Modeling of Interfacial Debonding Induced by IC Crack for Concrete Beam-bonded with CFRP

Lihua Huang , Zhiquan Yang

***Abstract*—Fiber reinforced polymer (FRP) has been widely employed in retrofitting concrete structures. Debonding of FRP from concrete is a typical failure mode in this technique. Fracture energy of interface is a key parameter governing the debonding behavior. Cohesive zone model (CZM) of fracture energy-based criteria is therefore an appropriate numerical approach to characterize the debonding behavior. This paper presents a simple but robust finite-element (FE) model with CZM for simulating the debonding procedure of CFRP from concrete induced by intermediate concrete(IC) crack. Parameters in CZM are determined by the related theories of concrete fracture mechanics and corresponding experiments. Based on the proposed FE model, the relationship of load to concrete crack mouth open displacements (CMOD), variations of stress in CFRP and concrete, as well as interfacial shear stress and slip in the case of different CMOD are identified, respectively. The peak points of load and debonding performance predicted by the presented FE model are well agreeable with the experimental results, which has verified the feasibility and precision of the proposed model for simulating interfacial debonding induced by IC crack of concrete beam.**

***Index Terms*—CFRP, Concrete beam, CZM, Debonding, FE modeling.**

I. INTRODUCTION

Fiber reinforced polymer (FRP) has been widely employed in retrofitting concrete structures [1]. One of the key factors that control the enhancement of FRP on concrete is the performance of interfacial bonding joint [2]. A large amount of experimental research and engineering application show that debonding of FRP from substrate or peeling of near surface concrete is the most often failure mode occurred in this technique [3]. Many formulas representing interfacial bond-slipping are proposed based on the corresponding experiments. The universality and accuracy of the models have been discussed by researchers, and the well accepted models are applied in the numerical analysis of RC beam externally bonded with FRP sheets [4].

When interfacial bond-slip is considered, bilinear elastic spring element of zero length is commonly used to simulate the interfacial joint in the FE models of concrete beam bonded with FRP. Normally and tangentially interfacial bonding and separation are represented by the relative displacements of initially coincident nodes of spring element, which is indeed different from the real brittle performance of debonding process. Interfacial debonding are recognized to be of two stages: an initially elastic manner where the shear stress linearly increases with the slip until it reaches to a maximum value and a softening behavior in which the shear stress decreases with slip, which is similar to the propagation of concrete cracking [5], [6]. Therefore, it is more appropriate to interpret the process of bond-slip by principles of non-linear fracture mechanics [7], [8]. Recently the cohesive zone model (CZM) of fracture energy-based criteria has drawn more and more attention in characterizing the constitutive behavior of debonding process. The softening and slipping of the interface can be controlled by the critical fracture energy that is also the energy required to break apart the interface surfaces in this model [9]. The whole debonding process from crack initiation-growth to slip can be unified into one model and easily formulated and implemented in numerical simulation through CZM. Based on this idea, Wang J L [10] has established the closed-form solution of CZM for IC crack-induced debonding. Lorenzis

Manuscript received March 06, 2016; revised March 29, 2016. This work was supported by Liaoning Science and Technology Project 2014020008.

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[11] and Cornetti [12] put forward an analytical approach of cohesive crack modeling for the edge debonding failure of FRP-plated beam. Chen [13] conducted debonding analysis of adhesively bonded interface between two balanced adjacent flexural cracks by CZM. Although the entire procedure of crack initiation and progress in the interface of FRP and concrete have been investigated in the many researches, the analytical solutions cannot be extended to the general case for the limitation of the strict boundary conditions.

Nowadays with the increasingly upgraded algorithm of CZM, interfacial debonding process can be well simulated and analyzed by this model. This paper presents a simple model of CZM for precisely simulating the interfacial debonding of FRP from concrete induced by IC crack through using FE package ABAQUS. With the application of CZM at concrete crack surfaces and FRP-to-concrete interface, the debonding process induced by propagation of IC crack is clearly revealed, and the performance of CFRP, concrete and the interface under various levels of external loads are clearly understood. The numerical analysis has been demonstrated to be well agreeable with the experimental results.

II. FE MODEL OF DEBONDING INDUCED BY IC CRACK

A. Profile of the Concrete Beams

The FE model of FRP-bonded concrete beam with pre-crack is taken from literature [14], as shown in figure 1. Five beams with different length, height and seam height ratio are listed in table I. CFRP is of the same length as concrete beam, but 50 mm width. To prevent conical shear failure around IC crack caused by local stress concentration, un-bonded length l_u=40 mm is set up near IC crack.

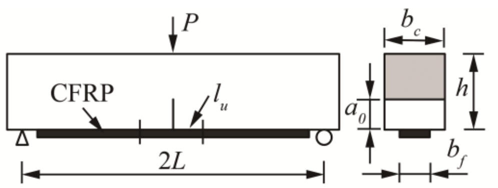


Fig.1 CFRP strengthened concrete beam

In this model, the splitting tension strength of concrete is 3.61 MPa, and the flexural strengths of concrete beams with 200 mm, 250 mm and 300 mm height are 3.02 MPa, 2.95 MPa and 2.63 MPa, respectively. Tensile strength of CFRP is 3916 MPa. Modulus of elasticity and Poisson's ratios of concrete and CFRP are 29.45 MPa, 250 MPa, 0.2 and 0.3, respectively.

TABLE I PROFILE OF THE CONCRETE BEAMS

Beams	$2L \times h \times b_c$/mm×mm×mm	Seam Height Ratio
P202	800×200×150	0.2
P203	800×200×150	0.3
P204	800×200×150	0.4
P253	1000×250×150	0.3
P303	1200×250×150	0.3

B. Finite Element Model

In the FE model, concrete is assumed as elastic material with different tensile and compressive strength because small stress and strain are developed for plain concrete beam with pre-crack in bending. Concrete beam is simulated by solid element C3D8R of mesh size 20 mm. CFRP is taken as elastic and isotropic material, and simulated by shell element S4R. The un-bonded interface near IC crack is represented by frictionless contact elements. Cohesive element COH3D8 is employed to simulate the propagation of concrete cracking and interfacial debonding of CFRP from concrete. Parameters of fracture properties in CZM are determined in the following sections. The mesh size of cohesive element is 10 mm for interface and 5 mm for concrete crack.

C. Concrete Fracture Properties

To simulate the propagation of IC crack, cohesive elements are placed at the cracking path of concrete. Fictitious cracking model is more appropriate for analyzing flexural cracks since there is no singularity at crack tip. According to the exponential model of concrete virtual crack proposed by Reinhardt [15], [16], the equivalent crack opening displacement ω_0=0.16mm when cohesive force deceases to zero. The maximum nominal stress criterion is applied for the initiation of concrete crack, where fictitious crack develops when normally tensile stress reaches to the flexural strength of concrete. Equation of cohesive force and crack opening with exponential softening of concrete is expressed by

$$f(\delta) = f_t \left[1 - \frac{1 - e^{-\alpha\left(\frac{\delta - \delta_0}{\delta_f - \delta_0}\right)}}{1 - e^{-\alpha}} \right] \tag{1}$$

$$\delta_0 = 1 \times \frac{f_t}{E_c} \tag{2}$$

where f_t is the flexural strength of concrete; default constitutive thickness of cohesive element of zero thickness is 1; δ_f represents the open distance of crack when cohesive force equals zero, namely $\delta_f = \omega_0$. Coefficient α is used to governing the decreasing shape of the exponential curve, which influences the softening of concrete.

The cohesive surface is open when normal displacement equals to ω_0. As to the specific concrete beam, coefficient α is different, which can be determined by the experimental data. For the beam analyzed in this paper, when α=10, the numerical peak loads P_{Num} are well coincident with the experimental results P_{Exp} from literature [14], as shown in table II. Each tested peak load is the average value of the four specimens, namely the peak load of beam 203 is actually within 6.648kN and 7.257kN. Because of the discreteness of concrete experiment, the margin of errors is rational. Based on the determined parameter, the properties of loads with respect to crack mouth open displacements (CMOD) of concrete beams are constructed as shown in figure 2, which are used in the simulation of concrete cracking.

TABLE II NUMERICAL AND EXPERIMENTAL PEAK LOADS

Beams	P_{Exp} /kN	P_{Num}/kN	Error/%
C202	9.4	10.07	7.13
C203	6.93	8.08	16.60
C204	5.65	6.05	7.08
C253	8.69	9.42	8.40
C303	9.92	10.02	1.01

D. Fracture Properties of CFRP-to-concrete Interface

The performance of interfacial bond-slip of CFRP-to-concrete is well expressed by bilinear model proposed by Lu[4] as follow.

$$\beta_\omega = \sqrt{\frac{2.25 - b_f / b_c}{1.25 + b_f / b_c}} \tag{3}$$

$$\tau_u = 1.5 \beta_\omega f_t \tag{4}$$

$$S_0 = 0.0195 \beta_\omega f_t \tag{5}$$

$$G_f = 0.308 \beta_\omega^{\ 2} \sqrt{f_t} \tag{6}$$

in which b_f / b_c is the ratio of the width of CFRP to concrete, f_t means the splitting tension strength of concrete.

From the above equations, the maximum shear stress in the analytical model is τ_u=5.94 MPa, fracture energy G_f= 0.7 N/mm, and the maximum slip $S_f = 2G_f / \tau_u$ = 0.236 mm before interfacial debonding.

The maximum nominal stress criterion is applied to determine the initiation of interfacial cracking, which means shear crack develops when shear stress reaches to the maximum τ_u. Interfacial performance of bond-slip is governed by linear softening model and fracture energy. Interfacial debonding occurs when the shear energy on the interface reaches to G_f.

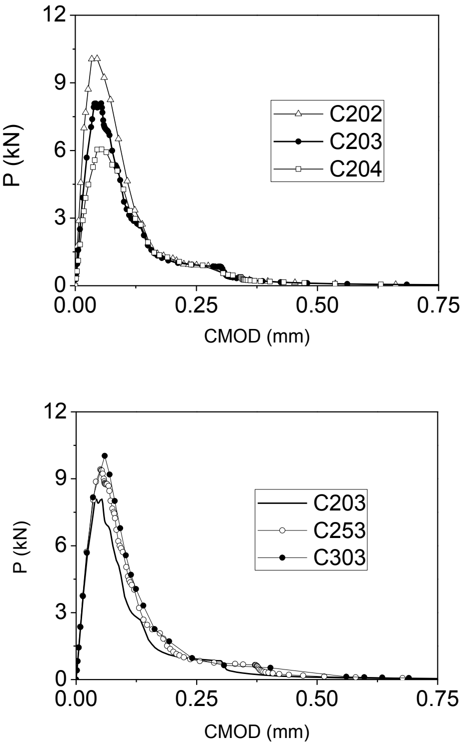


Fig. 2 Curves of load-CMOD of the specimens

III. INTERPRETATION OF NUMERICAL STUDY

A. Load to CMOD

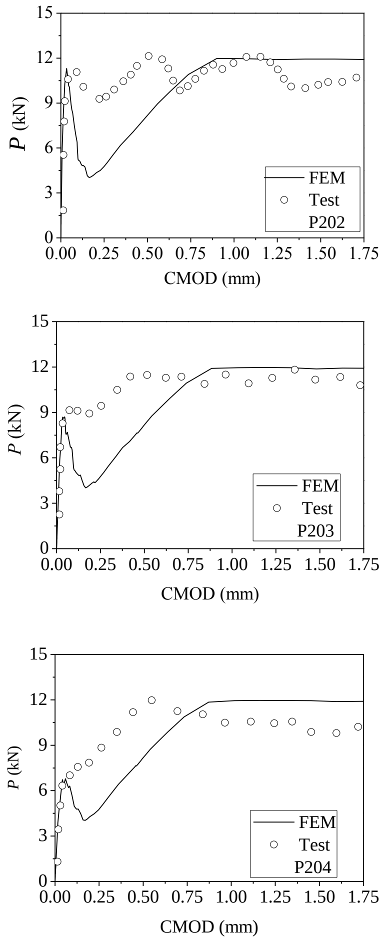
The five concrete beams bonded with CFRP are analyzed by applying the suggested FE model and fracture properties, and the corresponding load-CMOD curves are constructed as shown in figure 3. Interfacial crack initiation and progress

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

can be divided into three regions as indicated in the load-CMOD curves. Two peak loads P_{1max} and P_{2max} can be figured out from the curves. When the applied load is less than P_{1max}, it is linearly proportional to CMOD and the interface behaves in elasticity. After the first peak point, load decreases with the propagation of IC crack. After the activation of CFRP, the load rises again until to the second peak point, and the interfacial slip starts at this time. Two peak loads P_{1max} and P_{2max} obtained from the FE model of the five beams are compared with the experimental results and listed in table III. It is shown that the numerical results obtained from the FE model are well agreeable with the experimental data.

TABLE III COMPARISON OF PEAK LOADS OBTAINED FROM FEM AND TEST

Beams	$P_{1,Num}$ /kN	$P_{1,Exp}$ /kN	Error /%	$P_{2,Num}$ /kN	$P_{2,Exp}$ /kN	Error /%
P202	11.30	10.97	3.00	11.98	11.95	0.25
P203	8.71	9.07	3.97	11.97	11.66	2.66
P204	6.73	7.72	12.82	11.97	12.33	2.92
P253	9.88	11.18	11.63	11.96	12.80	6.56
P303	10.34	12.93	20.03	12.02	13.55	11.29



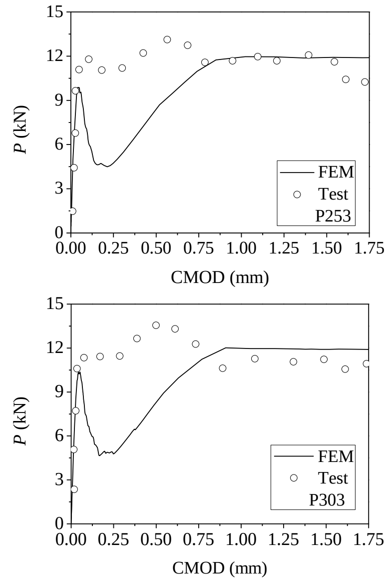


Fig.3 Comparison of load-CMOD obtained from FEM and test

B. *Stress of CFRP Sheet*

The following FEA results are taken from beam P203. Stress distribution along CFRP under different CMOD is constructed in figure 4. It is shown that the stress at the middle of CFRP linearly increases with CMOD before the applied load reaches to P_{2max}. When the applied load equals to P_{1max}, where CMOD equals to 0.046 mm as shown in figure 4, stress in CFRP remains in a low level, namely 88MPa. While, when the applied load equals to P_{2max}, where CMOD equals to 1.183 mm, stress in CFRP reaches to the highest value of 1430 MPa. After that the stress remains in a high level even though CMOD increases continuously, but the stress gradually transfers from the middle to the end of CFRP. It illustrates that the stress in CFRP is mainly caused by the concrete crack opening and interfacial slipping. As CMOD gets to 2.968 mm, most of the CFRP stays in a high stress level of 1430 MPa, as shown in figure 5.

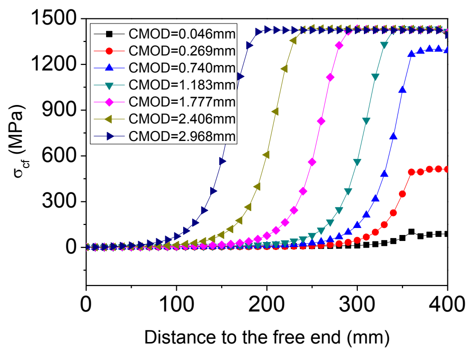


Fig.4 Stresses of CFRP under different CMOD

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

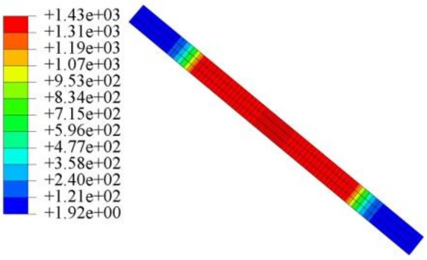


Fig.5 Stress contour of CFRP as CMOD=2.968 mm

C. *Interfacial Shear Stress and Slip*

Along with the increase of CMOD, the region of interfacial shear stress moves from the middle to the free end, as shown in figure 6. When the applied load equals to P_{1max}, where CMOD equals 0.046mm, the maximum interfacial shear stress is 0.5 MPa. Interface behaves in elastic with a low level of shear stress. Interfacial shear stress near the IC crack decreases to zero when the applied load increases to the second peak load P_{2max}, namely CMOD equals to 1.183 mm. Macro shear crack of 20 mm length occurs at this time. The interfacial shear stress gradually moves from the middle to the end of interface due to the enlargement of CMOD.

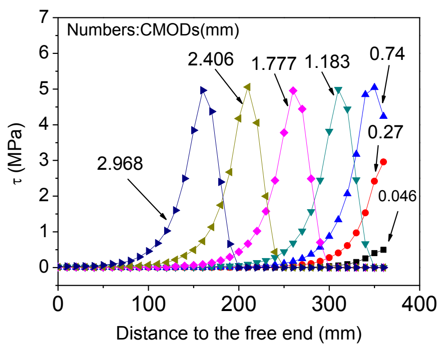


Fig.6 Variation of interfacial stress with CMOD

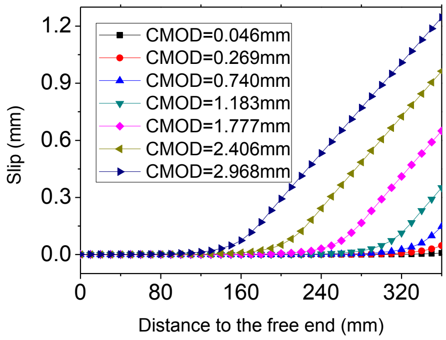


Fig.7 Variation of interfacial slip with CMOD

Variation of interfacial slip with CMOD is plotted in figure 7. Analogous to the interfacial shear stress, interfacial slip extends from the middle to the end of the interface following the enlargement of CMOD. The inflection points of the curves in figure 7 are corresponding to the maximum shear stresses represented in figure 6.

D. *Stress in Concrete*

Stress contour of concrete beam as CMOD equals 2.968 mm is shown in figure 8. It indicates that the concrete crack has propagated to the top of the beam, and most of the concrete stay in a low stress level because of IC cracking and interfacial slipping. Stress concentration is generated at the tips of concrete crack and interfacial shear crack, and the maximum stress value is close to the flexural strength of concrete. It is drawn that concrete can be assumed as elastic material in this model since interfacial analysis is actually related to the flexural strength of concrete.

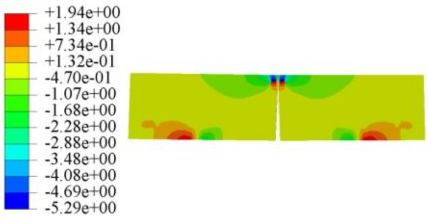
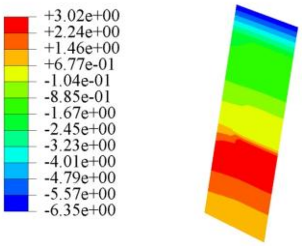
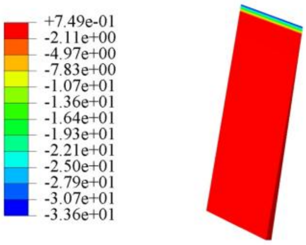


Fig. 8 Stress of concrete as CMOD=2.968mm

When the applied load reaches to P_{1max}, fictitious crack is of 55 mm length, and the cohesive tensile stress is 0.870 MPa near the initiation of concrete crack. No macro-crack is generated at the time. As the applied load gets to P_{2max}, the fictitious crack spreads 135 mm with respect to the initial position. Macro-crack extends to 105 mm at the time. Because of the extension of concrete crack, the loading capacity of FRP-bonded concrete beam gradually decreases after the applied load exceeds P_{1max}. Tensile stress in CFRP increases constantly with the enlargement of CMOD. As the applied load exceeds P_{2max}, most of the load is sustained by CFRP with little contribution of concrete. The corresponding normal stress contours of concrete cracks at the first and second peak loads of beam P203 are exhibited in figure 9.



(a) P_{1max}



(b) P_{2max}

Fig. 9 Stress contours of CZM at concrete crack

IV. Conclusion

A simple and robust finite element model of CZM is applied to simulate the interfacial fracture debonding induced by IC crack for concrete beam externally bonded with CFRP. The parameters adopted in CZM model are determined by concrete fracture mechanics and experimental results. The debonding procedure and peak loads obtained by the FE model are well agreeable with the experimental results. It is drawn that, through the application of CZM model, the loading capacity of IC crack beam strengthened with CFRP can be precisely predicted and the stresses in CFRP, concrete and interface can be clearly revealed with the variation of loadings and CMOD. The interfacial debonding process of CFRP from concrete induced by concrete cracking can be well explained by the FE model of CZM.

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ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)