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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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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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CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2
1.1—Introduction, p. 2
1.2—Scope, p. 2

CHAPTER 2—NOTATION AND DEFINITIONS, p. 2
2.1—Notation, p. 2
2.2—Definitions, p. 3

CHAPTER 3—FINITE ELEMENT MODELING APPROACHES FOR FRP-STRENGTHENED RC MEMBERS, p. 3
3.1—Modeling concrete compression, p. 3
3.2—Modeling of concrete cracking, p. 3
3.3—Defining concrete fracture energy, p. 4
3.4—Influence of shear retention factor, p. 4
3.5—Effect of bond between steel reinforcement and concrete, p. 5
3.6—Modeling of FRP-to-concrete interface, p. 5
3.7—Influence of mesh size and element type, p. 6
3.8—Modeling FRP sheets and fabrics, p. 7
3.9—Calibration of material parameters, p. 8

CHAPTER 4—EXISTING STUDIES ON THE NUMERICAL MODELING OF DEBONDING FAILURE IN FRP-PLATED RC MEMBERS, p. 8
4.1—Finite element (FE) simulations of debonding failure models for beams strengthened in flexure, p. 8
4.2—Modeling of shear-strengthened RC members using FRP, p. 10
4.3—Reinforced concrete members strengthened in torsion using FRP, p. 13
4.4—Modeling of FRP-to-concrete joints, p. 14
4.5—Axially strengthened RC columns using FRP, p. 15

CHAPTER 5—CONCLUSIONS AND RECOMMENDED MODELING APPROACHES FOR FIBER-REINFORCED, POLYMER-STRENGTHENED REINFORCED CONCRETE MEMBERS, p. 16

CHAPTER 6—REFERENCES, p. 16
Authored documents, p. 16

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

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L = length
L_{ch} = crack band width used to calculate shear retention factor
r_g = shear retention factor
s_i = slip at location i, in bond slip curve of FRP to concrete interface
s_F = shear factor coefficient relating the normal and shear stiffness of a crack
t_f = thickness of FRP plate
ν = Poisson's ratio
ε_F = normal crack opening strain
$\varepsilon_{f,i}$ = fiber-reinforced polymer strains measured in the direction of the fibers at location i
$\varepsilon_{f,i+1}$ = fiber-reinforced polymer strains measured in the direction of the fibers at location i+1
σ = normal stress within FRP to concrete interface
ϕ = friction coefficient
τ = shear stress at location i, in bond slip curve of FRP to concrete interface

2.2—Definitions

Please refer to the latest version of "ACI Concrete Terminology" for a comprehensive list of definitions.

CHAPTER 3—FINITE ELEMENT MODELING APPROACHES FOR FRP-STRENGTHENED RC MEMBERS

3.1—Modeling concrete compression

This chapter outlines some of the challenges facing researchers to numerically quantify the behavior of various materials such concrete, FRP, adhesive, and their interaction using the FE method.

Concrete is a quasi-brittle heterogeneous material that can incur tensile cracking and compressive crushing. The compressive response of concrete is highly nonlinear and can be described numerically using several approaches: 1) representation of the stress-strain behavior by curve-fitting methods (Chen 2007); 2) linear and nonlinear elasticity theories (Ortiz 1985); 3) elastoplastic models (Han and Chen 1985; Grassl et al. 2002); and 4) the endochronic theory of plasticity (Bažant 1978). Of the available approaches used to represent the stress-strain behavior of concrete under multiaxial stress states, damage plasticity models have become the most popular; however, success has also been achieved using other approaches (Wong and Vecchio 2003). Damage plasticity models apply the plasticity theory in the compression zone and fracture mechanics to represent the damage behavior due to cracking. The plasticity theory captures the accumulation of irreversible strains resulting from loading beyond the yield limit. The yield limit in concrete is defined as the compressive strain level beyond which behavior ceases to be linear elastic and permanent deformation occurs. Plasticity models are also useful for the modeling of concrete subjected to triaxial stress states because the yield surface at a certain stage of hardening can be correlated with the strength envelope of concrete. Furthermore, the total concrete strain is usually split into elastic and plastic components, which has been found to realistically represent the observed deformations in confined compression so that unloading can be described well (Grassl et al. 2013). When defining the parameters of concrete compressive strength within a numerical model, standard test procedures, such as crushing of concrete cylinders or cubes, should always be used to determine the average concrete compressive strength that is representative of the concrete used. The Poisson's ratio of concrete has been found to range between 0.2 (AS 3600-2009; BS EN 1992-1-1:2005) to 0.15 (CEB-FIB Model Code 2010/2012) for normal-strength concretes. Further, ACI 363R reports that Poisson's ratio for high-strength concrete within the elastic range is comparable to the expected values for normal-strength concrete.

3.2—Modeling of concrete cracking

The tensile behavior of concrete is considered as approximately linear elastic until fracture is reached, resulting in a sudden loss of strength. Concrete cracking is a highly localized phenomenon that can be modeled using either discrete crack or smeared crack models.

3.2.1 *Discrete crack models*—Discrete crack models rely on simulating individual cracks as geometrical identities within a model by introducing discontinuities within an FE mesh at element boundaries. As a result, crack location and orientation are dependent on the geometry and topology of the mesh that inevitably introduces mesh bias. To capture crack propagation, a continuous change in nodal connectivity is required, which is inconsistent with the nature of the FE displacement method (Rots and Blaauwendraad 1989). This drawback can be overcome by introducing automatic remeshing algorithms; however, these approaches are demanding on computational resources (Rabczuk et al. 2008) and plagued by numerical difficulties associated with topology changes due to remeshing (Chen et al. 2012). Higher success has been achieved by incorporating interface elements within the original mesh along predefined locations of potential cracking. Using this approach, the discrete cracks are mobilized by assigning interface elements with crack initiation criteria such as a stress violation condition, which is where the interface properties are changed when a maximum stress limit is reached using a constitutive model. Modeling approaches include predefining the potential crack locations at all element boundaries (as opposed to a limited number of probable crack locations) and permitting the fracture to propagate anywhere between the element boundaries (De Borst 1997).

3.2.2 *Smeared crack models*—In the smeared crack models, the cracked material is treated as a continuum and the deterioration caused by the crack is spread across the element by changing the element stiffness. In general, the smeared crack approach has grown more popular and demonstrated greater advantages than the discrete crack method. However, the smeared crack strategy tends to spread crack formation over a band of elements and fails to predict localized fracture (Kalfat 2014). Smeared crack models can be divided into two main categories—fixed and rotating. Fixed crack models use a constant crack orientation during the entire computational process. In rotating crack models, however,

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