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Construction and Building Materials 20 (2006) 412–424
Construction and Building MATERIALS
www.elsevier.com/locate/conbuildmat

Finite element simulation of debonding in FRP-to-concrete bonded joints

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Received 23 February 2004; received in revised form 10 November 2004; accepted 31 January 2005
Available online 5 July 2005

Abstract

The behaviour of reinforced concrete (RC) structures strengthened with externally bonded fibre-reinforced polymer (FRP) reinforcement in the forms of thin plates or sheets is often dominated by debonding of the FRP reinforcement from concrete. As a result, a large number of studies have addressed debonding failures in FRP-strengthened RC structures, with many of them being focussed on understanding the behaviour of simple FRP-to-concrete bonded joints in which an FRP plate/sheet is bonded to a concrete prism and is subject to a tensile force. Despite the many existing studies, there are still substantial uncertainties and difficulties with the finite element modelling of debonding failures due to the complex behaviour of cracked concrete. This paper explores the use of different crack models in modelling and compares their predictions of the debonding behaviour of FRP-to-concrete bonded joints. The results presented in this study show that a non-coaxial rotating angle crack model (RACM) is required to accurately predict this debonding behaviour. Furthermore, the debonding mechanism is also examined using results obtained with a non-co-axial RACM.
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Keywords: FRP; Composites; Concrete; Bond; Interfaces; Debonding; Finite element models; Crack models; Pull tests; strengthening; Retrofit

1. Introduction

External bonding of fibre-reinforced polymer (FRP) plates or sheets (hereafter referred to as plates only 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 debonding of the FRP from the concrete (e.g. [1–12]). Therefore, for the safe and economic design of externally bonded FRP systems, a sound understanding of the behaviour of FRP-to-concrete interfaces needs to be developed.

In various debonding failure modes, the stress state of the interface is similar to that in a pull test specimen 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 bonded joints [13,14]. Existing studies suggest that the main failure mode of FRP-to-concrete bonded joints in such pull tests is concrete failure under shear, occurring generally at a few millimetres from the adhesive layer [13]. 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 behaviour of these bonded joints is that there exists an

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doi:10.1016/j.conbuildmat.2005.01.033

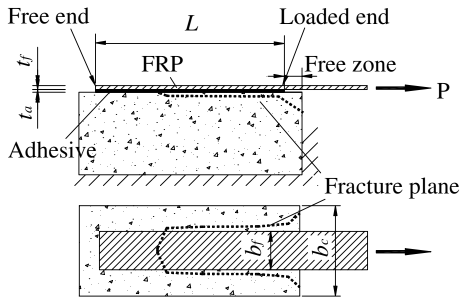

Fig. 1. Schematic of a pull test.

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

In general, debonding of FRP from concrete occurs within a thin layer of concrete instead of the adhesive layer unless a rather weak adhesive is used. Apart from experimental and analytical studies, the finite element (FE) method has also been used to study debonding in FRP-to-concrete bonded joints. Early FE studies of interfacial behaviour employed linear elastic analysis and were concerned with the elastic stress distribution in the interface (e.g. [15,16]). More recently, 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 failures 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 [17–20] 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 true predictive models, although they may be used with tests to verify/identify interfacial behaviour. In the second approach [19,21,22], 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.

Recent work [22] on the modelling of debonding failures using the second approach has shown that it is difficult to simulate debonding using the concrete constitutive models available in commonly used general-purpose FE software packages such as ANSYS [23], MSC.MARC [24] or ABAQUS [25]. This paper therefore presents an FE method of the second approach in which a non-coaxial rotating angle crack model (RACM) is employed so that debonding failures of FRP-to-concrete interfaces can be accurately predicted. The weaknesses of other crack models are also explored and demonstrated.

2. Crack models for concrete

Current research on the numerical simulation of debonding failures of FRP plates from concrete is generally conducted using one of the commonly available general-purpose FE packages such as ANSYS [23], MSC.MARC [24] or ABAQUS [25]. These packages are capable of solving complex nonlinear problems and have included in them constitutive models for concrete. It is therefore convenient to directly use these packages to simulate debonding failures based on the second approach mentioned above, in which an interface layer is not included.

The crack models for concrete in all these packages are based on the smeared crack model with fixed orthogonal cracks [26,27]. It is referred to as the orthogonal "fixed angle crack model" (FACM) hereafter. The basic concept of this model is as follows: a crack is evenly distributed as tensile straining over a representative zone of concrete and the behaviour of cracked concrete is modelled by modifying the constitutive law of concrete. Once a crack appears, the direction of the crack will remain unchanged; that is, the orientation of the crack is fixed. For a 3-D finite element model, there are at most 3 cracks at a single gauss integration point, and these cracks are orthogonal to each other. The incremental stress–strain relationship for an orthogonal FACM under a plane stress condition when one crack has appeared can be expressed as [28]:

$$\begin{Bmatrix} \Delta\sigma_{nn} \\ \Delta\sigma_{tt} \\ \Delta\sigma_{nt} \end{Bmatrix} = \begin{bmatrix} k_{soft}E & 0 & 0 \\ 0 & E_0 & 0 \\ 0 & 0 & \eta G_0 \end{bmatrix} \begin{Bmatrix} \Delta\varepsilon_{nn} \\ \Delta\varepsilon_{tt} \\ \Delta\varepsilon_{nt} \end{Bmatrix}, \quad (1)$$

where σ_{nn} and ε_{nn} are the direct stress and strain normal to the crack; σ_{tt} and ε_{tt} are the direct stress and strain parallel to the crack; σ_{nt} and ε_{nt} are the shear stress and shear strain; E_0 and v are the elastic modulus and Poisson's ratio of concrete; G_0 is the elastic shear modulus of concrete; k_{soft} is a factor representing the tensile

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