Effect of slitting of carbon fiber-reinforced plastic strip on flexural properties of reinforced concrete

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Abstract

In this study, reinforced concrete was manufactured by attaching a carbon fiber reinforced plastic (CFRP) strips to the surface of the concrete. Strips with the same total area were slitted into one, two, three, four, and six pieces and attached to the upper, lower, and side parts of the concrete. The flexural strength and fracture toughness of the reinforced concrete were investigated. As the number of slits in the strip increased, for the upper reinforcement, the flexural strength gradually increased from 7.88 MPa to 11.21 MPa; for the lower reinforcement, the flexural strength increased significantly from 7.88 MPa to 26.48 MPa and then gradually increased to 33.90 MPa; and for the side reinforcement, the flexural strength increased from 7.12 MPa to 13.96 MPa and then gradually decreased. In the adhesive fracture toughness test, the fracture toughness energy significantly increased from 142.38 J m⁻² to 516.63 J m⁻² as the contact area between the adhesive and the strip increased. Therefore, in reinforcing concrete using a CFRP strip, it was confirmed that the reinforcement effect was enhanced when the strip was slit and then attached.

1. Introduction

As a concrete structure ages, its structural performance deteriorates, and repair and reinforcement are required. Accordingly, if an efficient repair method is used, the structural performance of a concrete structure can be better than that of the existing design strength at a lower cost. Several studies have investigated the flexural performance of concrete after reinforcing it with fibers. In particular, reinforcement with carbon fibers is known to quickly and efficiently reinforce concrete structures owing to their light weight, high strength, corrosion resistance, low thermal conductivity, and ease of handling [1].

There exist two methods for the reinforcement of concrete using fibers: inserting the fibers during concrete construction and attaching the fibers after concrete construction. In the former case, the structure is reinforced by embedding various types of fibers or fiber-reinforced plastics (FRPs) into the concrete. This approach is not suitable for post-construction reinforcement because the fibers need to be inserted during construction. In the latter case, a fiber or FRP sheet is attached to the constructed concrete. Attaching a fiber sheet can shorten the construction time owing to the wide width of the sheet; however, continuous construction is difficult owing to the possibility of sagging of the fiber sheet, its non-uniform attachment, and low-adhesion problems [2–7].

To date, various experimental and analytical studies have been conducted on concrete reinforced with FRPs [8–18]. In particular, concrete bridges and building structures are commonly reinforced by attaching carbon fiber-reinforced plastic (CFRP) strips to the surface of the concrete. This is recognized as an extremely effective method for reinforcing structures owing to its excellent construction performance and overall mechanical performance. However, in concrete reinforced with CFRP strips, various fracture shapes appear, such as concrete compression fractures, shear failures, interfacial adhesion failures between the concrete and CFRP strip, and concrete drop-off failures [19]. The destruction caused by the detachment of a CFRP strip owing to an interfacial adhesion failure is recognized as a typical failure phenomenon. In other words, to maximize the effect
of reinforcing concrete using CFRP strips, a sufficient attachment area between the concrete and CFRP strip is required to integrate the concrete structure and CFRP strip [20–24].

Therefore, in this study, unlike the general CFRP strip-attachment method, illustrated in figure 1, a CFRP strip in the form of a rectangular plate was slitted and attached to the concrete in a longitudinal direction, as shown in figure 2. While the same amount of the CFRP strip was used for the reinforcement, the number of slits

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**Table 1. CFRP strip specifications.**

| Reinforcement   | Matrix   | Forming method | Fiber volume fraction (%) | Thickness (mm) | Flexural strength (GPa) | Flexural modulus (GPa) |
|-----------------|----------|----------------|---------------------------|---------------|-------------------------|------------------------|
| UD Carbon fiber | Epoxy resin | Pultrusion      | 56                        | 1.3           | 1.122                   | 42.278                 |
was increased, and the specimen was prepared by attaching the strip to the upper, lower, and side parts of the concrete. The effect of the effective adhesive area between the concrete and CFRP strips on the concrete reinforcement was investigated by measuring the flexural strength and adhesive fracture toughness ($G_{IC}$) of the upper, lower, and side-reinforced concrete specimens.

2. Experimental

2.1. Materials

CFRP strips with a width of 60 mm, length of 300 mm, and thickness of 1.3 mm were used for reinforcement in the experiment. Table 1 lists the specifications of the CFRP strips used in this experiment. The 60 mm strips were slit into pieces with 30, 20, 15, and 10 mm widths. Figure 3 depicts a split CFRP strip. The concrete specimens used in the experiment were formulated to have a compressive strength ($\sigma_{ck}$) of 350 kg cm$^{-2}$ at 28 d of aging similar to ordinary concrete with a water–cement ratio (w/c) of 0.40 and a slump value of 12 cm. Type-1 ordinary Portland cement was used, with a fine-aggregate fineness modulus of 2.21 and specific gravity of 2.66, a coarse-aggregate fineness modulus of 6.19 and specific gravity of 2.64, and a maximum aggregate size of 10 mm. For adhesion between the concrete and CFRP strip, an epoxy-based resin for plate products was used as the main ingredient (SK-CPA10, SK Chemicals Co., Korea). A modified aliphatic polyamine component was used as a hardener and mixed in a 2:1 ratio.
2.2. Preparation of CFRP reinforced concrete

To prepare the specimen, the adhesive was uniformly applied with a 0.5 cm thickness to the concrete using a guide; subsequently, the slitted CFRP strip was attached with a 20 N load. To evaluate the reinforcement effect of the slitted strip, the same amount of CFRP strip was attached to the concrete specimens. Therefore, one 60 mm strip, two 30 mm strips, three 20 mm strips, four 15 mm strips, and six 10 mm strips were attached at regular intervals to the concrete specimens. The prepared specimens were dried at room temperature for 24 h, and their

Figure 6. Geometry and images of the flexural-strength test setup: (a) upper reinforcement, (b) lower reinforcement, and (c) side reinforcement.
Flexural properties and fracture toughness were measured. Figure 4 presents a schematic for the process of attachment of the CFRP strips to the concrete, and figure 5 illustrates the specimens with the attached CFRP strips.

Figure 7. Geometry and image of the DCB test setup for the specimens.

Figure 8. (a) Load-displacement curve and (b) flexural strength of the basic concrete specimen and the upper-reinforced concrete specimen with the strip.
2.3. Characterization

The flexural strength of the concrete reinforced with strips was measured using a universal mechanical tester (UT-301, R&B Co., Korea). The flexural test was carried out using the four-point-bending method, according to ASTM C 1609, and the tests were divided into cases in which the strips were used to reinforce the upper, lower, and side regions. Figure 6 illustrates the geometry and images of the flexural-strength test setups. The adhesive fracture toughness was measured using a double-cantilever-beam (DCB) Mode I interlaminar fracture test, according to ASTM D 5528-01. Figure 7 depicts the geometry and images of the DCB test setup for the specimens. The width, length, and initial delamination length of the specimens were 70, 300, and 63 mm, respectively, and the crosshead speed was 5 mm min$^{-1}$. The interlaminar fracture toughness ($G_{IC}$) was calculated using the following equation (1):

$$G_{IC} = \frac{3P\delta}{2ba}$$

where $G_{IC}$ is fracture toughness at the initial crack stage, $P$ is the load, $\delta$ is the load-point displacement, $b$ is the specimen width, and $a$ is the delamination length.

After the adhesive fracture-toughness test was conducted, the cross section of the specimen was observed using an optical microscope (DM500, Leica, Germany).

Figure 9. (a) Load-displacement curve and (b) flexural strength of the basic concrete specimen and the lower-reinforced concrete specimen with the strip.
3. Results and discussions

3.1. Upper reinforcement flexural strength

Figure 8 depicts the load-displacement curve and flexural strength of the basic concrete specimen and the upper-reinforced concrete specimen with the strip. As illustrated in figure 8, the breaking load of the specimen without strip reinforcement is 562.8 kgf and the flexural strength is 7.88 MPa. The flexural strengths of the specimens with strip reinforcement are higher than this value. In addition, as the number of slits in the strip increases, the flexural strength also gradually increases. The specimen reinforced with four 15 mm strips demonstrates the highest maximum load (947.2 kgf) and a flexural strength of 11.21 MPa, which is 42% higher than that of the basic specimen. This is because when the strip is reinforced with the same amount of CFRP, the effective

![Figure 10. Fracture phenomenon for (a) upper reinforcement and (b) lower reinforcement.](image)

![Figure 11. (a) Load-displacement curve and (b) flexural strength of the basic concrete specimen and the side-reinforced concrete specimen with the strip.](image)
adhesive area between the strip and the adhesive increases with an increase in the number of slits in the strip. This is owing to the fact that the adhesive also forms a contact with the bottom and sides of each slit strip. However, for the specimen reinforced with six 10 mm strips, which is a relatively large number of slits, the flexural strength is lower than that of the specimen reinforced with four 15 mm strips. This is because as the number of slit strips increases, the distance between each strip decreases, and the high-viscosity adhesive does not penetrate between the strips, making it difficult to transmit external forces. Therefore, even for reinforcement with six 10 mm strips, the best flexural strength is expected only if the distance between each strip is sufficiently wide.

3.2. Lower reinforcement flexural strength

Figure 9 illustrates the load-displacement curve and flexural strength of the basic concrete specimen and the lower-reinforced concrete specimen with the strip. Figure 9 indicates that the flexural strength for the lower reinforcement, like that of the upper reinforcement, increases with an increase in the number of strip slits. In addition, the reinforcing effect is found to significantly increase with the attachment of an unslitted strip to the concrete. The specimen reinforced with a single 60 mm strip demonstrates a breaking load of 2,212.8 kgf and a flexural strength of 26.48 MPa, which is 235% higher than that of the basic concrete specimen (562.8 kgf, 7.88 MPa). When four 15 mm strips are used for the reinforcement, the breaking load is 2,865.2 kgf, and the flexural strength is 33.90 MPa, which is the highest value. This value is 329% higher than that of the basic concrete. However, as the number of slits in the strip increases, the rate of increase is not as high as that of the upper reinforcement, and the flexural strength decreases for reinforcement with six 10 mm strips. Similar to the upper reinforcement, as the strip is slit for the lower reinforcement, the effective adhesive area between the adhesive and strip increases, and thus, the flexural strength increases. However, unlike the upper reinforcement, the flexural strength for the lower reinforcement significantly increases compared with that of a concrete specimen.
without a strip. This is because the strip prevents the occurrence of cracks due to flexion at the bottom of the concrete specimen. Figure 10 depicts the fracture phenomenon in the case of the upper and lower reinforcements. Such fractures are observed because when six 10 mm strips are used, the strip used is slit in too many pieces, and the distance between each strip is decreased, which decreases the effective adhesive area and causes the strip to fall off owing to an external force. Therefore, it can be expected that the best flexural strength will be exhibited if the distance between the respective strips is sufficiently wide. As a result, in the general method of concrete reinforcement with strips for construction, the lower reinforcement was found to be three times more effective than the upper reinforcement for the same amount of CFRP.

3.3. Side reinforcement flexural strength

Figure 11 depicts the load-displacement curve and flexural strength of the basic concrete specimen and side-reinforced concrete specimen with the strip. As illustrated in figure 11, the results for the side reinforcement are different from those for the upper/lower reinforcements. In the upper/lower reinforcements, the breaking load and flexural strength increased with the number of slits in the strip; however, the breaking load and flexural strength was found to decrease for the side reinforcement. Nevertheless, by simply attaching any type of strip, the reinforcement effect on the specimen was found to increase. When a single 60 mm strip is used for reinforcement, the breaking load is 1,189.0 kgf, and the flexural strength is 13.96 MPa, which is 96% higher than that of the basic concrete and demonstrates the best reinforcement effect. Thereafter, it gradually decreases. For the upper/lower reinforcements, regardless of the number of slit strips, the total area and thickness of the strips subjected to an external force are the same. However, for the side reinforcement, considering the direction of the external force, the width of the strip represents the thickness of the reinforcement. Hence, the thickness of the strip subjected to the external force decreases when the number of slit strips increases. This is because the flexural strength increases in proportion to the square of the thickness of the material. Therefore, for the upper/lower reinforcements, the flexural strength is affected only by the effective adhesive area, and for the side reinforcement, the effective adhesive area increases as the number of slit strips increases; however, it appears to be more affected by the decrease in the thickness of the reinforcement.

3.4. Adhesive fracture toughness

Figure 12 depicts (a) the load-displacement curve and (b) adhesive fracture toughness obtained by the DCM Mode I test of reinforced concrete according to the number of slit strips. As indicated in figure 12(a), the initial fracture load increases with the number of slit strips. The initial fracture load of the specimen reinforced with a single 60 mm strip is 5,386 kgf; however, the initial fracture load of the specimen reinforced with four 15 mm strips is 10,014 kgf, which is an increase of 86%. The initial fracture load of the specimen reinforced with six 10 mm strips decreases, as observed in the flexural test. This indicates that the increase in the effective adhesive area owing to an increase in the number of slit strips increases the interfacial adhesive force between the adhesive and
the strip, and this, in turn, increases the fracture-delamination resistance of the strip. As illustrated in figure 12(b), the fracture toughness increases significantly as the number of slit strips increases. The fracture toughness of the specimen reinforced with a single 60 mm strip is 142.38 J m⁻²; however, the fracture toughness of the specimen reinforced with four 15 mm strips is 516.63 J m⁻², which is an increase of 263%. This is because according to equation (1), the load-point displacement was large when the first crack was generated.

Figure 13 depicts an optical-microscope image for the cross section of the specimen reinforced with four 15 mm strips and the specimen reinforced with six 10 mm strips. Figure 13(a) confirms that the effective adhesive area increases when the adhesive is sufficiently filled between each strip; however, as can be seen in figure 13(b), the high-viscosity adhesive does not appear to be sufficiently filled between the strips owing to the narrow distance between each strip. This indicates that the fracture-toughness energy increases with an increase in the contact area between the adhesive and strip, which results from the slitting of the strip. Consequently, when using an adhesive for construction, a high-viscosity adhesive must be used to prevent dripping when applied to a wall; however, even if the slitting increases, the reinforcement effect is expected to be greater if the strips are sufficiently separated.

4. Conclusions

The effect of the effective adhesive area on the flexural strength and fracture toughness of concrete reinforced with slitted CFRP strips were investigated. The conclusions drawn are as follows.

- When upper, lower, and side CFRP strips were used to reinforce concrete, the flexural strength increased compared with that of basic concrete. As the number of slits in the strip increased, for the upper reinforcement, the flexural strength gradually increased from 7.88 MPa to 11.21 MPa; for the lower reinforcement, the flexural strength increased significantly from 7.88 MPa to 26.48 MPa and then gradually increased to 33.90 MPa; and for the side reinforcement, the flexural strength increased from 7.12 MPa to 13.96 MPa and then gradually decreased. This indicates that the effect of the upper/lower reinforcement is due to the fact that an increase in the contact area between the adhesive and CFRP strip increases the effective adhesive area, and the effect of the side-reinforcement is due to the fact that the effect of the reinforcement thickness is greater than that of the effective adhesive area.

- In the adhesive fracture-toughness test of the concrete specimens reinforced with CFRP strips, as the number of slits in the strip increased, the effective adhesive area between the adhesive and the strip increased, resulting in a significant rise in the fracture toughness energy from 142.38 J m⁻² to 516.63 J m⁻². However, if the distance between the slit strips was too narrow, the reinforcing effect was found to be rather low because the high-viscosity adhesive did not sufficiently fill between the strips.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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