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Improvement of Flexural and Shear Strength of RC Beam Reinforced by Glass Fiber-Reinforced Polyurea (GFRPU)

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Abstract

The Glass Fiber-Reinforced Polyurea (GFRPU) which is the composite by the elastic polyurea and milled glass fiber have the mechanical characteristics to enhance tensile strength as well as ductility. It must be reinforcement materials in repair and retrofit applications for strengthening structural capacity and has a merit of simple construction of spray coating to prevent the debonding from concrete surfaces unlike the existing strengthening methods such as Fiber-reinforced polymer (FRP) or steel plate. This work compares the improvement degree in load-carrying capacity as well as flexural ductility of RC beam reinforced externally by polyurea or GFRPU. Seven specimens of four reinforced concrete (RC) beams for evaluating flexure-resisting capacity and three beams for shear-strengthening capacity are tested. The mechanical behavior and characteristics of the specimens reinforced by local and global reinforcement method classified according to strengthened area are compared. It is shown that the polyurea- or GFRPU- reinforcement leads to the enhancement in the load-resisting capacity up to 8~11% and flexural ductility within the range of 8.41~13.9 times of the non-reinforced beam. And the global reinforcement method has more improvement in the shear- and flexure-resisting capacity than the local method. It is also observed that the GFRPU can be more effectively utilized in enhancing the structural shear-resisting capacity than the flexure-carrying capacity.

Keywords: Milled Glass Fiber; Polyurea; Ductility; Load-carrying Capacity; Shear; Flexure; Reinforcement.

1. Introduction

RC members have been deteriorated by a variety of internal and external causes such as the change of design loads or the deterioration of load-resisting capacity, the increase in service periods, the change of occupation use, and the change of unexpected environment, etc. The structural members should be repaired or strengthened for enhancing the structural performance and durability. Strengthening is accomplished by either reducing the magnitude of internal forces or by enhancing the member's resistance to them. The load-carrying capacity of concrete beams should have been enhanced by strengthening techniques such as section enlargement, post-tensioning, adhesively bonded steel plates or Fiber Reinforced Polymer (FRP).

Steel plates and FRP wrap laminates have been utilized as one of the common used strengthening techniques. Nguyen et al. [1] investigated time-dependent deflections of cracked glass fiber-reinforced polymer (GFRP) and hybrid GFRP/steel RC beams. Ghomi and El-Salakawy [2] showed improved the improved seismic performance of FRP-RC beams reinforced with steel plates. The steel plate bonding techniques have been utilized in strengthening the

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concrete beams owing to their economic aspect and ductile characteristics. Barnes et al. [3] compared the plate attachment methods of adhesive bonding and bolting to the external surfaces of concrete beams through experiments. Ying et al. [4] introduced a simplified anchoring system of direct shear bolt-plate system at RC beams to strengthen with steel plates. Thamrin and Sari [5] performed the experimental study on the flexural capacity of strengthened RC beams with web bonded steel plate. They observed that web bonded steel plates increase stiffness of the beam and flexural capacity, and avoid the debonding of steel plates. Aykac et al. [6] investigated the effects of beam ductility depending on the plate thickness and the anchorage of the plate. Ozbek et al. [7] studied the ductility and the strength of flexural beam according to end connection of steel plates and concrete beam. The steel plate bonding method has the principal drawbacks of its high weight and its vulnerability against corrosive environments.

FRP is a composite material consisting of high strength carbon, aramid, or glass fibers in a polymeric matrix where the fibers are the main load-carrying element. FRP has increasingly been used for external reinforcement of existing concrete structures owing to high strength-weight ratio, high stiffness-weight ratio, flexibility in design, and non-corrosiveness. The flexible glass fiber sheets to have the high flexural and shear capacity are very effective for strengthening of RC beams. The properties of FRP composites and their versatility have resulted in significant saving in construction costs as compared to the bonded steel plate technique.

Adsam Gideon and Alagusundaramoorthy [8] observed that RC structural members retrofitted with CFRP lead to the increase in ultimate load-carrying capacity and stiffness. Li et al. [9] investigated the shear capacity of RC beams strengthened by carbon fiber reinforced fabrics according to the composite fabrics. Salih et al. [10] observed the improved maximum strength and ultimate displacement of RC beams under the cyclic loading in using FRP sheets. Wang et al. [11] investigated the anchorage systems of FRP composites to improve the performance of strengthened structures. Wang et al. investigated the anchorage systems of FRP composites to improve the performance of strengthened structures. Alferjani et al. [12] proposed a simple method to strengthen the RC beam with Carbon Fiber-Reinforced Polymer (CFRP) for practical applications. FRP strengthening techniques must be one of the strengthening methods to enhance ultimate load-carrying capacity and stiffness. Despite the merits, it has a disadvantage debonding at the end anchorage of the beams at failure [13-15]. A disadvantage of using FRP for strengthening is the relatively high cost of the materials; in certain cases the costs can be less than that of steel plate bonding.

One of the weaknesses of FRP composites is poor fire performance and it leads to the 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. [16] provided a unified approach based on intermediate crack debonding for explaining moment rotation, member ductility, shear capacity, etc. Yang et al. [17] examined the strengthening effect of RC beams with CFRP grid-reinforced engineered cementitious composite matrix.

Polyurea spraying technique must be a strengthening technique to overcome the technical difficulties of steel plate and FRP strengthening techniques such as corrosion and debonding. And the polyuria spraying technique should be more economical and simple construction method than the other methods. Polyurea is an excellent water-proofing material with many mechanical characteristics such as high tensile strength, ductility, high rate of expansion and contraction, and so on. It has the capability of flexural and shear reinforcement for structural members rather than blast or impact mitigation. The polyurea coating also plays a role to improve the ductility and toughness, and the fiber needs to be added for more load-bearing capacity. Marawan et al. [18] investigated the technique of polyuria system for enhancing the flexural and shear capacity of RC beams. Parniani and Toutanji [18] developed theoretical model to estimate the maximum deflection depending on two levels of polyuria thichness. Tarigan et al. [20] compared the flexural strength of RC beams using steel plates, CFRP (Carbon FRP), and GFRP (Glass FRP). GangaRao and Vijay [21] evaluated the improvement degree in flexural strength of RC beams strengthened with carbon fiber wraps.

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

GFRPU (Glass Fiber-Reinforced Polyurea) is the composite by the elastic polyurea material and milled glass fiber using the characteristics of both materials to improve the tensile strength and ductility. It can prevent the debonding without end anchorage. The GFRPU coating systems could yield a multi-hazard retrofit material suitable for aging structures. It must be reinforcement system in repair and retrofit applications for strengthening structural capacity, improving seismic performance, and mitigating blast and impact damage. Greene and Myers [22] presented a strengthening technique of RC beams to lead to both flexural and shear capacity by externally-applied discrete chopped fiber-reinforced polyuria. Carey and Myers [23] developed a polyuria system to add chopped glass fiber for multi-hazard and/or repair-retrofit applications and observed the improved stiffness and strength while the polyuria base material provides. The mixture of chopped glass fiber during the spraying process has difficulties in the spraying work. The difficulties can be solved by replacing chopped glass fiber with milled glass fiber. Song et al. [24] observed the strengthening effect of RC columns by spraying the mixture of polyuria and milled glass fiber.

This work was performed to illustrate the validity, simplicity, and superiority of the GFRPU- reinforcement method in strength, ductility, simple construction, and economic aspects. This work compared the improvement degree in flexure- and shear-carrying capacity as well as flexural ductility of RC beam reinforced externally by polyurea or GFRPU. The mechanical behavior and characteristics of the specimens depending on local and global reinforcement method according to strengthened area of shear and flexure specimens are compared. Three RC beams for evaluating the shear-strengthening effect and four specimens for the flexure-strengthening effect were prepared. The applicability of the GFRPU spraying technique is illustrated in the experiments and the test results indicate that the GFRPU is feasible to enhance the shear-carrying capacity, the flexure-carrying capacity and the flexural ductility. And the GFRPU method should be more obvious reinforcement in shear strength than in flexure-strength.

This study is presented in the following structure: Section 2.1 describes the test specimens and the manufacturing method, and introduces the material property. Section 2.2 compares the test results depending on the test variables of the reinforcement types, failure modes, and reinforcing degree. Section 2.3 compares the load-deflection curves depending on the test variables. Section 3 summarizes the test results and findings. The research flow for this experimental study is shown in Figure 1.

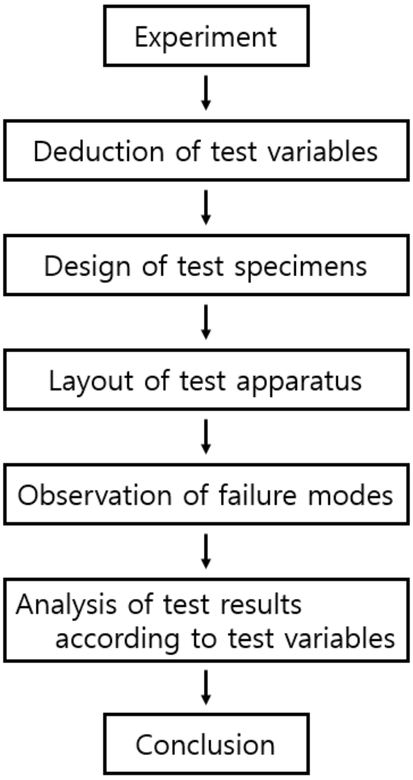


Figure 1. Flow chart of this experimental study

2. Experiments

2.1. Specimens

Elastic polyurea as a kind of elastomer has many mechanical characteristics such as high tensile strength and ductility. Glass fiber as a sort of fiber has mechanical properties to enhance the strength and modulus. The GFRPU is the composite to mix the polyurea of prepolymer and hardener, and milled glass fiber of length. It has another merit of simple construction. It is moved through hose after stirring prepolymer and fiber, and premixing prepolymer and hardener, and is completed by simply spraying through high pressure spray gun. It should be applied for improving structural performance and durability such as load-carrying capacity, seismic capacity, etc.

Table 1 represents the chemical constituents of the polyurea utilized in this experiment. The average tensile strengths of Polyurea and GFRPU performed based on KS F 4922 were measured as 14 and 16 MPa, respectively. These results displayed lower values than the strength above 20 MPa to provide at manufacturer. Despite such difference, it was observed that the tensile strength of the GFRPU was enhanced due to the addition of the milled glass fiber. It can be predicted that the strength of the GFRPU can be ensured by discuss with the manufacturer for the future work.

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

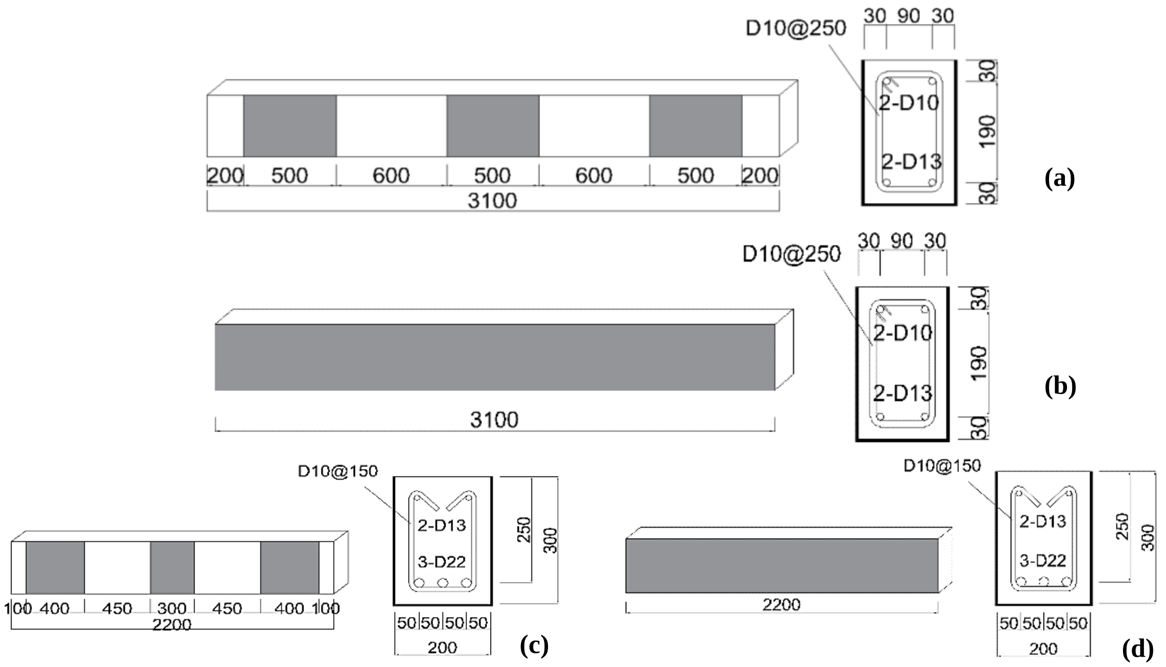


Figure 2. Strengthened area coated on the specimens (unit: mm): (a) local reinforcement of flexure specimen, (b) global reinforcement of flexure specimen, (c) local reinforcement of shear specimen, (b) global reinforcement of shear specimen

The tensile strength of the GFRPU showed some deviation depending on the dispersion of glass fiber contained in the polyurea. It indicates the possibility of the deterioration of load-carrying capacity in the local region of the concrete beam due to the difficulty of uniform execution. The artificial spraying by experts can also result in non-uniform spraying thickness. These limitations must be the technologies to be resolved for extended applications. The weight ratio of milled glass fiber of 300 μm length with respect to the polyurea was established as 5%. And the coating thickness on the specimens was 5 mm. Two coating methods of global and local reinforcements according to strengthened area at three faces except the top face of the beam section in Figure 2 were investigated: (1) global reinforcement of entire faces in the longitudinal direction of the beam and (2) local reinforcement at three different regions in the longitudinal direction of the beam. The test compares the reinforcement degree depending on the flexure- and shear-strengthening, and global and local reinforcements.

Testing RC beams were designed based on the consideration of the shear-strengthening and flexure-strengthening by polyurea or GFRPU coating. Two types of test beams were prepared. Shear specimens are the cross section of 200 mm in breadth and 250 mm in effective depth, and 2.2m in length and 3.0 in shear span to effective ratio. Longitudinal reinforcement bars of 3-D22 in tensile side and 2-D13 in compressive side were placed for preventing flexural failure. Flexure specimens are 3.1m in length and 4.5 in shear span to effective depth ratio. The cross section is 150 mm in breadth and 200 mm in effective depth. The longitudinal reinforcement bars of 2-D13 and 2-D10 in tensile and compressive sides, respectively, were designed so that they were failed by flexural failure prior to shear failure. The mechanical properties of the steel bars and average compressive strength of concrete utilized in the experiment are presented in Table 2. Four week compressive strength of concrete cylinder after concrete casting is 44.63 MPa for shear test and 25.33 MPa for flexure test. These strengths display higher values than the prescribed ones of 30 MPa and 24 MPa, respectively. The test beams were strengthened by polyurea or GFRPU coating at test three days ago. The GFRPU plays a role as the lateral as well as flexural reinforcement, and the enhanced strength and ductility were expected. The GFRPU spraying was completed by simply spraying through high pressure spray gun after mixing prepolymer containg the milled glass fiber with hardener. The polyurea coating was simply carried out by mixing prepolymer with hardener and spraying it. The beam test was performed at the seventh day after the spraying work.

Figure 3 exhibits the reinforcement placing drawing of the beam. The specimens without any external reinforcement were prepared as the control beam for shear and flexure tests. The specimens were classified using the sign shown in Figure 4. In the figure, the first alphabets N, PO, and PG denote the non-reinforcement, polyurea reinforcement, and GFRPU reinforcement, respectively. The next alphabets F and S denote the flexure and shear specimen, respectively. The next letters 3 and A indicate the local and global reinforcement in Figure 2, respectively.

Table 2. Mechanical properties of concrete and reinforcement bars

	Compressive strength (MPa)	Tensile reinforcing bar		Compressive reinforcing bar		Shear reinforcing bar
		Reinforcing bar	Yield strength (MPa)	Reinforcing bar	Yield strength (MPa)	
N-F PO-F-A PG-F-A PG-F-3	25.33	2-D13	408.0	2-D10	493.0	D10@150 Midspan D10@100 Both ends
N-S PG-S-3 PG-S-A	44.63	3-D22	516.3	2-D13	408.0	D10@250

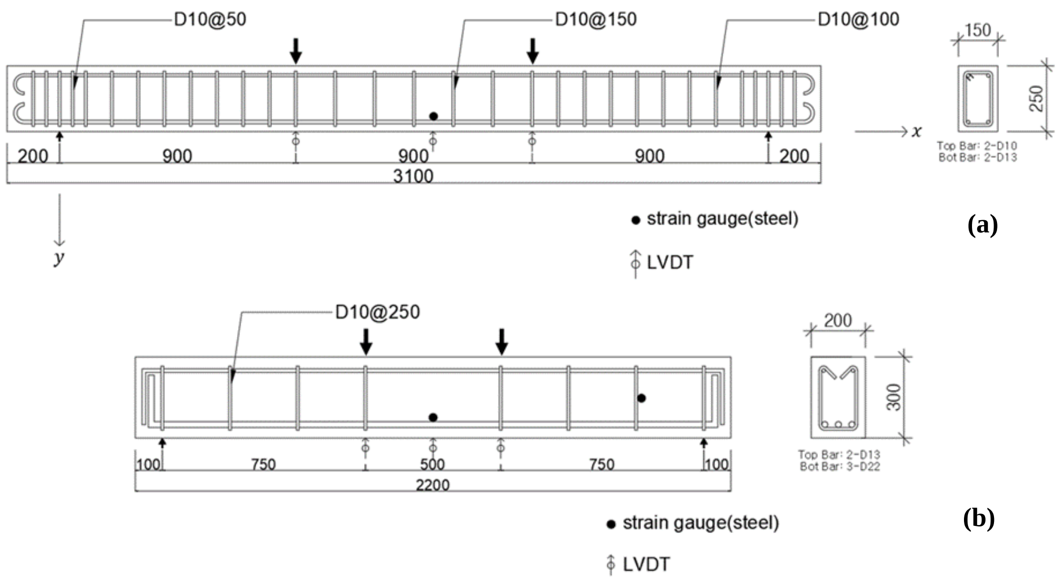


Figure 3. Reinforcement placing drawing of test beam (unit: mm): (a) flexure specimen, (b) shear specimen

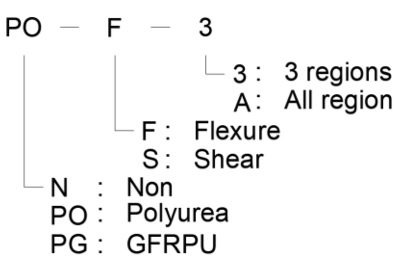


Figure 4. Specimen sign

2.2. Test Results

The experiment was conducted using four-point load test method as shown in Figures 3 and 5. The deflections by LVDTs were measured at the bottom face of beam section of the midspan and two loading points with the increase in the load. And the cracks as well as the deformation modes were observed at each load step.

Figure 6 represents the failure modes of the specimens. The flexure specimens exhibited flexural failure modes by concrete crushing at compressive region of the midspan. The flexural crack of the unreinforced N-F specimen initially appeared at the midspan. And the flexure cracks were progressively propagated in the direction of the upper part of the beam section as well as the end supports. After the tensile reinforcing bar yields, the deflection constantly increased under the similar loading and the specimens were ultimately failed with the abrupt deterioration of the load-carrying capacity.

Figure 5. Four-point load test of the beam

It was not easy to observe the cracks of the GFRPU- or Polyurea-RC specimens by naked eyes because the specimens are covered by opaque GFRPU or Polyurea coating. They were not debonded even at failure. It was observed that the specimens were failed by the concrete crushing in the compressive region between the loading points. Both sides of the beam section at the compressive region between the loading points are confined by the GFRPU or polyurea. The confinement effect was observed in the externally reinforced specimens. Comparing the consequent failure modes of the specimens, the externally reinforced specimens rarely revealed the deformed and damaged shapes including the cracks. It indicates that the extreme collapse of the beam was partially delayed by the external reinforcement.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Figure 6. Failure modes of specimens: (a) N-F, (b) PO-F-A, (c) PG-F-3, (d) PG-F-A, (e) N-S, (f) PG-S-3, (g) PG-S-A

Table 3 represents the summarized test results. It is shown that the peak load-carrying capacity of the flexure and shear specimens was enhanced within the range of 8-11% by the polyurea or GFRPU. And the flexural ductility was improved above 10%. It is defined in the moment-curvature results. More enhancement can be expected by designing the coating thickness of the polyurea or GFRPU and assuming the mechanical properties of the polyurea and GFRPU including the tensile strength above 25 MPa provided by the manufacturer. And we can expect more difference in the load-carrying capacity between the polyuria- and GFRPU-reinforcement specimens.

2.3. Load-deflection

Figure 6 exhibits the load-deflection curves of the flexural specimens. The external reinforcement leads to a little enhancement in the peak load-carrying capacity. It should be the result to strengthen the flexural capacity of the existing member. As shown in the plots, the load-deflection curve at the initial loading stage represents a linear relationship for the load to be proportional to the deflection and the specimens reach the first peak load. After the peak load, the load is constantly sustained or slightly increased despite the increase in the deflection. The strengthened specimens reached the second peak load than the first peak load.

The N-F specimen exhibited quite ductility after the peak load but abrupt loading reduction to 18% of the peak load. Similarly, the PO-F-A specimen exhibited the load reduction to 13% of the peak load. In the case of PG-F-3 and PG-F-A specimens, the load was gradually decreased after quite ductility. The mechanical behavior of all flexural testing specimens was similar because the tensile strength of the polyurea and GFRPU was barely improved perceptible. More enhancement in the strength can be secured by the increase in the coating thickness or tensile strength. It is necessary to perform a lot of research using these parameters. More information on the reinforcement effect of the beam can be obtained from the moment-curvature curves.

The shear specimens were designed so that they are failed by shear. The actual concrete strength of 44.63 MPa utilized in shear test beams was higher than the prescribed strength 30 MPa and the shear-resisting capacity carried by the concrete was more highly increased. The shear-strengthening effect by the GFRPU was clearly verified from Figure 8. The increase in shear-carrying capacity of the GFRPU specimens was more definitely observed than the enhancement in the flexure-carrying capacity of the flexure beams.

Table 3. Summary of test results

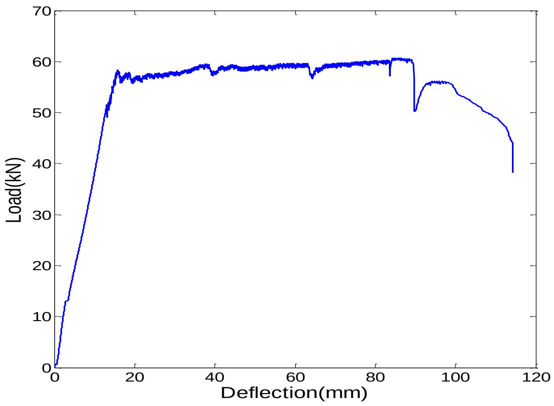
Specimen	Peak load (kN)	Load ratio	Deflection at peak load (mm)	Peak moment (kN · m)	Moment ratio	Curvature at peak moment (mm/mm)	Flexural ductility (kN · m)	Ductility ratio
N-F	60.69	-	96.4	27.3	-	4.2×10^{-6}	1.51×10^{-5}	-
PO-F-A	67.51	1.11	67.4	30.4	1.08	1.4×10^{-5}	1.27×10^{-4}	8.41
PG-F-3	65.65	1.08	31.9	29.5	1.08	6.0×10^{-6}	5.74×10^{-3}	
PG-F-A	65.41	1.08	52.5	29.4	1.08	2.05×10^{-5}	2.10×10^{-4}	13.9
N-S	353.34	-	26.2	132.5	-	2.07×10^{-5}	6.65×10^{-5}	-
PG-S-3	353.27	1.0	14.27	132.5	1.0	2.48×10^{-5}	7.32×10^{-4}	11.0
PG-S-A	382.64	1.08	21.09	143.5	1.08	2.76×10^{-5}	8.17×10^{-4}	12.3

* Load ratio, moment ratio, and ductility ratio denote the corresponding ratios with respect to the unreinforced flexure and shear specimens

The N-S specimen exhibited the initial flexural crack at the midspan during the initial loading. The cracks were propagated to the upper zone of the beam section and both end supports. And the diagonal tension crack was observed between the loading point and the bearing support with the increase in the loading. The specimen was finally failed by the concrete crushing and spalling in the compression zone as the strut action.

The PG-S-3 specimen was locally reinforced within three regions of the pure bending and shear span. The cracks couldn't find by the naked eyes because the concrete specimen was coated by the GFRPU. The PG-S-3 specimen exhibited the abrupt reduction of the load-carrying capacity due to the stress concentration and the deterioration in the compressive strength of the strut within the uncoated region. The specimen was failed by concrete crushing of compressive strut between the loading point and end support.

The PG-S-A specimen exhibited highly improved peak load. The compressive force of the compressive strut between the loading point and the end support must be enhanced. The shear-resisting capacity is also enhanced by the lateral confinement of the compressive strut. The specimen was ultimately failed by the concrete crushing between the loading points.



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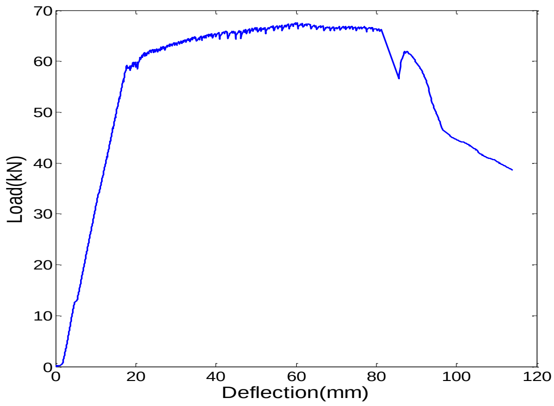

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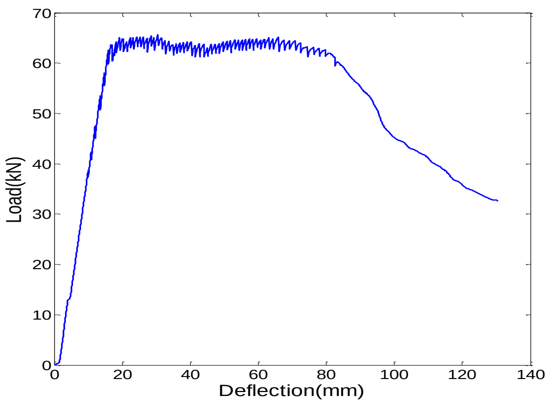

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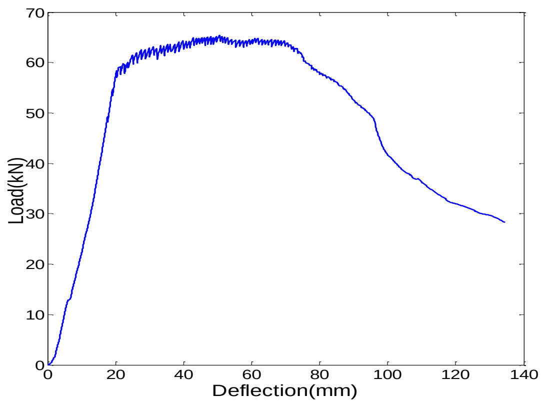

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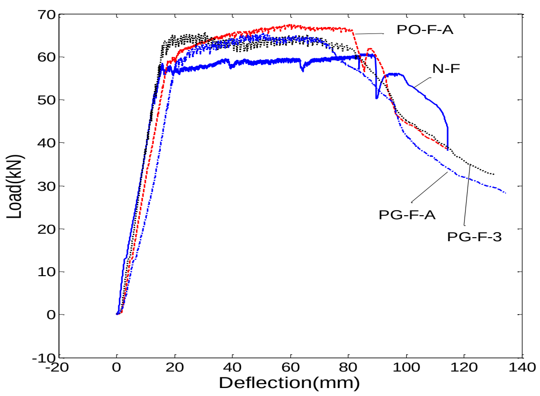
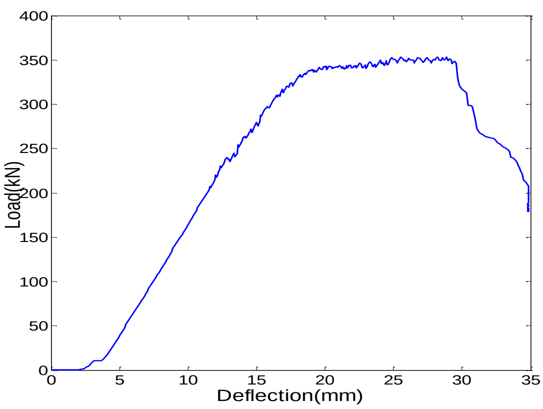


(e)

Figure 7. Load-deflection curve of flexure beams: (a) N-F, (b) PO-F-A, (c) PG-F-3, (d) PG-F-A, (e) comparison of load-deflection curves of flexure specimens



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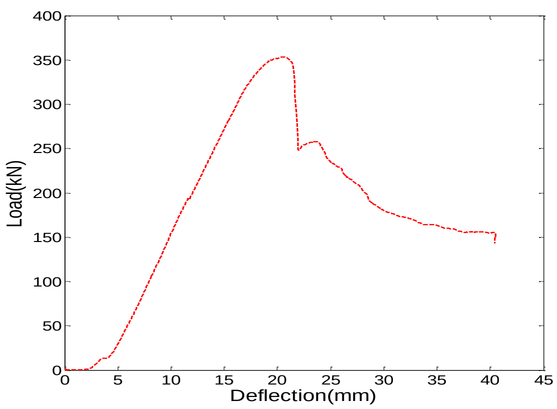

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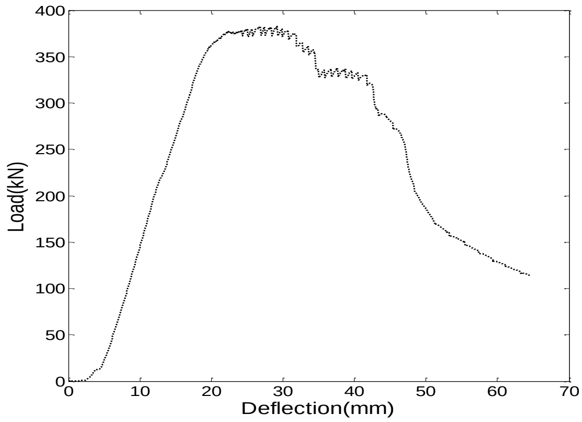

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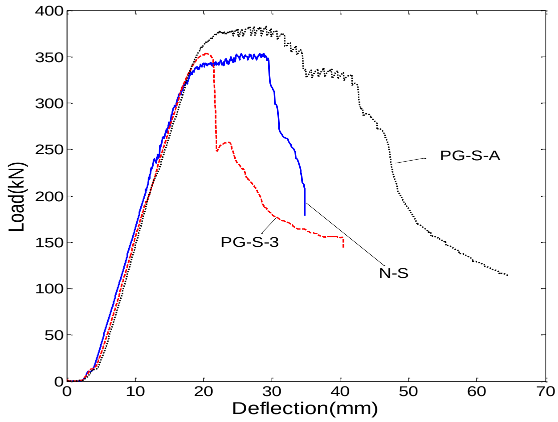


(d)

Figure 8. Load-deflection curve of shear specimens: (a) N-S, (b) PG-S-3, (c) PG-S-A, (d) comparison of load-deflection curves of shear specimens

2.4. Moment-curvature

The flexural behavior of flexural beam can be compared by moment-curvature relationship. Figures 8 and 9 represent the moment-curvature curves for investigating the flexural ductility and capability. The flexural curvature of the test beams was approximated using the deflection data measured at three LVDTs. A central difference approximation can be expressed by

$$Cur = \frac{y_L - 2(y_C) + y_R}{h^2} \tag{1}$$

Where Cur is the approximated curvature at the midspan and h is the distance between two successive LVDTs; And y_c, y_L, and y_R denote the deflections at the midspan and its left and right locations. The calculated curvature took the absolute value to plot the moment-curvature curve. The deflection in Figures 6 and 7 was quietly increased under almost constant load. Thus, the curvature calculated by Equation 1 after the peak load exhibited quite ductility with the increase in the deflection.

The flexural ductility was utilized for comparing the flexural behavior and was defined as the area under the moment-curvature curve to the instant that the moment is abruptly deteriorated. As shown in Table 3, the flexural ductility was highly improved with the increase in the degree of lateral confinement for the flexure and shear specimens.

Figure 8(a) represents the moment-curvature relationship of the N-F specimen without external reinforcement. The specimen reached the peak moment at the yielding of the tensile reinforcing bar and was failed after sustaining the flexural ductility. The flexure-resisting moment and flexural ductility were carried by the tensile as well as compressive reinforcing bars.

The flexure-carrying capacity was increased by the external reinforcement. The strengthening effect by Polyurea or GFRPU was clearly observed from the moment-curvature relationship and was compared according to the global and local reinforcement. The PG-F-3 specimen reinforced locally by the GFRPU exhibited a little enhancement in moment-resisting capacity in being compared with the PG-F-A specimen. After the peak moment, the N-F and PG-F-3 specimens represented similar behavior before failing. The local reinforcement rarely led to high enhancement in moment-resisting capacity and flexural ductility as much as the PG-F-A specimens reinforced globally. The failure of the PG-F-3 specimen originated from the local stress concentration at uncoated area between the coating surfaces with gradual decrease in the moment-carrying capacity.

The peak moment of the PO-F-A and PG-F-A specimens is exerted when the tensile reinforcing bars yield and the Polyurea or GFRPU reaches the maximum tensile strength. The enhancement is due to the increased tension-resisting force by the Polyurea or GFRPU at the tensile region and the lateral confinement of the concrete at the compressive region of the section. After reaching at the peak moment, the abrupt deterioration corresponding to about 15% of the peak moment was observed and the moment was constantly maintained before failing. The PO-F-A and PG-F-A specimens displayed more improved flexural ductility than N-F and PG-F-3 specimens. It indicates that the global reinforcement is more effective than the local reinforcement.

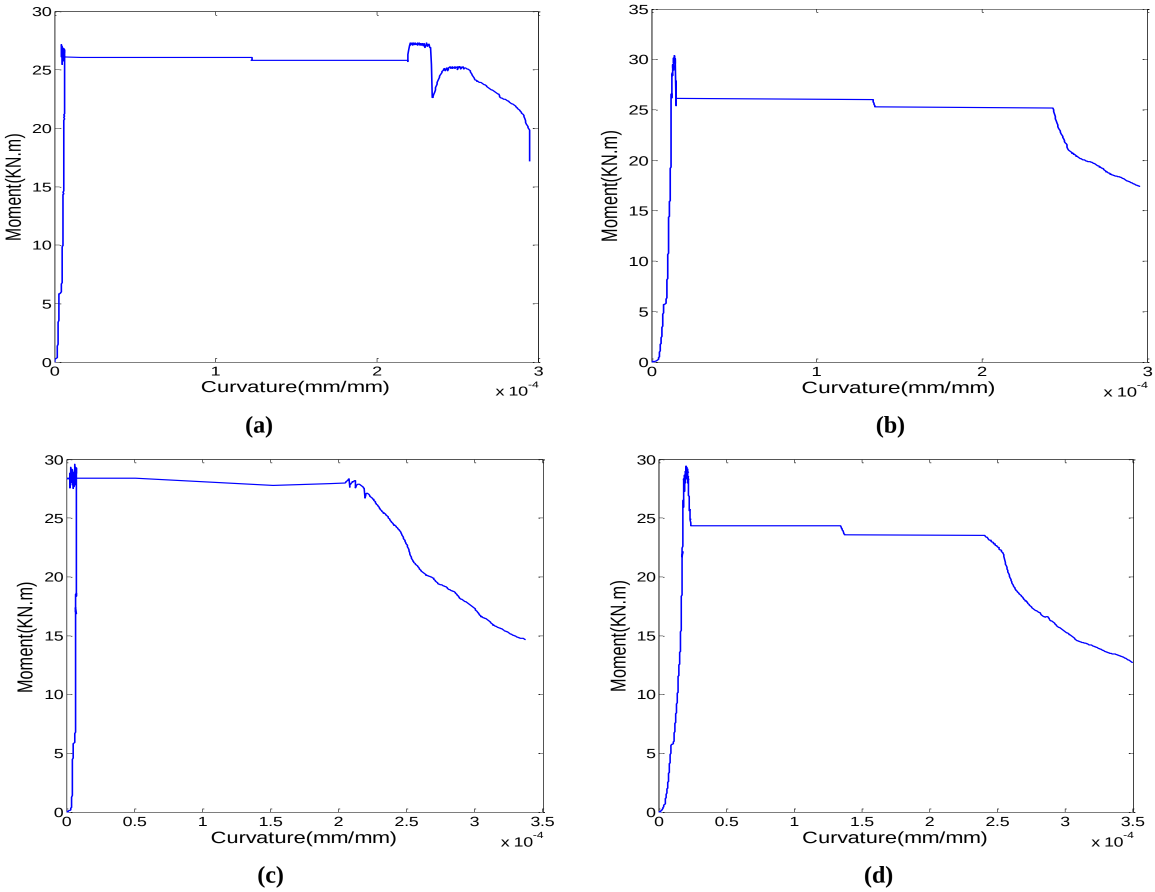
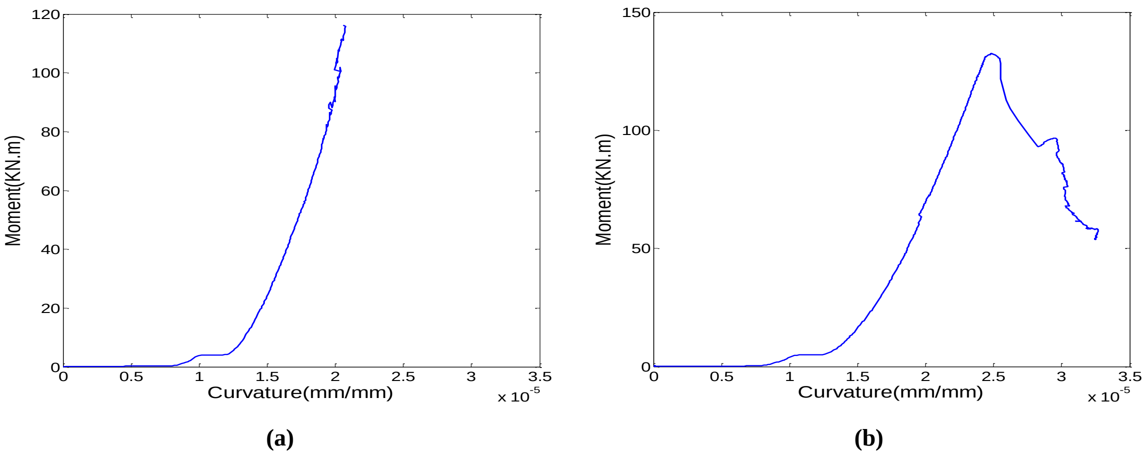
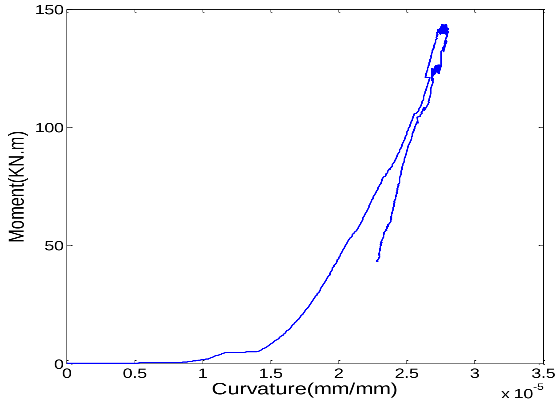


Figure 9. Moment-curvature of flexure specimens: (a) N-F, (b) PO-F-A, (c) PG-F-3, (d) PG-F-A

Figure 9 represents the moment-curvature curves of the shear specimens. The flexural curvature progressively increased before the peak moment. The moment highly increased prior to the peak moment. The curvature at the peak moment displays a tendency to improve according to the strengthening degree. The moment-curvature curve of the N-S specimen without any reinforcement exhibited the abrupt failure of the specimen after the peak moment in comparing with the load-deflection curve. The PG-S-3 specimen appeared some ductility after the peak moment due to the local strengthening. The moment-curvature curve of the PG-S-A specimen represents a tendency that the curvature is adversely decreased after the peak moment. The flexural curvature was approximated by three consecutive LVDTs of the midspan of the beam and its left and right points. While the load in the load-deflection curve is descending prior to the failure, the LVDTs at left and right locations did not properly measure the deflection because of the non-symmetric deflection and cracks. It is estimated that as the result, the adverse curvature was calculated.

It can be observed that the GFRPU reinforcement exhibits more clear reinforcement in shear than in flexure. It indicates that the GFRPU plays an important role as the lateral reinforcing bars to enhance the shear-resisting capacity. Thus, it is concluded that the GFRPU can be more effectively utilized in strengthening the structural shear-resisting capacity rather than the flexure-carrying capacity.





(c)

Figure 10. Moment-curvature of shear specimens: (a) N-S, (b) PG-S-3, (c) PG-S-A

3. Conclusion

This study compared the enhancement in structural performance and mechanical behavior of RC beams strengthened by the GFRPU or Polyurea coating. The strengthening effect according to local or global reinforcement, and shear or flexure reinforcement was compared through the experimental results of seven specimens. The external reinforcement at the flexural specimens leads to the enhancement in the peak load-carrying capacity within the range of 1.08~1.11 times of the non-reinforced beam. The mechanical behavior of all flexural testing specimens was similar because the tensile strength of the polyurea and GFRPU was barely improved perceptible. More enhancement in the strength can be secured by the increase in the coating thickness or material strength. More information on the reinforcement effect can be obtained from the moment-curvature curves. The GFRPU reinforcement should be more effective in shear strengthening than in flexure strengthening because of the lateral confinement by the GFRPU to strengthen the shear-resisting capacity. The flexural ductility was highly improved within the range of 8.41~13.9 times of the non-reinforced beam with the increase in the degree of lateral confinement for the flexure- and shear-reinforcing specimens. It was shown from the load-deflection and moment-curvature curves that the GFRPU can be more effectively utilized in strengthening the structural shear-resisting capacity rather than the flexure-carrying capacity.

4. Declarations

4.1. Author Contributions

All authors contributed equally to this work and all authors have read and agreed to the published version of the manuscript.

4.2. Data Availability Statement

The data presented in this study are available in article.

4.3. Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

4.4. Conflicts of Interest

The authors declare no conflict of interest.

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