ONE DIMENSIONAL FINITE ELEMENT MODELLING ON AN FRP-TO-CONCRETE BONDED JOINT ANCHORED WITH INCLINED U-JACKETS

***Chuying Cui[1], Li Lijuan[1], †Fu Bing[1], Liu Feng[1]**

[1]School of Civil and Transportation Engineering, Guangdong University of Technology, Guangzhou 510006, China

*Presenting author: cuichuying@hotmail.com
†Corresponding author: cefubing@gdut.edu.cn

Abstract

Debonding failure in the form of either IC debonding or concrete cover separation commonly controls the load carrying capacity of RC beams flexurally strengthened with an externally bonded FRP plate, leading to a very low utilization rate (e.g., 20%-40%) of the FRP strength. A number of experimental studies carried by the authors' group and some other researchers indicate inclined FRP U-jackets as the end anchorage show to be highly effective in delaying or suppressing the debonding failures, resulting in significant enhancements in the structural performance of FRP-plated RC beams and utilization rate of the FRP strength. This paper presents a one-dimensional finite element model for FRP-to-concrete bonded joint anchored with inclined FRP U-jackets, in which interfacial cohesive elements are used to represent the force-slip behavior of the anchored joints. Comparisons between the FE predictions and test results have been made to demonstrate the accuracy of the proposed FE model. On the basis of the FE predictions, expressions of the force-slip model are proposed for the inclined FRP U-jackets, which considers the effect of vital parameters (e.g., inclination angle, width and thickness of U-jackets), and can be directly used in an FE model for the FRP-plated RC beams with inclined U-jackets.

Keywords: Fiber reinforced polymer (FRP), concrete, debonding, fiber anchor, finite element modelling

1. Introduction

Externally bonding of fiber reinforced polymer (FRP) plates has become a widely-used technique for the strengthening of reinforced concrete (RC) beams due to superior properties of the FRP materials, such as high strength-to-weight ratio and excellent corrosion resistance[1].Debonding failure in the form of either IC debonding (intermediate crack debonding) or concrete cover separation commonly controls the load carrying capacity of RC beams flexurally strengthened with an externally bonded FRP plate, leading to a very low utilization rate (e.g., 20%-40%) of the FRP strength[2].A number of experimental studies carried by the authors' group and some other researchers indicate that inclined FRP U-jackets as the end anchorage show to be highly effective in delaying or suppressing the debonding failures, resulting in significant enhancements in the structural performance of FRP-plated RC beams and utilization rate of the FRP strength. FRP U-jacketing at 45° to the beam axis at end anchorage is much more effective in delaying or suppressing the above two failure modes than vertical U-jacketing[3][4]. FRP U-jackets of different parameters have significantly various effects on anchorage, however, the force-slip behavior between the FRP U-jackets and concrete interface remains unclear. Bond testing on of FRP-to-concrete bonded joints anchored with inclined U-jackets is an attractive test approach to investigate the anchoring mechanism of FRP U-jackets in FRP-plated RC beams. Experimental studies including single shear tests, double shear tests and modified beam tests and theoretical studies by means of fracture mechanics analysis and finite element analysis are two vital measures for investigating interfacial debonding behavior of FRP-to-concrete bonded joints [5]-[9].

The authors' group has conducted several series of NES single-shear pull tests for a CFRP plate-to-concrete bonded joint anchored with inclined U-jackets, which considers the effect of vital parameters (e.g., inclination angle, width and thickness of U-jackets). In this paper, a one-dimensional finite element model for FRP-to-concrete bonded joint anchored with inclined FRP U-jackets is proposed, in which interfacial cohesive elements are used to represent the force-slip behavior of the anchored joints. Comparisons between the FE predictions and test results have been made to demonstrate the accuracy of the proposed FE model. On the basis of the FE predictions, expressions of the force-slip model are proposed for the inclined FRP U-jackets, and can be directly used in an FE model for the FRP-plated RC beams with inclined U-jackets.

2. Near-end supported single-shear pull test

The author has conducted a series of NES single-shear pull tests, taking the inclination angle, width and thickness of U-jackets as experimental variables, to study debonding behavior between FRP and concrete anchored with FRP U-jackets of different forms. The test program consisted of 10 concrete specimens. All used 220×300mm$\times$700mm concrete prisms. In this test program, the cylinder compressive strength of concrete $f_c^{'}$ was 34MPa. All CFRP plates had the same dimensions: 50mm in width and 1.2mm in thickness. The bond length of CFRP plates was 400mm, which was longer than the effective bond length. And the nominal thickness of single ply of CFRP plate used for U-jackets is 0.167mm. Details of specimens dimensions of U-jackets in different forms can be found in Fig. 1 and Table 1.

Figure 1. Test rig.

Table 1. Details of specimens and test results

Specimen	U-jackets				Rounder radius (mm)
	Width b_U (mm)	Plies	Bond length L_U (mm)	angle (°)	
CS1	—	—	—	—	—
I30P2W40L250C25	40	2	250	30	25
I45P2W40L250C25	40	2	250	45	25
I60P2W40L250C25	40	2	250	60	25
I90P2W40L250C25	40	2	250	90	25
I135P2W40L250C25	40	2	250	135	25
I45P2W50L250C25	50	2	250	45	25
I45P2W60L250C25	60	2	250	45	25
I45P1W40L250C25	40	1	250	45	25
I45P3W40L250C25	40	3	250	45	25

3. One-dimensional finite model

3.1. General

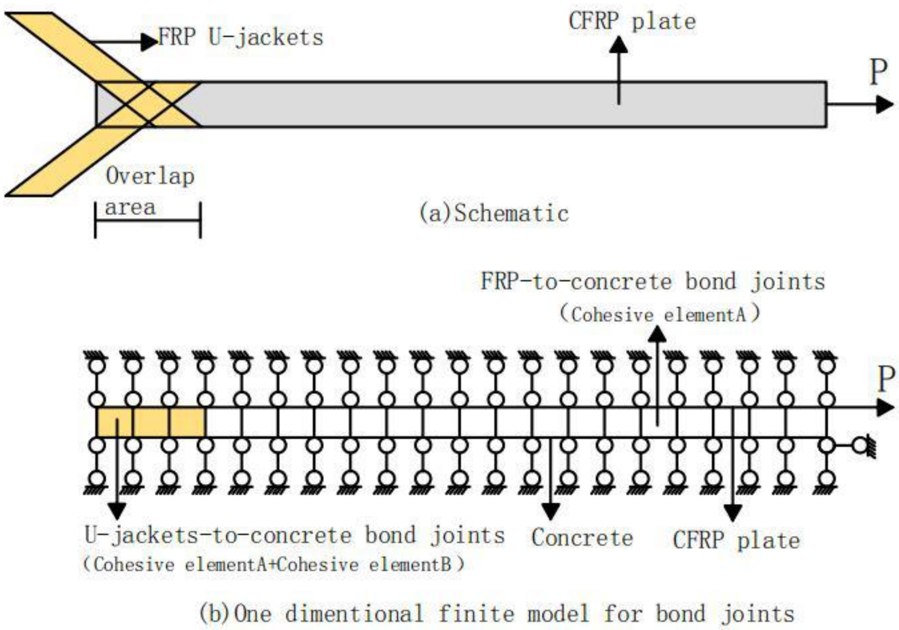


Figure 2. Pull test: (a) Schematic; (b) FE model

The one-dimensional interface finite element model in Fig. 2 contains two kinds of interfacial elements COH2D4, referred to hereafter as CA and CB, adopting two different constitutive laws to represent the debonding behavior of two different interfaces. In the CFRP-to-concrete bonded joint, the properties of the interfacial elements CA are defined by using the bi-linear bond-slip model of Lu et al. [9], while the proposed elastic-brittle bond-slip model accounts for the bond behavior of U-jacket-to-concrete using the interfacial elements CB. By employing the interfacial elements CB along the overlap area, as shown in Fig. 2, the bond bond strength among the overlap area can be significantly enhanced to reflect the anchoring effect of FRP U-jackets. The debonding failure of bonded joints depends only on the bond-slip behavior parallel to the interface, and the vertical displacement of top and bottom surfaces of interfacial elements are constrained as a result. So that top and bottom surfaces can be assumed to be the CFRP plate and the concrete prism, respectively.

The bonded joint model used in this paper has the following dimensions: the length of the bonded joint is 400mm, which is equal to the bond length of CFRP plates, and the out-of-plane thickness is 50mm, which is equal to the width of CFRP plates. The element size of 1mm is used for the interfacial element, and the shear strain of the element equals to the shear slip hence. After constraining the horizontal displacement of the bottom surface of interfacial elements at the loaded end, the interface slip can be accessed directly by the horizontal displacement of the top surface of interfacial elements at the loaded end.

3.2. Proposed bond-slip model

The proposed bi-linear bond-slip model is shown in Fig. 3(b), which features a linear ascending branch followed by the rapid failure of the interface element CB. According to the above model, the bond shear stress increases linearly with the interface slip until it reaches the peak value at which the interfacial slip corresponding to the applied load is defined as s_b hereafter. When the interfacial slip is greater than s_b, the bond stress reduces to zero immediately, indicating the failure of a local interface element. And the description of the local bond-slip relationship is proposed by following equations:

$$\tau = \begin{cases} Es & if \quad s \le s_b \\ 0 & if \quad s > s_b \end{cases} \tag{1}$$

where E is the slope of the ascending branch. Based on the above discussions, the local bond-slip model can be precisely denoted, as long as the value of the key parameters, including the slope of the ascending branch E and the ultimate slip s_0, are determined.

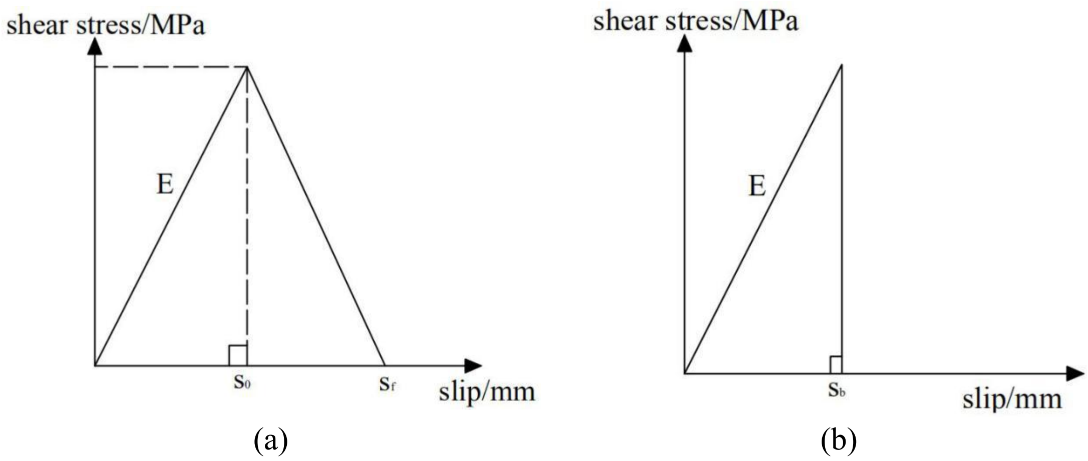


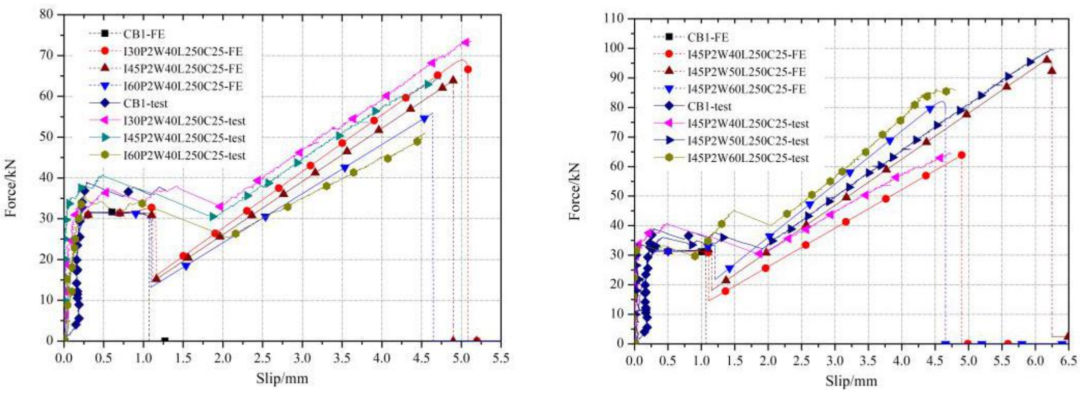
Fig 3. Bond slip model: (a) Lu's bi-linear model; (b) Proposed elastic-brittle model

4. Analysis results and discussions

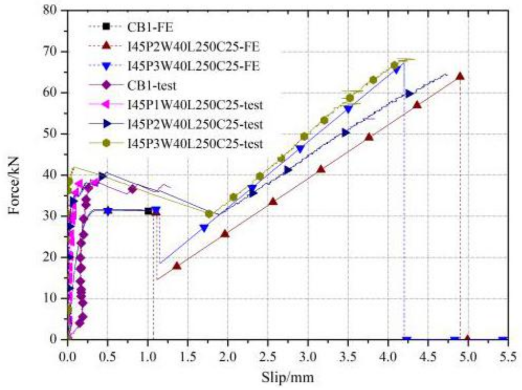
Table 2. Key parameters of proposed bond slip model

Specimen	Slope E(MPa)	Ultimate slip s_0(mm)
I30P2W40L250C25	3.0	3.2
I45P2W40L250C25	4.3	3.0
I60P2W40L250C25	5.6	2.8
I45P2W50L250C25	5.2	3.4
I45P2W60L250C25	6.1	2.3
I45P1W40L250C25	——	——
I45P3W40L250C25	6.4	2.2

Through multiple calculations, the values of slope E and the ultimate slip s_b in the proposed bond-slip model adopted by interfacial elements CB, which are employed among the overlap area, are shown in Table 2. Comparisons between the FE predictions and test results have been made to demonstrate the accuracy of the proposed FE model in Fig. 4. It can be seen that the proposed bond-slip model gives results in close agreement with the test results, showing the same development trend of load-slip curves, excluding the stage 4 of load-slip curves. It can be found that a sudden drop of the load-carrying capacity occurs in the stage 4 of the load-slip curve when it reaches a interface slip s_1 at a value around 1.1~1.2mm, followed by the load's linear increasing with the interfacial slip until the failure of the interface model. Nevertheless, the experimental curve only showed a slight downward trend in stage 4, revealing that there is only a mild decrease in the load-carrying capacity in stage 4. When the interface slip reaches a value around 2.0 mm, where the complete debonding of the CFRP-to-concrete bonded joint emerges, the load-carrying capacity increases linearly at a constant rate in stage 5 and converges with the FE prediction until the failure of the specimen. This inevitable difference appears in stage 4 of the force-slip response, on account of different loading schemes between the FE analysis and the experiment program. The force-control loading scheme is adopted by the test program, while the displacement-control loading scheme is used for the FE model, which makes it possible to capture rapid drop of the load-carrying capacity.



(a) (b)



(c)

Fig 4.FE versus test load-slip curves: (a) Inclination angle of U-jackets; (b) Width of U-jackets; (c) Thickness of U-jackets

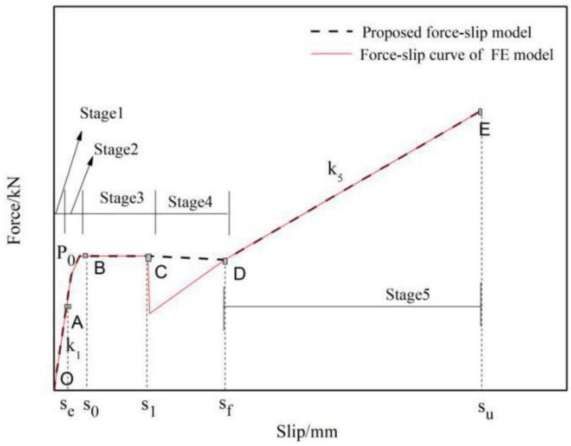


Figure 5. Proposed force-slip model and force-slip curve of FE model

P_0 is the peak load of the debonding duration of CFRP plates. s_0 is the slip corresponding to the test load reaches P_0; s_f is the slip of complete debonding of CFRP plates; P_u is the ultimate test load; s_u is the ultimate slip.

For the stage 4 of load-slip curves from FE predictions, the following simplification can be made to get a better fitting with experimental results. Make the extension line for the segment BC, intersecting with stage 5 at point D, where the corresponding interface slip can be defined as s_f. Accordingly, a load-slip model of the FRP-to-concrete bonded joint anchored with the inclined U-jackets is proposed through the finite element analysis by replacing the fold line in the stage 4 of the FE model with the linear segment CD, as the dotted line shown in Fig. 5. Based on the observations, the load-slip response can be closely predicted by the proposed bond-slip model.

5. Conclusions

This paper presents a one-dimensional finite element model for FRP-to-concrete bonded joint anchored with inclined FRP U-jackets, in which interfacial cohesive elements adopting the proposed bond-slip model are used to represent the force-slip behavior of anchored joints. Comparisons between the FE predictions and test results have shown that the FE model can provide close predictions of the load-slip response of the bonded joint, demonstrating the accuracy of the proposed FE model with the bi-linear bond-slip model. The shape and several key parameters of the force-slip model of the FRP-to-concrete with the end anchorage can be determined through the proposed FE model.

6. References

[1] Smith, S. T., & Teng, J. G. (2002). FRP-strengthened RC beams. Ⅰ: review of debonding strength models. Engineering Structures, 24(4), 385-395.

[2] Kalfat, R. , Almahaidi, R. , & Smith, S. T. . (2013). Anchorage devices used to improve the performance of concrete structures retrofitted with FRP composites: a state-of-the-art review. Journal of Composites for Construction, 17(1), 14-33.

[3] Fu, B. , Chen, G. M. , & Teng, J. G. . (2017). Mitigation of intermediate crack debonding in FRP-plated RC beams using FRP U-jackets. Composite Structures, (176), 883-897.

[4] Fu, B., Tang, X. T., Li, L. J., Liu, F., & Lin, G. (2018). Inclined FRP U-jackets for enhancing structural performance of FRP-plated RC beams suffering from IC debonding. Composite Structures, 200, 36-46.

[5] Chen, J. F. , & Teng, J. G. . (2001). Anchorage strength models for FRP and steel plates bonded to concrete. Journal of Structural Engineering, 127(7), 784-791.

[6] Yao, J. , Teng, J. G. , & Chen, J. F. (2005). Experimental study on FRP-to-concrete bonded joints. Composites Part B Engineering, 36(2), 99-113.

[7] Yuan, H. , Teng, J. G. , Seracino, R. , Wu, Z. S. , & Yao, J. (2004). Full-range behavior of FRP-to-concrete bonded joints. Engineering Structures, 26(5), 553-565.

[8] Lu, X. Z. , Ye, L. P. , Teng, J. G. , & Jiang, J. J. (2005). Meso-scale finite element model for FRP sheets/plates bonded to concrete. Engineering Structures, 27(4), 564-575.

[9] Lu, X. Z. , Teng, J. G. , Ye, L. P. , & Jiang, J. J. (2005). Bond-slip models for FRP sheets/plates bonded to concrete. Engineering Structures, 27(6), 920-937.