Construction and Building Materials 68 (2014) 142–157

Contents lists available at ScienceDirect

Construction and Building Materials

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

Development of a simplified bond stress–slip model for bonded FRP–concrete interfaces

Hunebum Ko [a,*], Stijn Matthys [b,1], Aniello Palmieri [b,1], Yuichi Sato [c,2]

[a] Department of Architecture, Inha Technical College, 253 Yonghyun-dong 253, Nam-ku, Incheon 402-752, Republic of Korea
[b] Magnel Laboratory for Concrete Research, Department of Structural Engineering, Ghent University, Technologiepark-Zwijnaarde 904, B-9052 Gent, Belgium
[c] Department of Architecture and Architectural Engineering, Kyoto University, Kyoto-daigaku-Katsura 4, Nishigyo-ku, Kyoto 615-8540, Japan

HIGHLIGHTS

- 18 Double-shear bond tests have been conducted to evaluate FRP EBR.
- A critical review and assessment of existing bond stress–slip models was provided.
- The factors affecting the bond stress–slip behavior were investigated and evaluated.
- The newly proposed model is based on the bi-linear bond stress–strain relationship.
- The new model is derived by considering only concrete compressive strength.

ARTICLE INFO

Article history:
Received 18 March 2014
Received in revised form 19 June 2014
Accepted 24 June 2014

Keywords:
Bond stress–slip model
Concrete
Debonding
Fiber-reinforced polymer (FRP)
Interface
Externally bonded reinforcement (EBR)
Strengthening

ABSTRACT

An important need in assessing the performance of externally bonded fiber reinforced polymer reinforcement (FRP EBR) for RC structures is to have a constitutive model for the bond stress–slip behavior. Various bond stress–slip models have been proposed and their effectiveness has been verified based on experimental and analytical data. Nevertheless, the models show significant variations and degrees of complexity. In this paper, bond interface modelling of EBR is explored and experimentally supported by double bond testing on 18 test specimens as part of an international Round Robin Testing (iRRT), to investigate the bond mechanisms between FRP reinforcement and concrete. Investigation of the database of models proposed by researchers in literature, shows that often reference is made to the so-called bilinear bond stress–slip model for externally bonded reinforcement. This model is based on three parameters: maximum bond stress, slip at maximum bond stress, and maximum slip. Applicable to this bilinear bond stress–slip model, simplified engineering equations are proposed to define the bond behavior, considering the effect of concrete strength and FRP stiffness on the three parameters identified. The simplified model has been verified against a database of experimental results, showing good correlation (with a coefficient of determination of more than 0.9). It is expected that the model will provide engineers with a basic design guideline to design safe EBR systems, and be a simple model for designing FRP strengthening applications.

1. Introduction

Fiber-reinforced polymer (FRP) strips have been used to strengthen deficient RC structures damaged by durability issues, earthquakes, fires, and unexpected loads since the 1980s. Over the past few decades, external bonding of FRP has emerged as a popular method for the strengthening of reinforced concrete (RC) structures [1], in relation to their superior properties, such as light weight, high tensile strength, high fatigue strength, magnetic neutrality, easy of application in a confined space, and practically unlimited availability in size, geometry and dimension [2–4]. Current global research being done in architectural and civil engineering fields related to FRP is focused on achieving an easier and more economical approach to the process [1–7].

The effectiveness of the external FRP reinforcement and the mechanical performance of the strengthened RC structure are greatly affected by the bond performance between the FRP and

* Corresponding author. Tel./fax: +82 32 870 2257/2512.
E-mail addresses: hbko@inhatc.ac.kr (H. Ko), Stijn.Matthys@UGent.be (S. Matthys), aniello.palmieri@ugent.be (A. Palmieri), satou@archi.kyoto-u.ac.jp (Y. Sato).
[1] Tel./fax: +32 9 264 5535/5845.
[2] Tel./fax: +81 75 383 3288.

http://dx.doi.org/10.1016/j.conbuildmat.2014.06.037

the concrete. Hence, it is very important to evaluate the quantitative bond properties between the FRP and the concrete. Research on the bond behavior of the interface between the FRP and the concrete is being carried out experimentally by various test methods, including the double-shear pull test, double-shear push test, single-shear pull test, single-shear push test, and the bending (or beam) test [8–10]. Although various test methods have been proposed to examine the local bond behavior of externally bonded FRP systems [11,12], their implementation can lead to a wide range of results and a standard methodology has yet to be generally accepted.

Predicting the relationship between the bond stress and slip is mainly done through the analysis of factors that may affect the relationship, such as concrete strength, FRP bond length, FRP axial stiffness, FRP and concrete width ratio, adhesive strength, and adhesive stiffness. As a result, it is critical to understand and reveal the mechanical behavior of the interaction between the concrete and the FRP stripes. Although much research has been carried out to quantitatively evaluate these factors [13–20], it remains difficult to understand the quantitative attributes because the combined effects of these factors affect the bond characteristics. In addition, even though a number of models have been proposed regarding the bond stress–slip relationship [21–31], a proper bond stress–slip model has yet to be generally accepted due to its complexity and many parameters.

This study has two principal objectives. The first one is to investigate the feasibility of the double shear pull test as a standard method to evaluate the bond behavior and to investigate the mechanism of the bond between FRP reinforcement and concrete. For this objective the bond test investigated in an international Round Robin Testing program was applied, conducted experimental tests on18 test specimens. The second objective is to propose simplified engineering equations applicable to the bilinear bond stress–slip model for externally bonded FRP reinforcement. This new simple model for the FRP strip–concrete interface has been derived by investigating a database of existing experimental results, and by taking into consideration the characteristics of concrete, FRP, and adhesive.

2. Existing bond–slip models

An important step toward understanding bond behavior is to have characterization of the local bond stress–slip behavior, which is the most important thing to describe the interface performance between the concrete and the FRP. It further characterizes bond aspects, such as for example the effective bond transfer length and the strain distribution along the bond length. Despite the difficulties in obtaining local bond stress–slip curves from pull tests directly, models have been developed based on strain measurements or load–slip curves [32,33]. The tensile capacity (anchorage strength) in case of bond failure, the strain distribution of the FRP, and the bond stress distributions can be obtained from the bond stress–slip relationship, through analytical or numerical verifications. A number of bond stress–slip models have been proposed as follows: (a) cutoff type, (b) elasto-plastic type, and (c) tensile softening type (such as bi-linear, or Popovics) [32,34–43]. Fig. 1 shows a typical bond stress–slip model for each of these three types. When using the cutoff type or elasto-plastic type model, it is necessary to be careful because these models are unrealistic. The bilinear type model [44,45] is divided into an elastic ascending part and plastic descending part based on experimental data. The maximum bond stress in the elastic part is defined as τ_m, with s_τ the relative displacement (slip) corresponding to τ_m. The end of the plastic part, which corresponds to zero bond stress, has a relative displacement s_f. The Popovics type model [32] originated from Popovics numerical approach for a complete concrete stress–strain relationship [38]. The surface area underneath the bond stress–slip relationships expresses the fracture energy (G_f) of the bond system.

Several local bond stress–slip relationships collected from nine studies, and taking the comparative study from Lu et al. [28] as a starting point, are presented in Table 1, where τ is the local bond stress, τ_m is the maximum local bond stress, s is the local slip, s_τ is the local slip at τ_m, s_f is the local slip when local bond stress reduces to zero (maximum slip), s_e is the elastic component of local slip, β_w is the width ratio factor, β_c is the concrete influence factor, f_c is the concrete compressive cylinder strength, f_t is the concrete tensile strength, E_c is the elastic modulus of concrete, t_c is the effective thickness of concrete contributing to shear deformation, G_c is the elastic shear modulus of concrete, t_f is the thickness of FRP, E_f is the elastic modulus of FRP, $E_f t_f$ is the axial stiffness of FRP, t_a is the thickness of adhesive layer, E_a is the elastic modulus of adhesive, G_a is the elastic shear modulus of adhesive, b_c is the width of concrete prism, b_f is the width of FRP, t_m is the thickness of epoxy mortar layer, E_m is the elastic modulus of epoxy mortar layer, G_f is the interfacial fracture energy, G_f^a is the interfacial fracture energy for the ascending branch, K_a is the shear stiffness of adhesive layer, K_c is the shear stiffness of concrete. The relationships originate from the three mentioned types of models (Fig. 1), though most of the relationships have an ascending branch and a descending branch and are generally characterized by three parameters: maximum bond stress, slip at maximum stress, and ultimate slip at zero bond stress. The model of Neubauer and Rostasy [20,46], which is modified from Holzenkämpfer [47], seems unrealistic because it does not consider slip after maximum bond stress (Fig. 1a, cutoff type), though in [20] they also proposed a bilinear law (Fig. 1c). The models of Lu et al. [33] and Monti et al. [48], which are derived from that of Neubauer and Rostasy [46] and Brosens [34,45], consider maximum bond stress (τ_m) as a function of the concrete tensile strength (f_t) and a width ratio factor (β_w), which is a size effect parameter considering the influence of the bonded width of the FRP relative to the width of the concrete [34]. The slip at τ_m in the models of Monti et al. and Brosens et al. consider adhesive characteristics in addition to the concrete characteristics, while the slip at τ_m in the model of Lu et al. is composed of a function of concrete tensile strength and width ratio factor. Fracture energy (G_f) and maximum bond stress are considered to be factors of maximum slip in the simplified model of Lu et al. [33] and in the model of Brosens and Van Gemert [34], while only width ratio factor is considered in the model of Monti et al. [48].

The model of Savoia et al. [49] was obtained by some minor modification of that of Nakaba et al. [32], which only considers concrete compressive strength (f_c) as a parameter of maximum bond stress, while the slip at τ_m was decided by a specific value obtained from the least square minimization between theoretical and experimental data. The model of Dai et al. [51] developed from the model of Dai and Ueda [50] considers for the maximum bond stress interfacial fracture energy and an interfacial parameter (B), which depends on FRP and adhesive characteristics. For the slip at τ_m the model of Dai is a function of only the interfacial parameter B. The model of De Lorenzis et al. [36] considers maximum bond stress as a function of only FRP stiffness. Although many experimental tests to examine the bond behavior of externally bonded FRP systems have been executed, a proper bond–slip model has yet to be generally accepted due to various influential parameters and a wide range of values from the experimental results [52].

3. Experimental investigation

A total of 18 specimens using six different CFRP (carbon fiber based FRP) strengthening systems were tested as part of the international Round Robin Testing (iRRT) program [52,53]. The test matrix is given in Table 2, whereas test parameters