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Influence of Strengthening by Ultra High Strength Fibre Reinforced Concrete Panels on Shear Resisting Mechanism and Bond-Slip Behavior of Low Strength RC Members

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ABSTRACT

In this paper, a shear strengthening method, retarding the development of cracks around the ends of the RC beams by bonding with Ultra high strength Fiber reinforced Concrete (UFC) panels, is proposed to reinforce the low-strength RC structures. The performance has been demonstrated in the experiments. Group 1 and Group 2 of specimens were explored to evaluate the effects of the shear strengthening of UFC panels under different shear-span ratio (a/d = 2.5, 1.5), and Group 3 was developed to investigate the influence of UFC panels to the bond-slip law between the tensile rebars and concrete.

Experimental results demonstrate that the strengthening of UFC panels significantly enhances the bearing capacity and stiffness of the RC beams, and improves the failure mode, especially under a/d = 1.5. In addition, by using UFC panels, the peak bond stress enhanced and the adhesive fracture energy increased between concrete and rebar.

Keywords. UFC (Ultra high strength Fiber reinforced Concrete), shear resisting mechanism, low strength, RC, bond-slip relationship.

INTRODUCTION

Various studies have been conducted to evaluate the safety and the strengthening effect on RC structures. However, most of them are focusing on the effect of flexural strengthening, without considering the effect of shear strengthening. Studies have shown that many of factors would lead to the shear failure of RC structures, such as poor initial design and/or construction, lack of maintenance and/or accidental events (e.g., earthquakes).

The Ultra high strength Fibre reinforced Concrete (UFC) was demonstrated that its attributes include good quality to resist compression, ductility and longevity as shown in (Shah et al., 1971; Shah, 1991; Habel et al., 2003; Rossi, 2005). Other characteristics of UFC are high durability, corrosion resistance, reduced maintenance costs, chemical resistances and environmental resistances (such as freeze and thaw, salt water and so on) (Banthia et al., 2003). In recent years, the development of strong epoxy glue has led to a technique which has great potential in the field of upgrading structures. Here, a strongly epoxy glue is utilized to stick the UFC panels to the surface of the concrete, where UFC acts as a composite and helps concrete to carry loads. The strengthening effect of UFC panels bonded to web panel of plate girders was presented in (Morikawa et al., 2011). On the other hand, SETO et al. studied the effect of the shear strengthening of RC members bonded with UFC panels (Seto et al., 2011), which focused on the strengthening of stirrup. However, a more effective shear strengthening method is highly required to reinforce the existing RC structures with initial defect.

This paper describes a new shear strengthening method to reinforce low-strength RC members by retarding the development of cracks around the ends of the RC beams through bonding UFC panels. Two experimental groups, Group 1 and Group 2, were formed to conducted to measure the effects of UFC panel in terms of the mechanical performance and the shear resisting of RC members. And another experimental group, Group 3, was carried out to investigate the influence of UFC panels to the bond-slip relationship of the tensile rebars and concrete.

METHODOLOGY

Loading Test. The list of specimens is shown in Table 1. Four identical RC beams were used in the experiments, which were loaded with a four point bending configuration (240-mm of height, 150-mm of width and 1200-mm of length). The span was 1200 mm. All the beams were cast in steel moulds and were cured in the moulds under a wet hessian for two days.

To evaluate the performance of UFC strengthening, two experimental groups were formed based on the four RC beams with different shear span ratios, respectively. The conceptual figure of the relationship between shear span ratio and failure mode is shown in Figure 1 (Kobayashi, 2002). For Group 1, an assumption was made that all sorts of failure modes would occur in RC members when the load was settled to 2.5 (a/d = 2.5). For Group 2, the load was settled to 1.5 (a/d = 1.5) and the effects of UFC strengthening was evaluated when

Table 1. Description of specimens

<table>
<tr><th>Group</th><th>Specimen</th><th>Concrete strength (N/mm^2)</th><th>UFC panels</th><th>Dimensions (mm)</th><th>Shear-span ratio (a/d)</th><th>Cover (mm)</th></tr>
<tr><td rowspan="2">Group 1</td><td>N2.5</td><td rowspan="4">19</td><td>-</td><td rowspan="4">150*240*1200</td><td rowspan="2">2.5</td><td rowspan="4">-</td></tr>
<tr><td>U2.5</td><td>O</td></tr>
<tr><td rowspan="2">Group 2</td><td>N1.5</td><td>-</td><td rowspan="2">1.5</td></tr>
<tr><td>U1.5</td><td>O</td></tr>
<tr><td rowspan="4">Group 3</td><td>BN17(-1,2,3)</td><td rowspan="4">13</td><td>-</td><td rowspan="4">100*100*150</td><td rowspan="4">-</td><td rowspan="2">17</td></tr>
<tr><td>BU17(-1,2,3)</td><td>O</td></tr>
<tr><td>BN42(-1,2,3)</td><td>-</td><td rowspan="2">42</td></tr>
<tr><td>BU42(-1,2,3)</td><td>O</td></tr>
</table>

excessive shear force in the end of RC bridge (e.g., earthquakes, over-loading) occurred or the RC deep beams strengthened.

▪ Group 1: two beams, the control specimen N2.5 and the strengthened beam U2.5 bonded with UFC panels, were used. Figure 2 shows the dimension of RC beams. The longitudinal reinforcement consisted of three φ16 for tension and two D13 for compression, with tensile strengths of 439 MPa and 587 MPa, respectively. The corresponding yield stresses were 316 MPa and 406 MPa, respectively. The shear reinforcement consisted of φ6 with a yield stress of 324 MPa.

▪ Group 2: two beams, the un-strengthened RC beam N1.5 and the strengthened beam U1.5 bonded with UFC panels, were used. Figure 3 shows the dimension of RC beams. The longitudinal reinforcement consisted of three D16 for tension and two D13 for compression, with tensile strengths of 516 MPa and 563 MPa, respectively. The corresponding yield stresses

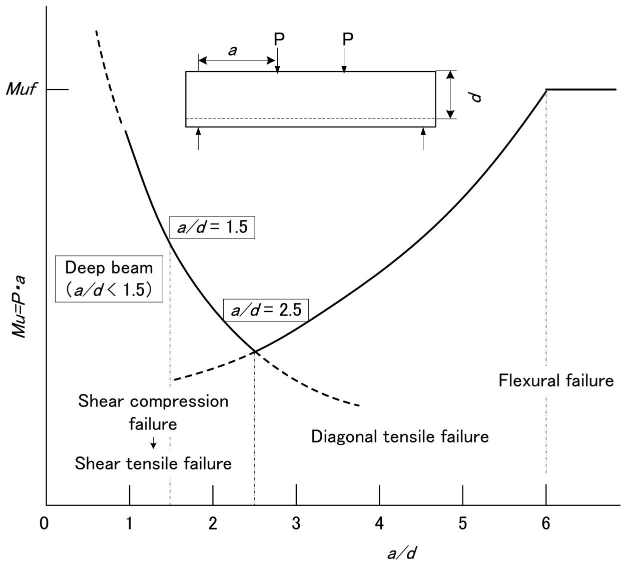


Figure 1. Conceptual figure of the relationship between shear-span ratio and failure mode

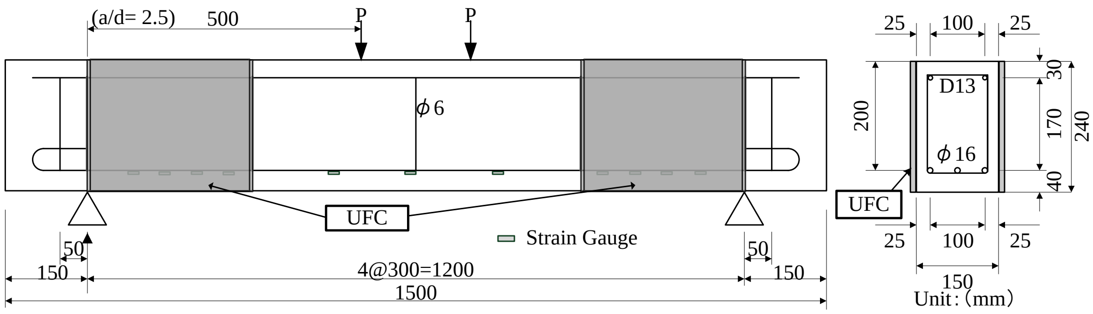


Figure 2. Dimensions of RC beams and Locations of UFC panel (Group 1)

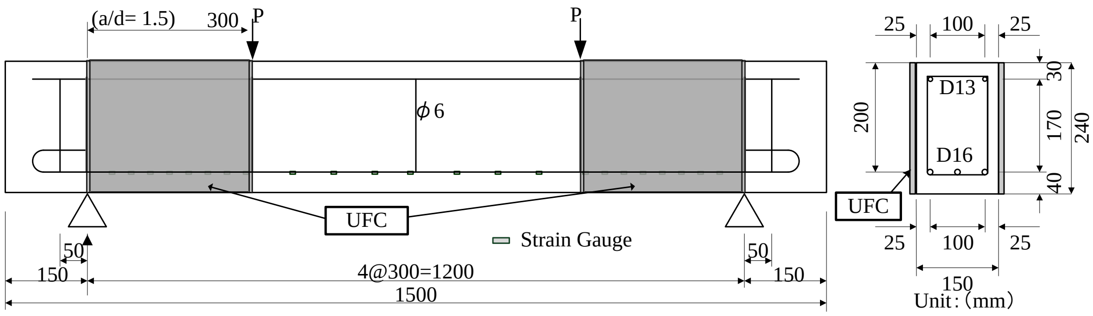


Figure 3. Dimensions of RC beams and Locations of UFC panel (Group 2)

were 344 MPa and 384 MPa, respectively. The shear reinforcement consisted of ϕ 6 with a yield stress of 415 MPa.

Pull-out Test. Group 3 was used to investigate the influence of UFC panels on the bond-slip stress of tensile rebars embedded in concrete. Twelve test blocks were conducted in the experiments (refer to Figure 4). The corresponding dimensions were 100mm, 100mm and 150mm. Considering the influence of UFC strengthening on the side tensile rebars and the centre one, two thicknesses of concrete cover were adopted (17mm and 42mm). To test the adhesion between rebars and concrete, the steel bar in the test blocks was tensioned in both sides of them.

The bond-slip stress s between the rebar and concrete is defined as

$$s = x - \frac{P}{E_s A_s} \times h, \tag{1}$$

where x is the amount of displacement measured by the displacement meter, A_s is cross-sectional area of rebar, E_s is the modulus of elasticity, P is the loading, and h ranges from the fixed position of the displacement meter to the surface of test block.

The average bond stress τ_0 is calculated as

$$\tau_0 = \frac{P - E_s A_s \varepsilon}{u \times \frac{l}{2}}, \tag{2}$$

where u is the circumference of rebar, l is the adhesive length, and ε is the value of the strain gauge in the center of rebar.

The adhesive side surface of RC specimen was grinded by using diamond grinding wheel. The specimens were bonded with the resin to adhere to the UFC panels (see Figure 5). Table 2 shows the material properties of the adhesive resin and Table 3 specifies the properties of the UFC panels. Empirically, the thickness of the panel was equal to 7mm.

Figure 5. UFC panel

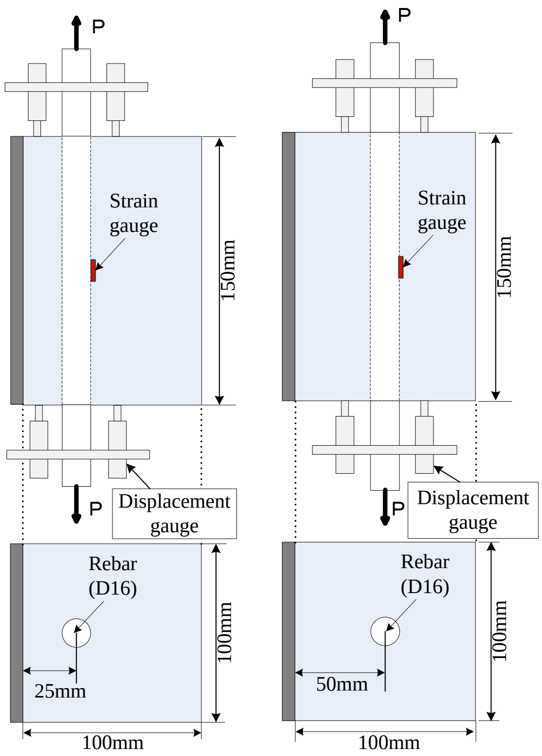


Figure 4. Dimensions of test blocks

Table 2. Material properties of adhesive resin

	Compressive strength (N/mm^2)	Tensile strength (N/mm^2)	Tensile modulus (kN/mm^2)
Adhesive resin	73.5	23.5	3.7

Table 3. Material properties of UFC

Density (g/cm^3)	Compressive strength (N/mm^2)	Flexural strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (kN/mm^2)
2.55	210	43	10.8	54

SHEAR RESISTING MECHANISM

The performances of UFC strengthening of Group 1 and Group 2 were evaluated in terms of load-deflection, crack patterns, and rebar strain distribution.

Group 1. Figure 6 and Table 4 show the load-deflection relationship and the loading test results, respectively. Comparing the control beam N2.5 with the strengthened beam U2.5, it shows that the reinforcement of UFC panels significantly affects on bearing capacity of the strengthened RC beam. Furthermore, the RC beam N2.5 resulted in the tensile shear failure, while the RC beam U2.5 resulted in the flexural failure. When UFC panels were bonded, the failure mode is transformed from shear failure to flexural failure. Thus, the UFC panels do have a very positive effect on the failure mode.

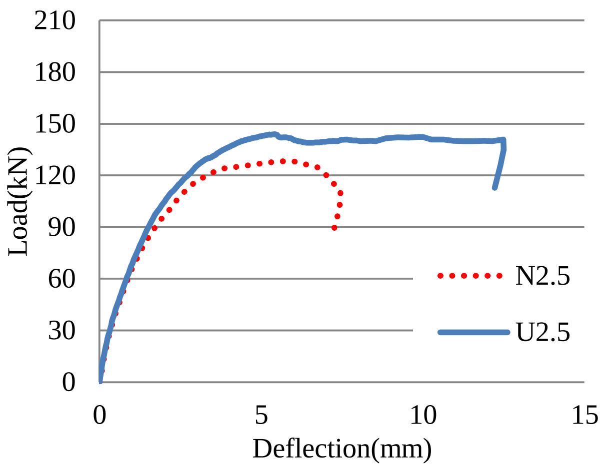
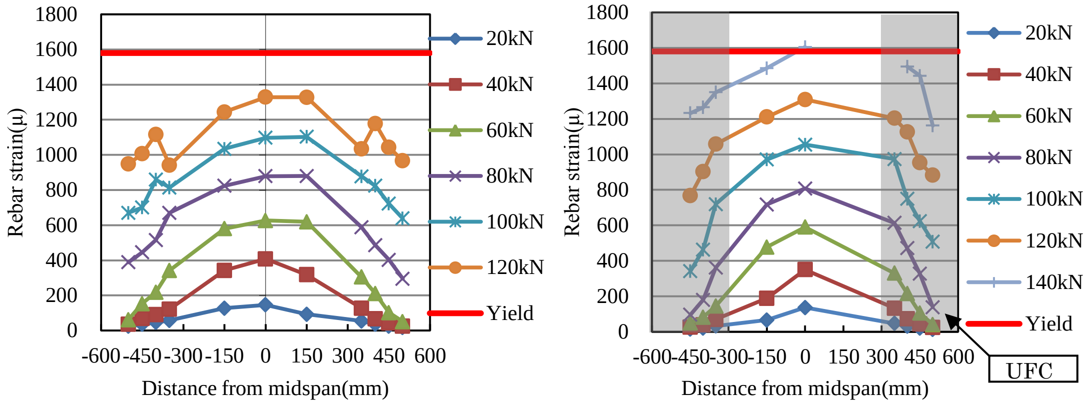


Figure 6. Load-deflection (Group 1)

Table 4. Loading test results (Group 1).

Specimen	Maximum load P_{max} (kN)	Strengthening effect	Stiffness at 30kN (kN/mm)	Strengthening effect	Failure mode
N2.5	128	-	86.8	-	Shear tensile failure
U2.5	144	1.12	94.3	1.09	Flexural failure



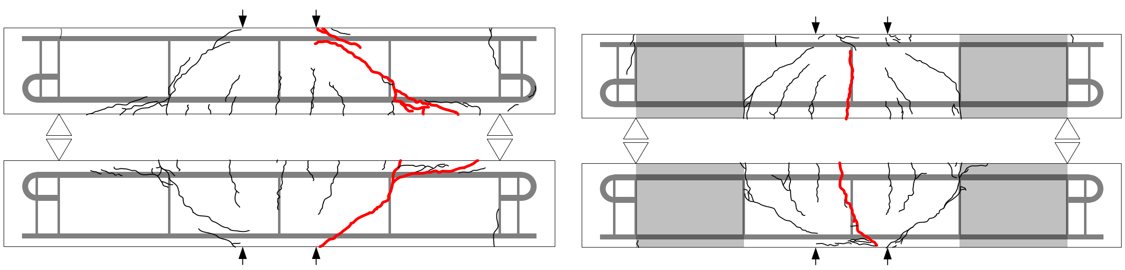
N2.5 **U2.5**

Figure 7. Rebar strain distribution (Group 1).

The rebar strain distribution of the experimental results is shown in Figure 7. The splitting occurred at the end of the tension steel bar of the control beam N2.5 when the load reached at 60kN, and further developed until the beam was broken down. On the contrary, for the strengthened beam U2.5, the strain of the tension steel bar was restrained at a low level until the flexure failure happened. The experimental results show that, using the UFC panels to strengthen the low strength RC beams restrains the debonding around the longitudinal steel bar with a result of flexural failure.

Figure 8 presents the crack patterns in the experimental results. It is observed that the RC beam N2.5 failed immediately after the horizontal cracks extended along the tension steel bar. On the other hand, for the beam U2.5, the cracks were concentrated to the middle range between the UFC panels and the failure mode was transformed to flexure failural (shear failure in beam N2.5).

Group 2. The load-deflection curves of the experimental results of Group 2 are shown in Figure 9 and the corresponding results of loading test are given in Table 5. The results show that the maximum load of the strengthened RC beam U1.5 is much greater than that of the control beam N1.5 (39% enhanced), and the performance of initial stiffness of the control beam in group 2 raised by 15%. In addition, RC beam N1.5 resulted in Shear compression failure, while RC beam U1.5 fractured in the blocking of the UFC and adjacent concrete (due to the low tensile strength of the RC beam U1.5) after the tensile rebars yielded. Compared with Group 1, it is concluded that under the shear span ratio 1.5, the strengthening of UFC



N2.5 **U2.5**

Figure 8. Crack condition (Group 1)

Table 5. Loading test results (Group 2).

Specimen	Maximum load P_{max} (kN)	Strengthening effect	Stiffness at 30kN (kN/mm)	Strengthening effect	Fracture mode
N1.5	189	-	140.0	-	Shear compression failure
U1.5	262	1.39	160.7	1.15	UFC blocking

panels significantly enhances the bearing capacity and stiffness of the RC beams, and improves the failure mode.

The rebar strain distribution of the experimental results is shown in Figure 10. It is observed that the splitting occurs at the end of the tension steel bar of the RC beam N1.5, when the load reaches 90kN. On the contrary, for the strengthened beam U1.5, the adhesion between steel bar and concrete was sustained until it reaches 150kN. The results indicate that strengthening the low strength RC beams using the UFC panels benefits the prevention of the debonding around the steel.

Figure 11 shows the crack patterns in the experimental results. In the RC beam N1.5, the shear cracks were obvious between the loading point and the supporting points. For RC beam U1.5, the bending cracks below the supporting points occurred at the

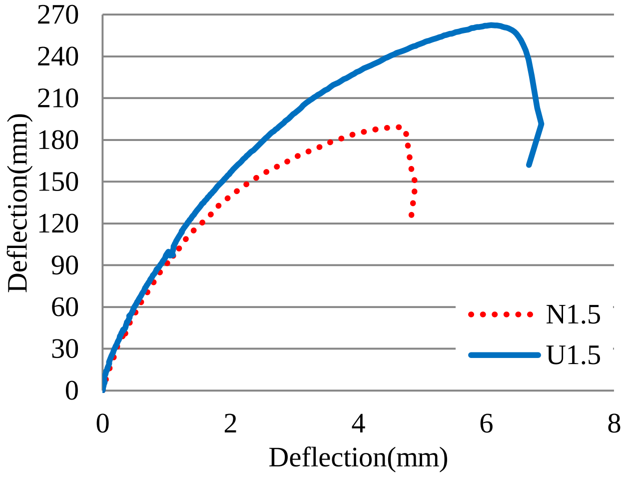
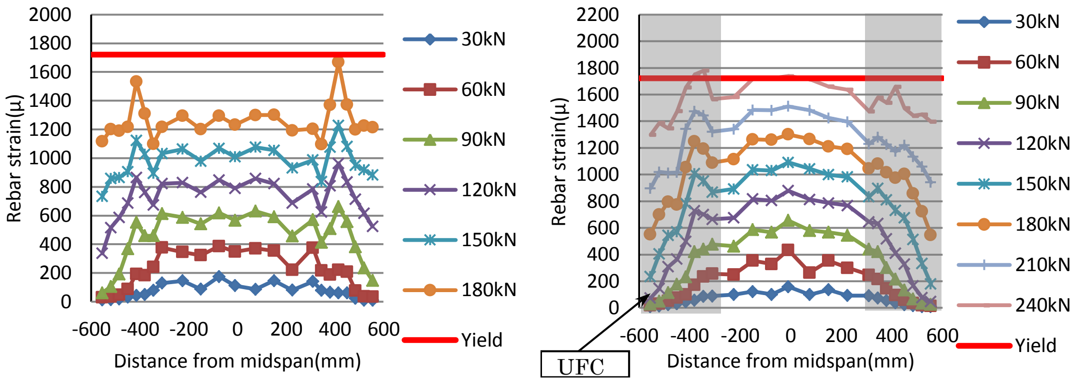
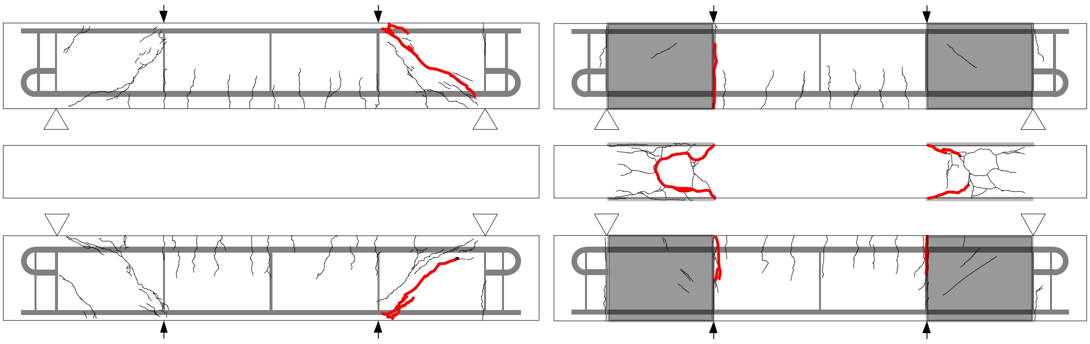


Figure 9. Load-deflection (Group 2)



N1.5 **U1.5**

Figure 10. Rebar strain distribution (Group 2).



N1.5 **U1.5**

Figure 11. Crack condition (Group 2)

load of 100kN, and then the cracks were significantly observed around the UFC panels at 140kN. After that, the cracks on the bottom of the beam developed and then the tensile rebars yield (see Figure 12). For a while, the cracks around the UFC panels extended to combine to each other Due to the low tensile strength, the RC beam fractured in the blocking of the UFC and adjacent concrete.

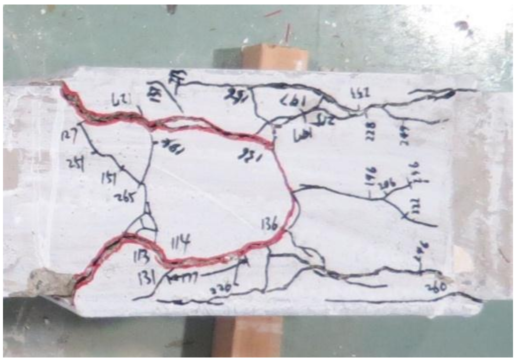
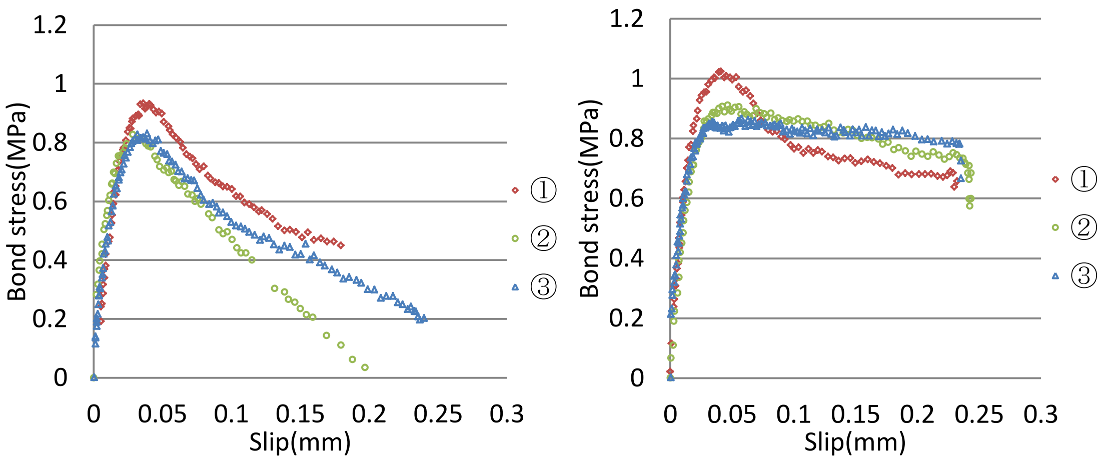


Figure 12. Cracks on the bottom of U1.5

BOND-SLIP RELATIONSHIP

Figure 13 shows the bond-slip relationships between BN17 and BU17. At the beginning stage, the bond-slip curves have the similar tendency, which becomes parabolic in form.



BN17 **BU17**

Figure 13. Bond-slip relationships

After the bond stress reaches about 40% to 50% of the peak value, the stiffness of these curves consecutively reduces as the bond stress increases and reaches zero at the peak of bond stress. After reaching the peak stress, different characteristics are observed in the diagram. For the bond-slip relationship of BN17 the curve decreases slowly and become parabola in form after the peak stress. On the other hand, the curves stay at high level values of the bond stress for a moment on the bond-slip curves of BU17. After the steel bars yielded, the tendency of bond-slip relationship was not gained in this experiment. However, when the range between UFC panels and rebars is close, the peak bond stress enhanced, and the adhesive fracture energy increased.

The bond-slip relationships of BN42 and BU42 are shown in Figure 14, with no big difference. As shown in the diagram, the bond-slip curves tend to become parabolic in form. A first steep ascending branch is followed by a plastic or softening region, until an ultimate slip reached. After the peak, the curve descends and becomes parabola in form again. It can be seen some fluctuations of the bond stress, while the peak bond stresses for BN42 and BU42 are nearly the same value. The results show that UFC strengthening less affects on the bond-slip relationship of the tensile rebars embedded in concrete, when the rebars are not located in the range of the influence of UFC panels.

CONCLUSIONS

In this paper, a shear strengthening method was proposed to reinforce low strength RC structures and experiments are conducted to evaluate the effects of UFC panel strengthening on the shear resisting mechanism and bond-slip behavior of RC members. The following conclusions can be drawn from this study:

▪ Under the shear span ratio 2.5 (a/d = 2.5), the UFC strengthening restrains the debonding around the longitudinal steel bar and has a very positive effect on the strength and stiffness of the RC beams. Furthermore, the cracks are concentrated to the middle range between the UFC panels and the failure mode is transformed from shear failure to flexural failure.

▪ When the load is settled to 1.5 (a/d = 1.5), the strengthening of UFC panels significantly enhances the bearing capacity (39%) and stiffness (15%) of the RC beams. Besides, using

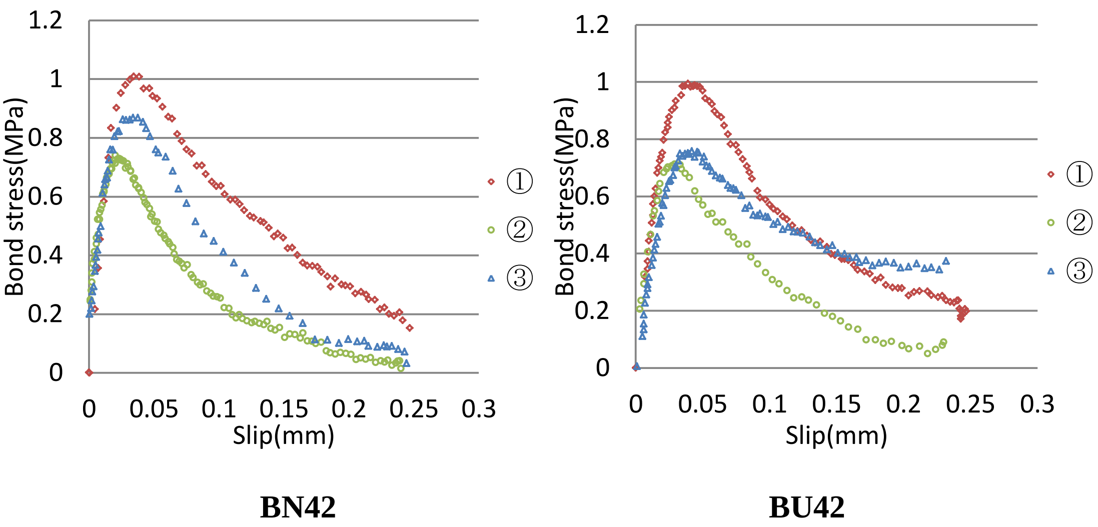


Figure 14. Bond-slip relationships.

UFC panels improves the failure model, the strengthened RC beam U1.5 resulting in the ductile failure.

▪ According to the pull-out test results, when the range between UFC panels and rebars is close, the peak bond stress and the adhesive fracture energy increased, which verify why the debonding around the longitudinal rebar is restrained in the strengthened RC members

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