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Research Article

A Study on the Improvement of Structural Performance by Glass Fiber-Reinforced Polyurea (GFRPU) Reinforcement

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Polyurea has a high tensile strength, elongation, and the capability to absorb the energy generated by dynamic and impulsive blast loading. Glass fibers are a reinforcement material for repairing and retrofitting the concrete members. The polyurea provides ductility, and the fibers provide improved stiffness and strength to the composite system. Glass-fiber reinforced polyurea (GFRPU) is a composite of polyurea and fibers and is applied as a reinforcement through a simple spraying method. GFRPU coating has a simple construction, and unlike existing strengthening methods such as fiber-reinforced polymer (FRP) or a steel plate, it prevents a debonding from the concrete surface. Seven beams of one externally nonreinforced concrete beam and six concrete beams with and without a reinforcing bar are tested using the thickness of the spray and the number of coating faces. The applicability of GFRPU was investigated through the experiments, and the test results indicate that the GFRPU strengthening method is feasible for enhancing the load-carrying capacity and flexural ductility.

1. Introduction

The structural performance of a reinforced concrete structure can deteriorate owing to an unexpected change in the external load or environment during the service period. Aged and deteriorated members, such as those at the end of their service life or undergoing steel corrosion or concrete spalling, should be repaired to enhance their strength and durability. The structural performance needs to be recovered for continuous and safe occupancy. The building structures need to implement effective and economical repair and strengthening methods.

The structural performance can be recovered using retrofitting techniques corresponding to the increased loading requirements, change in use, and structural deterioration. Structural strengthening techniques contain a section enlargement, reinforced jacketing, externally bonded steel elements, or FRPs, among other factors.

Numerous studies have attempted to introduce repair and retrofitting methods, such as a steel plate or FRP reinforcement method, to enhance the deteriorated strength and ductility. Steel plates have been utilized in the strengthening of concrete beams owing to their economic and ductile characteristics. Barnes et al. [1] compared experimentally the plate attachment methods of adhesive bonding and bolting to external surfaces of concrete beams. Ying et al. [2] introduced a simplified anchoring system using a shear bolt-plate applied directly onto the reinforced concrete beams for strengthening with steel plates. Thamrin and Sari [3] conducted an experimental study on the flexural capacity of strengthened reinforced concrete beams using a web-bonded steel plate. They observed that web-bonded steel plates increase the stiffness of the beam and the flexural capacity and avoid a debonding of the steel plates. Aykac et al. [4] presented the experimental results related with the beam ductility and the anchorage of the plate to the beam. Ozbek et al. [5] identified an increase in strength by the bonding of steel plates to the beams and maintained the ductility despite the increase in strength.

FRPs have been effectively utilized in structural engineering as internal and external reinforcements. FRPs are

made up of high-tensile-strength fibers embedded in an epoxy matrix. An explicit bonding for a sufficient adhesive ability between the FRPs and concrete structures is required for transferring the stress along them. FRPs with a high tensile strength and low weight have failed through a concrete cover separation and interfacial debonding.

Gideon and Alagusundaramoorthy [6] studied the flexural behavior and failure mode of prototype reinforced concrete (RC) beams of a high shear span ratio externally bonded with CFRP laminates. Li et al. [7] found that the shear capacity of the strengthened beam varies strongly depending on the strengthened area. Alferjani et al. [8] observed that an epoxy resin is favored in terms of strengthening and an end anchorage is needed to eliminate the debonding failure. FRP-strengthened beams have resulted in enhanced ultimate load carrying and stiffness and exhibit failure modes of the debonding at the ends of the beams without end anchorages and a rupture of the FRP in the beams with an end anchorage [9–16].

One of the weaknesses of an FRP composite is a poor fire performance, leading to an interface debonding between the FRP composites and concrete substrates. There have been many attempts to investigate FRP debonding and intermediate crack bonding. Oehlers et al. [17] presented a single mechanism based on intermediate crack debonding mechanics for explaining the structural behavior of FRP RC beams. Yang et al. [18] proved the prevention of plate-end and midspan debonding using an epoxy adhesive to bond a prefabricated CFRP grid-reinforced engineered cementitious composite (ECC) plate.

An elastomer is a class of polymetric materials. Polyurea as an elastomer is an excellent water-proofing material with many mechanical characteristics, such as a high tensile strength, ductility, and high rate of expansion and contraction. It has the capability of flexural and shear reinforcement for structural members rather than blast or impact mitigation [19]. The reinforcing fibers can be utilized for obtaining more load-carrying capacity. The polyurea coating plays a role in improving the ductility and toughness, and fibers need to be added for more load-bearing capacity. Marawan et al. [20] observed an increase in the flexural and shear capacities of small- and large-scale beams strengthened using a sprayed polyurea system depending on the polyurea thickness. Parniani and Toutanji [19] investigated the behavior of concrete beams strengthened using a polyurea coating system. They found that the polyurea coating system increases the flexural capacity and ductility of RC beams. Tarigan et al. [21] compared the flexural strength of reinforced concrete beams using steel plates, CFRP, and GFRP. Gangarao and Vijay [15] compared the flexural strength of reinforced concrete beams strengthened with carbon fiber wraps and bonded steel plates.

Glass fiber is divided into two types of chopped and milled glass fibers. The milled glass fibers are created by cutting E-glass fibers into shorter pieces. E-glass fibers have an excellent electrical insulation property and can be processed into various shapes and are mainly applied in the reinforcement of plastics. This is effective in improving not only the strength but also the surface condition and dimensional stability. They are also used as a reinforcement and filler medium in a plastic composite, adhesives, and coatings used to enhance the mechanical properties, increase the modulus, improve the dimensional stability, and minimize the distortion under elevated temperatures. Chopped glass fibers are longer fibers used to increase the tensile and compressive properties of any resin and building materials including concrete.

GFRPU is a composite using a strengthened elastic polyurea material and milled glass fibers. The GFRPU coating systems can yield a multihazard retrofitted material suitable for aging structures and can be used in repair and retrofit applications for strengthening the structural capacity, improving the seismic performance and mitigating the blast and impact damage. Greene and Myers [22] investigated the flexural and shear reinforcement capabilities of the systems provided by externally applied discrete fiber-reinforced polyurea (DFRP) coating systems. A DFRP system is a composite system used to simultaneously spray the polyurea and chopped glass fibers into a spray pattern. They found measurable strengthening in both flexural and shear capacities and substantial gains in ductility. In addition, they mentioned that an increased fiber length significantly reduces the ductility. Carey and Myers [23] also considered the addition of discrete chopped fibers into the polyurea for greater strength and developed a fiber characterization of the polyurea system.

In the existing fiber-reinforced polymer sheet (FRPS) methods, the FRF and polyurea are separately constructed on the members. In this study, milled glass fibers are utilized as reinforcing fibers, and the strengthening is completed by simply spraying the GFRPU without the process to bond the fiber on the members. This study was planned for evaluating the strengthening effect of the GFRPU, and the validity was investigated in the concrete beam test. A GFRPU coating is applied by spraying the premixed polyurea and glass fibers. Seven beams, namely, one externally nonreinforced concrete beam and six concrete beams with and without a reinforcing bar, are tested based on the spraying thickness and number of spraying faces. The superiority and applicability of the GFRPU for strengthening concrete members are illustrated in the experiments, and the test results indicate that the GFRPU may enhance the load-carrying capacity and flexural ductility.

2. Experiment

2.1. GFRPU. GFRPU is a composite manufactured using the polyurea made of a prepolymer and a hardener and milled glass fibers with a length of 300 μm. After stirring the prepolymer and fibers and premixing the prepolymer and hardener, the GFRPU is pushed through a hose using a high-pressure spray gun. Table 1 shows the chemical constituents of the polyurea utilized in this experiment.

The GFRPU spraying proceeds as follows. First, the primer is painted onto the surface of the concrete member, as shown in Figure 1(a), after the laitance, foreign substances, and pollutants are removed to improve the bonding performance. After curing for 24 h, the prepolymer and milled glass fibers are mixed and stirred, as shown in

Table 1: Chemical constituents of polyurea.

	Chemicals	Content (%)
Prepolymer	α-(2-Aminomethylethyl)-ω-(2-aminomethylethoxy) poly[oxy(methyl-1,2-ethanediyl)]	60~70
	ar,ar-Diethyl-ar-methylbenzenediamine	20~30
	Poly[oxy(methyl-1,2-ethanediyl)], α, α', α''-1,2,3-propanetriyltris[ω-(2-aminomethyl-ethoxy)-	1~10
	Titanium dioxide	1~2.7
	1,4-Benzenedicarboxylic acid, bis (2-ethylhexyl) ester	1~10
	etc.	1~10
Hardener	Polyurethane resin	90~100
	4-Methyl-1,3-dioxolan-2-one	1~10

Figure 1: GFRPU coating operation of (a) primer painting; (b) mixing of prepolymer and fibers; (c) GFRPU spraying; (d) primer painting.

Figure 1(b), and the premixed prepolymer and glass fibers are sprayed out onto the member surface through the hose along with the hardener, as shown in Figure 1(c). After the GFRPU is sprayed, the coating is finished with a primer painting, as shown in Figure 1(d). The GFRPU coating is completely bonded to the member without an anchorage.

2.2. Specimens. Seven concrete beams, one without an external reinforcement as a control, three without reinforcing bars, and three fully reinforced concrete beams were prepared for testing. The six specimens other than the control beam were strengthened using polyurea or GFRPU. Previous experiments have indicated that the optimum weight ratio of milled glass fibers of 300 μm in length for enhancing the load-carrying capacity and flexural ductility is within the range of 5%–7%. The flexural ductility of the test beams is estimated based on the area under the load-deflection curve prior to failure. The test parameters include the coating thickness and number of spraying faces under a constant weight-to-content ratio of 5%. Coating thicknesses of 3 and 5 mm, and the spraying of one or three faces, as shown in Figure 2, are applied for testing. The specimens are classified using the sign shown in Figure 3. In the figure, the letters U and R denote the concrete beams without and with a reinforcing bar, respectively. The numbers 3 and 5 indicate the coating thickness, and P is the spraying using polyurea only. The last numbers 1 and 3 represent the number of faces sprayed.

The four-week compressive strength of concrete after concrete casting was shown to be 43.07 MPa. AD10 reinforcing bar with a yield strength of 493 MPa is utilized. The test beams are strengthened using polyurea or GFRPU applied three days in advance. The polyurea and GFRPU act

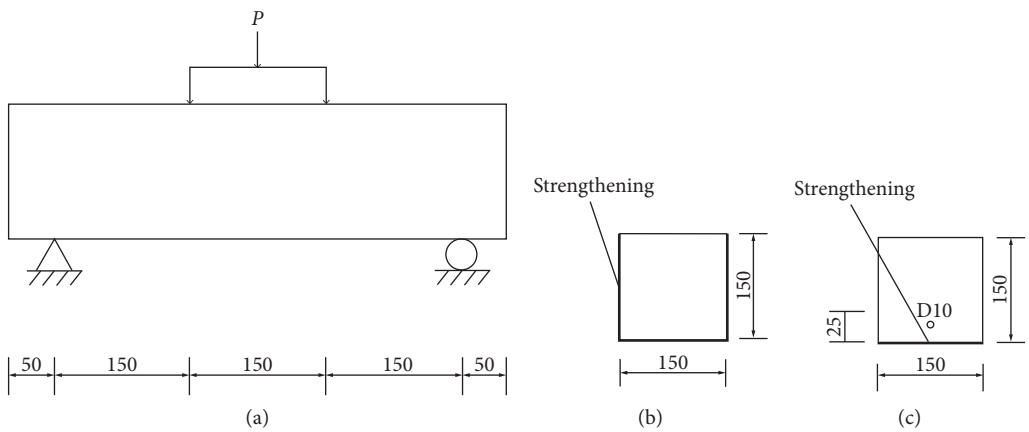


Figure 2: (a) Experiment of coated beam (unit: mm) of specimen under two-point loading, (b) strengthening at three faces without reinforcing bar, and (c) strengthening at a single face with reinforcing bar.

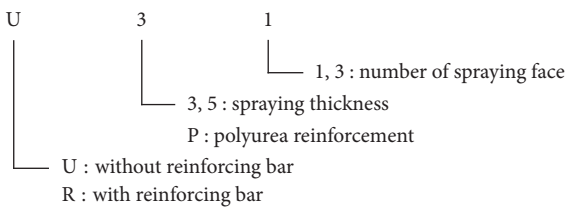


Figure 3: Specimen sign.

as a lateral reinforcement and lead to an enhanced strength and ductility.

2.3. Experimental Results. Steel forms of 150 mm × 150 mm × 550 mm for testing the flexural strength of concrete were prepared, the concrete was casted into the required forms, and the concrete was cured after demolding during three days. The loading of the specimen was applied at two points, as shown in Figure 4, and pure bending occurred in the midspan region. Based on the experiment results, the mechanical performance such as the load-carrying capacity and flexural ductility of test beams was compared.

The initial crack began at the bottom face of the midspan section because of the low tensile strength of the concrete. The failure modes of the U-series specimens are shown in Figure 5. The U-series specimens strengthened by polyurea or GFRPU exhibit an abrupt reduction in the load-resisting capacity during the moment of occurrence of the initial cracking. Diagonal-tension cracking cannot be observed, and the concrete beams retain sufficient shear-resisting capacity. The load after the initial cracking gradually increases, and it is carried by the polyurea or GFRPU on the tension side without the development of diagonal cracks. The specimens with a three-faced reinforcement retain more load-carrying capacity than those of a one-face reinforcement owing to a confinement through the reinforcement.

The GFRPU exhibits a similar mechanical behavior as the tensile reinforcing bar. The increase in tension-resisting region and capacity leads to an enhanced peak load-carrying capacity. The specimens reaching the second peak load carry the tension force through the polyurea or GFRPU. The

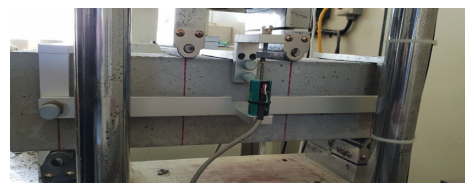
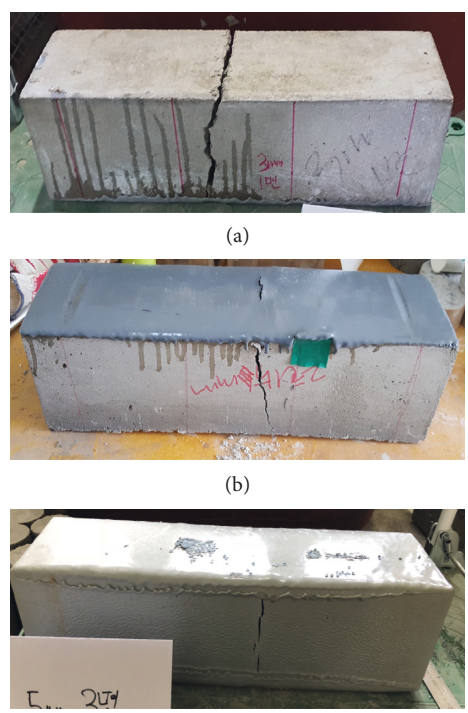


Figure 4: Setting of the specimen in UTM.



(a)

(b)

(c)

Figure 5: Failure modes of U-series specimens of (a) U31, (b) U51, and (c) U53.

development of diagonal cracks can rarely be observed by the naked eye. The additional cracks and their widths are gradually propagated within the neighborhood of the midspan region with an increase in load. The polyurea or

GFRPU controls the development without peeling from the concrete surface. Eventually, the strengthened specimens exhibit flexural failure modes.

The R-series specimens also represent a similar mechanical behavior as the U-series. The specimens ultimately fail through a flexure because they retain a sufficient concrete-carrying shear strength. The R51 specimen shown in Figure 6(c) exhibits a failure mode by the diagonal-tension cracking through the additional loading after testing.

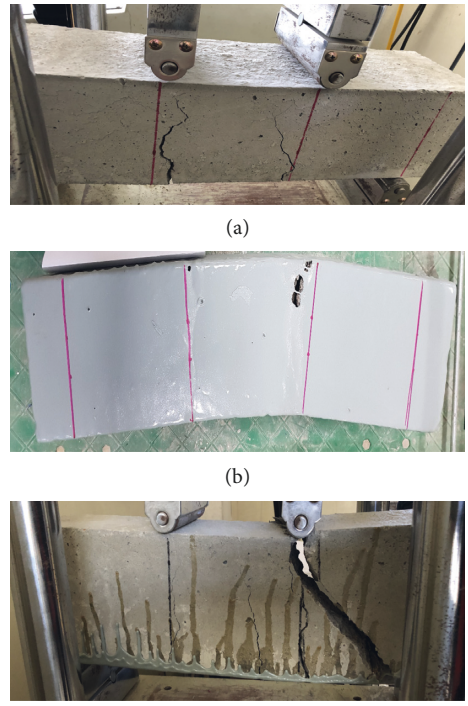
Tables 2 and 3 summarize the experiment results. The flexural ductility is estimated by the area under the load-deflection curve prior to failure. In addition, the ratio is calculated by dividing the ductility of the coated beams through the ductility of the control beams U31 and RP of the U- and R-series specimens, respectively. The peak load-carrying capacity ratio is determined as the peak load-carrying capacity of the strengthened concrete beams with respect to the control beams. After the occurrence of cracks, the beam exhibits an additional load and sufficient ductility and reaches the second peak load-resistance capacity. The concrete beam without any reinforcement abruptly fails at the bisection at the peak load of 29.17 kN corresponding to the flexural tension strength of 3.89 MPa. It was demonstrated that the flexural tension strength of the U-series specimens from the GFRPU reinforcement is enhanced 1.45–1.47 times as much as the unreinforced concrete beam. It was observed that the load-carrying capacity is more sensitive to the number of coating faces than the coating thickness. The load-carrying capacity and flexural ductility must be improved through a lateral confinement of the beams such as lateral reinforcing bars. This concept can be expanded to a seismic-reinforced design because of the enhanced load-carrying capacity as well as the improved flexural ductility.

The R-series specimens exhibit a flexural failure mode by flexural cracks in the pure bending region. The flexural strength of the GFRPU-reinforced concrete beams corresponds to 1.19-and 1.25-times that of the control beam without the GFRPU reinforcement. The increase in flexural strength among the RP, R33, and R51 specimens shown in Table 3 corresponds to the flexural strengthening effect. The shear failure mode of the specimens can rarely be observed. In addition, the specimens resist the shear force by the concrete and GFRPU. The concrete-carrying shear strength is specified by $1/6\sqrt{f'_c}b\ d$ in the Korean structural design code, which is calculated as 42.6 kN. Thus, it can be predicted that the GFRPU carries at least a shear strength of 34.57 and 31.05 kN at specimens R33 and R51, respectively, under the premise of a flexural failure.

The analytical flexural capacity of the GFRPU-reinforced beam shown in Table 3 is derived as follows. Considering the flexural strength of the beam reinforced using a tensile reinforcing bar and GFRPU in Figure 7 and neglecting the tensile strength of concrete, the following equilibrium requirement should be satisfied:

$$C = T_s + T_p, \tag{1a}$$

$$0.85 f'_c ab = A_s f_y + A_p f_p. \tag{1b}$$



(a)

(b)

(c)

Figure 6: Failure modes of R-series specimens of (a) RP, (b) R33, and (c) R51.

The area of the GFRPU in tension is calculated using

$$A_p = 2(h - c)t_p + bt_p. \tag{2}$$

Substituting equation (2) into equation (1b) and using $a = \beta_1 c$, c can be calculated. Here, β_1 denotes the ratio between the height of the equivalent rectangular concrete compression stress block and neutral depth. The centroid of the GFRPU-carrying tensile force is calculated using

$$d_p = \frac{(h - c)^2 t_p + (b/2)t_p^2}{A_p}, \tag{3}$$

where d_p is the distance from the tension face to the centroid of the coating cross-section below the neutral axis (mm).

Taking the moment at the centroid of the reinforcing bar, the nominal flexural strength can be derived by

$$M_n = 0.85 f'_c ab\left(d - \frac{a}{2}\right) - A_p f_p\left(d_p - s\right), \tag{4}$$

where s is the distance from the centroid of the reinforcing bar to the extreme tension fiber (mm) and d is the distance from extreme compression fiber to the centroid of the reinforcing bar (mm).

If the mechanical properties of the GFRPU are given, the nominal flexural strength of the specimens can be calculated, as listed in Table 3. It can be seen that the analytical flexural strength properly predicts the actual experiment results.

Figure 8(a) shows the load-deflection curves of the U-series specimens. The load-resistance capacity is abruptly reduced at the same time as the occurrence of concrete cracks on the tension face despite the GFRPU reinforcement.

Table 2: Summary of test results (without reinforcing bar).

Specimen	Load-carrying capacity		Flexural tensile strength ratio	Flexural ductility	
	Peak (kN)	Ratio		Ductility (kN · mm)	Ratio
U	29.17	—	1		
U31	43.01	1	1.47	248.7	1
U51	42.37	0.99	1.45	249.35	1.00
U53	45.94	1.07	1.57	474.37	1.91

Table 3: Summary of test results (with reinforcing bar).

Specimen	Load-carrying capacity (exp.)		Load-carrying capacity (anal.)		Flexural ductility	
	Peak (kN)	Ratio	Peak (kN)	Anal./exp.	Ductility (kN · mm)	Ratio
RP	61.65	1	69.8	1.13	298.2	1
R33	77.17	1.25	80.8	1.05	1,085.7	3.64
R51	73.65	1.19	76.6	1.04	999.6	3.35

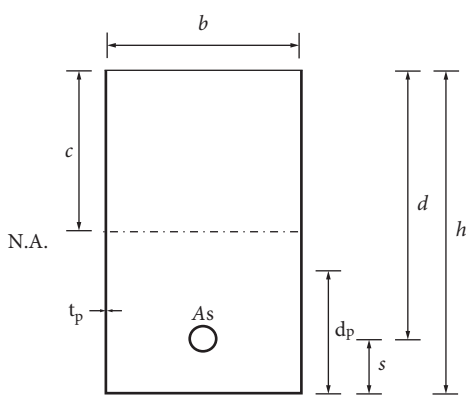


Figure 7: GFRPU-reinforced concrete beam.

The deteriorated load at the moment a concrete crack occurs is carried by the GFRPU, and its resistance capacity is enhanced when the spraying thickness and the number of coating faces are increased. After this stage, the load-carrying capacity and the flexural ductility are retained to a certain degree and the specimens ultimately fail through a flexure. It can be observed that the load-carrying capacity is sensitive to the coating thickness and the number of spraying faces because they are related to the flexural tension force.

Figure 8(b) shows the load-deflection curves of the R-series specimens. It can be observed that the strengthening by the GFRPU leads to an enhanced load-carrying capacity as well as an improved flexural ductility. In addition, they are more sensitive to the number of coating faces than the coating thickness in that the side-reinforcement of the beam section provides a greater flexure-resisting capacity.

Figure 9 shows the peak load and ductility ratios according to the specimen. It can be seen that the peak load and flexural ductility of specimen U31 are 7% and 90% higher than those of specimen U53, respectively. In addition, the peak load of specimens R33 and D51 is 25% and 19% higher than that of specimen RP, respectively. Their ductility is 3.64 and 3.35 times as much as that of specimen RP. It can be seen that the GFRPU is effective in strengthening the flexural strength and improving the ductility and can also be utilized in strengthening the shear strength.

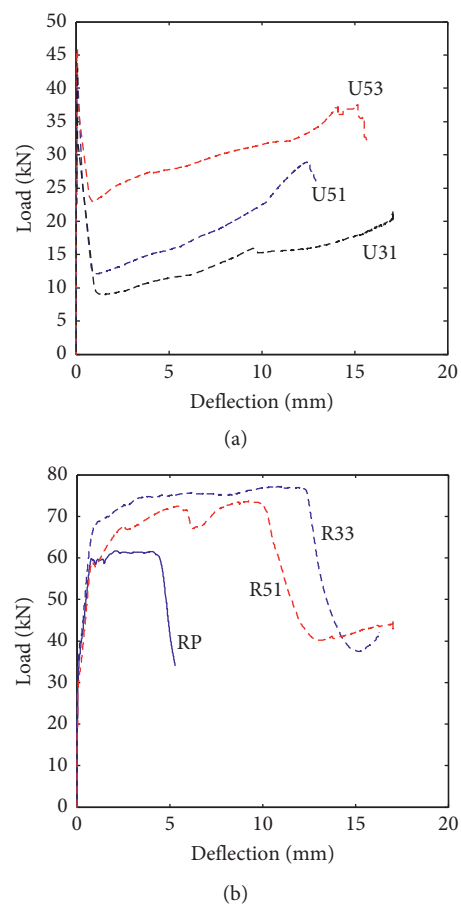


Figure 8: Load-deflection curves of (a) U-series and (b) R-series.

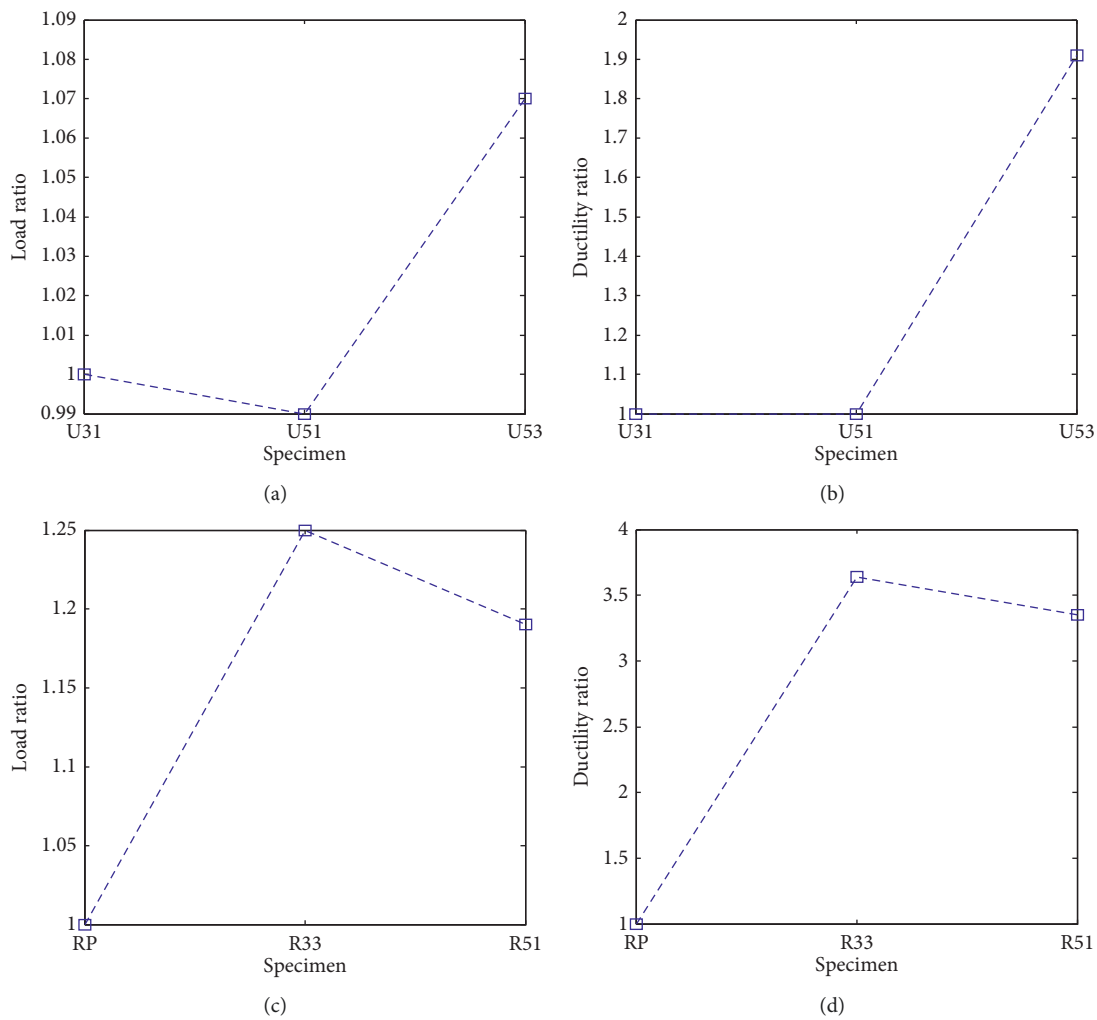


Figure 9: Peak load ratio of (a) U-series and (c) R-series; ductility ratio of (b) U-series and (d) R-series.

3. Conclusions

The structural performance of the GFRPU composite of polyurea and glass fibers was evaluated in this study. The GFRPU reinforcement can prevent an abrupt concrete spalling and failure by debonding. In addition, it is simply completed through a spraying method. The GFRPU reinforcement leads to an enhanced load-carrying capacity as well as an improved flexural ductility. Assuming the use of GFRPU as a tensile reinforcing bar, the analyzed flexural strength can properly predict the strength found experimentally. The experimental results on the flexural strength are more sensitive to the number of spraying faces than the spraying thickness because the side-reinforcement provides a greater flexure-resisting capacity. In addition, it has been estimated from the analytical results that the GFRPU reinforcement retains the shear-resistance capacity.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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