Composites Part B 137 (2018) 111–122

Contents lists available at ScienceDirect

Composites Part B

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

An incremental inverse analysis procedure for identification of bond-slip laws in composites applied to textile reinforced concrete

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ARTICLE INFO

Keywords:
Fabrics/textiles
Fibre/matrix bond
Finite element analysis (FEA)
Mechanical testing

ABSTRACT

Textile reinforced concrete (TRC) is a novel composite building material, its structural behavior is substantially influenced by the bond interface between the reinforcing textile fabrics and concrete. The bond interface can be characterized by a nonlinear bond-slip law. The pull-out test is a common experimental procedure for determination of the bond-slip law. In this paper, a general finite element procedure is proposed to calibrate the bond-slip law according to the results of pull-out tests. By adopting a generic multilinear bond-slip law and solving each piece of the law sequentially, the conventional curve fitting procedures employing optimization algorithms, which are computationally expensive and sometimes non-convergent, can be avoided. Pull-out tests of TRC specimens with varying anchorage lengths were carried out and the test results were used as the input data for the calibration procedure. It is found that the calibrated bond-slip law is independent of the specimen length. Using the calibrated bond-slip laws, the pull-out force vs. displacement curves are numerically reproduced. The numerical results agree well with the experimental data.

1. Introduction

Compared to the conventional steel reinforcement, textile fabrics made of carbon, aramid, glass or basalt fiber bundles have higher strength and better corrosion resistance. These advantageous properties enable the production of thin and lightweight TRC components [1,2]. The bond between the reinforcing textile and concrete is one of the key factors determining the macroscopic behavior of the composite [3–6]. A common way in modelling the composite materials for construction is to represent the bond behavior by a bond-slip law, i.e., the shear stress in the interface as a function of the relative slip between matrix and reinforcement [7–16]. The pull-out test has become a quasi-standard procedure to determine such bond-slip laws in composite materials for construction. It has been adopted to characterize the bond in steel reinforced concrete [17–20], concrete reinforced by fiber reinforced polymer (FRP) bars [21–25], textile reinforced concrete [26,27] as well as natural fiber reinforced concrete [15]. In the case of strengthening/retrofitting of existing structures, the test method is also referred to as the lap pull-out test [28] or the lap shear test [29–34]. The influences of different test setups on the bond properties were studied in [35].

In those tests, if the reinforcement is bonded externally to the matrix, the surface strains can be measured [36] using, e.g., the digital image correlation technique as documented in Refs. [35,37,38]. Taking the externally bonded FRP sheet as an example, if its strain profile is known then the shear stress in the bond interface can be determined using a difference formula, and the corresponding slip can be found by a numerical integration of the measured axial strains [39]. However, when the reinforcement is embedded inside the matrix as in the pull-out tests of TRC, it is generally not possible to measure a bond-slip law directly due to the lack of straightforward and precise measuring techniques for the strain field along the reinforcement within the embedded length.

A variety of calibration methods have been developed to identify the constitutive laws that cannot be directly measured in experiments. These methods can be classified into two categories: those using optimization algorithms to minimize the lack of fit between the experimental result and the numerical simulation [15,22,23,26,40–44]; and those giving analytical or semi-analytical solutions [19,28,45,46]. The procedures employing optimization algorithms, while being more intuitive and easier to formulate, are usually computationally expensive and allow only a limited number of free parameters in the assumed constitutive models. Moreover, convergence of the optimization algorithms and uniqueness of the solutions cannot be guaranteed [42]. On the other hand, the analytical solutions are more difficult to derive and less flexible compared to the methods in the first category. Such solutions are only applicable to the given boundary conditions and to the particular form of constitutive law.

In the present paper, we propose a novel method of inverse analysis

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https://doi.org/10.1016/j.compositesb.2017.11.014
Received 11 April 2017; Received in revised form 19 September 2017; Accepted 2 November 2017

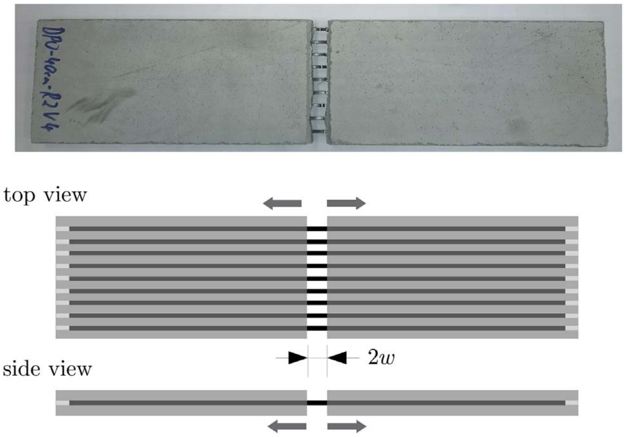

Fig. 1. Schematic diagram of a double-sided pull-out specimen with the pre-defined crack at the center, w is the pull-out displacement from each side.

to identify a multilinear bond-slip law based on a finite element formulation of the pull-out problem. We describe the applied method of implementing the procedure using modern, open-source utilities for scientific computing and provide the executable code. At the same time, we present an example of a calibration and validation procedure utilizing a recently developed test setup shown in Fig. 1. The motivation for development of this symmetric, double-sided pullout-test was to appropriately reflect the condition of a typical crack bridge as it occurs in structural TRC members under tensional or bending loads.

2. The direct and inverse pull-out problems

The idealized geometry and boundary conditions of a pull-out test are shown in Fig. 2. The measured output of such a test is typically provided as the relationship between the pull-out force P and the displacement w. Two related problems can be formulated based on the pull-out test, the direct pull-out problem and the inverse pull-out problem. The direct pull-out problem provides a prediction of the experimental results in terms of the pull-out force vs. displacement curve for a given bond-slip law. The inverse pull-out problem is used to determine the unknown bond-slip law given an experimentally measured force-displacement pull-out curve.

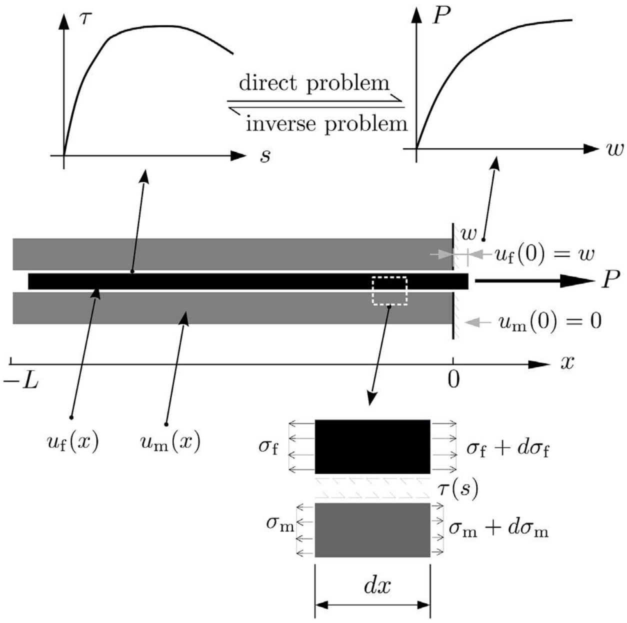

Fig. 2. A mechanical model of the pull-out problem.

The mathematical idealization of the direct pull-out is formulated as an initial boundary value problem reflecting equilibrium and compatibility conditions, as well as the material behavior of bond, matrix and reinforcement. In the considered case of cementitious composites with a negligible shear deformation the problem can be regarded as one-dimensional. The bond between the reinforcement and the matrix is assumed in form of a general nonlinear function $\tau(s)$ coupling the shear stress τ with the slip s.

With the described assumptions, the equilibrium condition of an infinitesimal segment of the reinforcement shown in Fig. 2 can be expressed as

$$A_f \sigma_{f,x} - p\tau(s) = 0, \tag{1}$$

where the index $(.)_{,x}$ denotes the derivative with respect to the spatial coordinate x. The cross-sectional area and the perimeter of the reinforcement are denoted as A_f and p, respectively. Similarly, the equilibrium of the matrix can be expressed as

$$A_m \sigma_{m,x} + p\tau(s) = 0, \tag{2}$$

where A_m is the cross-sectional area of the matrix.

The slip in the bond interface is defined as

$$s = u_f - u_m, \tag{3}$$

where u_f and u_m denote the reinforcement displacement and matrix displacement, respectively. The second derivative of s reads

$$s_{,xx} = \varepsilon_{f,x} - \varepsilon_{m,x}, \tag{4}$$

where ε_f is the reinforcement strain and ε_m is the matrix strain. The constitutive laws of the reinforcement and the matrix are given as

$$\sigma_f = D_f(\varepsilon_f),\ \sigma_m = D_m(\varepsilon_m), \tag{5}$$

which in combination with Eqs. (1) and (2) leads to

$$\varepsilon_{f,x} = \frac{1}{A_f}\frac{\partial C_f}{\partial \sigma_f} p\tau(s),\ \varepsilon_{m,x} = -\frac{1}{A_m}\frac{\partial C_m}{\partial \sigma_m} p\tau(s), \tag{6}$$

with the material compliances of the matrix and reinforcement given as $C_{(.)} = D_{(.)}^{-1}$. Substituting Eq. (6) into Eq. (4) the following second order differential equation is obtained,

$$s_{,xx} = \left[\frac{1}{A_f}\frac{\partial C_f}{\partial \sigma_f} + \frac{1}{A_m}\frac{\partial C_m}{\partial \sigma_m}\right] p\tau(s). \tag{7}$$

Thus, the direct pull-out problem shown in Fig. 2 involves the solution of the following boundary value problem for a given bond-slip law $\tau(s)$,

$$\begin{aligned} s_{,xx} &= \gamma p \tau(s), \\ s_{,x}(-L) &= 0, \\ s(0) &= w, \end{aligned} \tag{8}$$

where

$$\gamma = \frac{1}{A_f}\frac{\partial C_f}{\partial \sigma_f} + \frac{1}{A_m}\frac{\partial C_m}{\partial \sigma_m}. \tag{9}$$

Here w represents the control displacement of the reinforcement at the end being pulled out. For special types of the bond-slip law, analytical solutions of the problem are available [45–49]. For more general cases, numerical procedures such as the finite difference method or the finite element method can be employed. With the solution $s(x)$ for a given displacement w at hand, the corresponding pull-out force P can be obtained as an integral of the shear stress along the interface,

$$P(w) = \int_{-L}^{0} \tau(s(x; w))dx. \tag{10}$$

The pull-out response $P(w)$ is determined by solving Eq. (8) repeatedly for an increasing control displacement w and then evaluating the corresponding pull-out force P according to Eq. (10).

The aim of the inverse pull-out problem is in turn to identify a bond-slip law $\tau(s)$ that reproduces the experimentally measured pull-out