Technical paper

DOWEL EFFECTS ON INTERFACE SHEAR BOND FORCE TRANSFER IN CONCRETE BEAMS STRENTHENED WITH FRP SHEETS

Jianguo DAI *1, Tamon UEDA*1 and Yasuhiko SATO*1

ABSTRACT: This paper discusses the effects of dowel force acting on FRP sheets on the shear bond force transfer capacity of FRP sheet-concrete interface. It is found that the dowel force affects the initiation of interface peeling significantly. Moreover, dowel deformation ability of FRP sheets in concrete beams strengthened with FRP sheets decreases greatly with increasing the pullout force in FRP sheets. However, ultimate interface shear bond force capacity is negligibly affected by the dowel deformation if a sufficient anchorage length is provided and if the dowel deformation is limited under a suggested value. **KEYWORDS**: FRP sheet, flexural strengthening, dowel effects, interface shear bond

1. INTRODUCTION

RC beams flexurally strengthened with FRP sheets have high possibilities to fail due to the peeling initiating from the tips of cracks in the mid-span of beams rather than the debonding at the ends of FRP sheets near two supports, because FRP sheets have rather small thickness and they are easy to be extended toward supports. To prevent the mid-span debonding, stress in FRP sheets is given limitations in various design specifications. Those limitations are generally determined based on shear bond stress-slip law of FRP sheet-concrete interface, flexural crack spacing, anchorage length and so on [1,2,3].

Through pullout test, the interface bond performances can be evaluated under the failure caused by interface slip. However, the real cracks in RC beams strengthened with FRP sheets are flexural-shear ones, which are inclined and include both crack opening and crack sliding displacements. Thus the latter exerts dowel force on FRP sheets and may cause vertical interface peeling accompanied with slip failure. It has been mentioned by many researchers that mix-mode interface failure has complex mechanisms and design details should be given to avoid it in the FRP flexural strengthening cases. Up to now, however, no appropriate experimental or analytical study has been performed to observe directly the interface peeling-off that is triggered by combined actions of dowel force and pullout force in FRP sheets. It is not clear as well how the dowel force on the FRP sheets) in RC beams strengthened with FRP sheets. The objective of this paper is to study quantitatively the bond performances of FRP sheet-concrete interfaces under combined loading conditions based on a new test method.

2. EXPERIMENTS

2.1 TEST MATERIALS

Properties of CFRP (Carbon FRP) sheets used in the study are shown in **Table 1**. The applied resin (FR-E3P) and primer (FP-NS) have the elastic modulus of 2.41GPa and the Poisson ratio of 0.38. The mixing ratio of resin/hardner by weight is 2:1. Concrete with mixing ratio of W:C:S:A=160:301:742:1160 was used. The concrete has the test compressive strength of 45MPa.

^{*1} Division of Structural and Geotechnical Engineering, Hokkaido University, Dr. Eng., Member of JCI

Table 1 Properties of CFRP sheets					
Туре	ρ	f_t	E_{f}	t_f	\mathcal{E}_{u}
_	(g/m^3)	(MPa)	(GPa)	(mm)	(%)
FTS-C1-20	200	3550	230	0.11	1.5

2.2 TEST SETUP

A test setup is developed based on a universal testing machine, which has an accurate displament control system. This test can introduce different system stress conditions into the FRP sheet-concrete interface through loading FRP on strengthened concrete beams in different ways. As shown in Fig. 1, a steel bar is connected to the loading system. The bar can impose the dowel force onto FRP sheets vertically through a ball hinge and a hard plastic plate. In addition, a steel framework is set inside the testing machine. This framework offers reactive bending loads to the concrete beams strengthened with FRP

Note: ρ = fiber density; f_t = tensile strength; E_f = elastic modulus; t_f = thickness; ε_u = fiber fracturing strain





sheets. Consequently the pullout force can be introduced into the FRP sheets then the mix-mode loading condition can be achieved by adding the dowel force and bending load simultanuously.

2.3 TEST SPECIMENS AND TEST INSTRUMENTS

Six concrete beams with rectangular sections and externally bonded 2 layers of FRP sheets were prepared. Each beam has the span length of 1.0 m and the cross-section areas of 150×200 mm. The test beams have two cross sections (see 1-1 and 2-2 in **Fig. 2**). The section 1-1 is higher than section 2-2, where trapezoid blocks and a cylinder with half height of the concrete beams were preset to accommodate test equipments necessary for imposing dowel forces. In order to reinforce the concrete around the hole, four 13 mm steel bars were arranged in all the beams internally. In addition, 10 mm stirrups with 10 cm spacing were used to prevent shear failure occurring before flexural failure (see all detailed sizes in **Fig. 2**). CFRP sheets were bonded to concrete beams one week after concrete casting and cured for another one week till the tests. A 2 cm long unbonded area was set between the FRP sheets and concrete at the outermost location of constant moment zone.



Fig.2 Details of test specimens

Fig.3 Arrangement of test instruments

The only test variable is loading condition. 2 of 6 specimens were loaded under dowel force and bending load respectively. The left 4 specimens were loaded under a combination of two types of loading. The mix-mode loading way is to keep constant dowel forces, which are 35%, 50%, 70% and 90% of the maximum dowel force respectively (refer to **Table 2** in the latter section). As shown in **Fig. 3**, mid-span deflections of beams, open displamencts between FRP sheets and concrete (CMOD) at the starting point of unbonded area, slips between concrete and FRP sheets at the starting point of bonding area, and the strains of concrete, steel bars, and the FRP sheets were recorded. More details can be found in Ref. [4].

3. TEST RESULTS

3.1 INTERFACE BOND UNDER DOWEL FORCE ONLY







Fig. 4 shows obtained relationships between dowel force and interface CMOD, which is defined as the vertical relative displacement between FRP sheets and concrete at the starting point of un-bonded area (see 10 and 11 in **Fig.3**). The CMOD increases with the dowel force almost linearly until the peeling of FRP sheet-concrete interface. Dowel force bringing the initial local peeling of FRP sheets is about 17



N/mm (force per unit width). Thus the small dowel force resistance of FRP sheet is negligible when evaluating the shear capacity of RC beams externally strengthened with FRP sheets. However, the dowel deformation ability of FRP sheets is rather large (over 15 mm at final) and the dowel force increases a bit with the development of interface peeling toward two supports. CMOD can be regarded as vertical sliding displacement of concrete crack in RC beams strengthened with FRP sheets. In order to observe how long the effective bond length is needed corresponding to a given CMOD, Fig. 5

gives relationships between CMOD and strains on FRP sheets at several locations. From **Fig. 5** it can be known how much the corresponding CMOD is when the interface peeling occurs at a specific location, because the local peeling can be related to a sudden change of strain in FRP sheets. On the other side, the peeled interface length under a given CMOD can be known. **Fig. 6** shows the relationship between CMOD and peeled interface length. It can be seen that the ratio of CMOD to peeled interface length is almost constant (≈ 0.1), meaning that the peeling angle keeps almost constant during the peeling process. Therefore, bond length just longer than ten times of a given CMOD can prevent the deficiency by dowel failure caused by that CMOD.

3.2 INTERFACE BOND UNDER COMBINED DOWEL AND PULLOUT FORCES

3.2.1 Bending load ~ mid-span deflection curves



Table 2 Experimental results No Dowel Ulitmate Calculated Dowel force bending Maximum force (N) load Strain in ratio* (kN) FRP sheets 2000 **B**1 0 0 100% **B**2 0 62.02 7172 0% **B**3 700 61.83 7194 35% **B**4 1000 57.4 7021 50% **B5** 1400 53.6 6234 70% **B6** 1800 55.6 5747 90%

Fig. 7 Bending load-mid span deflection relations

*Ratio of added dowel force to the maximum one.

Fig. 7 shows the bending load-mid span deflection curves of all tested beams under bending only and combined loading conditions. The ultimate bending load of each beam achieved and the imposed dowel force are listed in **Table 2**. It is shown that both the stiffness and bending capacity decreases with the increase of dowel forces (refer to **Table 2** and **Fig. 7**). In comparison with the beam (B1) loaded under bending load only, the beam with 70% dowel ratio (B5) decreases its bending capacity by 13.6%. Of course, reinforcing bars in tensile zone of concrete beams makes contribution to the observed ultimate bending capacity, **Table 2** also gives the ultimate tensile strains reached in FRP sheets in all beams, which were back-calculated based on conventional RC beam theory and observed height of neutral axis, strains in steels, and external bending load during experiments [4]. The maximum horizontal strains of FRP sheets cannot be obtained directly because FRP sheets have bending and peeling angle. From the back-calculated strains, which are related to flexural strengthening efficiency of FRP sheets, it can be said that combined loading condition does not decrease the interface shear force transfer significantly.

3.2.2 Permitted dowel deformation of FRP sheets under different bending load levels

In RC beams strengthened with FRP sheets, the peeling of FRP sheets initiates easily from the tips of flexural-shear cracks, the opening and vertical sliding displacements of which trigger horizontal and vertical peeling of FRP sheets from concrete respectively. Generally, the vertical deformation of adhesive

layer is very limited. Therefore, a rather small vertical concrete crack sliding inevitably brings a vertical local peeling of FRP sheets from concrete in a short distance from the crack location. Then the vertical deformation compatibility can be kept through the contribution of FRP sheets' dowel deformation. То prevent this local bond deterioration from destroying whole flexural strengthening efficiency of FRP sheets, quantified information is needed to know the effects of tensile stress in FRP sheets on its dowel deformation ability. Through knowing that engineers can conclude how much dowel deformation of FRP sheets around cracks is permitted to achieve



Fig. 8 Bending load-mid span deflection relations

expected pullout force capacity in FRP sheets.

Fig. 8 shows the relationships between added bending load and the interface CMOD. It can be seen clearly that CMOD decreases gradually with the increase of bending load under all dowel force levels. In other words, the higher pullout force expected to achieve in FRP sheets is, the smaller vertical crack sliding in FRP strengthened RC beams is permitted. The left circled point in **Fig. 8** indicates that permissible dowel deformation of FRP sheets are very large without introducing the tensile force in FRP sheets, whereas the dotted tendency line shows that it decreases suddenly with a bit increase of the bending load any longer if the CMOD can be controlled under 1.0 mm. Dowel deformation may need to be limited more strictly in the case of ensuring the bond capacity of FRP sheets, the dowel force component will increase if a constant peeling angle is kept. To avoid the peeling by dowel force meanwhile to ensure the interface pullout force capacity, one solution is to limit dowel deformation and another is to increase the bond length as much as possible. Both ways lead to the decrease of peeling angle.

3.2.3 Local debonding of FRP sheet-concrete interface under both dowel and pullout forces





Fig. 9 Strains on FRP sheets at different locations (Dowel force ratio: 35%)



Discussions in the last section indicate that controlling the dowel deformation under a specific level can eliminate the dowel effects on the shear bond force transfer capacity of an FRP sheet-concrete interface with long bond length. In other words, the interface bond failure is still governed by shear under that dowel deformation. However, things will be different if we observe the local interface bond behaviors. The combined actions of dowel force and pullout force on FRP sheets actually affect the initiation of local interface peeling significantly because the interface becomes considerably weaker under the combination of shear and tensile stress according to Mohr-Coulomb failure criteria. To know the critical pullout force bringing the initial local peeling at different dowel force levels, Fig. 9 and Fig. 10 show the developments of strains on FRP sheets with the increase of bending loads. The local peeling of FRP sheets can be considered to have occurred when two continuous gages on FRP sheets near the location where the dowel force is added show almost the same values suddenly. The effective bond length of FRP sheet -concrete interface under dowel force action is rather small, just about 1cm as reported in Ref. [4], and the strain value on FRP sheets generally changes distinguishingly at the location where the peeling occurs. Therefore, the bending loads corresponding to initiation of local interface peeling can be defined as the circled points shown in Fig. 9 and Fig. 10. By this way, Fig. 11 shows the bending loads at initial interface peeling in concrete beams strengthened with FRP sheets under various dowel force ratios. The ultimate bending capacity of all beams is also given in **Fig.11** meanwhile. It can be seen that the dowel force induced on FRP sheets affects the local debonding significantly although its affect on ultimate bending capacity is rather small. The locally weakened interface bond is the reason why stiffness of strengthened beams decreases greatly in cases of high dowel force ratios (see **Fig. 7**).

Generally, two approaches can be used to avoid the interface peeling failure in FRP flexurally strengthened RC beams: (1) limit of tensile stress in FRP sheets is simply related to the maximum pullout force of FRP sheet-concrete interface with long bond length. By following this approach, the authors suggest to extend the FRP sheets in anchorage part till the supports since it can eliminate the negative effects of dowel deformation on the overall interface anchorage capacity. Meanwhile, it is a safe consideration to neglect the interface shear force transfer between neighboring flexural-shear cracks since



Fig. 11 Dowel force ~ bending load envelope curve

4. CONCLUSIONS AND RECOMMENDATIONS

spacing has not been made up to now; (2) The tensile stress limit in FRP sheets is determined by considering bond force transferred in anchorage zone as well as those transferred between neighboring flexural-shear cracks. In this case, the local bond deterioration caused by dowel effects should be considered because the crack spacing is small and dowel effects on local debonding are significant as shown in **Fig. 11.** Neglecting the dowel effects on the interface shear bond force transfer may lead to unsafe design.

its dependence on dowel deformation and crack

- 1. The experimental method developed in this paper offers a quantitative approach to study the concerned dowel effects on the shear force transfer capacity of FRP sheet-concrete interface in RC beams externally strengthened with FRP sheets.
- 2. Dowel deformation ability of FRP sheets decreases significantly when FRP sheets undertake dowel force and pullout force simultaneously. Thus the vertical sliding of crack in FRP sheet strengthened RC beams should be strictly controlled to achieve expected flexural strengthening efficiency. Through experimental study on concrete beams strengthened with two layers of FRP sheets, it is found that dowel deformation less than 1 mm hardly affects the ultimate shear capacity of FRP sheet-concrete interface with sufficient bond length. Dependence of the dowel deformation limitation on the FRP amount used for strengthening can be obtained based on similar studies by changing FRP stiffness.
- 3. Existence of dowel force on FRP sheets brings an earlier local peeling of FRP sheets from concrete though its effect on the ultimate bond force capacity (overall interface peeling) is small. Consideration of shear force transferred between neighboring flexural-shear cracks, which is significantly affected by both dowel deformation and crack spacing, should depend on accurate interface analysis by developing a mix-mode interface bond law rather than a shear bond stress-slip law only.

REFERENCES

- 1. Externally Bonded FRP Reinforcements for RC Structures, fib technical report, Bulletin 14, 2001.
- 2. Design and Construction Guideline of Continuous Fiber Reinforced Concrete, AIJ, 2001.

3. Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets, JSCE, Concrete Library, 2000, 7

4. DAI J.G. et al., Experimental Study on Mix-Mode Fracture of FRP Sheet-Concrete Interfaces, Proceedings of JCI International Symposium: Latest Achievement in Technology and Research on Retrofitting Concrete Structures, July, 2003, Kyoto, 113-120.