Computers and Structures 117 (2013) 105–117

Contents lists available at SciVerse ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Three-dimensional meso-scale finite element modeling of bonded joints between a near-surface mounted FRP strip and concrete

J.G. Teng [a,*], S.S. Zhang [a], J.G. Dai [a], J.F. Chen [b]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[b] Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh, EH9 3JL, Scotland, UK

ARTICLE INFO

Article history:
Received 20 March 2012
Accepted 3 December 2012
Available online 27 December 2012

Keywords:
Three-dimensional (3-D) analysis
Meso-scale modeling
Finite element (FE) modeling
Near surface mounted (NSM) FRP
Strip
Bond behavior

ABSTRACT

This paper presents a three-dimensional (3-D) meso-scale finite element (FE) model for near-surface mounted (NSM) FRP strip-to-concrete bonded joints established using the general-purpose FE software package MSC.MARC. In the FE model, elements of the order of 1 mm in size are employed. The concrete is simulated using the orthogonal fixed smeared crack model while the FRP and the adhesive are treated as linear brittle-cracking materials. The FE model is calibrated and verified using results of well-documented bonded joint tests. Using the verified FE model, the failure process of NSM FRP strip-to-concrete bonded joints is carefully studied; furthermore, the local bond stress distributions and the bond-slip relationships are extracted and analyzed. This 3-D meso-scale FE model offers a powerful tool for deployment in further investigations to establish bond-slip models and bond strength models for NSM FRP strip-to-concrete bonded interfaces. While the present study is focused on NSM FRP strips, the proposed modeling approach is generally applicable to NSM FRP bars of other cross-sectional shapes.

1. Introduction

Reinforced concrete (RC) members can be strengthened with near-surface mounted (NSM) FRP bars of various cross-sectional shapes [1]. Over recent years, the NSM FRP strengthening method has become an attractive alternative to the popular technique of externally bonded FRP plates/sheets [2]. To develop a reliable design theory for the NSM FRP technique, a fundamental issue to clarify is the bond behavior between NSM FRP and concrete. The conventional approach for studying this bond behavior is to conduct tests on NSM FRP-to-concrete bonded joints (simply referred to as bonded joints for simplicity where appropriate) [3–8]. However, test data of NSM FRP-to-concrete bonded joints are still very limited compared with those available for externally bonded FRP reinforcement.

The behavior of NSM FRP-to-concrete bonded joints is more complicated than that of externally bonded FRP-to-concrete joints as the former depends on many more parameters including the material, shape, surface configuration and size of the NSM FRP bar, the shape and size of the groove, and the properties of both the concrete substrate and the adhesive filler (generally an epoxy). As a result, it is very difficult to achieve a comprehensive understanding of the effects of all these factors on the bond behavior between NSM FRP and concrete through (exhaustive) laboratory tests only. In addition, it is highly challenging if not impossible to accurately capture the local details of bond behavior between NSM FRP and concrete in a laboratory test (e.g. the local bond-slip response) due to difficulties in placing strain gages on the NSM FRP bar without disturbing the bond properties; this is in contrast to externally bonded FRP plates/sheets where strain gages can be attached to their surface to monitor the local bond behavior. Given the above considerations, reliable finite element (FE) studies are very attractive to supplement experimental studies in understanding the bond behavior between NSM FRP and concrete.

A review of the existing literature indicates that an accurate FE model for NSM FRP-to-concrete bonded joints, with sufficient details in terms of constitutive laws for the constituent materials, is not yet available. Lundqvist et al. [9] used the damaged plasticity model for concrete to study the anchorage length of NSM FRP strips in beam pull-out tests but did not succeed in predicting the failure loads of the tests because the analysis stopped prematurely due to numerical problems. Lundqvist et al. [10] examined only the linear elastic behavior of NSM FRP-to-concrete bonded joints. In other existing studies e.g. [3,11], interface elements with an assumed bond-slip relationship were used to simulate the behavior of NSM FRP-to-concrete bonded joints; these FE models are not truly predictive as their predictions depend on the bond-slip relationship adopted for the FE model.

In contrast to the lack of FE studies on NSM FRP-to-concrete bonded joints, extensive research has been undertaken on externally bonded FRP-to-concrete bonded joints e.g. [12–14]. This work

* Corresponding author.
E-mail address: cejgteng@polyu.edu.hk (J.G. Teng).

0045-7949/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruc.2012.12.002

has shown convincingly that a reliable FE model employing elements of very small sizes (referred to as meso-scale elements) can be a powerful and economical alternative to laboratory testing to gain a full understanding of the complex behavior of FRP-to-concrete bonded joints and to generate numerical results for the development of a local bond-slip relationship model. Lu et al. [12] developed the first reliable 2-D meso-scale FE model using elements of the order of 0.5 mm and an orthogonal fixed smeared crack model to simulate the local bond-slip behavior and local failure process of externally bonded FRP-to-concrete bonded joints. Adopting a similar approach, this paper presents a 3-D meso-scale FE model for NSM FRP-to-concrete bonded joints. The present paper is focused on the FE modeling of bonded joints between NSM FRP strips (i.e. bars of narrow rectangular section) and concrete for the simulation of failure process and the prediction of the local bond-slip relationship, although the proposed modeling techniques can also be employed to model the bond behavior of NSM FRP bars of other cross-sectional shapes.

2. Bond tests and FE modeling

2.1. Bond test methods

Two popular bond test methods have been adopted by researchers to investigate the bond behavior of FRP bars near-surface mounted to concrete: (1) the beam pull-out test, and (2) the direct pull-out test. The beam pull-out test for NSM FRP bars was derived from the pull-out bending test for assessing the bond characteristics of conventional steel bars and was used to study the bond behavior of NSM FRP bars by Nanni et al. [15]. The direct pull-out test is conducted on a concrete block embedded with an NSM FRP bar and is usually conducted under displacement control. The direct pull-out test setup has three main variations: traditional one-side direct pull-out test e.g. [4,6], two-side direct pull-out test e.g. [16], and C-shaped block direct pull-out test e.g. [3]. In the present study, the NSM CFRP strip-to-concrete bonded joint specimens analyzed are from Li et al. [6], in which the one-side direct pull-out test approach (Fig. 1) was adopted. These specimens were selected for analysis because all needed details of the tests including the measured strain distributions of the FRP strip are readily available to the authors.

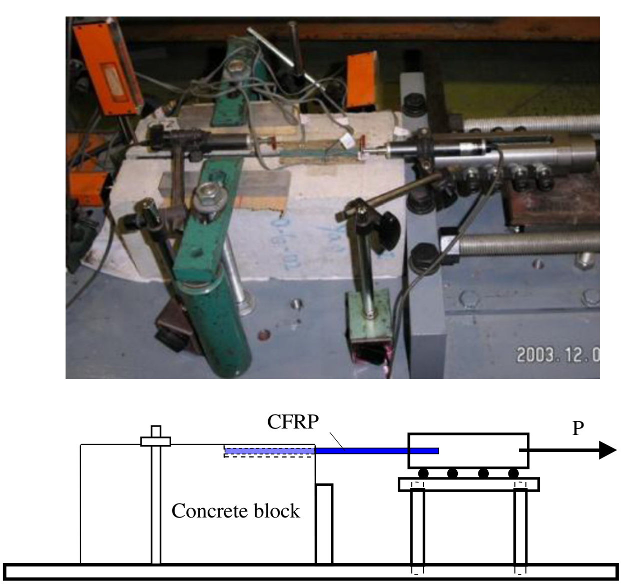

Fig. 1. Test setup of Li et al. [6].

2.2. Li et al.'s pull-out tests

A total of five NSM CFRP strip-to-concrete bonded joints were tested by Li et al. [6], with the bond lengths being 30 mm, 100 mm, 150 mm, 200 mm and 250 mm respectively. The concrete block had a square section of 150 mm × 150 mm and a length of 350 mm, and the bonded region of the NSM strip started at 50 mm away from the loaded end (Fig. 1). The groove size had a design width w_g of 8 mm and a design height h_g of 22 mm, but post-preparation measurements indicated that the actual values were about 9 mm and 22 mm.

The concrete had an averaged cube compressive strength f_{cu} of 29 MPa. The cylinder compressive strength f_c can be estimated from

$$f_c = 0.8 f_{cu} \tag{1}$$

and the tensile strength f_t can be estimated as [17]

$$f_t = 1.4\left(\frac{f_c - 8}{10}\right)^{\frac{2}{3}} \tag{2}$$

The groove-filling material was a two-component epoxy adhesive with a mixing ratio of 2 (resin):1 (hardener) by weight. The tensile strength and elastic modulus of the adhesive averaged from five tensile coupon tests were 42.6 MPa and 2.62 GPa respectively. The Poisson's ratio of the epoxy is assumed to be a typical value of 0.35. The CFRP strips had a thickness of 2 mm and a width of 16 mm. The ultimate tensile strength and elastic modulus of the CFRP strips were 2068 MPa (according to the manufacturer) and 151 GPa (deduced from readings of strain gauges installed on the exposed part of the NSM CFRP strip in the bonded joint tests), respectively. Two CFRP strips were bonded together using the groove filling adhesive, forming a compound strip whose total thickness was approximately 5 mm (i.e., 4 mm of CFRP plus about 1 mm of adhesive), whereas the width was still 16 mm. The use of a compound strip instead of a normal strip is to allow the installation of strain gauges between the two strips of a compound strip so that the strain gauges would not interfere with the interfacial behavior. It should be noted that the elastic modulus of the compound strip for FE modeling in this study was modified according to its real thickness as follows: E_f = 151 × 4/5 = 120.8 MPa. The Poisson's ratio of the CFRP compound strip was assumed to be 0.2. The effect of using a nearly zero Poisson's ratio (0.002) was also explored before choosing this Poisson's ratio for use in the parametric study; it was found that such a small Poisson's ratio led to load–displacement curves which are almost identical to those obtained with a Poisson's ratio of 0.2 with the ultimate loads differing by less than 1%. Details of the specimen are listed in Table 1.

2.3. Finite element model for bonded joint specimens

The FE model was built using the general-purpose FE software package MSC.MARC [18] with the tension-softening curves and the shear retention factor models for the cracked concrete incorporated through user-defined subroutines. Based on the configuration of the test setup, only half of the specimen was modeled by taking advantage of symmetry; that is, the horizontal displacements on the plane of symmetry (Fig. 2) were prevented. Furthermore, the 50 mm high bottom layer of concrete was not taken into account to reduce significantly the computational time; this simplification should only have an insignificant effect on the crack propagation near the NSM bar as was found through some preliminary FE analyses. The bottom surface of the numerical model was restrained against vertical displacements but was allowed to move horizontally (Fig. 2). The horizontal restraints at the loaded end of the concrete block and the vertical restraints at the far