FLEXURAL PERFORMANCE OF RC BEAMS BONDED WITH UV-GFRPR SHEETS

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This study presents the flexural performance of reinforced concrete (RC) beams externally bonded with UV-curable glass fiber reinforced polyester resin (UV-GFRPR) sheets onto their soffit surface. UV-GFRPR sheets can be cured by UV irradiation. The UV-GFRPR sheets after hardening have about one-seventh of the yield strength of normal steel (SS400), which is lower than FRP sheets such as carbon, aramid, and glass fibers. However, the UV-GFRPR sheets are easily attached to the surfaces of substrates for repair and preventive maintenance and have excellent durability with impermeability of moisture and corrosion factors. The aims of this study are to assess the flexural performance and the strengthening effect of RC beams bonded with two and three laminated layers of the UV-GFRPR sheets in four-point bending tests. The test results showed that the ultimate load-carrying capacities of the specimens with two and three laminated layers were 1.13 and 1.37 times higher than that of the control beam. The RC beams with the UV-GFRPR sheets failed in bending due to rupture of the UV-GFRPR sheets. The load-carrying capacity and the flexural performance were also predicted using the cross-sectional analysis.

Keywords: Repair, Strengthening, Load-carrying capacity, Cross-sectional analysis.

1 INTRODUCTION

Many studies have been conducted on repair and strengthening of reinforced concrete (RC) structures with fiber reinforced polymers/plastics (FRPs). FRP sheets such as carbon, aramid, and glass fibers are externally bonded onto the surfaces of substrates. This method enhances their load-carrying capacity and mechanical performance.

This study uses a UV-curable glass fiber reinforced polyester resin (UV-GFRPR) sheet, instead of FRP sheets. The UV-GFRPR sheet consists of a polyester resin and chopped glass fibers with a length of 25 mm. The UV-GFRPR sheet after being cured by UV irradiation has lower tensile strength and Young’s modulus than FRP sheets using several fibers mentioned above. However, the UV-GFRPR sheet can be cut with scissors and easily glued to steel and concrete structures for repair and preventive maintenance. Furthermore, the UV-GFRPR sheet has excellent durability with impermeability of moisture and corrosion factors. In the previous study, bending tests were conducted on small concrete beams bonded with the UV-GFRPR sheets (Mitsukawa et al. 2020a) and the strengthening effect was confirmed.

In this study, four-point bending tests for RC beams were carried out to evaluate the flexural performance and the load-carrying capacity with the number of laminated layers as the parameter.
Furthermore, the flexural performance and the load-carrying capacity were predicted using the cross-sectional analysis.

2 EXPERIMENTAL PROGRAMS

2.1 Properties of Materials

The compressive strength of concrete in the flexural test obtained from three cylinders with a diameter of 100 mm and a height of 200 mm was 36.5 N/mm². Two kinds of reinforcing bars, D13 and D16 were used for the upper and lower reinforcements, respectively. The yielding strength was 374 N/mm² for D13 and 370 N/mm² for D16. The tensile stress and strain curve of a UV-GFRPR sheet with a width of 40 mm and a thickness of about 1.6 mm after cured by UV irradiation was obtained (Mitsukawa et al. 2020b). Multiple cracks were generated in the polyester resin at a tensile strain of about 2,500 µ. After that, the chopped glass fibers in the polyester resin carried the tensile stress. Finally, the cracks were localized, and the UV-GFRPR sheet failed. The stress and strain curve was modeled by a bi-linear relationship from the tensile test results as shown in Figure 1, and the averaged mechanical properties are shown in Table 1.

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Table 1. Mechanical properties of UV-GFRPR sheet.

![Figure 1. Stress and strain curve of UV-GFRPR sheet.](image1.png)

![Figure 2. UV-GFRPR sheet adhesion.](image2.png)

Two kinds of adhesives were used to bond the UV-GFRPR sheet in this study. An epoxy adhesive was used between the concrete and the UV-GFRPR sheet, and an acrylic adhesive was used between the UV-GFRPR sheets as shown in Figure 2. The amount of application of epoxy and acrylic adhesives was 500 g/m², and each density was 1.3 and 1.1, respectively.

2.2 Specimens and Measurements

Three RC beams with a height of 200 mm, a width of 300 mm, and a length of 2,000 mm were prepared as shown in Figure 3. Two D13 bars for the upper reinforcement and three D16 bars for the lower reinforcement were arranged with a cover concrete thickness of 30 mm. However, after the tests, it was confirmed that the upper reinforcing bars were unfortunately settled down due to the construction defect as presented in Figure 3. Therefore, in the following analysis, an actual
measured depth of the upper reinforcing bars was used. The RC beams were cured for over 28 days in the laboratory-controlled temperature of 20 ± 2°C. The soffit surface was ground and wiped off with acetone in advance to remove any weak surface layer and dust. The epoxy adhesive was used at an interface between the concrete and the first layer of the UV-GFRPR sheet and was cured for 24 h in the laboratory-controlled temperature of 20 ± 2°C. After that, a 70 W UV lamp was used to harden the UV-GFRPR sheet at a distance of 300 mm for 30 min. For the second and third layers of the UV-GFRPR sheet, the acrylic adhesive was used and cured for 30 min. After that, as with the first layer, a 70 W UV lamp was used to harden the UV-GFRPR sheet at a distance of 300 mm for 30 min for each layer. As shown in Figure 3, the UV-GFRPR sheets were glued onto the soffit surface with a length of 1,700 mm between the supports.

Figure 3. Configuration of RC beam with UV-GFRPR sheets.

The deflection, and the strains of the concrete, the reinforcing bars, and the surface of the UV-GFRPR sheet were measured. The deflection was measured using linear variable difference transducers (LVDTs) with a 50 mm capacity. The strain on the top surface of the concrete was measured using a 30 mm long strain gauge. The strains of the reinforcing bars and the surface of the UV-GFRPR sheet were measured using 2 mm and 5 mm long strain gauges. These measured positions are also shown in Figure 3.

2.3 Test Methods

The beams were tested under the four-point bending condition with a span length of 1,800 mm and a loading span length of 300 mm as shown in Figure 3 and Figure 4. For damage induced considering existing bridge RC slabs, two RC beams bonded with the UV-GFPRP sheets later were loaded until the strain of the lower reinforcing bars was 600 µ in advance. This strain value agrees with the design stress limitation of 120 N/mm² in the specification for road bridge slabs in Japan. After this pre-loading, the UV-GFRPR sheets were bonded onto the soffit surface.

3 CROSS-SECTIONAL ANALYSIS

3.1 Stress and Strain Models

Numerical analysis was also carried out based on strain compatibility and cross-sectional force equilibrium in this study. The assumptions below simplify the problems: (1) The composite performance remains between the concrete and the UV-GFRPR sheets until failure; (2) The plane
condition holds for the cross-section; (3) The adhesive layers are negligible in the mechanical interaction. For the UV-GFRPR sheet and the reinforcing bars, each bi-linear stress and strain relationship was used as shown in Figures 1 and 5(a). The stress and strain curves in the compression and tension of the concrete are shown in Figures 5(b) and 5(c).
The compressive stress is a constant value when the strain is over 0.002. For concrete under tension up to its tensile strength calculated from Eq. (1), as shown in Figure 5(c), the linear stress and strain relationship was used. After cracking of the concrete, the stress and crack opening relationship (Cornelissen et al. 1986) used is expressed in Eq. (2):

\[ \frac{f_t}{f_c} = 0.269 f_c^{2/3} \]  
\[ \frac{w}{c} \left( 1 + \left( \frac{w}{w_{cr}} \right)^3 \right) \exp \left( -c \frac{w}{w_{cr}} \right) - \frac{w}{w_{cr}} (1 + c) \exp(-c) \]  
\[ w_{cr} = 5.0 \frac{G_f}{f_t} \]  
\[ G_f = 10 (d_a f_c^2)^{1/3} \]

where \( f_t \) and \( f_c \) are the tensile and compressive strengths (N/mm²), \( \sigma \) is the tensile stress (N/mm²), \( w \) is the crack opening (mm), \( w_{cr} \) is the critical crack opening (mm) calculated from Eqs. (3) and (4), \( c_1 \) and \( c_2 \) are taken as 3.0 and 6.93, respectively, \( G_f \) is the fracture energy (N/m), and \( d_a \) is the maximum size of the coarse aggregate (mm).

The crack opening was converted to the tensile strain by using the crack band width (Bažant and Oh 1983). In this study, the crack band width was taken as \( 3d_a \). The Young’s modulus of concrete was calculated using JSCE (2017) as 29.6 kN/mm².

### 3.2 Cross-sectional Force Equilibrium

The equilibrium of the internal force is expressed by the following Eq. (5):

\[ F'_c - F'_s - F'_a - F'_p = 0 \]

where \( F'_c \) is the internal force in the compressive concrete, \( F'_s \) is the internal force in the upper reinforcing bars, \( F'_a \) is the internal force in the tensile concrete, \( F'_s \) is the internal force in the lower reinforcing bars, and \( F'_p \) is the internal force in the UV-GFRPR sheets.

The neutral axis position can be determined from Eq. (5). After that, the internal moment and the externally applied load are calculated. The mid-span deflection can be calculated from the curvature distribution along the beam length using the elastic load method (Mohr’s theorem).

### 4 RESULTS AND DISCUSSION

#### 4.1 Load and Deflection Curves

The control RC beam failed in the crushing of the compressive concrete after yielding of the lower reinforcing bars. The RC beams with two and three laminated layers failed in the fracture of the UV-GFRPR sheets at the mid-span after yielding of the lower reinforcing bars as shown in Figure 6. Any debonding of the UV-GFRPR sheets was not observed until they ruptured. The load and the mid-span deflection for each beam with the analytical result is shown in Figure 7. In this analysis, three main points such as the initial cracking, the yielding of the lower reinforcing bars, and the ultimate state are shown. The analytical results agree well with the whole behavior of the test beams. The strains in the other part were also evaluated with the analytical results.

#### 4.2 Load-carrying Capacities

Table 2 shows the comparison of the test and analytical results on the yielding and ultimate loads. The cross-sectional analysis predicts the load-carrying capacity well in the tests. From the test and analytical results, the increase of the load-carrying capacities of RC beams using the UV- GFRPR
sheets can be expected as about 1.13 times for two layers and 1.37 times for three layers in the ultimate load.

Table 2. Load-carrying capacities.

<table>
<thead>
<tr>
<th>No. of layers</th>
<th>Yielding load (kN)</th>
<th>Ultimate load (kN)</th>
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<tr>
<td>Non</td>
<td>Exp. 85.6</td>
<td>Exp. 102.1</td>
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<td>Exp./Ana. 0.92</td>
<td>Exp./Ana. 0.97</td>
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<tr>
<td>Ana.</td>
<td>92.6</td>
<td>104.8</td>
</tr>
<tr>
<td>Two</td>
<td>Exp. 101.4</td>
<td>Exp. 115.2</td>
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<td></td>
<td>Exp./Ana. 1.01</td>
<td>Exp./Ana. 0.98</td>
</tr>
<tr>
<td>Ana.</td>
<td>100.6</td>
<td>117.0</td>
</tr>
<tr>
<td>Three</td>
<td>Exp. 116.8</td>
<td>Exp. 139.6</td>
</tr>
<tr>
<td></td>
<td>Exp./Ana. 1.06</td>
<td>Exp./Ana. 1.03</td>
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<tr>
<td>Ana.</td>
<td>110.0</td>
<td>135.6</td>
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Figure 6. Fracture of UV-GFRPR sheets.

Figure 7. Load and mid-span deflection.

5 CONCLUSIONS

In this study, RC beams with two or three UV-GFRPR sheets and the control RC beam were tested and analyzed. The ultimate load-carrying capacity of the specimens with two and three laminated layers were 1.13 and 1.37 times higher than that of the control beam. Consequently, the strengthening effect was confirmed and the cross-sectional analysis agreed well with the test results.

References