The Flexural Improvement of RC Beams Using an Inserted Plate between Concrete and FRP Bonding Surface

Woo Young Jung, Min Ho Kwon, Bu Seog Ju

***Abstract*—**The primary objective of this research is to improve the flexural capacity of FRP strengthened RC Beam structures with Aluminum and Titanium laminates. FRP rupture of flexural strengthened RC beams using FRP plates generally occurs at the interface between FRP plate and the beam. Therefore, in order to prevent brittle rupture and improve the ductility of the system, this research was performed by using Aluminum and Titanium materials between the two different structural systems. The research also aims to provide various strengthening/retrofitting methods for RC beam structures and to conduct a preliminary analysis of the demands on the structural systems. This was achieved by estimation using the experimental data from this research to identify a flexural capacity for the systems. Ultimately, the preliminary analysis of current study showed that the flexural capacity and system demand ductility was significantly improved by the systems inserted with Aluminum and Titanium anchor plates. Further verification of the experimental research is currently on its way to develop a new or reliable design guideline to retrofit/strengthen the concrete-FRP structural system can be evaluated.

***Keywords*—**Reinforced Concrete, FRP Laminate, Flexural Capacity, Ductility.

I. Introduction

ONE of the methods to support the flexural strength of the reinforced concrete beam was attaching the FRP plate underneath the reinforced concrete beams. Many theoretical and/or experimental studies have been conducted in this field [1]-[5]. In the case of epoxy resin attached to the outside of FRP plate, the stress transfer between FRP and concrete is generally required. The behavior of reinforced concrete beams flexurally strengthened with steel plate showed typical flexural failure behavior in addition to various failure modes in accordance with design variables, which is lower than the expected performance from construction design.

The behavior of these premature failure modes can be classified into two: (1) the failure mode caused by the stress concentration from interfacial shear stress and peeling stress based on geometric discontinuity of strengthening plates externally bonded to RC structures; (2) flexural crack-induced interfacial debonding dominated by crack propagation in the concrete parallel to the bonded plate and adjacent to the adhesive-to-concrete interface [6].

Debonding failure mode corresponding to intermediate flexural and flexural shear crack was typically observed. This is an important failure mode to understand failure mechanism in the strengthening RC structures.

In this study, thin and smooth surface aluminum and/or titanium alloy laminate was attached to the concrete by the anchor system at the interface between reinforced concrete beams and stiffener, in order to improve the system ductility and the plate-end premature debonding failure by the crack propagation. Therefore, this study was to prevent the premature failure of flexural strengthening of beams caused by crack propagation due to flexural and flexural shear stress and to improve the performance of FRP-strengthened RC structures.

II. Overview of Failure Modes of FRP-Strengthened RC Structures [6]

Many works in terms of the failure modes of RC structures bonded with FRP plates had been conducted in early 1990s. Fig. 1 (a) shows a FRP rupture failure. This failure mode basically occurs after yielding of the longitudinal steel bar in RC structural systems. However, it is important to avoid the compressive failure of the concrete structure before the longitudinal steel yields. Fig. 1 (b) showed the shear failure mode as an example of brittle failure mode. Typical reinforced concrete beams are designed to the flexural failure rather than shear failure as the brittle mode. However, by attaching FRP plate to improve the bending, shear failure could occur. Also, in the case of plate-end debonding failure, the separation of concrete cover starting from one or two ends of lower plate and FRP plate separation underneath the reinforced concrete beams are commonly observed in FRP-strengthened RC structures, as shown in Fig. 1 (c). The cause of this failure is analyzed as a combination of large shear at the boundaries and/or the nominal stress of the end plate, which is greater than the strength of the concrete, the weakest component. Thin concrete layer remain attached to the plate after the failure, therefore the failure occurs in concrete adjacent to concrete-to-adhesive interface. The intermediate crack-induced interfacial debonding failure occurs by the flexural shear cracks and/or bending at the far from the plate ends, as shown in Fig. 1 (d). Also, the failure occurs near surfaces between concrete and adhesive through thin concrete layer attached to the plate.

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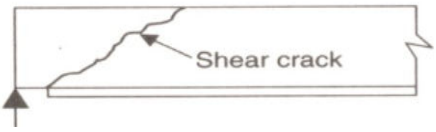
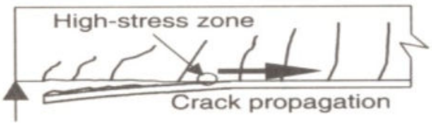
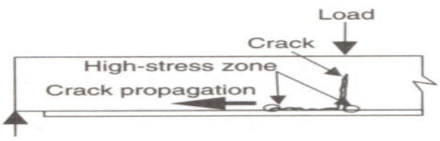
(a) Flexural failure



(b) Shear failure



(c) Plate-end debonding failure



(d) Interface failure

Fig. 1 FRP-strengthened RC structure failure modes [6]

III. Specimen of an Intermediate Element for Flexural Strengthening

A. Description of Strengthened RC Structures

Following structure was carried out in order to prevent the premature shear failure of the FRP soffit plate caused by the flexural-shear cracks and/or by bending from concrete cracks. The metal plate system such as aluminum or titanium was inserted before FRP plate was being attached to reinforced concrete structure. The cross-section of the reinforced concrete beam specimens can be found in Fig. 2. The specimens were designed with width (200mm), height (300mm), and length (2200mm), making a total of five beams; 2-D10 for compression reinforcement, 2-D13 for tensile, and D10 for stirrups with 150 interval, except for the center section (350mm), as a doubly reinforced concrete beam. The compressive strength of concrete used in this experiment was 24*MPa*, and the mean compressive strength after 28 days was 28*MPa*. The FRP reinforcement thickness was 1.5mm, and the width and length was about 100mm and 1860mm, respectively. Aluminum and titanium reinforcement used as a intermediate insert plate, had width of 0.2mm, which was about 13.3% of total FRP plate, and the length was 1860mm, which was same as FRP reinforcement. Epoxy or bolt was used for attachment to boundary surface, depending on the specimen types. Using a displacement control, the load was applied at a velocity of 1mm/min with a 100t actuator, and the width of crack was measured every 1 min.

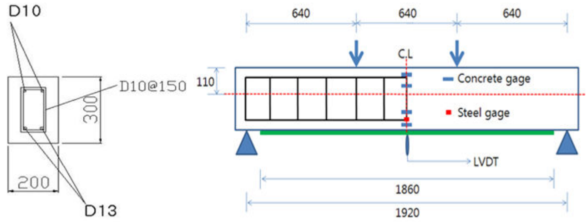


Fig. 2 Schematic design of strengthened RC structures

B. FRP Plate Bonding

Epoxy glue was used for attachment of reinforcement. To prevent the premature shear failure at the surfaces, the U-stirrup reinforcement in both ends were applied to ensure the full adherence. In order to improve the adhesion of epoxy glue before adhesion, the surface of concrete and reinforcements were grounded to increase the surface roughness of FRP. Alcohol washing was followed to remove the dusty powders from grinding. Epoxy glue was uniformly applied with consistent thickness using a trowel (Fig. 3). In addition, anchor was used for the adhesion of reinforcement in the reinforced concrete structures, which lead to the implementation of the integrated behavior. Fig. 4 showed the cross section of the design, and Fig. 5 showed the attachment process of anchor system and the reinforcements.

Fig. 3 FRP plates

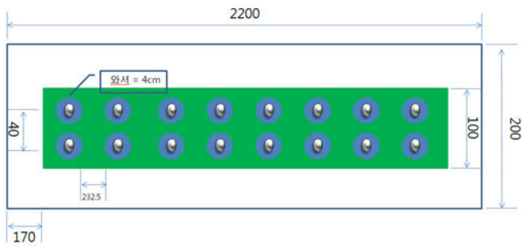


Fig. 4 FRP-plate with anchor systems

Fig. 5 Anchor systems

C. Intermediate Laminate Bonding

The characteristics of most strengthened beams with reinforcements were fairly poor due to the shear at the end. To improve this, attachment of the laminate inserts using anchor system, at the end, where receive high flexural stiffness in the bending test, followed by attaching reinforcement laminate on top of it were applied. In this case, the premature debonding and shear failure of overall reinforcement can be prevented.

While the concrete-FRP were completely attached in the case of FRP reinforcement attachment, the intermediate laminates were incomplete attachment between concrete and FRP. In both cases, the flexural stiffness would be affected when the actual bending load was applied. Differences are the fact that the complete attachment would experience the brittle failure underneath the concrete, and the incomplete attachment would experience the FRP plate debonding failure, the failure of the intermediate element, or dropping of anchor, rather than the brittle failure. Also, the intermediate element was only attached to the end, not in the middle, which can create initial gap caused by the non-adherence. This can be separated according to the load. Figs. 6 and 7 showed the process of the attaching the intermediate laminates as suggested by the cross-sectional design, and the LVDT attachment process. Furthermore, the FRP plate was installed between the anchors, to create the U-stirrup effect.

Fig. 6 Intermediate laminates and LVDT setup

Fig. 7 Intermediate laminate FRP-strengthened RC structure

D. Experimental Tests

The flexural experiment on the reinforced concrete beam was designed as 4-point bending test. Upon installation, the distance between each point was about 1920mm, and the load was controlled at 3 points in 640mm beams to induce pure bending at the center of the beam. The deflection was monitored and using data-logger (TDS-303) with LVDT installed in the middle. Two steel gauges, 2 concrete gauges and 4 FRP gauges were connected to each other, and the strain rate was measured. Fig. 8 showed the equipment and the loading specimen, as well as the diagram of gauge installation.

Fig. 8 Experimental test

IV. Performance Evaluation of Intermediate Laminate Strengthened RC Structures

A. Load-Displacement Relationship

Based on the structural system with intermediate laminates and without intermediate laminates, Fig. 9 showed the bending test results of each beam specimen. In the case of B_FRP, overall strength, ductility, and energy were decreased, in comparison to A_Al (Anchored Aluminum) and A-Ti (Anchored Titanium), which contained the intermediate elements. Fig. 9 illustrated that A_Al and A_Ti, the initial stiffness was lower than that of B_FRP. However, the stiffness and energy increased with time. In the case of B_FRP, the structure was behaving along with reinforcement, which can lead to higher stiffness. In the case of A_Al and A_Ti, the intermediate laminates only attached to the end, and no attachment was made at the center. When the actual bending force was applied, RC beam started to receive the flexural strength, and sequentially the flexural stiffness from FRP reinforcement because of the capacity of stiffness and ductility of hybrid elements.

As a result, the time-dependent integrated behavior of the intermediate laminates and RC beam, allowed it to maintain the function of reinforcement material. Overall, the structural behavior (load, deflection, and yielding etc.) results were significantly improved, as shown in Figs. 10 and 11.

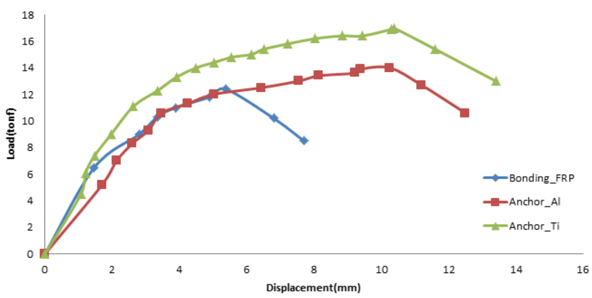


Fig. 9 Load-Deflection curves of the structural systems

B. Performance of the Structural Systems

The relationship between deflection-strain and load-strain of each specimen can be found in Fig. 12. The yield point of B_FRP and A_Al was similar, yet the ductility of A_Al increased slightly more than B_FRP. A_Al and A_Ti did not experience the plate-end debonding failure after yielding. Besides, after yielding, the yield load increased significantly from the reinforcement. This can be noted that the effect of intermediate elements was quietly effective in yielding control, more than B_FRP. Based on this result, the order of effectiveness was A_Ti, A_Al, and B_FRP, in terms of the resistance to yield stress of the steel from the reinforcement.

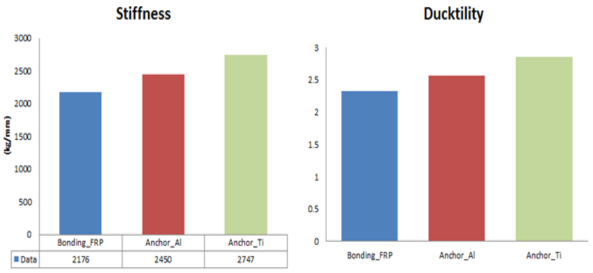


Fig. 10 Stiffness and ductility of the systems

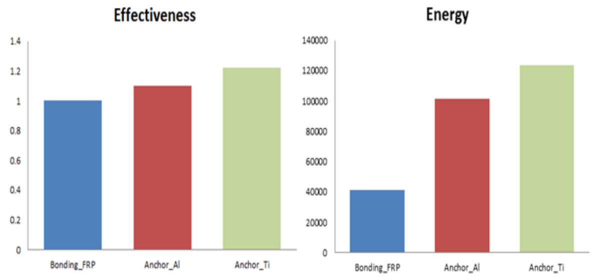


Fig. 11 Energy and effectiveness of the systems

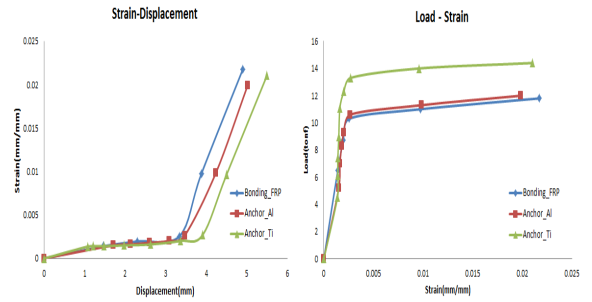


Fig. 12 Strain-Deflection and Load-Strain relationships of the systems

C. Failure Modes

Failure mode of bonded FRP (B_FRP) occurred at the center of the beam, but no failure was observed at the end, as a result of U-stirrup effect (Fig. 13).

Failure mode of anchored Aluminum (A_Al) reinforcement occurred as shear failure due to stress concentration of the anchor system at the end, especially right after the first flexural crack. The phenomenon of local premature debonding failure did not occur until the maximum load application, as can be seen in Fig. 14. In addition, Failure mode of anchored Titanium (A_Ti) reinforcement was similar to that of aluminum reinforcement failure mode. The shear failure, also, occurred due to stress concentration of the anchor system at the end. Fig. 15 showed the failure mode of FRP-strengthened RC structures with intermediate laminate using Titanium elements.

Fig. 13 Bonded FRP failure mode

Fig. 14 Anchored aluminum strengthened RC structure failure mode

Fig. 15 Anchored titanium strengthened RC structure failure mode

V. CONCLUSIONS

In this study, the performance evaluation of reinforced concrete beams with intermediate laminates using Aluminum and Titanium was conducted, as an improvement of the premature failure of the FRP plates. Based on the researches on the reinforced concrete and inserted plate at the interface of FRP attachments, following conclusions were drawn.

1. For the load-deflection relationship of intermediate elements, specimen used Titanium plates, which was attached by anchor systems showed 1.22 times increment to the specimen with FRP bonded plates. Also, the specimen used Aluminum plates as an intermediate laminate element fixed by anchor systems showed 1.1 times increment to the specimen with FRP bonded plates. Therefore, the higher performance of the structural system with intermediate laminates was achieved.
2. A complete attachment subjected to four-point bending showed the behavior characteristics of high initial flexural stiffness. However, tensile failure of underneath concrete can occur with constant load condition, and it can stop the behavior. However, in the case of non-adherence case, the stiffness of FRP reinforcement can be cooperated and behave as the stiffness of hybrid elements, as time goes on. It can lead to the ductile behavior, therefore, showed the higher energy of the elements. As for the anchor structures, as a method of attachment of intermediate laminates, the performance was superior to the bonded plates from current experience. However, the shear failure caused by the stress concentration around the anchor points was

disregarded in the design of current experience. As a result, the initial flexural cracks from the failure of anchor-attached beam, lead to the initial flexural crack, and ultimately progressed to the failure through the shear crack from the end point.

3. In most cases based on shear failure, the final failure occurred at the reinforcement matrix from the shear failure, when anchor was applied. This can be a cause of complete failure depending on the reinforcement material, unlike the local concrete debonding failure at the interface of concrete-FRP. In order to prevent the shear failure of matrix due to the anchor installation, utilization of different shear stirrups, and design of FRP reinforcement material within the proper safety rate were tried and proposed in this study. In consideration of previous researches, and the finding of current study suggests the use of anchor-typed insert plate. The results of current study can practically aid in future development of reinforcement system.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MEST) (No. 2012-0008762)

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