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Bond-slip behavior of fiber reinforced polymer strips-steel interface

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HIGHLIGHTS

- Single-lap shear tests on CFRP-to-steel joints using a linear adhesive.
- A review of existing bond-slip models is conducted.
- A new bond-slip model is developed.
- The developed model is proved to be accurate according to numerical analysis.

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ABSTRACT

Fiber reinforced polymer (FRP) composites have been widely and successfully applied for externally bonded strengthening of steel structures. The bond between FRP and steel substrate plays a key role on the strengthening effectiveness of FRPs. The bond-slip relationship is essential to understand the mechanisms involved in the bond failure process. This paper experimentally studied the bond behavior of carbon fiber reinforced FRPs (CFRP)-to-steel joints through a single-shear lap testing method. The load-displacement relationship and bond-slip relationship were firstly presented. In addition, a new bond-slip model was developed based on observed experimental behavior of strengthened components. According to the developed bond-slip model, a computed result of the load-displacement relationship was obtained using numerical analysis method by ANSYS software. Comparison between computed and experimental result of the load-displacement relationship showed a good accordance, indicating the reliability of the developed bond-slip model. Finally, comparison of computed results obtained from the developed model and the existing models demonstrated that the proposed model was more accurate than the existing models.

1. Introduction

Strengthening of steel structures with adhesively-bonded fiber reinforced polymer (FRP) composites (plates or sheets) has attracted many attentions in the past decade. As revealed, the bond between CFRPs and steel substrates is usually the weakest link, and debonding of CFRPs from steel substrate is one of the main failure modes. Therefore, the bond-slip relationship between FRP and steel substrates is an essential component for modeling the debonding failure process and predicting the structural behavior of CFRP strengthened steel members [1–3]. In order to understand the CFRP-to-steel bond mechanisms and to carry out numerical simulation of the mechanical properties of a FRP-to-steel structure, an accurate model of the bond-slip relationship is necessary to be developed.

Extensive research works have been conducted to develop bond-slip relationship (τ-δ) of FRP adhesively bonded to concrete systems [4–10]. In general, the bond-slip relationship can be obtained through three methods [4,6,10]: (a) direct method, the relationship is obtained from axial strains of the FRP plate measured with closely spaced strain gauges by experimental tests such as pull-off tests (e.g. Nakaba et al. [8]); (b) indirect method, the relationship is derived from strain–slip curves (slip at the loaded end) by experimental test results (e.g. Dai et al. [6]); (c) the third one is based on finite element analyses (e.g. Lu et al. [4]).

As regards to the FRP-to-steel system, the directed test method is commonly used to obtain the bond-slip relationship, including the single lap shear joint or double strap joint methods. The single lap shear test set-up allows easy monitoring and inspection of the failure process as only one path of debonding is possible. The

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double strap joint test is convenient to be conducted and needn't a special set-up. Zhao and Zhang [11] recommended the double strap joint method for CFRP sheets, and single lap shear joint for CFRP plates in establishing the bond–slip relationship between CFRP and steel.

To the best of knowledge of the authors, only five models had been developed on the bond-slip relationship for the FRP-to-steel system (see Fig. 1), by Teng et al. [12], Fawzia et al. [13], Fernando [14], and Dehghani et al. [15]. The models were obtained according to the shape of the bond-slip relationship measured by many strain gauges. In theory, the bond–slip curves obtained at different locations were similar [16]. However, the curves from test results were inconsistent at different locations, as shown in Fig. 2. The maximum shear stress was from 22.5 MPa to 30 MPa and the maximum slip was from 0.3 mm to 0.5 mm. Taking the ascending branch for example (from 0 mm to 0.1 mm in Fig. 2), Fernando [14] proposed two models, namely bilinear model and simplified model. A linear function in bilinear model and an exponential function in simplified model were used to describe the bond-slip relationship at the ascending branch. It was clearly seen that the two curves all were located in the test result region (see Fig. 2). However, it couldn't be known that which model was more accurate.

Based on the bond-slip model, the load-displacement relationship could be computed by numerical analysis method. Meanwhile, the load-displacement relationship could be measured using only two LVDTs, when the computed result of the load-displacement relationship agreed well with the experimental one, it was demonstrated that the assumed bond-slip model was accurate.

In the present paper, according to the approximate shape of the bond-slip relationship from experimental results, a new bond-slip model was developed. Based on the developed bond-slip model, a computed result of load-displacement relationship was obtained using numerical analysis method by ANSYS software. The developed bond-slip model was validated by the comparison between the computed result and experimental result.

The study has two principal objectives. The first one is to develop a bond–slip model for externally bonded FRP reinforcement for steel members, while the second one is to supply a method to validate the bond-slip model using numerical analysis method.

2. Existing bond-slip models

Existing five bond-slip models available in literature are summarized in Table 1. Where τ (MPa) is the local shear stress and δ (mm) is the local slip. τ_f (MPa) is the peak interfacial shear stress. δ_1 (mm) is the relative slip corresponding to the peak interfacial shear stress, hereinafter referred to as the maximum elastic slip. δ_2 (mm) is the relative slip when the shear stress begins to decrease. δ_f (mm) is the maximum slip. f_a (MPa) is the tensile strength of adhesive. G_a (MPa) is the shear modulus of adhesive. t_a (mm) is the thickness of adhesive. G_f (N/mm) is the interfacial fracture energy which is equal to the area under the bond–slip curve. P_u (kN) is the ultimate load.

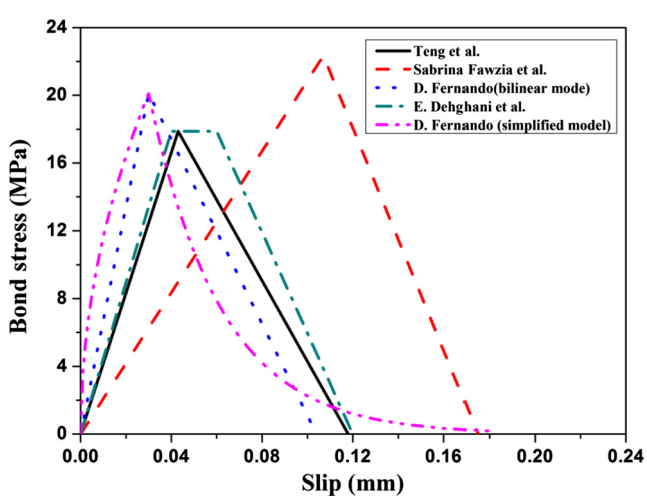

Fig. 1. Existing models for bond–slip relationship of CFRP-to-steel interface.

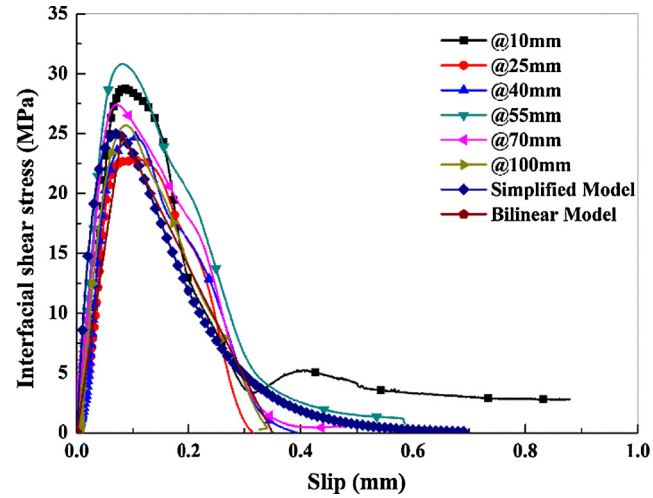

Fig. 2. Typical experimental bond-slip curves and two bond-slip models.

2.1. Model proposed by Teng et al. [12]

Teng et al. [12] firstly presented a bond–slip model for CFRP-to-steel joints. A single-shear test was adopted to investigate the effects of the type and thickness of the adhesive on the behavior of CFRP-to-steel joints. Four thicknesses were used: 1 mm, 2 mm, 4 mm, and 6 mm. It was found that the thickness of the adhesive layer had a significant effect on the failure mode. When an adhesive layer of realistic thickness (<2 mm) was used, debonding was likely to occur within the adhesive layer with a ductile failure process, but when a thick adhesive layer was used, debonding was likely to occur by plate delamination. Plate delamination was a brittle failure mode and should be avoided in practice. Three different adhesives were used in the test program: adhesive A, adhesive B and adhesive C and the properties of adhesives were shown in Table 2.

Along the length of the CFRP plate, some strain gauges were installed to determine the axial strains in the FRP plate and to deduce the interfacial shear stresses and slip. The interfacial shear stress and the slip can be found from readings of the strain gauges attached on the surface of the CFRP plate [8]. From the curves of the bond-slip relationship, it was found that a bilinear bond-slip model could approximate the tested curves. Thus, the bilinear model was defined by three key points: the initial point (0, 0), the peak shear stress point (δ_1, τ_f), and the ultimate point (δ_f, 0), with the area under the curve being the interfacial fracture energy (G_f). This model was based on the bilinear model of FRP-to-concrete interface proposed by Monti et al. [17], as given by Eq. (1):

$$\begin{cases} \tau = \tau_f \frac{\delta}{\delta_1}, if\ \ \delta \leqslant \delta_1 \\ \tau = \tau_f \frac{\delta_f - \delta}{\delta_f - \delta_1}, if\ \ \delta_1 < \delta \leqslant \delta_f \\ \tau = 0, if\ \ \delta > \delta_f \end{cases} \tag{1}$$

Based on the test results, it was evident that the maximum interfacial shear stress was closely related to the tensile strength of the adhesive and didn't depend on the adhesive layer thickness,