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

Reported by Joint ACI-ASCE Committee 447

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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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Ganesh Thiagarajan, Chair

Jian Zhao, Secretar

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Syed Mizanur Rahman
Victor E. Saouma
Frank J. Vecchio
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

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, the crack direction changes during loading in accordance with the principal stress directions. Important limitations of the fixed-smeared crack model have been discovered relating to excessive stress rotation where rotation of the axes of principal stress ceases to coincide with the axes of principal strain and stress buildup after cracking when relatively high shear retention factors are employed, resulting in models that are too stiff (Rots and Blaauwendraad 1989). Shear retention refers to the ability of a concrete crack to transfer shear stresses across its width due to the presence of aggregate interlock. Researchers have found that acceptable fixed crack results can only be achieved when a near-zero shear retention factor is used, as this has been found to reduce the excessive stress rotation. In contrast, the rotating smeared crack concept provides acceptable stress/strain rotations and a better prediction of model stiffness because of the shear retention function that provides coaxiality between the principal stresses and strains. One disadvantage of the general rotating crack concept is its inability to retain memory of damage orientation, which can lead to errors when inactive cracks are erased from the model on activation of new cracks. This is particularly problematic when the model is subjected to loading and unloading, or when the loading in multiple directions is not proportional to each other (Rots and Blaauwendraad 1989). However, in some of the newer models such as Moharrami and Koutromanos (2016), this has been resolved. This also has been overcome to some extent by the introduction of various plastic damage models developed for the purpose of retaining plastic damage development (magnitude and orientation) in rotating crack procedures, such as Vecchio and Bucci (1999).

3.2.3 *Discrete crack versus smeared crack approach*—Using appropriate modeling techniques, researchers have successfully replicated the various failure modes of FRP-strengthened RC beams and the modes of FRP debonding obtained from experimental tests. Both intermediate crack-induced debonding (shearing of concrete along the bond surface from the tip of a diagonal crack) and concrete cover separation failure (shearing of concrete along the tension reinforcement level) have been successfully simulated using both smeared and discrete crack methods with good correlations with the experimental data; it was demonstrated that both crack modeling approaches could yield similar results (Pham et al. 2006). This observation was also confirmed by Chen et al. (2011) who demonstrated that when the crack band model is adopted, the discrete crack and smeared crack models yield approximately the same results, provided that the crack opening displacement in the discrete crack model is taken as the cracking strain accumulated over the width of the crack band in a smeared crack model. This will overcome strain localization and mesh objectivity problems present in early smeared crack models (Bažant and Planas 1998).

For accurate modeling of RC members retrofitted with FRP composites, including debonding failure modes, modeling of localized shear and flexural cracking is imperative. To accurately model discrete cracks using the smeared crack methodology, Chen et al. (2011) summarized three criteria that have to be fulfilled: 1) the constitutive model for cracked concrete has to be accurate and realistically capture the post-cracking behavior of concrete; 2) an accurate bond-slip model representing the bond behavior between concrete and FRP has to be defined; and 3) an accurate bond-slip model between the internal steel reinforcement and the concrete should be defined. Without all the above criteria being fulfilled, the FE model cannot be relied on to provide a realistic prediction of results.

3.3—Defining concrete fracture energy

To determine the load at which FRPs debond from the concrete substrate using fracture mechanics principles, the single most important parameter is the concrete fracture energy G_f. Fracture energy is defined as the energy required to open a unit area of crack surface. The fracture energy can be calculated using the area under the descending branch of the bond-slip curve. Fracture mechanics have demonstrated three modes in which a crack can propagate: Mode-I fracture (G_F^I) is classified as an opening mode where the tensile stresses are normal to the plane of the crack. Mode-II (G_F^{II}) is a sliding mode where crack propagation is propelled by shear stresses acting parallel to the plane of the crack and normal to the crack front. Mode-III fracture (G_F^{III}) is classified as a tearing mode with shear stresses acting parallel to the crack plane and parallel to the crack front. Research into FRP debonding has proven that, despite the FRP-to-concrete interfacial bond stresses being predominantly through shear, the initiation of debonding is still regarded as a Mode-I fracture of concrete (Achintha and Burgoyne 2013). Furthermore, researchers have investigated the use of both Mode-I and Mode-II fracture energy values in various numerical simulations and concluded that Mode-I fracture energy gives strength predictions that result in closer correlations with the test results in the majority of cases (Aram et al. 2008; Chen et al. 2011; Zhang and Teng 2014).

Currently available Mode-I fracture energy correlations are empirical formulations derived from experimental procedures (Bažant and Planas 1998). Consequently, most fracture energy models are based on maximum aggregate size, concrete strength, and water-cement ratio (*w*/*c*) (Van Mier 1997; Trunk and Wittmann 1998; Neubauer and Rostasy 1999; Bažant and Becq-Giraudon 2002; Ulaga et al. 2003; Elsayed et al. 2007; Freddi and Savoia 2008). Such models may be used in numerical simulations in the absence of experimental data. However, a preferred approach is to use standard test procedures such as a notched beam test (JCI-S-001 2003) to obtain a more accurate estimation of concrete fracture energy. Further, Hoover and Bažant (2014) investigated the effect of varying member sizes on the fracture process zone and found it to be mode-dependent, and that the impact can be eliminated only when the test is conducted at a variety of member sizes. This should be considered when developing experimental procedures to estimate concrete fracture parameters.

3.4—Influence of shear retention factor

Shear retention in concrete refers to the ability of a concrete crack to transfer shear stresses across its width. Shear transfer is dependent on the crack width and aggregate