occurs in moderately reinforced, moderately strengthened sections (Saadatmanesh and Ehsani [1991], Beam A).
3. Cover delamination failure primarily occurring after yielding of steel reinforcement. This failure mode initiates at the FRP curtailment due to stress

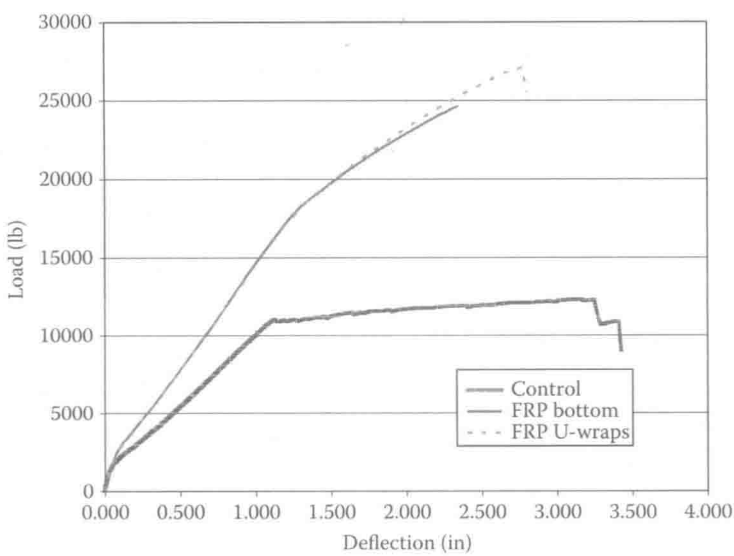

FIGURE 1.2 Response of unstrengthened and CFRP-strengthened identical beams showing limited stiffening compared to strengthening.

concentration at the plate or sheet tip. Once cracking starts at an angle, it changes to a horizontal crack parallel to steel reinforcement at the level of primary steel because the steel stirrups inside the beam arrest the inclined crack. The FRP and the entire concrete cover delaminates (e.g., Arduini, Tommaso, and Nanni [1997], Beam A3 and A4).

4. Plate or sheet debonding along the interface plane due to the intermediate crack mechanism typically after yielding of primary steel reinforcement when the flexural cracks widen. The horizontal crack occurs along the adhesive layer or parallel to it within the concrete cover. This failure mode is especially applicable to beams with end U-wrap anchorage, thus delaying failure in item 3 (e.g., Arduini, Tommaso, and Nanni [1997], Beam B3).
5. Concrete crushing failure for over-reinforced beams or cover delamination failure in beams with short FRP plates prior to primary steel yielding (e.g., Fanning and Kelly [2001], Beam F10).

Shallow beams may also be strengthened with near-surface-mounted (NSM) bars. This strengthening reinforcement is typically made of FRP bars or FRP tape inserted in near-surface cut grooves and then sealed with resin adhesive that fills the groove surrounding the bar or tape, as shown in Figure 1.3 (Rasheed et al. 2010).

FRP in this application behaves similarly to externally bonded FRP plates and sheets. However, failure modes are typically limited to

1. FRP rupture after yielding of primary steel.
2. Concrete crushing after yielding of primary steel.
3. Concrete crushing before yielding of primary steel

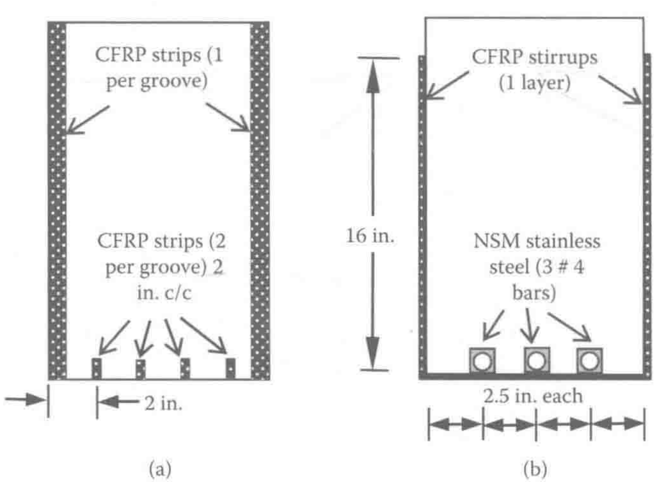

FIGURE 1.3 Strengthening identical beams with (a) CFRP tape and (b) NSM bars.