Influence of bending and dowel action on the interface bond in RC beams strengthened with FRP sheets: An experimental investigation

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ABSTRACT: This paper presented the test results on a series of RC beams externally bonded with FRP sheets under coupled bending and dowel actions. The main focus was to investigate how the dowel force acting on the FRP sheets influences the shear transfer capacity of the bond between the FRP and concrete. A loading system was developed to simultaneously introduce shear and normal stresses into the FRP-concrete interfaces. Interfacial failure criteria under different loading conditions were discussed. It was found that the dowel force on the FRP sheets affected greatly the initiation of local interface peeling which led to a decrease of the beam's stiffness. However, the ultimate flexural capacity was not significantly influenced by the existence of the dowel action if a sufficient anchorage length was available. The paper also provided a benchmark database that can be used for calibrating the mix-mode bond constitutive laws for FRP-concrete interfaces.

1 INTRODUCTIONS

Extensive tests have indicated that reinforced concrete (RC) beams flexurally strengthened by Fiber Reinforced Polymer (FRP) can hardly reach their full composite capacity due to the premature debonding at the FRP-concrete interface. Up to now, knowledge related to the failure modes, strength and stiffness properties of the FRP strengthened RC beams have been well built up (Saadatmanesh and Mohammad. 1991, Garden et al. 1998, Buyukozturk and Hearing, 1998, Teng et al. 2001). It is noticed that, for the RC beams externally strengthened with FRP sheets, particular attentions will be paid to the failure due to the mid-span debonding of FRP-concrete interface, which is triggered by the stress concentration at the tips of flexural or flexural-shear cracks. The critical crack leading to ultimate debonding failure usually is an inclined one including both crack opening in the direction of parallel to the bond interface and sliding deformation in the direction of perpendicular to the bond interface. The latter component imposes a dowel action on the FRP sheets and eventually causes vertical interface fracture coupled with the slip-induced shear debonding failure. To suppress this kind of mix-mode failure, solutions in the current design codes are to limit the strain levels in FRP, which are generally derived by considering the shear bond stress-slip law of the FRP sheet-concrete interfaces, flexural crack spacing, anchorage length, etc. (*fib*. 2001, JSCE. 2000, ACI, 2002). In the meantime, it is conceptually suggested that the mix-mode interface bond failure induced by the flexural-shear cracks can be suppressed by additional shear strengthening. However, no direct experimentations have been performed to investigate this interface peeling under the coupled flexural and shearing actions. No any comprehensive mix-mode bond constitutive laws for the FRP-concrete interfaces have been proposed either. Hence the issue of whether or how much the dowel action perpendicular to the FRP sheet-concrete interface influences the interface shear force transfer (flexural strengthening efficiency of the FRP sheets) in the FRP strengthened RC beams remains unclear.

Limited literatures (Karbhari and Engineer 1996, Wan et al, 2004) performed mix-mode loading tests for FRP-concrete interfaces by producing different interface peeling angles between the FRP sheets and concrete in their tests. Their main purposes were to enable the determination of both Mode I and Mode II components of the interfacial fracture energy and to allow a quantitative comparison of interface adhesion mechanisms and energies. Few other researchers (Wu et al. 2005, Dai et al. 2006) conducted other types of mix-mode tests, such as one-dimensional push-off tests or two-dimensional punching shear tests, to investigate the FRP-concrete bond failures under the dowel action. Engineering background of these studies was to bond FRP sheets to concrete structures to prevent the falling of deteriorated concrete blocks. On the whole, there are almost no any direct tests on the FRP/concrete interface subjected to a combined bending and dowel action.

By using a proposed test method, this research aimed to investigate experimentally the interface debonding mechanisms in FRP strengthened RC beams under coupled dowel and bending actions, and also to provide a database for developing more comprehensive fracture criteria for the FRP sheet-concrete bond interface under mix-mode loading conditions.

2 EXPERIMENTAL PROGRAM

2.1 *Experimental materials*

Properties of Carbon FRP (CFRP) sheets used in this study are shown in Table 1. The applied resin (FR-E3P) and primer (FP-NS) had the elastic modulus of 2.41GPa and the Poisson ratio of 0.38, respectively. The mixing ratio of resin/hardner by weight was 2:1. High strength concrete with mixing ratio of W:C:S:A=160:301:742:1160 by weight was used. The concrete had the test compressive strength of 45.0MPa at the time of beam testing.

Table 1 Properties of CFRP sheets

Type	ρ (g/m^3)	f_t (MPa)	E_f (GPa)	t_f (mm)	ε_u (%)
FTS-C1-20	200	3550	230	0.11	1.5

Note: ρ = fiber density; f_t = tensile strength; E_f = elastic modulus; t_f =design thickness of FRP sheets; ε_u = ultimate strain of fiber

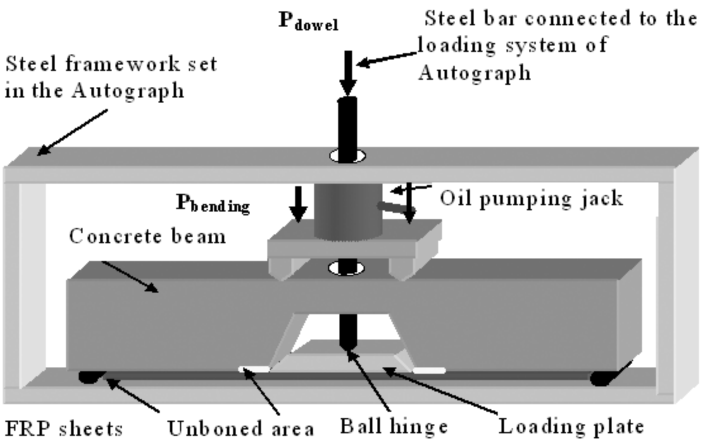

Figure 1. Test setup

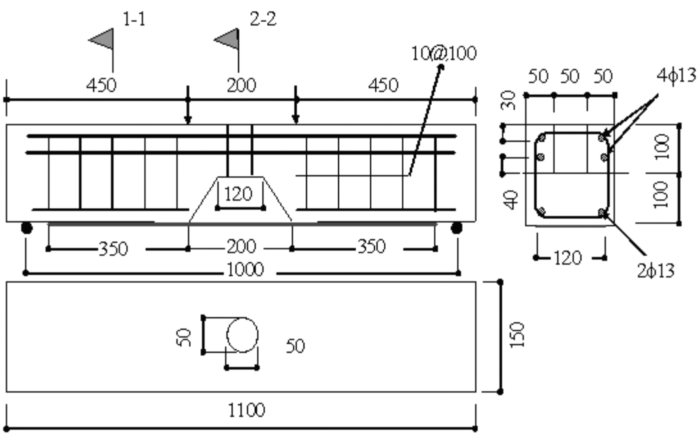

Figure 2. Details of test specimens

2.2 *Test setup*

A test setup was developed based on a universal test machine namely Autograph system, which had an accurate displacement controlling system. The completed system made it possible to introduce different stress conditions into the FRP sheet-concrete interface through loading the FRP strengthened RC beams in different ways. As shown in Fig. 1, a high strength steel bar was connected to the loading part of the Autograph system. The bar was used to impose the dowel force vertically onto the FRP sheets through a ball hinge and a stiff plate to create a localized mode I stress condition in the bond interface. In addition, a close-formed steel framework was set inside the Autograph system. This framework provided reactive bending force to the strengthened RC beams. As a result, the pullout force was introduced into the FRP sheets and a mode II interfacial stress condtion was generated. Consequently, the mix-mode loading condition could be achived through exerting the dowel force and bending force couplingly(see Fig.1).

2.3 *Details of specimens*

Six RC beams with rectangular section and externally bonded with two layers of CFRP sheets were prepared. CFRP sheets were bonded to RC beams one week after concrete casting and cured for one more week till the tests. Each beam had the span of 1.0m and the cross-section of 150×200mm. All test beams had two different cross sections (see section 1-1 and 2-2 in Fig. 2). The section 1-1 was larger than section 2-2, at which a 100 high void trapezoid block and a 100 high hollow cylinder were pre-set inside the beams to accommodate all equipments used for imposing the dowel force (See Fig.1). The trapezoid shape was chosen for the void block to simulate the direction of actual diagonal flexural-shear cracks. Four 13 mm steel bars were arranged in the beams' upper parts to reinforce the concrete around the void cylinder (see Fig.2). In addition, 10mm stirrups with the spacing of 100mm were used to prevent the beams from shear failure before the FRP debonding (see all the details in Fig.2). A 20mm long initial crack (un-bonded area) was set between the FRP sheets and concrete beams at the outermost of constant moment zone (see Fig.1). The only test variable was the dowel ratio, which was the ratio of the dowel force imposed onto the interface to its dowel force capacity. Two of the six beams were subjected to only dowel and only bending action, respectively. The remaining four specimens were loaded under a combination of two actions. The way to introduce the coupled bending and dowel actions was to keep the dowel force at a constant level (35%, 50%, 70% and 90% of the interface dowel force capacity respectively as listed in the Table 2) through adjusting the height of the high -strength steel bar when the bending force was added increasingly.

2.4 *Test instruments*

As shown in Figure 3, transducers were arranged to measure the mid-span deflection of the beams (see 1 and 2 in Fig.3), the peeing crack opening displacement (hereinafter ''the PCOD'') that was defined as the interface crack opening displacement between the rigid plate and the concrete beam at the starting point of the un-bonded area (see 10 and 11 in Fig. 3), and the relative displacement (interfacial slip) between the concrete and the FRP sheets at the starting point of bonding area (see 8 and 9 in Fig.3). Strain gages were mounted on concrete (see 3, 4 and 5 in Fig.3), steel bars (see 6, 7 in Fig.3) and the upper and bottom sides of FRP sheets (see 12 in Fig.3) at the mid-span location. Three gages with long bonding basements were attached on concrete at the location of 15mm, 45mm and 75mm respectively measured from the top of beams. From the starting point of un-bonded area to the beams' supports, strain gages were mounted continuously on the outer surface of FRP with a 10 mm interval from the most inner side of the shear span for the first 120 mm bond length (see 13 in Fig.3) and with a 20mm interval for the remaining part (see 14 in Fig.3).

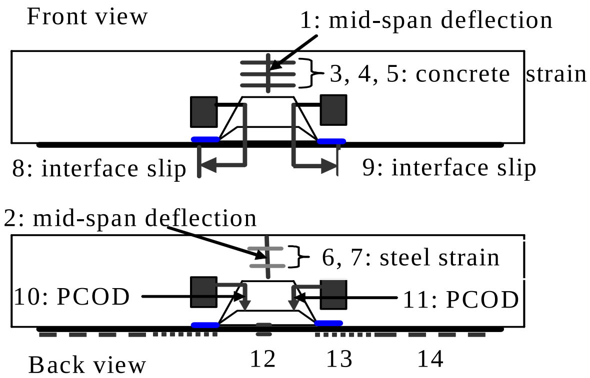

Figure 3. Arrangement of test instruments

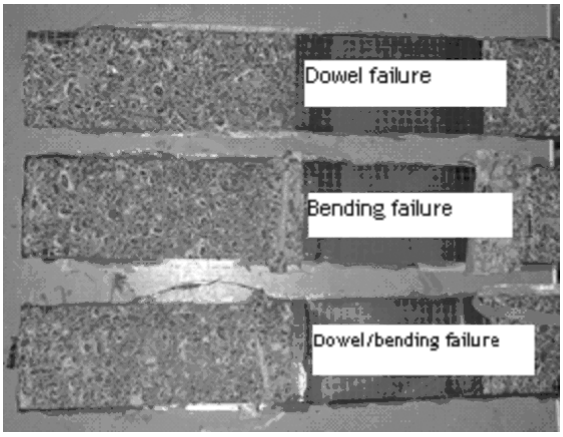

Figure 4. FRP sheets after peeling

3 TEST RESULTS

3.1 *General description of the failure mode*

All the beams failed due to the peeling of FRP sheets with a thin concrete layer from the substrate. Fig. 4 shows the peeled FRP sheets under different loading conditions. It was found that that the volumes of concrete attached to the peeled FRP sheets under dowel, bending and their coupled actions were similar. Bending cracks only occurred within the constant moment zone, where the beam had a small section (see section 2-2 in Fig. 2). No cracks were observed in the shear span of the RC beams. Also, no bond failure initiated at the end of FRP sheets. So the designed beams succeeded in reproducing an interface debonding failure initiating from the mid-span.

3.2 *Bending force versus deformation response*

Figure 5 shows the load vs. middle span deflection curves of all tested beams, where the load is expressed as the sum of bending and dowel load. The ultimate bending capacity of each beam and the imposed dowel force are listed in Table 2 as well. It is shown that both stiffness and bending capacity decreased with the increase of dowel forces imposed (see Fig.7 and Table 2). In comparison with the beam (B2) that was only subjected to bending force, the beam with the dowel ratio of 70% (B5) decreased its bending capacity by 13.6%. A more direct way to see how the dowel action influenced the interfacial bond force transfer in the strengthened beams is to compare the maximum tensile strains achieved in the FRP sheets in all test beams since they are direct indices indicating the force transfer capacity in the bond interface, whereas the obtained bending force at the ultimate state also included partially the contribution of reinforcing bars. However, it was difficult to obtain the FRP's tensile strain directly due to the curvature of FRP induced by the dowel action. To solve this difficulty, the maximum tensile strain in the FRP sheets was back-calculated from the ultimate bending load based on plane section assumption. Since the strain distribution profiles of concrete and the steel reinforcement within the constant moment zone were all recorded, the height of neutral axis could be obtained and the only unknown factor for calculating the ultimate bending load was the maximum strain in FRP.

Table 2 lists the calculated maximum bending-induced strains in the FRP sheets in all beams. The back-calculated strains are consequently directly related to flexural strengthening efficiency of FRP sheets. It can be concluded that that coupled bending and dowel actions did not decrease the overall interface shear force transfer significantly. Comparatively, it seems that the dowel action probably had more effects on the member stiffness as shown in the Fig.5 because of the dowel induced local debonding.

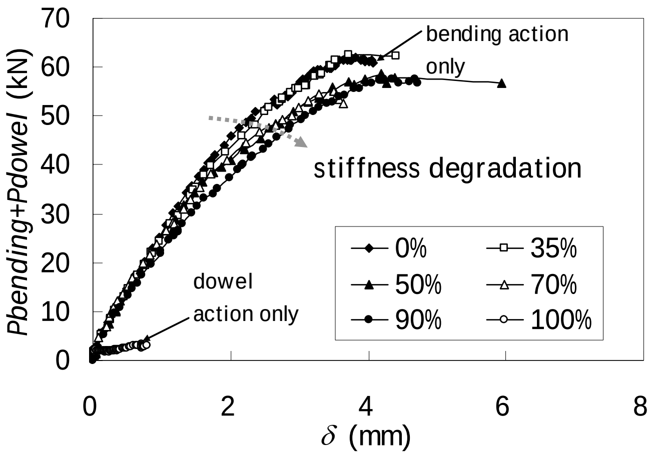

Figure 5. Load-deflection curves of all tested beams

Table 2 Summary of experimental results

No	P_{dowel} (N)	$P_{bending,\ max}$ (kN)	$\varepsilon_{frp,max}$	*Dowel ratio* (%)
B1	2000	0	0	100%
B2	0	62.02	7172	0%
B3	700	61.83	7194	35%
B4	1000	57.4	7021	50%
B5	1400	53.6	6234	70%
B6	1800	55.6	5747	90%

Note: P_{dowel}: dowel force added; $P_{bending,\ max}$: maximum bending force achieved; $\varepsilon_{frp,max}$: maximum tensile strain of FRP sheets due to bending; and dowel ratio means the ratio of the imposed dowel force to the interface dowel capacity.

3.3 *Bending force versus peeling crack opening*

Extensive reports have shown that the critical peeling of the FRP sheets leading to the failure of whole strengthened system usually initiates from the tip of a flexural-shear crack, and the opening and vertical sliding displacements of the crack tip trigger the horizontal and vertical peeling of FRP sheets from concrete, respectively. Generally, the vertical deformation ability of adhesive layer is very limited. Therefore, a small vertical concrete crack sliding inevitably results in a local peeling of FRP sheets from concrete in vertical direction at the crack location. Then the deformation compatibility to the interface in the vertical direction can be kept from the contribution of FRP sheets' dowel deformation. To prevent this dowel-induced bond deterioration from destroying the overall flexural strengthening system, quantified information is needed to know the effects of tensile stress in the FRP sheet on its dowel deformation ability. By knowing that, engineers can conclude how much the dowel deformation of FRP sheets around cracks can be permitted to achieve expected pullout force capacity in the FRP sheets.

Figure 6 shows the relationships between the added bending load and the dowel deformation of FRP sheets at the crack mouth, namely the interface PCOD. It is clearly seen that the PCOD decreased gradually with the increase of bending load under all dowel ratios. In other words, the higher the pullout force is expected to be achieved in the FRP sheets, the smaller the vertical crack sliding in FRP strengthened RC beams should be allowed. However, it can be seen from Fig. 6 that the increase of the bending load did not influence the PCOD noticeably if the PCOD was under a certain level. The current tests showed that 1.0mm might be a threshold value for the dowel deformation under which the flexural strengthening efficiency would not be reduced in case of using two layers of CFRP sheets. It is considerable that the threshold value relies on the tension/bending stiffness of FRP and the bond length as well. Further experimental testing and numerical simulations are needed to build up their mutual relationships.

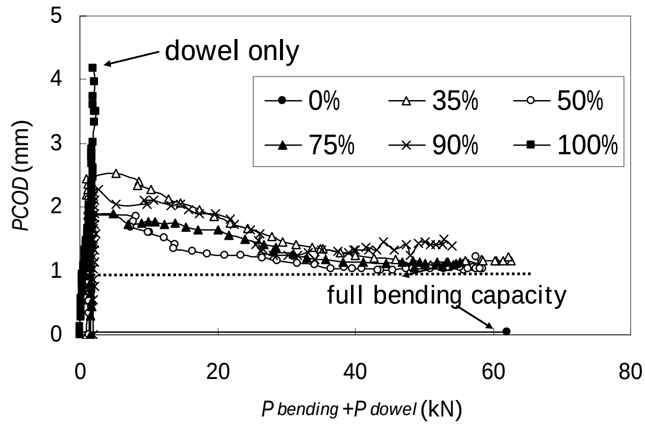

Figure 6 Load-PCOD relationships under different levels of dowel actions

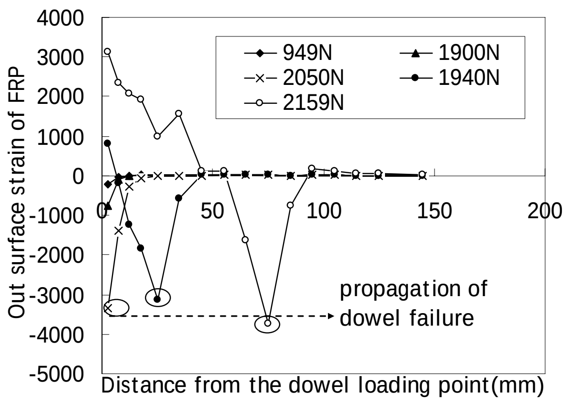

Figure 7 Strain distributions of FRP sheets under dowel actions

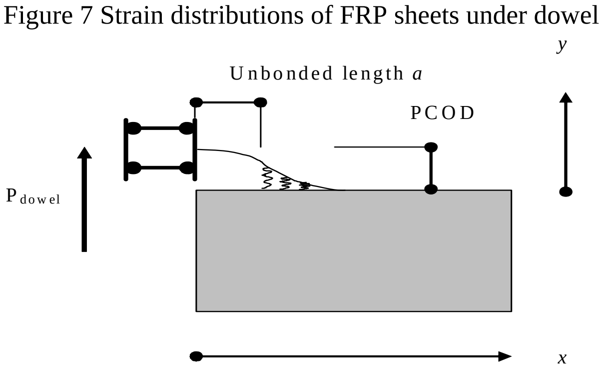

Fig.8 modeling the initial interface peeling under dowel action

3.4 *Fracture criteria of the FRP-concrete bond interface*

3.4.1 *Interface fracture under dowel action*

Figure 7 shows the distribution of outer surface strains of FRP sheets under different levels of dowel forces. It was noticed that there was a negative peak value of FRP strain at the initiation of a local dowel failure. The negative strain values showed that the out surface of FRP was subject compressive stresses before dowel failure instead of the tensile stress under pure flexural load. Therefore, it indicated that the local FRP sheet behaved like a beam before the initiation of the dowel failure.

In order to study the initiation of the dowel peeling, the concrete block was assumed to be a rigid block in this study. With this assumption, the FRP sheet can be approximately simulated as a beam on an elastic foundation and the adhesive layer can be simulated as a series of springs as shown in Fig.8.

The differential equation governing the behaviors of the FRP sheets bonded onto concrete beam can be written as:

$$-EI\frac{d^4y}{dx^4}=q \qquad (1)$$

where $q=0$ at un-bonded area and $q=ky$ at bonded area; EI is the bending stiffness of the FRP sheets; $k=E_a b_f/t_a$, in which E_a and t_a are the elastic modulus and thickness of adhesive layer, respectively; and b_f is the width of FRP sheets.

Through the solution of Eq.1, the relationship between the dowel force and the PCOD (see Fig. 8) can be expressed as following (Dai 2003):

$$PCOD=\frac{P_{dowel}a^3}{6EI}-\frac{(\beta a+1)(\beta^2a^2+1)P_{dowel}}{4\beta^3EI} \qquad (2)$$

where $\beta^4=k/4EI$; and a is the un-bonded length.

The interface Mode I fracture energy can be obtained by using the compliance theory:

$$G_{fI}=\frac{P_c^{\ 2}}{2b_f}\frac{dC}{da} \qquad (3)$$

where $C=PCOD/P_{dowel}$, P_c is the peak dowel force.

In this study, values of E_a and t_a were taken as 2.41GPa and 0.6mm, respectively, and the length of un-bonded area was 22mm. The thickness of two layers of FRP including the impregnating resin was taken as 1.8mm through measuring and EI was 1.64×10^6N.mm^2 by calculation. The b_f was 120mm. Therefore, the mode I interfacial fracture energy can be obtained by using Eqs. 2 and 3:

$$G_{fI}=0.12N/mm \qquad (4)$$

The Mode I fracture energy obtained through the current dowel test is similar to those obtained from three point bending tests (Dai et al. 203, Qiao 2004). This fracture energy can be used to predict the interface dowel force capacity. It should be noted that assuming the FRP sheet as a bending beam is reasonable only when the initial interface crack length (unbonded length) is short. In such case, the initiation of the dowel failure can be approximately treated as a mode I dominated loading condition. When the dowel-induced peeling continues to propagate in the interface, the FRP sheet-concrete interface is subjected to the mix-mode loading condition. The FRP sheet behaves more like a truss element during the peeling propagation. Detailed debonding mechanisms of FRP sheet/concrete interfaces and derivation of the Mix-mode interface fracture energy under the dowel action are presented in a paper by Dai et al., 2007.

The movement of the location with the maximum negative strain as shown in Fig.7 indicates where the initial interface crack had propagated under a certain dowel deformation (PCOD). Therefore, the relationships between the peeled interface length and the PCOD can be drawn in Fig.9. It is clearly shown that the ratio of the PCOD to the peeled interface length is almost a constant value, indicating there is a critical peeling angle during the propagation of the dowel failure. It is reasonable to extrapolate that the dowel force component will be increased if there is an additional pullout force introduced into the FRP sheets by bending action under the condition of a constant peeling angle. To suppress the dowel-induced interface peeling while maintaining a high pullout force level in the FRP, the solution is to decrease the interface peeling angle by either limiting the dowel deformation or increasing the bond length. On the other hand, in the case of FRP sheet-concrete interfaces with short bond lengths, such as the bond interfaces between two adjacent cracks, neglecting the dowel deformation may lead to overestimating the bond capacity of resisting debonding failure.

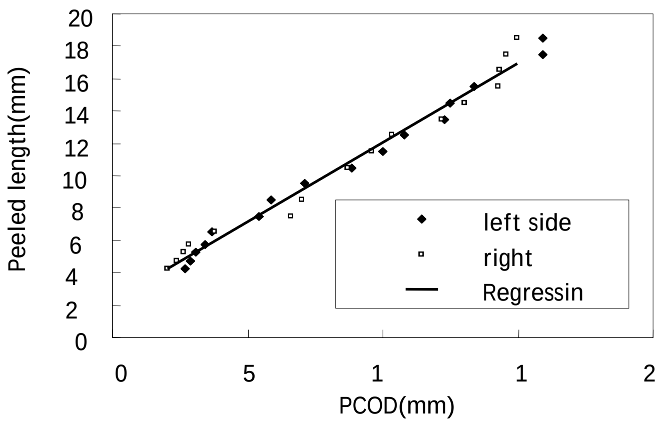

Figure 9. Relationship between peeled length and PCOD

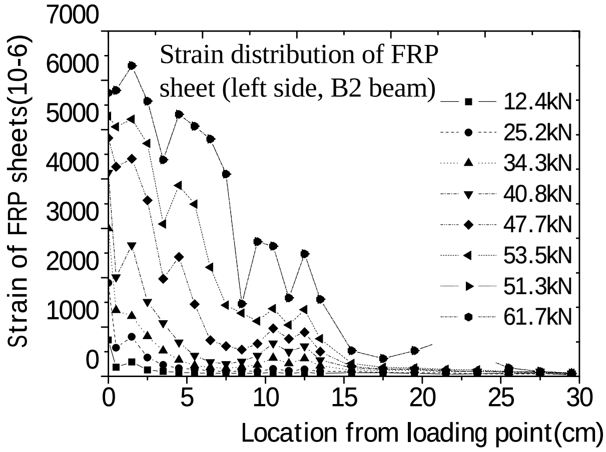

Figure 10. Strain distributions in FRP sheets under different bending load levels

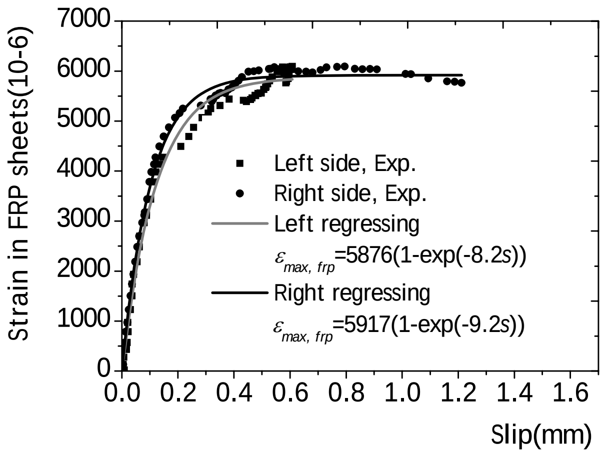

Fig.11 Relationship between the strains of FRP sheets and the slips at the loaded point

3.4.2 *Interface failure under bending action*

Bending action on the FRP strengthened RC beam introduced pullout force into FRP sheets and caused a mode II interface failure. Fig. 10 shows the strain distribution in FRP sheets under different bending load levels for B2 beam. The shapes of FRP sheets' strain distribution are almost same as that observed in direct pullout test, indicating that the bending test can generate a shear stress condition similar to that in direct pullout test for the FRP concrete-sheet interface. Generally, the bending test is more convenient to set up in comparison with the direct pullout load test.

Concerning the FRP sheet-concrete interfaces subjected to mode II type loading, Dai et al. (2005) developed a new approach to define the interfacial fracture energy and the bond stress-slip laws through obtaining the relationship between the pullout force (or the stain ε of the FRP sheets) and the interface slip s at the loaded point of the interface, in other words, at the tip of the initial interface crack. Conceptually, the crack-tip slip can be obtained through either integrating the strains of FRP sheets or reading the displacement transducers (see 8 and 9 in Fig.3). Fig.11 presents the experimentally obtained relationship between the strain of FRP and the crack-tip slip, in which the crack-tip slip was calculated by integrating the strains of FRP sheets. According to the methods of Dai et al. (2005), the following formula can be obtained:

$$\varepsilon = \varepsilon_{\max}(1-\exp(-Bs)) \quad (5)$$

$$G_{fII} = \frac{E_f t_f \varepsilon_{\max}^2}{2} \quad (6)$$

$$\tau = 2G_{fII} B(\exp(-Bs) - \exp(-2Bs)) \quad (7)$$

where G_{fII} is the mode II fracture energy, which was 0.87N/mm in this research, and B is an empirical factor reflecting the interface bonding stiffness, which was 8.7mm^{-1} in this research. They can be obtained by regressing the experimental data in Fig.11. It was noticed that typical values of G_{fII} *and B* obtained from the pullout test using the same test materials were 1.19N/mm and 10.4mm^{-1}, respectively. It seems that the mode II fracture energy obtained in pullout test is higher than that from the current bending test. The change of shear span/height ratio of beam possibly affects the calibration of the Mode II fracture energy.

3.4.3 *Interface failure under coupled actions*

Discussions on the load-deflection relationships (section 3.2) and the dowel failure characteristics (sections 3.4.1) have indicated that either controlling the dowel deformation or increasing the bond length can suppress the negative effects of dowel action on the shear bond force transfer in the FRP sheet-concrete interfaces. In other words, the sufficiently long bond length may guarantee that interface bond failure is still a shear-dominating one. However, it is different when the local interface bond failure is focused on. As a matter of factor, the combined actions of the dowel and pullout force in FRP sheets influence the initiation of local interface peeling significantly because the interface becomes considerably weaker un der the combination of shear and tensile stress according to the Mohr-Coulomb failure criteria. To know the critical pullout force causing the initial local peeling at different dowel ratios, Fig. 12 and Fig. 13 show the developments of strains on the FRP sheets at different locations with the increase of bending forces. The local peeling of FRP sheets was assumed to occur when two continuous gages on the FRP sheets close to the crack tip suddenly showed almost same strain values. Although the local outer surface strains of the FRP sheets under the coupled dowel and bending actions did not make this change as dramatically as they did in the case of dowel action only, the bending force corresponding to the initial local dowel failure was still distinguishable (see circled points in Fig.12 and Fig.13). By this way, the relationship between the bending forces correspondent to the initial local peeling and the dowel ratios was obtained and is shown in Fig. 14. The ultimate bending capacity of all tested beams is also given in Fig.14 for the comparison purpose. It can be seen that the dowel force imposed on FRP sheets affects the local interface debonding significantly although its effect on the ultimate bending capacity is very small. The locally deteriorated interface bond might be the reason why the stiffness of strengthened beams decreases greatly in cases of high dowel force ratios (see Fig. 5).

To look more insightfully at the fracture mechanisms of the FRP sheet/concrete interfaces under the coupled bending and dowel actions, modeling for separating the mode I and mode II fracture energy components and building up fracture energy envelope criteria seems necessary. Based on that a comprehensive interfacial bond constitutive law under the mix-mode loading can be proposed to reproduce and interpret the current test results. These work remains for study in a further step.

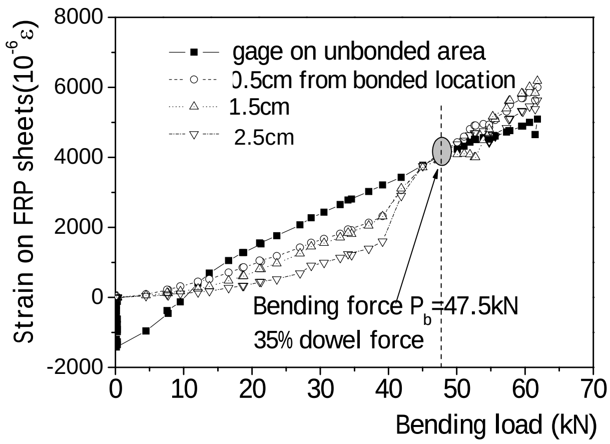

Fig. 12 Strains on FRP sheets at different locations in B2

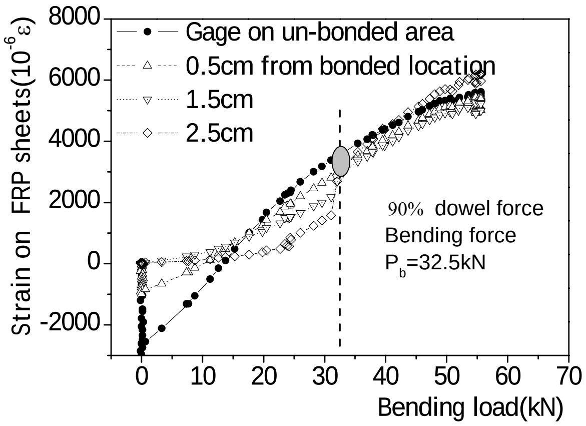

Figure 13. Strains on FRP sheets at different locations in B3

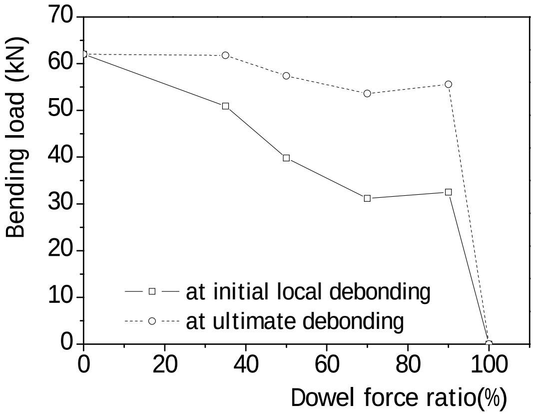

Figure 14. Interface failure envelope curve under the coupled bending and dowel actions

4 CONCLUSIONS

1. This research has developed a general test method which can evaluate the bond of FRP/concrete interfaces under different fracture modes, in particular, under the coupled dowel and bending actions.
2. For a local interface bond failure induced by the dowel action only, a model deriving the interface mode I fracture energy was proposed based on the beam on elastic foundation theory and compliance method.
3. The interface mode II fracture energy can be calculated using the maximum tensile strain in the FRP sheets obtained from the bending test. The mode II fracture energy obtained from the bending tests was smaller than that from pullout tests. The beam's shear span/depth may affect the calibration of the mode II fracture energy when a bending test method is applied.
4. If there is a long bond length, existence of dowel action on FRP sheets brings marginal effects to the ultimate interface bonding capacity although it brings an earlier local debonding. However, in the case of short bond length, such as the interface between adjacent flexural-shear cracks, the interface bond force transfer may be significantly affected by the dowel action and the bonded length (crack spacing), both of which affects the interface peeling angle. Therefore, a comprehensive mix-mode interface bond law instead of the pure shear bond stress-slip law should be developed for interface analysis in order to refine the strain limits of FRP for the flexural strengthened RC beams in the design codes.
5. Dowel deformation ability of FRP sheets decreased significantly with the increase of bending force at the beginning stage. However, test results shows there may be a low bound value for the dowel deformation, under which the existence of dowel deformation will not influence the flexural strengthening efficiency of the FRP

sheets. This low bound was 1.0 mm in the current study. Obliviously, this value is influenced by the tension stiffness of FRP and the effective bond length.

6. This paper provides a database for calibrating the bond constitutive laws for FRP sheet-concrete interfaces under mix-mode loading. Modeling for separating the mode I and mode II components for the current test method and proposing a universal energy criterion that governs the fracture of FRP sheet-concrete interfaces under various stress conditions remain for a further-step study.

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