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Bond strength model for interfaces between near-surface mounted (NSM) CFRP strips and concrete

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BOND STRENGTH MODEL FOR INTERFACES BETWEEN NEAR-SURFACE MOUNTED (NSM) CFRP STRIPS AND CONCRETE

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ABSTRACT

This paper presents an accurate bond strength model for carbon-fibre-reinforced polymer (CFRP) strips near-surface mounted (NSM) to concrete where debonding failure happens in the concrete layer adjacent to the interface between FRP and concrete. Both bonded joints with a sufficient bond length and those with an insufficient bond length are covered by the proposed model. The bond strength model was developed on the basis of an existing analytical solution as well as a recently proposed bond-slip model for such bonded joints. Numerical comparisons between the proposed bond strength model and 51 test specimens collected from the existing experimental studies as well as the only existing bond strength model for such joints demonstrate the accuracy of the proposed model and its superiority over the existing bond strength model, especially for joints with insufficient bond lengths.

KEYWORDS

Near-surface mounted (NSM), carbon-fibre-reinforced polymer (CFRP), strip, concrete, bond strength model, effective bond length

INTRODUCTION

The near-surface mounted (NSM) FRP strengthening technique (De Lorenzis and Teng 2007) has attracted significant attention worldwide as an effective alternative to the externally bonded FRP strengthening technique. In the NSM FRP strengthening method, grooves are first cut in the cover concrete of RC members (or the surface layer of other structural members); FRP bars together with adhesive are then placed in the grooves to bond the FRP bars to the concrete. FRP bars used in the NSM strengthening method may have various cross-sectional shapes, including round, square, elliptical and rectangular. In the present study, only FRP strips, as a special form of rectangular bars with a large section height-to-width (thickness) ratio, are considered. FRP strips are a common form of NSM FRP reinforcement due to their advantage over FRP bars of other shapes in bond performance: an FRP strip usually has a much larger perimeter (and hence a much larger area for interfacial bonding) for the same cross-sectional area than an FRP bar of other shapes, which leads to a fuller utilization of the tensile strength of the FRP material (e.g. El Hacha and Rizkalla 2004). FRP strips made of CFRP are particularly attractive as the high strength of CFRP leads to a small cross-sectional area, which is desirable for NSM strengthening applications. The present study is thus focused on CFRP strips. These CFRP strips are typically procured bars with unidirectional fibres oriented in the longitudinal direction; they often have a rough surface texture for enhanced bonding with the adhesive.

Several debonding failure modes have been observed in tests on NSM CFRP strip-to-concrete bonded joints. Among these failure modes, the commonest and most desirable mode is debonding due to cohesion failure in the concrete near the epoxy-concrete interface. Existing test results have indicated that cohesion failure-induced debonding can be expected provided that the surfaces of concrete and FRP are properly prepared and the adhesive is appropriately selected. A bond-slip model has recently been proposed by the authors (Zhang et al. 2013) for NSM CFRP strip-to-concrete interfaces in which failure occurs in the concrete near the bi-material interface. This paper reports briefly on the development of a bond strength model for such bonded joints on the basis of this bond-slip model. A full description of the study can be found in Zhang et al. (2014). For simplicity, only CFRP strips are explicitly referred to in the subsequent discussions, although some of the observations and equations are equally applicable to NSM strips of other FRP materials.

BASIC EQUATIONS

Following the fracture mechanics-based approach used in predicting the bond strength of various bonded joints (e.g. Yuan et al. 2004), the basic equations for calculating the bond strength of an NSM CFRP strip-to-concrete bonded joint take the following form:

$$P_u = \sqrt{2G_f E_f A_f C_{failure}} \le P_t \quad \text{when } L_b \ge L_e \tag{1}$$

$$P_u = \beta_L \sqrt{2G_f E_f A_f C_{failure}} \le P_t \quad \text{when } L_b < L_e \tag{2}$$

where G_f (N/mm) is the interfacial fracture energy; L_b (mm) is the bond length; L_e (mm) is the effective bond length; E_f (MPa) and A_f (mm^2) are the elastic modulus and the cross sectional area of the CFRP strip respectively; $C_{failure}$ (mm) is the cross-sectional contour of the failure surface which is taken to be composed of the three sides of the groove surrounding the adhesive layer (i.e. $C_{failure}$ is the sum of the three side lengths of the groove); β_L is a reduction factor to account for the effect of insufficient bond lengths and is thus a function of the bond length, and P_t (N) is the full tensile capacity of the CFRP strip. The interfacial fracture energy can be calculated using the following equation proposed by the authors (Zhang et al. 2013):

$$G_f = 0.40\gamma^{0.422} f_c^{0.619} \tag{3}$$

where γ is the groove height-to-width ratio and f_c (MPa) is the concrete cylinder compressive strength. Eq. 3 was obtained through a regression analysis of numerical results from a parametric study conducted using a meso-scale finite element model (Zhang et al. 2013). Using Eqs. 1 and 3, the bond strength of an NSM CFRP strip-to-concrete bonded joint with a sufficient bond length can be calculated.

BOND-SLIP MODEL

The bond-slip model proposed by the authors (Zhang et al. 2013) was adopted in the present study to obtain the effective bond length of NSM CFRP strips and the corresponding reduction factor. This bond-slip model is as follows:

$$\tau(s) = A\left(\frac{2B-s}{B}\right)^2 \sin\left(\frac{\pi}{2}\cdot\frac{2B-s}{B}\right) \quad \text{with} \quad s \le 2B \tag{4}$$

$$A = 0.72\gamma^{0.138} f_c^{0.613} \tag{5}$$

$$B = 0.37\gamma^{0.284} f_c^{0.006} \tag{6}$$

where $\tau(s)$ (MPa) and s (mm) are the shear bond stress and the shear slip between the NSM CFRP strip and the concrete respectively. Obviously, the interfacial shear stress varies across the adhesive layer thickness and around the perimeter of the CFRP strip, so $\tau(s)$ is the average shear stress on the defined failure contour.

EFFECTIVE BOND LENGTH

A parametric study was conducted using a simple finite element (FE) model to obtain the effective bond length and to examine the effect of bond length on bond strength. For this purpose, a simple beam-spring FE model was employed. Part of the beam-spring model near the loaded end is shown in Figure 1. In the FE model, the CFRP strip is simulated using beam elements, the concrete is assumed to be a rigid body, and the CFRP-to-concrete interface is simulated using cohesive elements with a very large normal stiffness. The shear stiffness of the cohesive elements is defined using the local bond-slip model given by the authors (Eqs. 4 to 6), and no interaction is assumed between normal stresses (strains) and shear strains (stresses) of the cohesive elements.

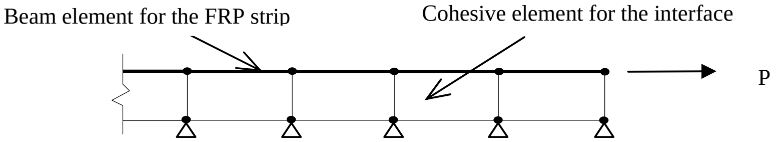


Figure 1. FE model of NSM CFRP strip-to-concrete bonded joint

Table 1. Effect of bond length on bond strength

Bond length (mm)	Bond strength (kN)								
	C20-t2-h10-E150	C20-t2-h20-E150	C20-t2-h30-E150	C30-t2-h10-E150	C30-t2-h20-E150	C30-t2-h30-E150	C40-t2-h10-E150	C40-t2-h20-E150	C40-t2-h30-E150
0	0	0	0	0	0	0	0	0	0
25	6.980	11.95	17.18	8.942	15.31	22.02	10.66	18.26	26.26
50	13.52	23.27	33.52	17.21	29.72	42.84	20.39	35.30	50.95
75	19.25	33.77	48.93	24.00	42.55	61.88	27.88	49.92	72.84
100	23.30	42.27	61.97	28.16	52.01	76.79	31.94	59.77	88.76
125	25.51	47.97	71.40	30.03	57.47	86.26	33.51	64.81	97.82
150	26.48	51.15	77.15	30.72	60.04	91.20	34.00	66.88	102.0
175	26.85	52.67	80.19	30.93	61.09	93.44	34.14	67.63	103.7
200	26.99	53.34	81.65	31.00	61.48	94.36	34.18	67.87	104.3
225	27.03	53.61	82.29	31.01	61.62	94.71	34.18	67.95	104.5
250	27.04	53.72	82.57	31.02	61.66	94.84	34.19	67.97	104.6
275	27.05	53.76	82.68	31.02	61.67	94.88	34.19	67.98	104.6
300	27.05	53.78	82.74		61.68	94.90		67.98	
350		53.78	82.75		61. 68	94.90			

Note: The name of each numerical case starts with a letter "C" and a two-digit number to represent the concrete strength (f_c), followed by a letter "t" and a one-digit number to represent the thickness of the CFRP strip (t_f), a letter "h" and a two-digit number to represent the height of the CFRP strip (h_f), and a letter "E" and a three-digit number to represent the elastic modulus of CFRP (E_f).

It has been shown (Zhang et al. 2013) that the groove height-to-width ratio and the concrete strength are the two main parameters for the bond behavior of NSM CFRP strips embedded in concrete, so these two parameters were chosen as the two main variables in the present parametric study. Three values were considered for both the concrete strength (i.e. 20 MPa, 30 MPa and 40 MPa) and the groove height-to-width ratio (i.e. 2.33, 4.00 and 5.67) in the parametric study, leading to nine combinations. For each combination, 12 cases were analyzed with the only difference between them being the bond length which varies from 25 mm to 300 mm at an interval of 25 mm; for 4 of the 9 combinations, one additional case with a bond length of 350 mm was included to obtain converged results. The details and results of all the numerical cases are summarized in Table 1.

Following Lu et al.'s (2005), the effective bond length is defined as the bond length over which the interfacial shear stresses offer a total resistance of 99% of the bond strength (i.e. ultimate load) for a joint with an infinite bond length. Then the effective bond lengths for all the 9 combinations can be obtained from the results summarized in Table 1, through interpolations for values between the discrete data points. Finally a relationship between the effective bond length L_e and the parameter η was found:

$$L_e = \frac{1.66}{\eta} \tag{7}$$

$$\eta^2 = \frac{\tau_{\max}^2 C_{failure}}{2 G_f E_f A_f} \tag{8}$$

REDUCTION FACTOR β_L

By plotting all the results of the parametric study (Table 1), the relationship between β_L and $\frac{L_b}{L_e}$ was obtained. It was found that this relationship is unique despite the different concrete strengths and groove height-to-width ratios. Based on the data in Table 1, the following equation is proposed as a best-fit expression for β_L :

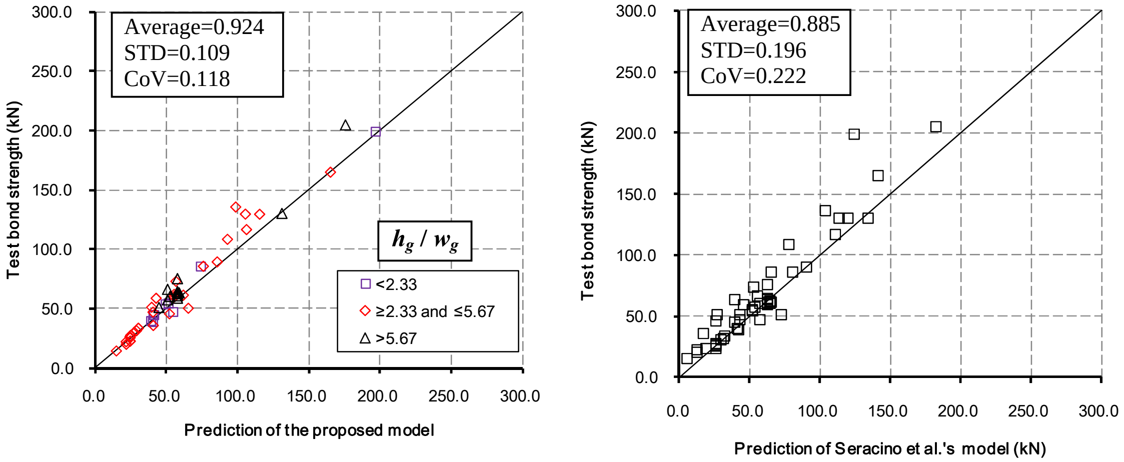
$$\beta_L^{99\%} = \frac{L_b}{L_e}\left(2.08 - 1.08\frac{L_b}{L_e}\right) \tag{9}$$

VERIFICATION OF THE PROPOSED BOND STRENGTH MODEL

The predictions of the proposed bond strength model are compared with the results of 51 test specimens collected from 7 existing studies as well as the predictions of the only existing bond strength model for such joints proposed by Seracino and his co-workers (Seracino et al. 2007; Oehlers et al. 2008; Rashid et al. 2008) (referred to as Seracino et al.'s model hereafter).

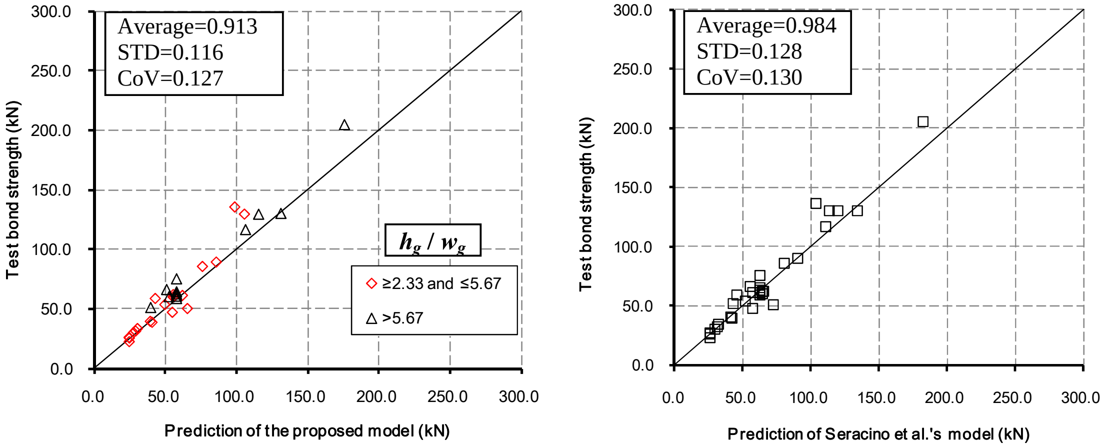
The bond strengths predicted by the proposed model (i.e. Eqs. 1 and 2) and those predicted by Seracino et al.'s model are compared with all the 51 collected test results in Figure 2. In general, both models provide reasonably accurate predictions of the test results, but the proposed model shows superior performance in terms of all the three statistical characteristics (i.e. the average, standard deviation (STD) and coefficient of variation (CoV)).

Figure 3 shows a comparison between the predictions of the two models and the test results of specimens with a sufficient bond length (32 tests in total). For these tests, the reduction factors predicted by the two models are both equal to 1.0 (i.e. no reduction). In this comparison, the performance of the two models depends solely on their respective interfacial fracture energy values. The comparison indicates that both models perform very well: Seracino et al.'s model has a slightly better average value, but the proposed model has slightly better values for the standard deviation and the coefficient of variation. The good average value of Seracino et al.'s model is as expected as among the 32 tests used in this comparison, 13 tests were used in the regression analysis of test results by Seracino et al. in developing their model.



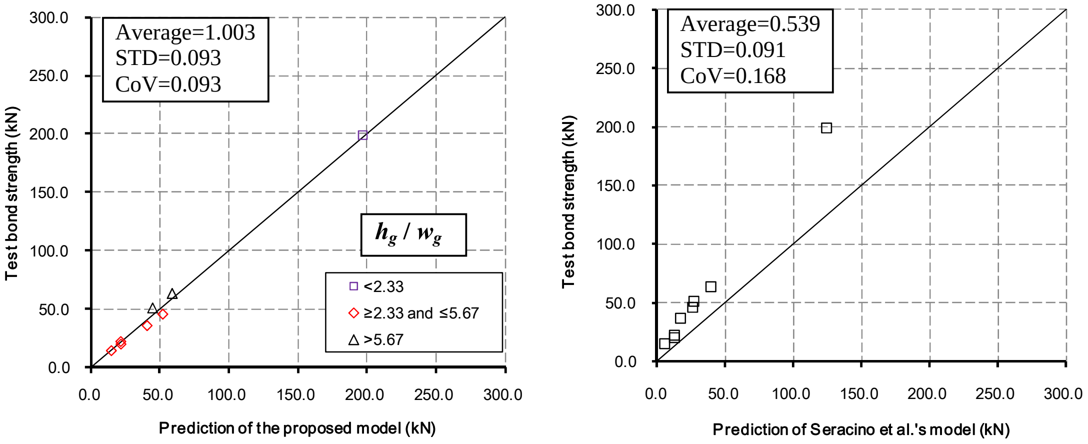
(a) between tests and the proposed model (b) between tests and Seracino et al.'s model

Figure 2. Bond strength comparison for all collected specimens



(a) between tests and the proposed model (b) between tests and Seracino et al.'s model

Figure 3. Bond strength comparison for specimens with a sufficient bond length



(a) between tests and the proposed model (b) between tests and Seracino et al.'s model

Figure 4. Bond strength comparison for β_L <1.0

Figure 4 compares the predictions of the two models and the test results of those specimens with a bond length shorter than that calculated by Eq. 7 (8 tests in total). For these tests, the reduction factors predicted by the two models are both less than 1.0. It is evident from Figure 4 that the proposed model performs very well and much better than Seracino et al.'s model which significantly underestimates the test results. Given that the fracture energy in Seracino et al.'s model provides reasonably accurate predictions of test results, it can be concluded that the errors seen in Figure 4 arise mainly from the equation for the effective bond length and the reduction factor.

CONCLUSIONS

A bond strength model for NSM CFRP strip-to-concrete interfaces has been presented in this paper. The predictions of the proposed model were compared with the results of 51 test specimens collected from 7 existing studies as well as the predictions of the only existing bond strength model. These comparisons indicated that for cases of insufficient bond lengths, the proposed model provide more accurate predictions for the effective bond length equation and the bond strength reduction factor. The proposed bond strength model, due to its accuracy, simplicity and applicability to a wide range of realistic cases, can be readily incorporated in design codes and guidelines.

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