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STUDY ON HYBRID STRENGTHENING FOR RC BEAMS DETERIORATED BY REBAR CORROSION

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Abstract: This study investigated the strengthening method based on a new idea for RC beams deteriorated by rebar corrosion. The notable point of the strengthening method in this study was that each strengthening was conducted without any taking measures of rebars themselves and adjustments of sectional dimension to the original ones. FRP strand sheet, fiber reinforced concrete (FRC) overlay and a combination of them were adopted as strengthening methods to increase flexural capacity. Moreover, a hybrid strengthening method, in which the FRP strand sheet was embedded into the fiber reinforced mortar, was investigated. As a result, each strengthening method could recover flexural performance. The hybrid strengthening method showed a significant increase in flexural capacity and no delamination and pullout of the FRP strand sheet were observed until failure even though the sheet was bonded by fiber reinforced mortar as same as bonded by epoxy resin.

1 INTRODUCTION

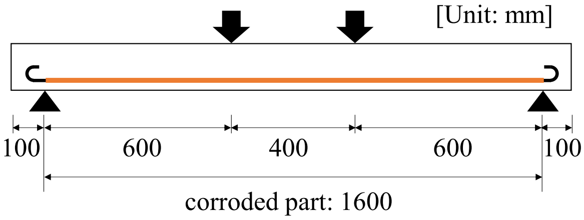
Several strengthening methods have been developed for deteriorated RC members. For the increasing of flexural capacity, the externally bonded FRP sheet was well known as one of the effective methods [1]. However, for adopting this method for the RC member with rebar corrosion, the sectional recovery is normally conducted by removing the concrete cover. The FRP sheets are bonded with epoxy resin onto the flat surface after the sectional recovery. This procedure needs not only a high technique of workers but also much time to complete the strengthening. Therefore, more easy, simple and fast methods are desired especially for the deteriorated RC structures in service existing around urban areas.

This study aims to evaluate the effectiveness of several strengthening methods for RC beams deteriorated by rebar corrosion. The strengthening methods adopted in this study are the FRP sheet bonding method on the bottom surface and the fiber reinforced concrete (FRC) overlay on the top surface. Both methods are typically used to improve flexural performance, however, no rehabilitation was applied against corroded rebars and sectional dimensions in this study. Each strengthening method was employed for RC beams deteriorated by rebar corrosion followed by the flexural loading test. Moreover, a hybrid strengthening of the FRP strand sheet and the fiber reinforced mortar was investigated and its possibility was evaluated as a strengthening method.

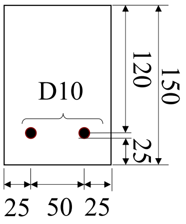
2 OUTLINES OF EXPERIMENT

2.1 RC Beams

Figure 1 shows an outline of the RC beam. RC beam has a length of 1800mm, a width of 100mm, and a height of 150mm. In the cross section, 2 rebars of D10 are placed at an effective height of 120mm to set a rebar ratio of 1.18%. Note that the RC beam is designed to fail in bending when the shear span length is set to 600mm in the loading test.



(a) Side view



(b) Section view

Figure 1: Outline of the specimen.

Table 1 shows the list of specimens. In the experiment, 6 beams were prepared, 1 specimen was a sound specimen and the others were subjected to an electrical corrosion test to be the same degree of corrosion. No strengthening was carried out to 1 specimen to evaluate the deterioration due to rebar corrosion. Rest 4 specimens were strengthened by each method as described later.

Table 1: Example of the construction of one table.

Name	Condition
case A	Sound
case B	No strengthening
case C	FRP strand sheet bonding (epoxy resin)
case D	FRP strand sheet bonding (fiber reinforced mortar)
case E	FRC overlay
case F	Combination case D and E

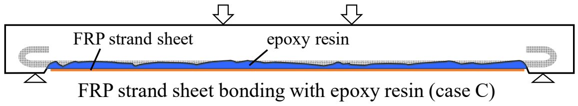
The electrical corrosion test was conducted by considering the target corrosion rate which was set as 15%. The electric current for 1 rebar was set as 0.42A by referring to the preliminary experiment by the authors, that is the magnitude of current density was about 8.75A/m^2. The electrification continued for 26 days, resulting in the accumulated current of approximately 260 A・hr. As a result of the electrical corrosion test, some horizontal cracks along rebars occurred and corrosion products appeared through them.

Compressive strength and Young's modulus of cylindrical specimen having a diameter of 100mm and a height of 200mm were 29.2N/mm^2 and 24.2kN/mm^2, respectively. Yield strength of D10 was 380N/mm^2.

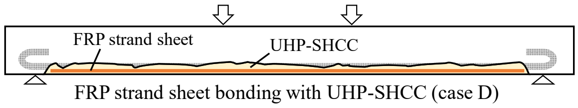
2.2 Strengthening methods

In this study, the FRP sheet bonding method and the FRC overlay were mainly adopted as the strengthening method. Although these methods are typical, the procedure of these methods is distinctive and different from others. That is, no treatment was carried out for the deteriorated part. Corroded rebars were kept as they were and no recovery of sectional dimensions due to spalling of cover was conducted.

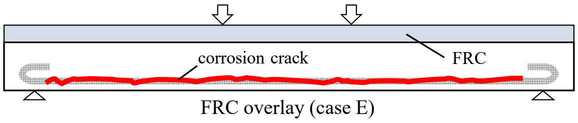
Figure 2 shows an overview of each strengthening method, case C, case D, case E and case F, respectively.



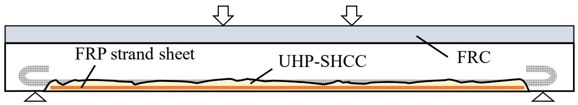
FRP strand sheet bonding with epoxy resin (case C)



FRP strand sheet bonding with UHP-SHCC (case D)



FRC overlay (case E)



FRP strand sheet bonding with UHP-SHCC and FRC overlay (case F)

Figure 2: Overview of each strengthening method.

For case C and case D, the FRP sheet bonding method was employed on the bottom part after removing the concrete cover. In this study, the FRP strand sheet [2] was applied as an FRP sheet. The thickness of the sheet was 0.33mm and their mechanical properties were as followings; fiber density was 616 g/m^2, tensile strength was 4290 N/mm^2 and Young's modulus was 262 kN/mm^2. An FRP strand sheet having a 100mm width was used for both cases. The difference between case C and case D was characterized by the materials used for bonding. Elastic epoxy resin, which is typically used for, was applied for case C, while fiber reinforced mortar having high strength and high ductility was applied for case D. Here, case D can be regarded as one of hybrid strengthening of FRP sheet and fiber reinforced mortar. For case C, approximately 2800g of epoxy resin was used so that the thickness of the resin was presumed to be about 18mm. The mortar used for case D was Ultra-High strength Strain Hardening Cementitious Composite (UHP-SHCC) [3], which compressive strength obtained from cylindrical specimens having a diameter of 50mm and a height of 100mm was 84.0N/mm^2. And tensile strength and elongation capacity of the dumbbell shaped specimens, that is average strain for 100mm long, under direct uni-axial tensile test almost exceeded 1.5N/mm^2 and 1.0%, respectively, as shown in Figure 3.

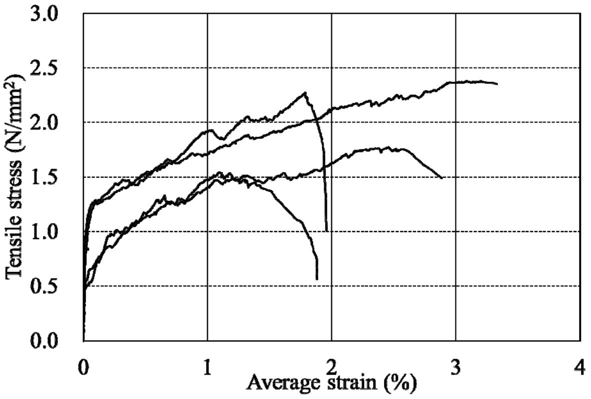


Figure 3: Results of direct uni-axial tensile test.

An FRP strand sheet was separated into two layers, with each layer thinning out 5 strands to make space for filling UHP-SHCC among the strands, as shown in Figure 4. After that, the 2 sheets were placed on the rebars, and UHP-SHCC was cast until the cover was completely recovered.

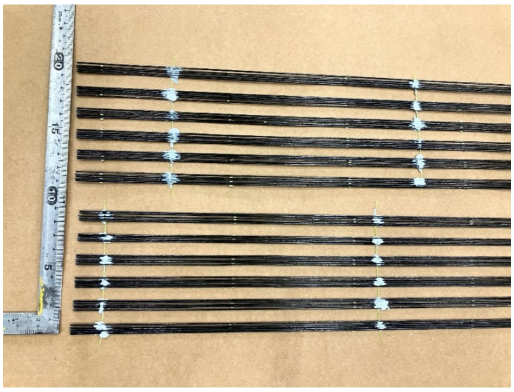


Figure 4: Overview of separated FRP strand sheets.

Polypropylene FRC was adopted for overlay strengthening, for case E and case F. The used polypropylene fibers have a length of 48mm and a diameter of 0.7mm. Young's modulus and tensile strength of fibers are 12kN/mm^2 and 640N/mm^2, respectively. The water to cement ratio of FRC was set as 0.60 and the unit weight of water was 180kg/m^3. The dosage of polypropylene fiber was set as 0.5vol%. Compressive strength and Young's modulus of the FRC obtained from cylindrical specimens having a diameter of 100mm and a height of 200mm were 35.2N/mm^2 and 29.1kN/mm^2, respectively. The FRC overlay was conducted on the top surface of RC beams, where the epoxy resin was previously applied as adhesion. The thickness of the overlay was set as 30mm considering the specimen size, even though it would be typically designed as 50mm in real construction sites.

3 RESULTS AND DISCUSSION

3.1 Load-deflection relationships and failure modes

Figure 5 shows the load-deflection relationships obtained from the loading test. Case A, the sound specimen, exhibited flexural-tensile failure behavior, in which the deflection increased after the rebar yielded at approximately 20kN. The failure occurred when the deflection exceeded 35mm due to the crushing of the concrete at the compressive area near the loading points. In case B, in which no strengthening was implemented, the yield load decreased to about 15kN due to the rebar corrosion. After the rebars yielded, the deflection increased, then at a deflection of 23 to 24 mm, a diagonal crack initiating from corrosion cracks opened drastically and propagated in a shear span, resulting in a sudden loss of bearing capacity. These yield loads almost corresponded to the calculated values not only sound specimen but also rebar corroded specimen if rebar corrosion of 15% could be assumed.

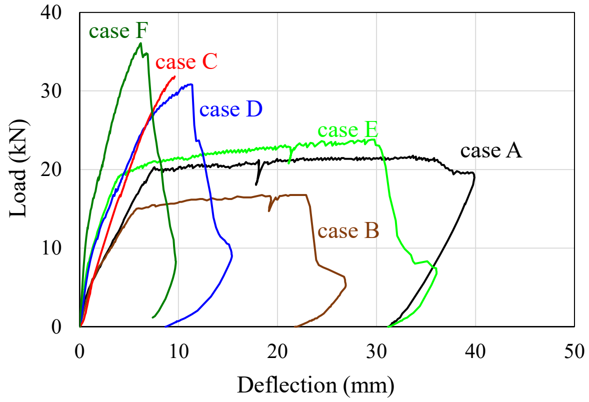


Figure 5: Load-deflection relationships.

Case C and case D reinforced with strand sheet showed load increasing without the yield even beyond 20kN. Subsequently, a sudden failure occurred around over 30kN due to the propagation of a diagonal crack in a shear span for both cases. In case C, the initial flexural stiffness was almost similar to that of case B, with no strengthening specimen. This is because no cross-sectional repair was applied. On the other hand, in case D, the initial flexural stiffness increased thanks to the effect of the tensile stiffness of the fiber-reinforced mortar.

In case E, strengthened by FRC overlay on the top surface, both the initial flexural stiffness and the yield load showed a significant effect of strengthening. The initial flexural stiffness was larger than that of the sound specimen, case A, and the yield load recovered to the same level as that of case A. This is because the second moment of area increased due to the overlay. After yielding of rebars, the deflection increased followed by the load decreased at a deflection of 30 mm due to spalling of the cover at the bottom attributed to rebar corrosion and development of a diagonal crack in a shear span.

Case F, the combination of case D and case E, also resulted in greater initial flexural stiffness than the other reinforcement methods. This could be attributed to the combined effect of the FRP strand sheet and UHP-SHCC on the bottom and the FRC overlay on the top surface. And the maximum load exceeded 35kN, which is the highest value among all strengthening. The failure mode was the same as case D not case E, with a diagonal crack propagating in a shear span.

Note that the failure mode of case C, case D and case F was almost attributed to the shear strength of original RC beams because all specimens have no stirrups arranged in shear spans in this study. The estimated values for those specimens calculated by the equation proposed by Niwa et al. [4] were 27.4kN for case C and case D with an effective depth of 120mm and 32.1kN for case E with one of 150mm, respectively.

3.2 Strain distribution of FRP strand sheet

Bond properties of materials are one of the important factors in the strengthening methods to maintain their effect as expected. The bond strength of the FRP strand sheet with mortar was expected to be weaker than that of epoxy resin, which is used for case D and case C, respectively. Therefore, the bond behavior of the FRP strand sheet with these materials was evaluated.

Figures 6 and 7 show the strain distribution of strands along the longitudinal direction of beams for case C and case D, respectively. Strain distributions at about 10kN, 20kN, 30kN and Maximum load are shown in these figures. Note that the positions of the loading points were 700mm and 11mm, and ones of supports were 100mm and 1700mm, respectively. If no pull-out behavior occurs and the FRP strand sheet bears the tensile stress, the strain of strands theoretically has a linear relationship depending on the flexural moment which increases due to span length.

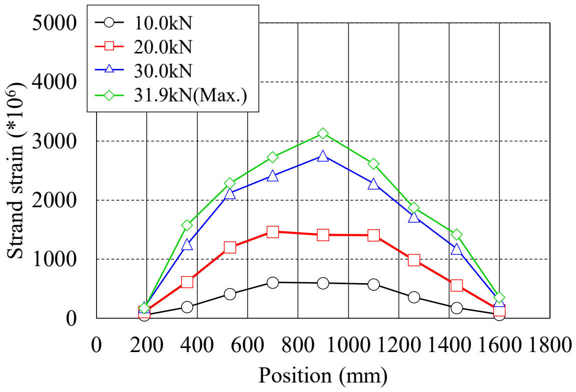


Figure 6 : Strain distribution of strands in case C.

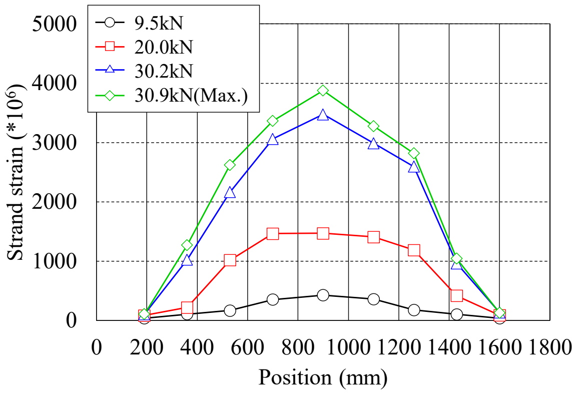


Figure 7: Strain distribution of strands in case D

As shown in Figures 6 and 7, the measured strain distributions had almost such relationships at every load level. And the strain at 200mm and 1600mm did not increase up to the maximum load so that the anchorage at the end still worked well was confirmed. Therefore, it was confirmed that, even in case D, where FRP strand sheets were embedded in UHP-SHCC, the resistance to tensile forces could be maintained until failure without pulling out similar to case C, in which the sheet was bonded using epoxy resin. It was clarified that this hybrid strengthening method, FRP strand sheet directly embedded into the mortar, was effective. More detailed investigations are necessary on the bond properties between FRP strand sheet and mortar to establish this strengthening method.

4 CONCLUSIONS

The effect of strengthening methods for RC beams deteriorated by rebar corrosion, the FRP sheet bonding method including the hybrid strengthening method embedded into the mortar, the FRC overlay, and the combination of them were evaluated. Every strengthening showed a sufficient increase in flexural performance even though no measure against the deteriorated parts was conducted. Especially, the hybrid strengthening method showed a significant possibility for the deteriorated RC beams due to rebar corrosion.

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