IN-LB	Inch-Pound Units
SI	International System of Units

Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide

Reported by ACI Committee 440

ACI PRC-440.2-23

American Concrete Institute
Always advancing

First Printing: November 2023
ISBN: 978-1-64195-233-0

Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

ACI PRC-440.2-23

Design and Construction of Externally Bonded Fiber-Reinforced Polymer (FRP) Systems for Strengthening Concrete Structures—Guide

Reported by ACI Committee 440

Maria Lopez de Murphy, Chair

John J. Myers, Secretary

Ehab Ahmed
Tarek Alkhrdaji
Charles E. Bakis
Abdeldjelil Belarbi
Brahim Benmokrane
Luke A. Bisby
Gregg J. Blaszak
Hakim Bouadi
Timothy E. Bradberry
Vicki L. Brown
John P. Busel
Lijuan Cheng

Raafat El-Hacha
Ehab F. El-Salakawy
Garth J. Fallis
Amir Z. Fam
Russell Gentry
Will J. Gold
Nabil F. Grace
Mark F. Green
Doug D. Gremel
Shawn P. Gross
Issam E. Harik
Kent A. Harries[†]

Mark P. Henderson
Ravi Kanitkar[*]
Yail Jimmy Kim
Michael W. Lee
Eric MacFarlane
Radhouane Masmoudi
Antonio Nanni
Ayman M. Okeil
Carlos E. Ospina
Maria Anna Polak
Max L. Porter
Hayder A. Rasheed

Sami H. Rizkalla
Rajan Sen
Rudolf Seracino
Venkatesh Seshappa
Xavier Seynave
Carol K. Shield
Pedro F. Silva
Jay Thomas
J. Gustavo Tumialan
David White
Sarah E. Witt

[*]Chair of the subcommittee that prepared this document
[†]Former Chair of the subcommittee that prepared this document

Consulting Members

P. N. Balaguru
Lawrence C. Bank
C. J. Burgoyne
Rami M. Elhassan
David M. Gale
Srinivasa L. Iyer
Koichi Kishitani

Howard S. Kliger
Ibrahim M. Mahfouz
Kyuichi Maruyama
Amir Mirmiran
Antoine E. Naaman
Hajime Okamura
Mark A. Postma

Surendra P. Shah
Mohsen Shahawy
Yasuhisa Sonobe
Minoru Sugita
Luc R. Taerwe
Houssam A. Toutanji
Taketo Uomoto

Paul Zia[‡]
Liaison Members
Scott Thomas Smith
Matthew J. Chynoweth

The committee acknowledges W. Ghannoum, W. Shekarchi, and J. Tatar for their contributions to this guide.

[‡]Deceased.

Fiber-reinforced polymer (FRP) systems for strengthening concrete structures are an alternative to traditional strengthening techniques such as steel plate bonding, section enlargement, and external post-tensioning. FRP strengthening systems use FRP composite materials as supplemental externally bonded or near-surface-mounted (NSM) reinforcement. FRP systems offer advantages over traditional strengthening techniques: they are lightweight, relatively easy to install, and noncorroding. Due to the characteristics of FRP systems as well as the behavior of members strengthened with FRP, specific guidance on the use of these systems is needed. This guide provides general information on the history and use of FRP strengthening systems; a description of the material properties of FRP; and recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. This guide is based on the knowledge gained from experimental

ACI PRC-440.2-23 supersedes ACI 440.2R-17 and was published November 2023. This guide was first published in 2017 and revised in 2023.

research, analytical work, and field applications of FRP systems used to strengthen concrete structures.

Keywords: aramid fibers; basalt fibers; bridges; buildings; carbon fibers; corrosion; cracking; development length; earthquake resistance; fiber-reinforced polymers; glass fibers; structural design.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The strengthening or retrofitting of existing concrete structures to resist higher design loads, correct strength loss due to deterioration, correct design or construction deficiencies, or increase ductility has traditionally been accomplished using conventional materials and construction techniques, including externally bonded steel plates, steel jackets, concrete section enlargement, and external post-tensioning.

Composite materials made of fibers in a polymeric resin, also known as fiber-reinforced polymers (FRPs), have emerged as a viable option for repair and rehabilitation. For the purposes of this guide, an FRP system is defined as the fibers and resins used to create the composite laminate, all applicable resins used to bond it to the concrete substrate, and all coatings applied to protect the constituent materials. Coatings used exclusively for aesthetic reasons are not considered part of an FRP system.

FRP materials are lightweight, noncorroding, and exhibit high tensile strength. These materials are readily available in several forms, ranging from factory-produced pultruded laminates to fabric reinforcement sheets that can be wrapped to conform to the geometry of a structure. The relatively thin profiles of cured FRP systems are often desirable in applications where aesthetics or access is a concern and FRP systems add little weight to a structure. FRP systems can also be used in areas with limited access where traditional techniques would be difficult to implement.

The basis for this document is the knowledge gained from a comprehensive review of experimental research, analytical work, and field applications of FRP strengthening systems. Areas where further research is needed are highlighted and compiled in Appendix B.

This version includes several revisions to ACI 440.2-17 as outlined herein. Basalt FRP (BFRP) is now included in the commercially available materials for FRP systems. The methodology for calculating FRP system mechanical properties has been revised in Section 4.3. Fatigue behavior of FRP systems has been updated to reflect recent research. Chapter 7 for field inspection, testing, and evaluation of FRP systems has been revised to be consistent with industry standards and specifications such as the IBC, ACI SPEC-440.12, and ACI CODE-562. The applicability of FRP systems for strengthening lightweight concrete is addressed in Section 9.1.1. In Section 9.2.1, the load combination for minimum structural fire resistance of a member for FRP strengthening has been revised to be consistent with ACI CODE-562. Sections 10.3.2 and 16.14 have been added to address FRP strengthening of members with unbonded prestressing steel. Fiber anchors for anchoring FRP U-wraps for shear strengthening are introduced in Sections 11.4.1.2 and 14.1.4. Section 13.7 for seismic strengthening of shear walls has been revised to include guidance for detailing of the FRP and for confinement of boundary elements in plastic hinge regions.

1.1.1 *Use of FRP systems*—This document refers to commercially available FRP systems consisting of fibers and resins combined in a specific manner and installed by a specific method. These systems have been developed through material characterization and structural testing. Untested combinations of fibers and resins could result in an unexpected range of properties as well as potential material incompatibilities and should be avoided. Any FRP system considered for use should have sufficient test data to demonstrate adequate performance of the entire system in similar applications, including its method of installation. ACI 440.8 provides a specification for unidirectional carbon and glass FRP systems made using the wet layup process.

The use of FRP systems developed through material characterization and structural testing, including well-documented proprietary systems, is recommended. A comprehensive set of test standards and guides for FRP systems has been developed by several organizations, including ASTM International, ACI, the International Concrete Repair Institute (ICRI), and the International Code Council (ICC).

1.1.2 *Sustainability*—Sustainability of FRP materials and systems may be evaluated considering environmental, economic, and social goals. These should be considered not only throughout the construction phase, but also through the service life of the structure in terms of maintenance and preservation, and for the end-of-life phase. This represents the basis for a life-cycle approach to sustainability (Menna et al. 2013). Life cycle assessment (LCA) takes into account the environmental impact of a product, starting with raw material extraction, followed by production, distribution, transportation, installation, use, and end of life. LCA for FRP composites depends on the product and market application, and results vary. FRP composite materials used to strengthen concrete elements can use both carbon fiber and glass fiber, which are derived from fossil fuels or minerals, respectively, and therefore have impacts related to raw material extraction. Although carbon and glass fibers have high embodied energies associated with production, on the order of 86,000 btu/lb and 8600 btu/lb (200 and 20 mJ/kg), respectively (Howarth et al. 2014), the overall weight produced and used is orders of magnitude lower than steel (having embodied energy of 5600 Btu/lb [13 mJ/kg]), concrete (430 Btu/lb [1 mJ/kg]), and reinforcing steel (3870 Btu/lb [9 mJ/kg]) (Griffin and Hsu 2010). The embodied energy and potential environmental impact of resin and adhesive systems are less studied, although the volume used is also small in comparison with conventional construction materials. In distribution and transportation, FRP composites' lower weight leads to less impact from transportation, and easier material handling allows smaller equipment during installation. For installation and use, FRP composites are characterized as having a longer service life because they are more durable and require less maintenance than conventional materials. The end-of-life options for FRP composites are more complex.

Although less than 1% of FRP composites are currently recycled, composites can be recycled in many ways, including mechanical grinding, incineration, and chemical separation (Howarth et al. 2014). However, separating the materials, fibers, and resins is difficult; therefore, the properties of the resulting recycled materials are generally of a lower grade than the source material.

Apart from the FRP materials and systems themselves, their use in the repair and retrofit of structures that may otherwise be decommissioned or demolished is inherently sustainable. In many cases, FRP composites permit extending the life or enhancing the safety or performance of existing infrastructure at monetary and environmental costs of only a fraction of those for replacement. Additionally, due to the high specific strength and stiffness of FRP composites, an FRP-based repair of an existing concrete structure will often represent a less energy-intensive option than a cementitious or metallic-based repair.

Within this framework of sustainability, FRP retrofit of existing structures may lead to benefits, contributing to the longevity and safety of retrofitted structures. Thus, FRP retrofit can be regarded as a viable method for sustainable design for strengthening and rehabilitation of existing structures (Maxineasa and Taranu 2018; Napolano et al. 2015). The environmental advantages of FRP, as evaluated by LCA investigations, have been enumerated by Moliner Santisteve et al. (2013), Zhang et al. (2012), and Das (2011).

1.2—Scope

This document provides guidance for the selection, design, and installation of externally bonded and near-surface-mounted (NSM) FRP systems for strengthening concrete structures. Information on material properties, design, installation, quality control, and maintenance of FRP systems used as external or NSM reinforcement is presented. This information can be used to select an FRP system for increasing the strength, stiffness, or both, of reinforced concrete members or the ductility of columns.

A significant body of research serves as the basis for this guide. This research, conducted since the 1980s, includes analytical studies, experimental work, and monitored field applications of FRP strengthening systems. Based on the available research, the design procedures outlined herein are considered conservative.

The durability and long-term performance of FRP systems have been the subject of much research which remains ongoing. The design guidelines in this document account for environmental degradation and long-term durability by providing reduction factors for various environments. Fatigue and creep are also addressed by stress limitations indicated in this document. As more research becomes available, these factors may be modified, and the specific environmental and loading conditions to which they apply will be better defined. Additionally, the coupling effect of environmental exposure and loading conditions requires further study. Caution is advised in applications where the FRP system is subjected simultaneously to extreme environmental and stress conditions.

Many issues regarding bond of the FRP system to the substrate remain the focus of a great deal of research. For both flexural and shear strengthening, there are different modes of debonding failure that can govern the strength of an FRP-strengthened member. While most of the debonding modes have been identified by researchers, more accurate methods of predicting debonding are still needed. Throughout the design procedures, significant limitations on the strain permitted in the FRP system (and thus, the permitted stress) are imposed to conservatively account for debonding failure modes. Future development of these design procedures should include more thorough methods of predicting debonding.

This document gives guidance on proper detailing and installation of FRP systems to prevent many types of debonding failure modes. Steps related to the surface preparation and proper termination of the FRP system are vital in achieving the levels of strength predicted by the procedures in this document. Research has been conducted on various methods of anchoring FRP strengthening systems, such as U-wraps, mechanical fasteners, fiber anchors, and U-anchors. This document contains design provisions for the use of fiber anchors for shear strengthening with FRP U-wraps. For other anchorage systems and applications, few design guidelines are currently available. The performance of any such anchorage system should be substantiated through representative physical testing that includes the specific anchorage system, installation procedure, surface preparation, and expected environmental conditions.