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Meso-scale finite element model for FRP sheets/plates bonded to concrete

X.Z. Lu[a,b], L.P. Ye[a], J.G. Teng[b,*], J.J. Jiang[a]

[a] *Department of Civil Engineering, Tsinghua University, Beijing, China*
[b] *Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

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Abstract

External bonding of fiber-reinforced polymer (FRP) plates or sheets has recently emerged as a popular method for the strengthening of reinforced concrete (RC) structures. The behavior of such FRP-strengthened RC structures is often controlled by the behavior of the interface between FRP and concrete, and this interfacial behavior is commonly studied through a pull test in which an FRP sheet or plate is bonded to a concrete prism and is subject to tension. In this paper, a meso-scale finite element (FE) model implemented with the MSC.MARC program is presented for the simulation of interfacial debonding failures in a pull test. In this model, very small nearly square elements (0.25–0.5 mm in size) are used with the fixed angle crack model (FACM) to capture the development and propagation of cracks in the concrete layer adjacent to the adhesive layer. The effect of element size is taken into account in modeling both the tensile and shear behavior of cracked concrete. Comparisons between the predictions of this model and test results are presented to demonstrate the capability and accuracy of this FE model. The debonding mechanism is also examined using results obtained with the FE model. Finally, a method for the determination of the local bond–slip curve of the FRP-to-concrete interface from the FE results is described.

Keywords: Meso-scale FE model; FRP sheets; FRP plates; Concrete

1. Introduction

External bonding of fiber-reinforced polymer (FRP) plates or sheets (referred to as plates only hereafter for brevity) has emerged as a popular method for the strengthening of reinforced concrete (RC) structures. In this strengthening method, the performance of the FRP-to-concrete interface in providing an effective stress transfer is of crucial importance. Indeed, a number of failure modes in FRP-strengthened RC members are directly caused by the debonding of the FRP from the concrete [1,2]. Therefore, for the safe and economic design of externally bonded FRP systems, a sound understanding of the behavior of the FRP-to-concrete interface needs to be developed. It should be noted that throughout this paper, the term “interface” is used to refer to the interfacial part of the bonded joint, including the adhesive and the adjacent concrete, responsible for the relative slip between the FRP plate and the concrete prism, instead of any physical interface in the joint.

In various debonding failure modes, the stress state of the interface is similar to that in a pull test in which a plate is bonded to a concrete prism and is subject to tension (Fig. 1). As a result, a large number of studies, both experimental and theoretical, have been carried out on pull tests on FRP-to-concrete bonded joints [3,4]. Existing studies suggest that the main failure mode of FRP-to-concrete bonded joints in pull tests is concrete failure under shear, occurring generally at a few millimeters from the adhesive layer [3]. The ultimate load (i.e. the maximum transferable load) of the joint therefore depends strongly on the strength of concrete. In addition, the plate-to-concrete member width ratio also has a significant effect. A very important aspect of the behavior of these bonded joints is that there exists an effective bond length beyond which an extension of the bond length cannot increase the ultimate load. This is a fundamental difference between an externally bonded plate and an internal reinforcing bar, for which a sufficiently long

* Corresponding author. Tel.: +852 2766 6012; fax: +852 2334 6389.
E-mail address: cejgteng@polyu.edu.hk (J.G. Teng).

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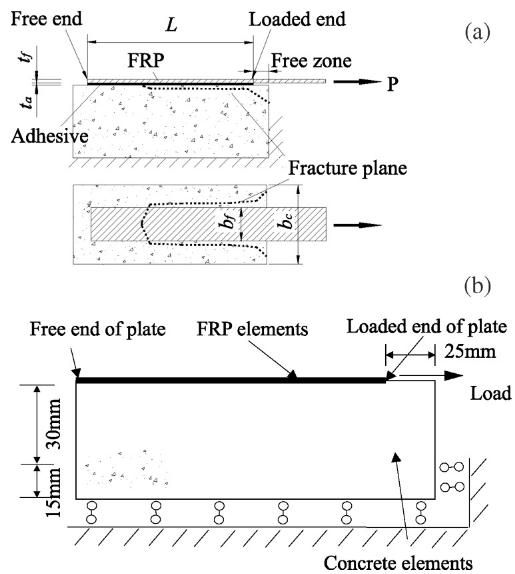

Fig. 1. Pull test: (a) Schematic; (b) FE model.

anchorage length can always be found so that the full tensile strength of the reinforcement can be achieved.

Apart from experimental and analytical studies, the finite element (FE) method has also been used to study debonding in FRP-to-concrete bonded joints. Earlier FE studies of interfacial behaviour employed linear elastic analysis and were concerned with the elastic stress distribution in the interface (e.g. [5,6]). In the latest studies, attention shifted to the nonlinear FE analysis of the concrete-to-FRP interface, aimed at the simulation of the entire debonding process. There are generally two approaches to the simulation of debonding in FRP-strengthened RC structures using a nonlinear FE model. One approach is to employ a layer of interface elements between the FRP and the concrete [7–10], in which debonding is simulated as failure of the interface elements. Obviously, the success of such an approach depends on the constitutive law (i.e. the bond–slip model) specified for the interface elements. Such models are not truly predictive models, although they may be used with tests to verify/identify interfacial behaviour. In the second approach [9,11–13], the use of interface elements is avoided; instead, debonding is directly simulated by modelling the cracking and failure of concrete elements adjacent to the adhesive layer. The advantage of this approach is that the debonding behaviour can be predicted using an appropriate constitutive model for concrete, without recourse to an interfacial bond–slip model. Indeed, such a model has the capability of predicting the bond–slip relationship for use in a model following the first approach. The second approach also provides a useful tool for understanding the debonding failure process and mechanism as only limited experimental observations of the debonding failure process can generally be made due to the microscopic details involved in and the suddenness of a debonding failure.

In general, the debonding of FRP from concrete occurs within a thin layer of concrete adjacent to the adhesive layer unless the adhesive is rather weak. The thickness of this concrete layer is about 2–5 mm. Recent work [12] on the modelling of debonding failures using the second approach mentioned above has shown that it is difficult to simulate debonding using the concrete models available in commonly used general-purpose FE packages such as ANSYS, MARC or ABAQUS. To simulate concrete failure within such a thin layer, with the shapes and paths of the cracks properly captured, the rotating angle crack model (RACM) [13,14] should be used if elements with a size comparable to the thickness of the concrete layer involved in the debonding failure are adopted. The RACM however has the major drawback that its constitutive parameters do not have clear physical meanings and have to be empirically derived from pull tests.

This paper presents a new FE model which can accurately simulate the entire debonding process in pull tests of FRP-to-concrete bonded joints. In this new FE approach, a fixed angle crack model (FACM) [15] is employed in conjunction with a very fine finite element mesh with element sizes being one order smaller than the thickness of the facture layer of concrete. This approach has the simplicity of the FACM, for which the relevant material parameters have clear physical meanings and can be much more easily determined than those for the RACM, but in the meantime retains the capability of tracing the paths of cracks as deformation progresses. The present model using very small elements is referred to as a meso-scale finite element model.

2. Meso-scale finite element model

2.1. General

To reduce the computational effort, the three-dimensional FRP-to-concrete bonded joint (Fig. 1(a)) was modeled in the present study as a plane stress problem using four-node isoparametric elements. In real pull tests, the width of the FRP plate and that of the concrete prism may be different. In comparing FE predictions with test results, the finite element results including the applied load and axial stresses/strains in the FRP plate are adjusted based on the following width ratio factor β_w proposed by Chen and Teng [3]:

$$\beta_w = \sqrt{\frac{2 - b_f/b_c}{1 + b_f/b_c}} \tag{1}$$

where b_f and b_c are the widths of the FRP plate and the concrete prism respectively. The adjustment involved the multiplication of the predicted values of the applied load and the stress and strain in the FRP plate based on the relationship of Eq. (1) by a factor.

The plane stress FE model for the FRP-to-concrete bonded joint is shown in Fig. 1(b). It should be noted that the concrete prism included in the FE model has a height of 45 mm, which is generally much smaller than the actual concrete prism in a bond test. The exclusion of the rest