

論文 A Numerical Analysis on Bonding Mechanism of FRP-strengthened Concrete Structures Using Nonlinear Fracture Mechanics

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ABSTRACT: A numerical analysis, with Nonlinear Fracture Mechanics (NLFM) based on the fracture energy criterion, is conducted to simulate the bond failure modes observed in the experiment and investigate the bonding mechanism along FRP-concrete interface. Through a parametric analysis on bond strength and fracture energy of the FRP-concrete interface, concrete fracture energy and initial imperfections in the concrete beams, it is shown that the bond strength is mainly responsible for the initiation of bond failure and the propagation of debonding is governed by the fracture energy of the interface.

KEYWORDS: fiber-reinforced plastics(FRP), failure mode, interface, debonding, fracture energy

1. INTRODUCTION

Fiber Reinforced Plastic (FRP) composites are increasingly used in the rehabilitation and retrofitting of existing civil infrastructures due to their high strength- and stiffness-to-weight ratios, corrosion resistance, environmental durability, inherent tailorability, ease of application in the field and cost-efficiency over their steel counterparts. Center to the performance of FRP-strengthened RC structures is the transfer of stresses from concrete to the FRP reinforcement through a thin adhesive layer. Failure in this transfer region may result in brittle bond failures, which is a major concern among several failure modes of the structure system. Generally, the possible reasons for bonding failure include imperfections in the spreading of the adhesive, flexural cracking in concrete, unevenness of the concrete surface and fatigue loading. Further investigations into the bond mechanism along FRP-concrete interface are thus critical to understand the different kinds of fracture and failure mechanism and evaluate the composite effects quantitatively.

Bond failures of either steel plates or FRP sheets epoxy-bonded to the tension zones of RC structures have been analyzed extensively in the past according to a variety of strength-based theories, recent research[1] [2] [3] [4] [5] has demonstrated that proper understanding and modelling of FRP-concrete interface-related phenomena and failures may be improved via the application of fracture mechanics theories. The linear elastic fracture mechanics (LEFM) methods is not justified when concrete starts to fracture. Naturally, this led to adoption of nonlinear fracture mechanics (NLFM) approaches. In this paper, based on the recent studies[2] [5], a numerical analysis, with NLFM based on the fracture energy criterion, is conducted to simulate the bond failure modes observed in the experiment and investigate the bonding mechanism along FRP-concrete interface. Some useful conclusions are drawn through a parametric analysis on the FRP-strengthened concrete beam..

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2. EXPERIMENTAL REVIEW

The primary objective of experiments[5] was the observation of the debonding occurrence, crack propagation, failure modes and bonding mechanism of FRP-strengthened concrete beams without reinforcing steel bars. A total of eighteen concrete beams 10×15×90cm were cast. Half of them were designed with notch 1.0×2.5×10cm located in the bottom of the beams at mid-span as shown in Fig.1. The effects of different concrete compressive strength, layer of CFRP sheets, bond strength and construction temperature on failure modes were investigated. The details of the material properties are shown as Table 1. All beams were tested in a three-point bend.

It was observed that there were mainly three typical failure modes: ① the bond fracture along the interface between epoxy layer and concrete or propagation through the concrete adjacent to the interface, ② debonding propagation within the adhesive layer due to different levels of imperfections in the spreading of the adhesive, and ③ rupture of FRP sheets. Among them, the first one is a dominant phenomenon in the practical application of FRP on concrete beams.

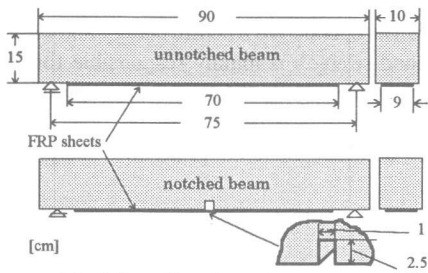


Fig.1 Details of specimens

Table 1 Summary of material properties

concrete	Young's modulus [MPa]	$2.15 \times 10^4 \sim 3.53 \times 10^4$
	compressive strength [MPa]	24.5, 39.2, 53.9
	Poisson's ratio	0.16
	slump [mm]	0.08, 0.105
CFRP sheets	Young's modulus [MPa]	2.30×10^5
	tensile strength [MPa]	3.2×10^3
	Poisson's ratio	0.3
epoxy	Young's modulus [MPa]	3.43×10^3
	Poisson's ratio	0.35

3. NUMERICAL ANALYSIS

3.1 NUMERICAL MODELS

(1) Fracture modes in concrete

Once cracking occurs, the stiffness matrix D_i on the crack surface should be expressed as equation (1) where the off-diagonal terms are set equal to zero because the coupling between the normal direction and the shear direction is considered to be less important and ignored in the present study.

$$D_i = \begin{bmatrix} D^I & 0 \\ 0 & D^{II} (D_0^{II}) \end{bmatrix} \quad (1)$$

in which D^I is mode I tensile softening modulus and D^{II} is mode II shear softening modulus. D_0^{II} is the initial shear modulus before the mode II softening is entered. The areas below the given stress-mode in which D^I is mode I tensile softening modulus and D^{II} is mode II shear softening modulus. D_0^{II} is the initial shear modulus before the mode II softening is entered. The areas below the given stress-displacement diagrams equal to the values of fracture energy for mode I and mode II respectively, as shown in Fig.2. The present formulation assumes mode I fracture to be initiated firstly when the principal stress reaches the tensile strength. With subsequent change of the principal stress axes a shear stress may develop across crack plane until its maximum value τ_{\max} thereafter the shear

softening branch is started.

Additionally, the unloading and reloading behaviors have been modelled using a secant path, which implies that upon unloading the stress follows a straight line back to the origin. This procedure has been adopted for both mode I and mode II fracture.

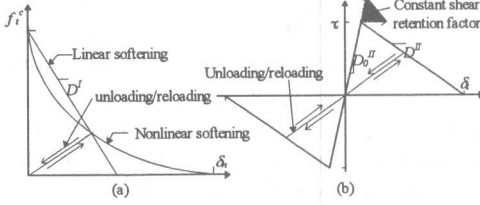


Fig. 2 (a) Mode I tensile softening
(b) Mode II shear softening

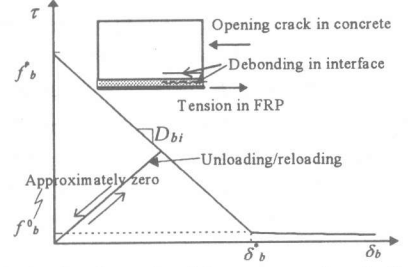


Fig. 3 Softening branch of shear stress-bond slip on interface

(2) Model of debonding along FRP-concrete interface

Debonding along the FRP-concrete interface is an important failure phenomenon in FRP-reinforced concrete. From the experimental observations, the debonding normally propagates through the concrete adjacent to the interface. Because the interface layer mainly functions to transfer stress from concrete to FRP sheets by means of shearing, shear stress within the interface is much more dominant than other stress components. Therefore, we assume that the interface crack propagation mode is similar to fracture mode II and the material stiffness D_b is

$$D_b = \frac{E_b}{1-\nu^2} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (2)$$

where E_b is the Young's modulus of FRP-concrete interface (set $E_b \approx$ the Young's modulus of concrete), ν is Poisson's ratio, 0.35.

The shear stress in the interface is caused by the difference of deformation between concrete and FRP sheets. When its value exceeds the bond strength f_b^0 that the interface can resist, the debonding occurs and subsequently propagates along the interface. Then, the shear stress will degrade following the relationship between shear stress and bond-slip (defined as the relative displacement between concrete and FRP sheets) (Fig. 3):

$$\Delta \tau = D_{bi} \cdot \Delta \delta_b \quad (3)$$

The area between softening branch curve and axes is defined as fracture energy (Mode II) consumed for debonding propagation. The unloading and reloading procedures are also considered in a similar way to those used in concrete.

(3) Model of FRP sheets

FRP sheets generally behave in linear elastic fashion until rupture. Unlike steels, FRP sheets are anisotropic and can not resist compression and bending but only tension stress along their longitudes. The rupture of FRP sheets is assumed to result in the sudden loss of loading-capacity of the whole structure.

3.2 NUMERICAL ANALYSIS

The notched concrete beam strengthened by FRP sheets (Fig. 1) is used in numerical analysis on bonding behavior. The bottom elements near the bond interface are numbered 1–35 from the end of FRP to the mid-span.

In this section, the effects of bond strength and fracture energy of the adhesive, concrete fracture energy and initial imperfection in the structure on the bonding behavior are mainly discussed. Set $E_b = 3.43 \times 10^4 \text{ MPa}$, the Young's modulus of concrete $E_c = 3.25 \times 10^4 \text{ MPa}$ and the other parameters can refer to Table 1. When discussing the effect of imperfection on the bonding behavior, the notched concrete beam strengthened by FRP with initial crack $1 \times 2 \times 10 \text{ cm}$ located at 13 cm away from the mid-span (this case is called “with imperfection” in this section) was computed and compared with the FRP-strengthened beam with notch (this case is called “without imperfection” in this section).

(1) Effect of bond strength and the fracture energy of the FRP-concrete interface on failure modes

The FRP-strengthened concrete beam with notch are analyzed on several cases by fixing the concrete tensile strength 2.715 MPa , concrete fracture energy $G_{IC} = 120 \text{ N/m}$ and changing the bond strength and the interface fracture energy, respectively. The results are shown in Table 2, Fig.4, Fig.5.

Table 2. Effects of bond strength and interface fracture energy on bonding behavior

Interface fracture energy G_{II} (N/m)	Bond strength f_b (MPa)	Load (N)		Number of debonding element
		Initial debonding	Debond propagation	
5	0.5	1114	9918	35
	2.0	4198	14166	8
20	0.5	1114	11510	14
	2.0	4198	12094	4
	4.0	10888	12382	4
	8.0	14104	14846	2
	18.0		15478	0

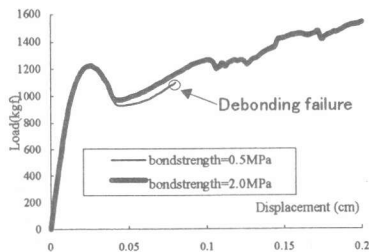


Fig. 4. Effect of different bond strength at the same interface fracture energy = 5 N/m

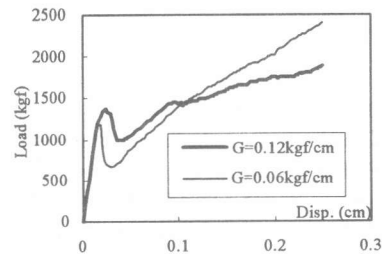
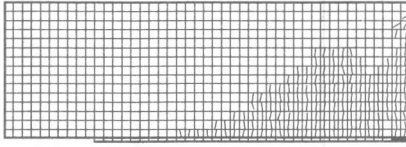


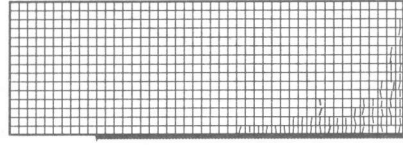
Fig. 6 Effect of different G_{IC} on bonding behavior

As seen from Table 2, initiation of bond failure is only dependent on the bond strength and when bond strength grows to a certain value, the debonding will not occur and may lead to the rupture of FRP sheets, which have been observed in the experiment. On the other hand, it is found that the propagation of debonding is governed by the interface fracture energy. From the computational results (Fig. 4 and Fig.5), the lower bond strength results in a early debonding occurrence, and subsequently a quick debonding propagation along the FRP-concrete interface happens due to its lower interface fracture energy. The quick debonding propagation is considered the main reason that stresses in FRP sheets increase very slowly and their strengthening effects are not fully utilized, which really simulates the imperfection in the spreading of adhesive. Cracks in concrete are mainly localized at the mid-span. For the concrete beam with higher bond strength, few debondings occur and are not followed by the

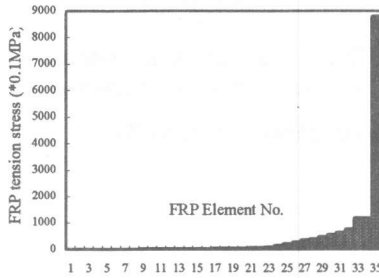
continuing propagation along FRP-concrete interface. Such a well bonded condition provides the effective stress transfer between concrete and FRP sheets. Although many flexural cracks in concrete happen and are distributed along the beam due to the constrain by bonded FRP-sheets, the load capacity is apparently higher than that of debonding failure concrete beam.



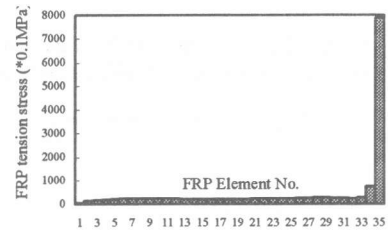
(a) crack pattern and debonding propagation



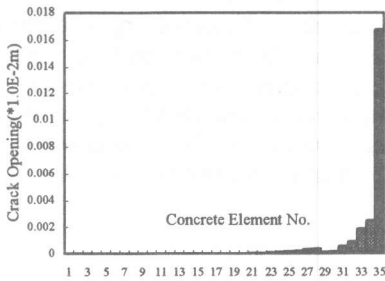
(aa) crack pattern and debonding propagation



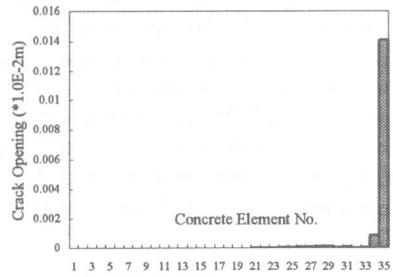
(b) Distribution of stresses in FRP sheets



(bb) Distribution of stresses in FRP sheets



(c) Distribution of crack opening in concrete
case 1 Bond strength=2.0MPa



(cc) Distribution of crack opening in concrete
case 2 Bond strength=0.5MPa

Fig.5 The structure responses at the debonding failure point

(2) Effect of concrete fracture energy G_{IC}

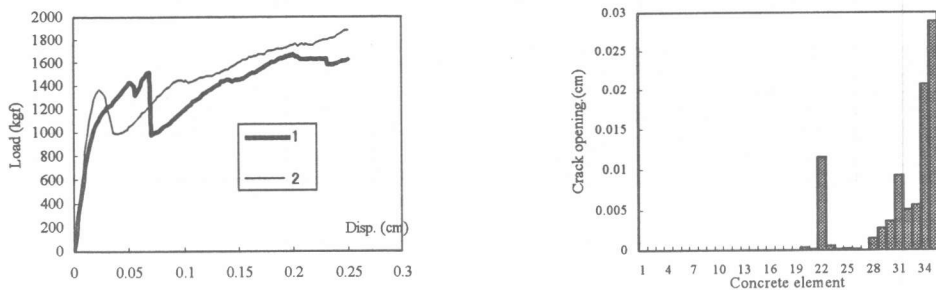
With the same concrete tensile strength 3.312MPa, bond strength 2.0MPa, and the interface fracture energy 20N/m, the FRP-strengthened concrete beam with notch is calculated according to the different concrete fracture energy 120N/m and 60N/m, respectively.

From the computational results(Fig.6), it is found that concrete with a lower fracture energy is easy to crack so that the tensile stresses in FRP sheets increase earlier to function the strengthening effects. This can be regarded as the reason why the load of the concrete beam with $G_{IC}=60\text{N/m}$ increases more quickly than that with $G_{IC}=120\text{N/m}$.

(3) Effect of the initial imperfections in the concrete

With the concrete tensile strength 3.312MPa, concrete fracture energy 120N/m, bond strength 2.0MPa, and the interface fracture energy 20N/m, the FRP-strengthened concrete beam with notch is computed to investigate the effect of the initial imperfection on bonding behavior.

From the computational results (Fig. 7), it is found that the imperfection location has a great effect on the distribution of crack opening in the concrete. An imperfection is easy to propagate the cracks in the concrete and cause debonding propagate along the FRP-concrete interface.



- (a) Effect of initial crack position on load-disp.
(1:with imperfection;2:without imperfection)
- (b) Effect of imperfection on distribution
of crack opening in the concrete

Fig. 7 Effect of different initial crack position on bond behavior at load=18KN

4. CONCLUSION

In the present paper, the debonding phenomena observed in the experiment are reviewed. In order to investigate the bonding mechanism along the interface of FRP-strengthened concrete beams, a numerical analysis based on NLFM is carried out. Focused on the bond behaviors, four parameters, bond strength and fracture energy of the FRP-concrete interface, concrete fracture energy and initial imperfections in the concrete beams were studied, it is shown that the bond strength is mainly responsible for the initiation of bond failure and the propagation of debonding is governed by the fracture energy of FRP-concrete interface. Besides, the fracture energy of concrete has a great effect on the crack propagation in concrete and so influence the bonding behavior of the interface. In addition, the numerical analysis method also shows good feasibility to treat crack localization in concrete and debonding propagation along the bonding interface.

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