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Report on the Modeling Techniques Used in Finite Element Simulations of Concrete Structures Strengthened Using Fiber-Reinforced Polymer (FRP) Materials

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

www.concrete.org

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Jian Zhao, Secretary

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Kaspar J. Willam

*Primary author.

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The strengthening of reinforced concrete (RC) members using fiber-reinforced polymers (FRPs) as externally bonded reinforcement has been widely used to enhance the flexural, shear, and axial capacity, or any combination thereof, of structural elements. Although experimental testing has been used predominantly as the sole method of investigation, numerical techniques such as the finite element (FE) method have also been gradually developed to provide predictive models for structural characterization. Well-calibrated FE models have the potential to expand the range of experimental data, provide information on important parameters difficult to measure using experimental instrumentation, and aid in the design of systems requiring complex FRP strengthening where testing may not be possible. This report provides a state-of-the-art review in the area of modeling of FRP-strengthened RC members and provides general guidelines on the best modeling practices that capture the complex phenomenon of concrete cracking and crushing, concrete shear retention, concrete fracture energy, steel-to-concrete bond behavior, FRP-to-concrete interface, FRP debonding failure modes, and FE mesh dependency.

Keywords: bond; fiber-reinforced polymer; finite element modeling; fracture energy; interface; reinforced concrete; shear retention.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Alongside the escalating demand to increase the strength of existing structures, new strengthening technologies have evolved such as fiber-reinforced polymer (FRP) materials, which can be used as externally bonded reinforcement. Fiber-reinforced polymer is used not only to increase strength, but also to increase stiffness and provide confinement in existing structures. The technology has found significant success in applications to reinforced concrete (RC) and post-tensioned (PT) structures due to the FRP's strength-to-weight ratio, stiffness-to-weight ratio, excellent durability performance, resistance to corrosion, cost-effectiveness, ability to conform to various shapes, and ease of application.

Fibers are most commonly manufactured using carbon, glass, aramid, and basalt, and are produced in the form of loosely woven mats, pultruded laminates, or bars that are applied to structural elements using high-strength epoxy resins (ACI 440.2R). Research has demonstrated that the use of externally-bonded FRP composites can improve the flexural, shear, torsional, and axial performance of concrete members. In spite of their potential benefits, complete fiber use is often not realized due to the occurrence of premature debonding, which can take one of several forms: concrete cover separation failure; plate-end interfacial debonding; intermediate flexural; or flexural-shear, crack-induced interfacial debonding that is otherwise known as IC debonding (Hollaway and Teng 2008), and shear-induced debonding (also referred to as critical diagonal crack (CDC) debonding [Wang and Zhang 2008]). However, debonding failures involve complex mechanisms and remains a subject of research.

Extensive numerical studies using the finite element (FE) method have been conducted to simulate the various modes of FRP debonding (Kotynia et al. 2008). Finite element simulations have the potential to provide a predictive model for structural failure, expand the range of experimental data, and provide information on key phenomena in the absence of experimental data (Zhang and Teng 2014). However, the simulation of FRP-strengthened RC members is numerically demanding due to the complex nature of concrete, as well as the bond between the externally-bonded FRP and concrete and the relative size of the bond critical zone to the overall member size. As a result, a variety of material models and modeling techniques have been introduced by researchers to quantify the concrete material behavior, the bond properties between the concrete and steel reinforcement, and the bond properties between the FRP and concrete resulting in numerical predictions to various degrees of correlation with experimental data.

1.2—Scope

This report summarizes the latest research for the FE modeling techniques of FRP-strengthened RC members, and attempts to provide general guidelines and recommendations on the best modeling practices that capture the complex phenomenon of concrete cracking and crushing, concrete shear retention, concrete fracture energy, steel-to-concrete bond behavior, FRP-to-concrete interface, FRP debonding failure modes, and issues related to FE mesh dependency.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_g = aggregate size
c = cohesion
f_c' = compressive strength of concrete
f_{ct} = tensile strength of concrete
G_c = shear modulus of concrete
G_F^I = Mode I concrete fracture energy
G_F^{II} = Mode II concrete fracture energy
G_F^{III} = Mode III concrete fracture energy
K_{tt} = tangential stiffness of bond slip curve