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# Numerical studies on the entire debonding propagation process of FRP strips externally bonded to the concrete substrate

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## HIGHLIGHTS

- Calibration of a FE model to predict the load-displacement responses of FRP strips debonding from concrete substrate.
- Analysis of numerical predictions to develop the solutions for describing the bond behavior of FRP-concrete interface.
- Verification of numerical predictions and proposed solutions with test measurements of load and displacement.

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## ABSTRACT

Debonding of FRP strips from concrete substrate is an important issue in FRP-strengthened concrete structures. While a great number of expressions have been published to determine the strength of the FRP-concrete bond, few closed-form solutions are available to well predict the entire load-displacement responses. This paper has numerically studied the full-range behavior of FRP strips debonding from concrete substrate by using Finite Element (FE) predictions which show good correlation with experimental results. Based on the numerical predictions, solutions have been developed to describe the load-displacement responses at each loading stage. The impacts of the strip width, the bond length, the thickness and the elastic modulus of FRP strips on the proposed solutions have been discussed. The proposed solutions show good accordance with the experimental results and the numerical predictions, indicating its reliability in predicting the interfacial behavior of FRP-concrete bond.


## 1. Introduction

Over the past decade, the usage of Fiber Reinforced Polymers (FRP) in the rehabilitation of concrete structures has progressively increased because of its light-weight, high strength, nonmagnetic properties, high corrosion resistance, and relative ease of installation [1–14]. Typically, FRP strips are bonded to concrete substrate with fibers oriented in the direction needing additional tensile strength. The key of this strengthening method is the performance of the FRP-concrete bond [15–36]. While a great number of equations have been developed to determine the strength of the FRP-concrete bond, few are capable of describing the entire debonding process. For the economic and safe design of FRP-strengthened concrete structures, a sound understanding of FRP strips debonding from concrete substrate needs to be developed.

Debonding generally starts at a major crack. It then propagates along the FRP-concrete interface towards the end of the strip at which the strip completely peels off. The debonding of the FRP-concrete interface can be described as bond stress-slip relations. Based on the bond stress-slip relations, numerical models and analytical solutions can be developed to describe the full-range behavior of the interfacial bond at each loading stage. Pull tests have been conducted to study the nonlinear behavior of the interfacial bond [15–26]. A few closely spaced strain gauges at the centerline of the long effective load-transfer length have been used to determine the bond stress-slip relations [17–21]. In fact, it is hard to capture the debonding process with a few axially arranged strain gauges because unpredictable cracks in concrete produce considerable and irregular fluctuations of the axial strain measurements. Instead, the nonlinear debonding process can be more reliably obtained from the direct load and displacement measurements at the end of the strip [22–26]. Finite element (FE) models have been also developed to provide a convenient alternative for the study of the interfacial bond [27–33]. Based on the mesco-scale FE simula-

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tions, expressions have been developed to determine the bond stress-slip relations [27,28]. Although those expressions have been widely accepted in the modeling of the FRP-concrete bond [34–36], they are unable to describe the debonding propagation process. It would be much easier to obtain the bond behavior from closed-form solutions than from FE simulations. In particular, 1 mm or smaller elements are required in the modeling the FRP-concrete interface [29–33]. Yuan et al. [37] have developed analytical solutions to predict the load-displacement responses of FRP strips debonding from concrete substrate. The load-displacement curve is linear elastic until it reaches the maximum bond stress. Then, the softening curve starts as the load increases more slowly than the corresponding slip does. When the bond strength is developed, debonding occurs and propagates towards the end of the strip. A descending curve initiates at the remained bond length which fails to develop the bond strength. The strip completely peels off at the ultimate strip displacement. The accuracy of solutions is determined by the local bond stress-slip relations which can be obtained from either available bond models or experimental measurements. Similarly, Pan et al. [38] have developed closed-form solutions from a simplified bond stress-slip model. Although those solutions [37,38] have been validated with a few experimental results, the reliability of the solutions for the strips with various properties such as various widths, thicknesses, bond lengths and elastic moduli, has not been fully studied.

In this paper, a recently proposed bond model [39] has been used in FE simulations to study the full-range behavior of FRP strips debonding from concrete substrate. The numerical predictions have been used to determine the effective bond length, the bond strength and its corresponding strip displacement as well as the ultimate strip displacement. Based on the numerical predications, closed-form solutions are given to describe the load-displacement responses. Those solutions are validated by extensive experimental results obtained from the specimens with various strip and concrete properties. The paper has two principal objectives: (a) to calibrate a computational tool to study the full-range behavior of FRP strips debonding from concrete substrate; and (b) to provide easy and robust solutions describing the load-displacement responses which would serve as a good reference for designing the FRP-strengthened concrete structures.

## 2. Solutions derived from a bond stress-slip model

The previous study indicates that the bilinear model is capable of capturing the bond stress-slip responses [39]. As shown in Fig. 1, the bilinear model is linearly ascending up to the maximum stress $\tau_m$ at which the corresponding slip is $s_0$. This linear relation produces the elastic stage in Fig. 2. Interfacial softening initiates along with the loss of bond stress as the interfacial slip $s$ further increases from $s_0$ to the final slip $s_f$. After the softening stage, debonding initiates at the FRP-concrete interface. The debonding propagation towards the end of the strip produces the plateau stage in Fig. 2 (a). While the remained bond length fails to develop the bond strength, a descending curve shows up at the unloading stage. The bond model [39] can be mathematically expressed as:

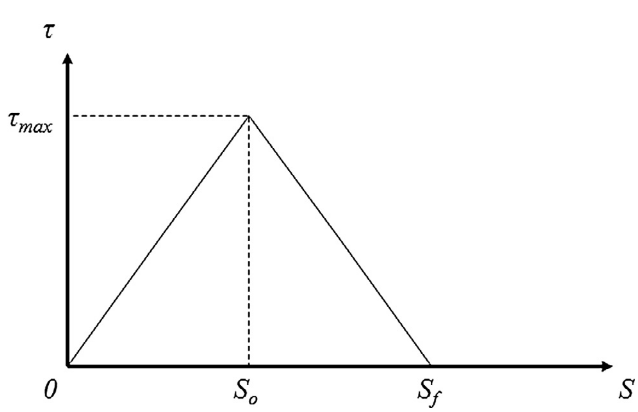


**Fig. 1.** Bilinear bond stress-slip model.

$$\tau = \begin{cases} (\tau_m/s_0)s & s \leqslant s_0 \\ \tau_m(s_f - s)/(s_f - s_0) & s > s_0 \end{cases} \tag{1}$$

$$\tau_m = 1.35 + 0.25\beta_w f_t + 0.62 f_t \tag{2}$$

$$s_0 = 0.016 - 0.0046\beta_w f_t + 0.11\beta_w \tag{3}$$

$$s_f = -0.06 + (0.88 - 0.23\beta_w^2) f_t^{-0.5} \beta_w^{0.5} \tag{4}$$

in which

$$\beta_w = \sqrt{\frac{1.9 - b_f/b_c}{0.9 + b_f/b_c}} \tag{5}$$

$$f_t = 0.62\sqrt{f'_c} \tag{6}$$

where

$f_t$ is the concrete tensile strength;
$f'_c$ is the cylinder compressive strength of concrete;
$\beta_w$ is the width factor;
$b_c$ is the prism width;
$b_f$ is the strip width.

Previous studies [37–39] indicate that the effective bond length $l_e$ has great impacts on the load-displacement responses. With an inadequate bond length, i.e. the bond length $l_f$ shorter than the effective bond length $l_e$, the bond strength increases along with the increase of the bond length. For the strip with an adequate bond length, a further increase of the bond length beyond the effective bond length produces few strength increases but improves the debonding ductility. The bond strength $P_u$ obtained from an adequate bond length can be mathematically described by Eq. (7) [20,24]:

$$P_u = b_f\sqrt{2E_f t_f G} \tag{7}$$

where

$E_f$ is the elastic modulus of the FRP strip;
$t_f$ is the thickness of the FRP strip.

The interfacial fracture energy $G$ obtained from Fig. 1 can be described by the following expressions:

$$G = \begin{cases} \tau s/2 & s \leqslant s_0 \\ (s\tau_m + \tau s - s_0\tau)/2 & s > s_0 \end{cases} \tag{8}$$

Before the debonding initiation, the displacement ($\Delta$) of the FRP strip with an adequate bond length is assumed to be equal to the interfacial slip ($s$) [37]. The load-displacement responses in the elastic stage ($\Delta \leqslant s_0$) and the softening stage ($s_0 \leqslant \Delta \leqslant s_f$) as shown in Fig. 2 (a) are therefore described by Eq. (9):

$$P = \begin{cases} b_f\sqrt{E_f t_f \tau\Delta} & \Delta \leqslant s_0 \\ b_f\sqrt{E_f t_f(\Delta\tau_m + \tau\Delta - s_0\tau)} & s_0 < \Delta \leqslant s_f \end{cases} \tag{9}$$

Then, the bond strength can also be described by Eq. (10):

$$P_u = \begin{cases} b_f\sqrt{E_f t_f \tau_m s_f} & l_f \geqslant l_e \\ \beta_l b_f\sqrt{E_f t_f \tau_m s_f} & l_f < l_e \end{cases} \tag{10}$$