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Civil Engineering Journal

Vol. 6, No. 10, October, 2020

Shear Strength of Reinforced Concrete Columns Retrofitted by Glass Fiber Reinforced Polyurea

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Received 28 June 2020; Accepted 21 September 2020

Abstract

Aged structures and structures constructed based on outdated non-seismic design codes should be retrofitted to enhance their strength, ductility, and durability. This study evaluates the structural performance of Reinforced Concrete (RC) columns enhanced via polyurea or Glass Fiber Reinforced Polyurea (GFRPU) strengthening. Four RC column specimens, including a reference specimen (an unstrengthened column), were tested to evaluate the parameters of the strengthening materials and the strengthened area. The tests were carried out under a combined constant axial compressive load and quasi-static cyclic loading. The experimental results show that the composite strengthening provides lateral confinement to the columns and leads to enhanced ductility, shear-resistance capacity, and dissipated energy. The shear strength provided by the composites depends on the degree of lateral confinement achieved by the composite coating. The specimens finally failed through the development of diagonal tension cracks within the potential plastic hinge regions. The specimen treated with GFRPU strengthening showed greater strength and dissipated more energy than the specimen treated with polyurea strengthening. Furthermore, by modifying ATC-40, this study proposed an equation to estimate the shear capacity provided by the composites.

Keywords: Retrofit; Coating; Polyurea; Strengthening; Reinforced Concrete Column; Shear Crack.

1. Introduction

Deteriorated or aged Reinforced Concrete (RC) members should be rehabilitated or strengthened using appropriate methods to recover their structural performance. The seismic design code in Korea was published in 1988; hence, a number of older structures were constructed based on non-seismic design codes. Consequently, it has become necessary to enhance the structural performance of such structures without their demolition and reconstruction owing to concerns regarding environmental pollution, wasted resources, and natural disasters such as earthquakes.

The structural performance of structural members deteriorates because of reasons such as the aging of construction materials, fire damage, changes in use, deficiencies in the design, or construction errors. Thus, members should be strengthened to improve their structural performance, increase their load-carrying capacity, and enhance their seismic performance.

There are two approaches to the seismic retrofitting of concrete structures: global and local. Global methods involve strengthening the entire structure at the structural level using methods such as cross bracing, shear walls, and base

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http://dx.doi.org/10.28991/cej-2020-03091587

isolation. Local methods involve increasing the local capacity of deficient practical members by adding concrete, steel, or composite materials to the outside of the members.

RC columns should be enhanced to improve deteriorated performance and increase their seismic resistance so that they can retain their energy dissipation and shear resistance capacities. There are three strengthening techniques for RC columns: RC jacketing, steel jacketing, and Fiber-Reinforced Polymer (FRP) jacketing. Several studies have been conducted on the use of column jacketing for retrofitting.

Raza et al. [1] presented a state-of-the-art review of six types of strengthening and repair methods for RC columns: RC/mortar jacketing, steel jacketing, externally bonded FRP jacketing, near-surface-mounted FRP jacketing, shape memory alloy jacketing, and hybrid jacketing. The externally bonded FRP strengthening technique has been reported to be the most popular method. Juntanalikit et al. [2] investigated the effect of applying an externally bonded Carbon Fiber Reinforce Polymer (CFRP) on the enhancement of the shear capacity and confinement of RC columns. They observed that the shear strength of the strengthened columns under reverse cyclic loading was improved, as was the displacement capability. Lee et al. [3] reported a method to enhance the shear strength of RC columns through strengthening by a sprayed FRP system such as chopped glass and carbon fibers with epoxy or vinyl ester resin. Wang et al. [4] found that the ductility and energy-dissipation capacities of non-ductile RC columns could be improved by retrofitting with CFRP wraps at the ends of the columns. Zoppo et al. [5] observed increases in the capacity and ductility of columns reinforced with externally bonded FRP and an increase in the shear capacity with the application of discontinuous CFRP strips. Seible et al. [6] introduced a jacket design and retrofitting criteria with several considerations. Colomb et al. [7] evaluated the mechanical characteristics of continuously or discontinuously reinforced CFRP. Capani et al. [8] studied the effectiveness of CFRP reinforcement for strengthening damaged RC specimens. Realfonzo and Napoli [9] investigated the effects of reinforcement with CFRP or glass fiber reinforced polymer (GFRP), CFRP wrapping, and longitudinal steel angles in terms of the strength, ductility, and energy dissipation capacity. Huang et al. [10] investigated the improvement in bearing capacity and observed different failure modes in comparison with unstrengthened RC columns. Anand and Sinha [11] investigated the enhancement of the strength of an RC column jacketed with RC under axial loads through numerical simulations. Noroozieh and Mansouri [12] performed a parametric study on the strengthening of RC columns with the combined use of near-surface-mounted rebar and FRP jackets using a finite element modeling approach. Ghatte et al. [13] investigated the seismic performance of full-scale substandard columns with extended rectangular cross sections retrofitted with CFRP jacketing. Zhou et al. [14] evaluated RC columns strengthened with externally wrapped steel plates and proposed a formula to calculate the bearing capacity.

Polyurea, which is mainly used as a water-proofing material, exhibits excellent characteristics, such as high tensile strength and ductility, when it is used for strengthening structural members. Glass fibers can be classified as either milled or chopped types. Milled glass fiber can improve characteristics such as the strength, modulus, and dimensional stability. The addition of milled glass fiber to resin can improve the properties of various materials, such as their hardness and anti-cracking properties. Chopped glass fibers with a length of 6 mm are used with polyester resin and epoxy resin.

Greene and Myers [15] investigated the flexural and shear reinforcement capabilities of structural members and evaluated the merits of a reinforcement method based on externally applied discrete fiber-reinforced polyurea (DFRP). They observed substantial improvements in ductility and strengthening. Carey et al. [16] investigated the blast mitigation performance of RC panels based on polyurea and externally applied DFRP coating systems. Glass fibers can also be mixed with polyurea to improve its strength. Song et al. [17] compared the load-carrying capacity and flexural ductility of reinforcement composites made of steel fibers, milled glass fibers, and polyurea with carbon nanotubes. In addition, Song et al. [18] investigated the applicability of Glass-Fiber Reinforced Polyurea (GFRPU) for enhancing the load-carrying capacity and flexural ductility. Carey and Myers [19] considered the addition of discrete chopped fibers to polyurea to increase strength and developed a fiber characterization of the polyurea system.

This study considers the structural and seismic retrofitting of RC columns. Four RC column specimens were tested to evaluate the parameters of structural strengthening methods using polyurea and GFRPU; partially and fully strengthened areas were also considered. The tests were conducted under a constant axial compressive load and quasi-static cyclic loading. The externally coated composites restricted the RC column section. The shear-resistance capacity and ductility of the RC columns were improved through lateral confinement with the composites and by increasing the strengthened area. GFRPU strengthening achieved a greater reverse cyclic load-carrying capacity than simple polyurea strengthening. By modifying ATC-40, this study also presents an equation to estimate the shear capacity provided by the composites.

The remainder of this paper describes the test specimens, experimental work, test results and analysis, and proposed formula to describe the effect of the GFRPU strengthening method. The research was performed according to the flow chart in Figure 1.

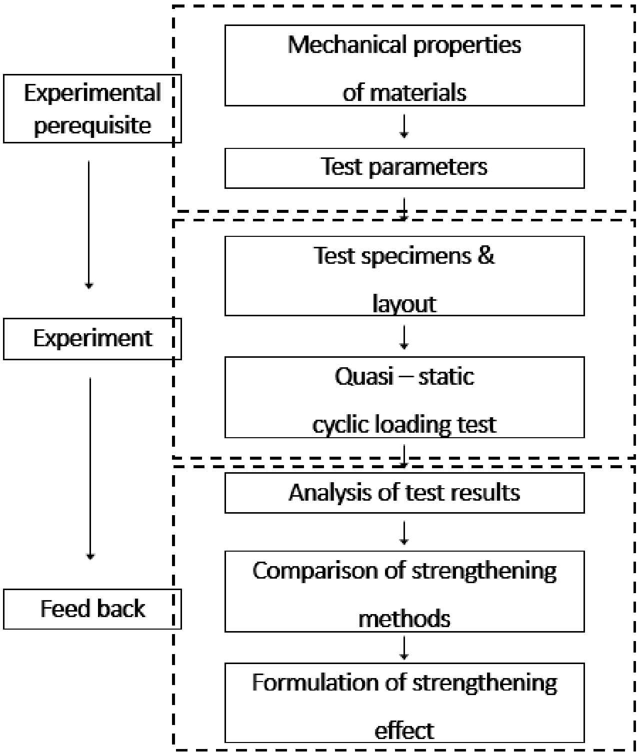


Figure 1. Flow of this research

2. Specimens

Various external jacketing methods have been used to strengthen RC members. This study compares the lateral shear-resistance capacity of RC columns with and without the application of externally sprayed polyurea or GFRPU. Polyurea is an elastomer extracted from the reaction product of an isocyanate component and a synthetic resin blend component. Polyurea coatings have high tensile strength, flexibility, hardness, and water resistance. It has been reported [20–22] that the modification of polyurea through the addition of filler materials such as milled glass fibers or fly ash can yield composites with enhanced properties.

Spraying is simpler to perform than bonding, and it can reduce the amount of materials needed, the construction period, and labor costs. Polyurea reinforcement can be expected to enhance the strength and ductility of RC members owing to its intrinsic properties. Additional improvements in strength can be achieved through the addition of milled glass fibers with a length of 300 μm.

Four RC column specimens were tested with structural strengthening methods using polyurea and GFRPU coatings, and partially and fully strengthened areas were also considered. The structural strengthening effects of polyurea (PO) and GFRPU (PG) coatings with a thickness of 5 mmwere compared with regard to the complete (A) strengthening of the column or partial strengthening (E) within the potential plastic hinge regions at both ends of the columns. The coating lengths at both ends were established as the depth of the cross-section, i.e., 300 mm. The unstrengthened specimen (NON-C) was used as a reference for comparison with the strengthened specimens.

In the tests, the compressive strength of the concrete had an average value of 22.6 MPa. The yield strengths of the D10 and D16 reinforcing bars were 556.7 and 635.7 MPa, respectively. The average tensile strengths of the polyurea and GFRPU were 15 and 16 MPa, respectively. The strength of GFRPU was approximately 10% higher than that of polyurea owing to the addition of milled glass fibers. According to the manufacturer, the tensile strength of the polyurea was within the range of 25–30 MPa. However, the experimental results showed much lower values, and the strength of the GFRPU was also low. The average elongation rates of the polyurea and GFRPU were 328.7% and 335%, respectively; these values were similar regardless of the addition of glass fibers. This indicates that the ductility and dissipated energy depend on the mechanical properties of the polyurea.

The specimens consisted of fixed vertical columns at both ends. Each column had a cross-section of 300 mm × 300 mm and a length of 1660 mm. The shear span ratio, a/h, was 5.5, where a is the shear span length and h is the depth of the cross-section of the column. The upper and lower ends of the specimens were anchored to the heavily reinforced beams. Four D16 longitudinal bars were used to achieve a longitudinal reinforcement ratio of 0.88%. The transverse hoops were constructed of D10 rebar with a spacing of 100 mm for all specimens. The specimens were designed based on a non-seismic design code because the aim of this study was to compare methods for the retrofitting of RC columns constructed prior to the implementation of seismic design codes. Therefore, the specimens were created with lateral reinforcement bars that provided inadequate lateral confinement. The columns were tested under a combined constant axial compressive load and quasi-static cyclic loading. The axial load ratio, $P/(A_g f_c')$, was varied in the range of $\pm 0.008 - \pm 0.009$, where P is the axial compressive load, A_g is the gross area of the column section, and f_c' is the compressive strength of the concrete. The axial load ratio was minimized to evaluate the lateral confinement and shear strength due to cyclic loading. Therefore, the longitudinal bars were designed to have the minimum reinforcement ratio. Figure 2 shows the cross-section of the specimens and the reinforcement layout.

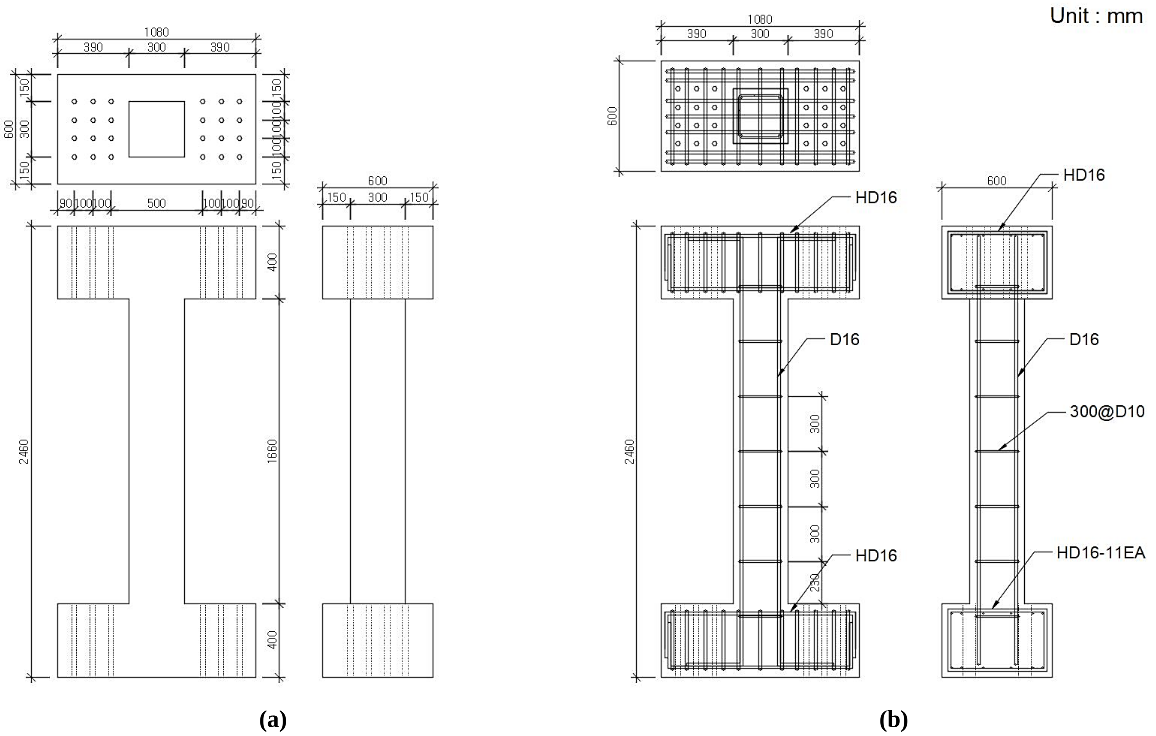


Figure 2. Test column: (a) cross section , (b) reinforcement layout (unit: mm)

Quasi-static lateral cyclic loading with a loading rate of 0.15 mm/sec. (shown in Figure 3) was performed at the position designated in Figure 4. The tests were conducted under displacement control. The loads were measured using load cells, and the displacements were measured using two linear variable displacement transducers (LVDTs) at mid-height. The strains of the longitudinal reinforcement bars and lateral reinforcement bars were measured with strain gauges at the four positions shown in Figure 5.

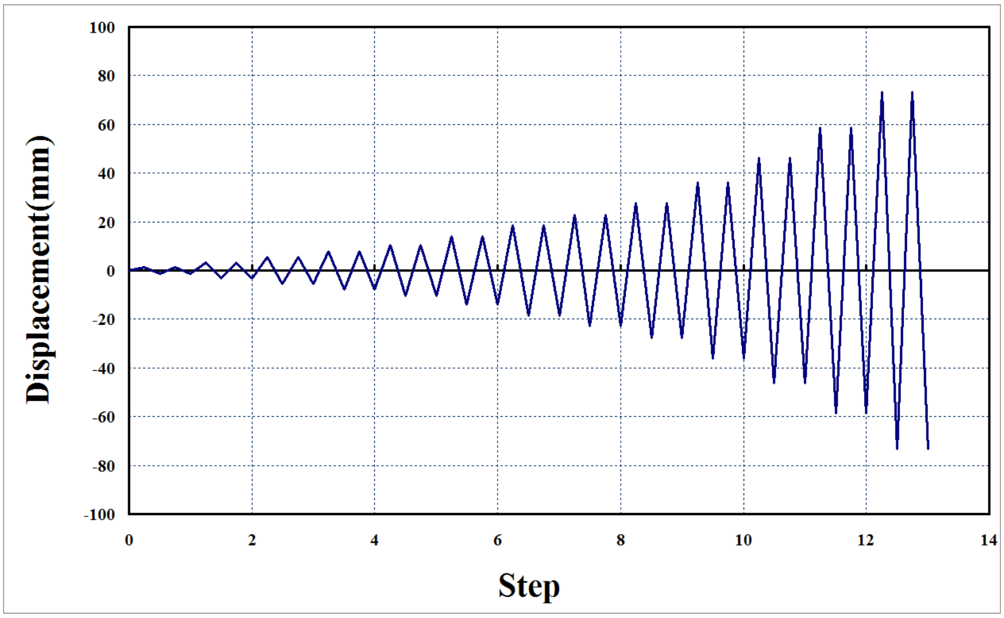


Figure 3. Quasi-static reversed-cyclic loading cycle

Figure 4. Test set up and load pattern

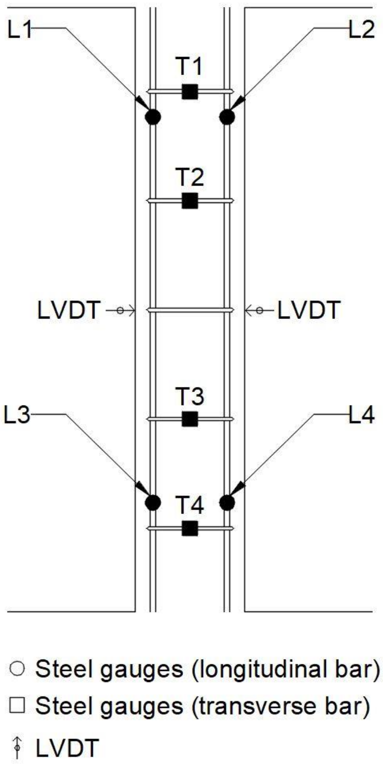


Figure 5. Locations of strain gauges and LVDTs

3. Experimental Results

Table 1 summarizes the experimental results including the peak loads, corresponding lateral displacements, and displacements at the ultimate load. Owing to the strengthening, the shear-resistance capacity increased in the range of 8–9%. The shear strength can be considered to have improved as a result of the composites. The GFRPU strengthening provided a more conservative increase in the positive and negative directions under reverse cyclic loading than the polyurea strengthening.

As indicated in Table 1, the PO-A specimen exhibited a lower shear strength in the positive direction under reverse cyclic loading than in the negative direction. A large displacement ductility or dissipated energy was observed in the specimens strengthened using the composites, and the GFRPU specimen with complete strengthening achieved a higher load-carrying capacity than the specimen with partial strengthening. This indicates that lateral confinement within the entire range of the shear span is more effective for improving the shear strength and ductility than partial confinement within the plastic hinge ranges. If polyurea with a higher tensile strength is used, the load-carrying capacity can be further enhanced. The experimental results indicate conservative enhancements in the load-carrying capacity and displacement ductility with composite strengthening.

Table 1. Summary of the test results

Specimen	(+) direction				(-) direction			
	P_{peak} (kN)	$\delta_{ult.}$/DR (mm/%)	δ_{peak}/DR (mm/%)	V_T/FR (kN/%)	P_{peak} (kN)	$\delta_{ult.}$/DR (mm/%)	δ_{peak}/DR (mm/%)	V_T/FR (kN/%)
NON-C	114.38	23/1.39	9.28/0.56	-	120.59	19/1.14	11.81/0.71	-
PG-E	120.15(5%)	28/1.69	12.67/0.76	124.38/58	130.36(8.1%)	28/1.69	12.43/0.75	130.59/97.7
PG-A	124.08(8.5%)	28/1.69	12.82/0.77	124.99/87	131.28(8.9%)	36/2.17	12.79/0.77	131.79/95.4
PO-A	116.11(1.5%)	28/1.69	9.67/0.58	125.58/16	131.49(9.0%)	36/2.17	13.02/0.78	131.19/102.8

* The number in parentheses indicates the percentage increase in the load-carrying capacity with respect to the NON-C specimen.

P_peak: peak load (kN)

δ_(ult.): lateral displacement at the ultimate strength (mm)

δ_peak: lateral displacement at the peak load (mm)

DR: drift ratio (%)

FR: shear strength ratio provided by the composite (V_(f,act)/V_(f,cal) ×100%)

V_(f,act): actual shear strength of the composite (kN)

V_(f,cal): shear strength of the composite calculated with Equation 3 (kN)

3.1. Failure Modes

The longitudinal bars, compressive concrete, lateral reinforcement bars, and composites in the RC column specimens act to resist external cyclic loading. All the specimens failed with diagonal shear cracks at both ends because the lateral reinforcement bars and/or composites did not delay the crack development. Figure 6 shows the failure modes of the reference and retrofitted specimens after testing. The mechanical behavior of specimens subjected to low axial force and cyclic lateral loading is largely governed by their shear-resistance capacity. The cracks could not be observed directly because they were covered by the opaque composites. Shear cracks with an ‘X’ shape were found at the plastic hinge lengths at both ends of all of the specimens. With increasing crack width, the cracks propagated gradually beyond the column depth. As a result, the end regions were inflated by debris of the cracked and spalled concrete in the composites, but the composites were not torn out. Upon reaching the shear-resistance capacity, the columns failed owing to the spread of diagonal cracks and the increase in width. The composites prevented the concrete debris from falling away from the column, which is dangerous. However, very few cracks were observed at the mid-height of the column.

(a) **(b)**

(c)

(d)

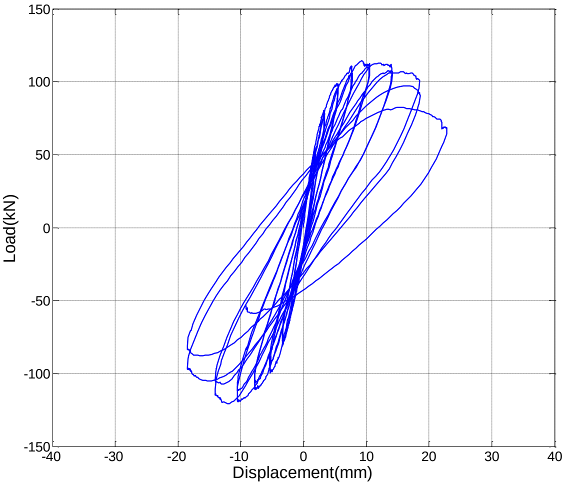
Figure 6. Failure modes: (a) NON-C, (b) PG-E, (c) PG-A, (d) PO-A

The composites delayed the development of shear cracks below the coating layer, and very few cracks could be identified directly. Very few instances of debonding between the RC columns and the composites were observed.

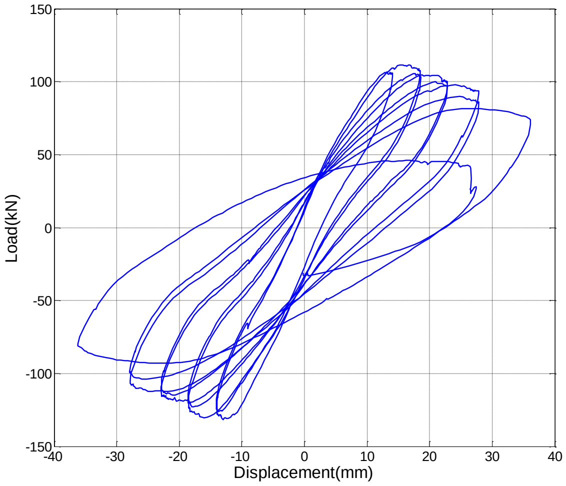
In the case of the NON-C specimen, the concrete cover was debonded and spalled along the shear surface. In the PG-E column specimen, diagonal cracks developed beyond the column depth from the top and bottom surfaces. This is why the composites restrict the development of cracks within the strengthening regions. Very few crack patterns in the PO-A and PG-A specimens could be observed directly because of the composite coatings. However, the occurrence of similar cracks as in the NON-C specimen was expected. This could reduce the risk or damage due to the dropping out of the column surfaces because the composites were not debonded or torn out from the column surfaces.

3.2. Lateral Load–displacement Curves

The reinforcement effect of polyurea or GFRPU strengthening on RC columns designed based on a non-seismic design code is verified in Figure 7. The shear strength increased gradually in the following order: NON-C, PG-E, PO-A, and PG-A. The loading was terminated assuming failure of the RC columns when the lateral force-resistance capacity had decreased to 70% of the peak load. The load–displacement curves for the PO-A and PG-A specimens were recorded after a prescribed number of load–displacement cycles had been executed from the initial stage. Thus, during the initial stage, these specimens exhibited less stiffness than the other specimens.



(a)



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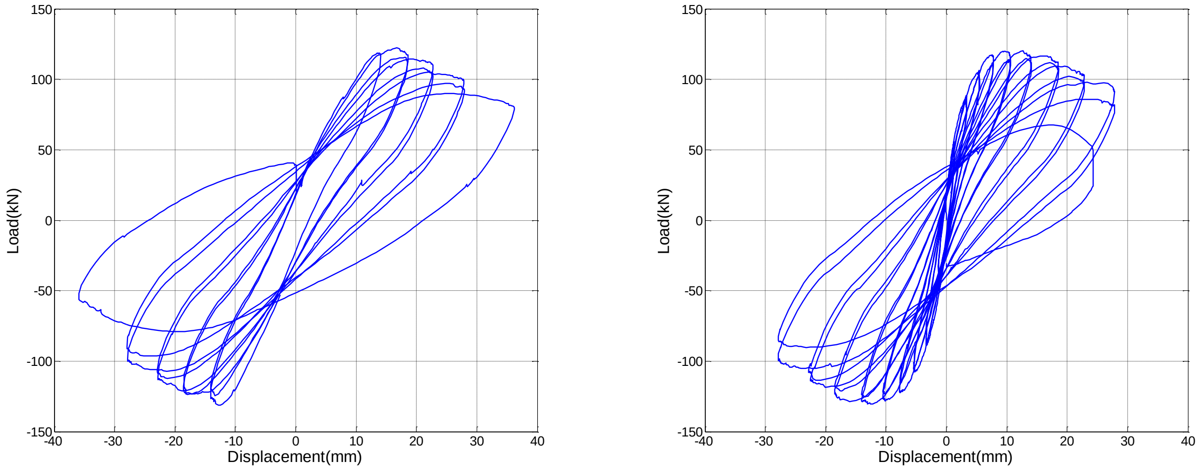


(c) **(d)**

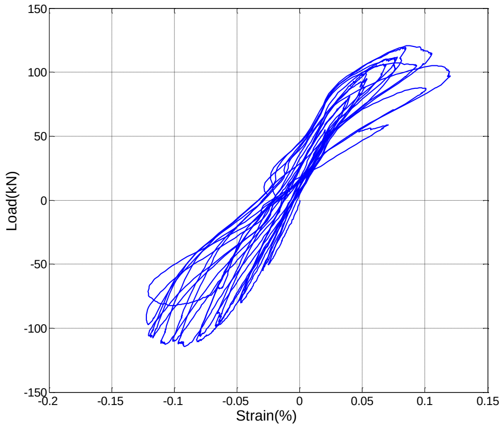
Figure 7. Later load- displacement curves: (a) NON-C, (b) PO-A, (c) PG-A, (d) PG-E

The specimens with partial or complete polyurea or GFRPU strengthening exhibited enhanced load-carrying capacity and significantly improved dissipated energy and ductility compared to the NON-C specimen. The peak load of the strengthened specimens was approximately 9% higher than that of the unstrengthened specimen. The strength enhancement provided to RC columns through the use of polyurea was 25 MPa or greater, according to the manufacturer's test report. Figure 7(c) shows that the addition of milled glass fibers led to a more conservative and higher reverse cyclic load-carrying capacity. This is due to the lateral confinement effect of the composites, which improves the shear-resistance capacity and corresponding ductility. The composites bridge the gap in the load-carrying capacity between the unstrengthened and strengthened specimens. The PG-A specimen exhibited greater shear strength than the PO-A specimen owing to the added glass fibers.

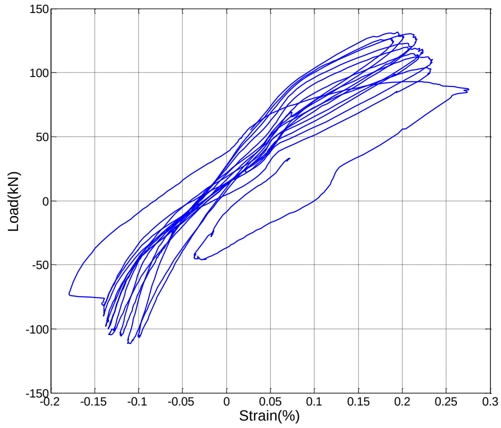
3.3. Strains of Reinforcement Bars

The seismic design code stipulates the use of a large number of lateral reinforcement bars to ensure suitable seismic performance. The number of lateral reinforcement bars in the specimens designed based on the non-seismic design code in this study was insufficient. Additional lateral strengthening is thus required to satisfy the newly established seismic design code. This can be achieved using composites instead of lateral reinforcement bars. The strain in the longitudinal reinforcement bars repeats the tension and compression owing to the reverse loading cycles.

Figures 8 and 9 show the strain curves for the lateral reinforcement bars and longitudinal bars, respectively, with respect to the lateral load. The strain in the lateral reinforcement bars increases in the same order as the shear strength, i.e., NON-C, PG-E, PO-A, and PG-A. This indicates that the shear strength is strongly related to the lateral confinement. The NON-C specimen has inadequate shear strength owing to the insufficient number of lateral reinforcement bars. It failed before the yielding of the lateral reinforcement bars, as shown in Figure 8(a). This indicates that the core concrete is constrained despite the yielding of the longitudinal bars, as shown in Figure 9(a). The PG-E specimen with partial strengthening at both ends also failed before the yielding of the lateral reinforcement bars. This implies that there is less lateral confinement of the core concrete in this specimen, as shown in Figure 8(d). The PG-E specimen exhibited a greater strengthening effect than the NON-C specimen in terms of strain at the ultimate load, as shown in Figures 8(a) and (d). However, the longitudinal bars in the PG-E specimen did not reach the yielding strain at the ultimate load because of inadequate lateral confinement of the core concrete including the longitudinal bars, as shown in Figure 9(d). It is thus concluded that the shear strength and ductility can be enhanced through greater lateral confinement of the composites. The lateral reinforcement bars in the PO-A and PG-A specimens represent the post-yielding strain. The composites control the occurrence and development of cracks by improving the confinement capacity and ductility. The composites provide lateral confinement and overall strengthening, which increase the shear strength. The PG-A specimen showed higher strain in the lateral reinforcement bars than the PO-A specimen after yielding. This illustrates that the GFRPU composite provides a more positive lateral confinement effect. Completely coating a column with polyurea or GFRPU may provide greater shear-resistance capacity, ductility, and dissipated energy.



(a)



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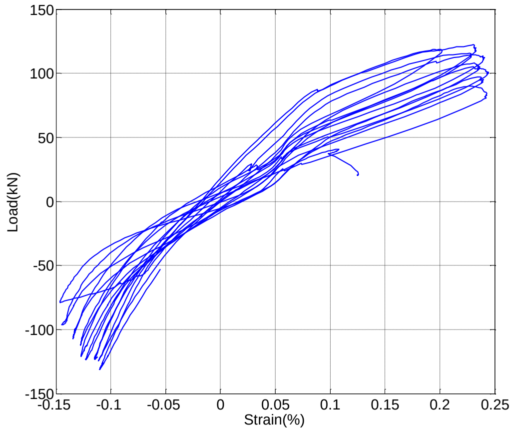

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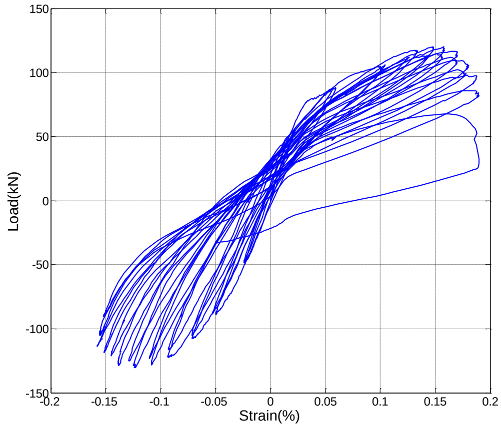
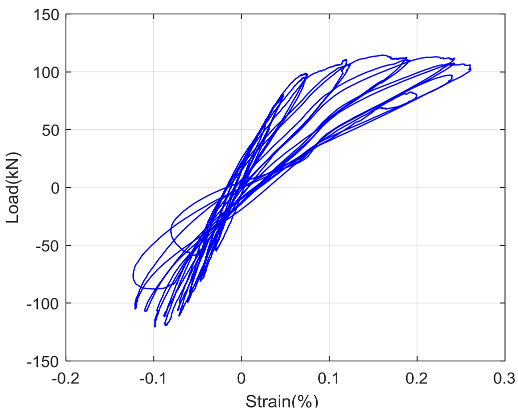
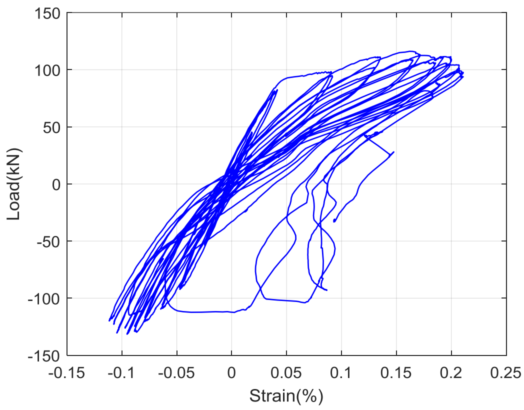


(d)

Figure 8. Curves of lateral load and strain of lateral reinforcement bars: (a) NON-C, (b) PO-A, (c) PG-A, (d) PG-E



(a)



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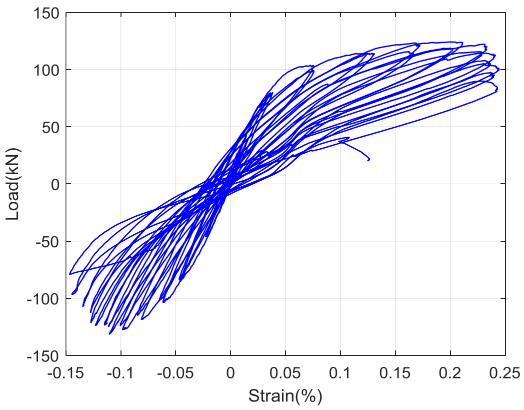

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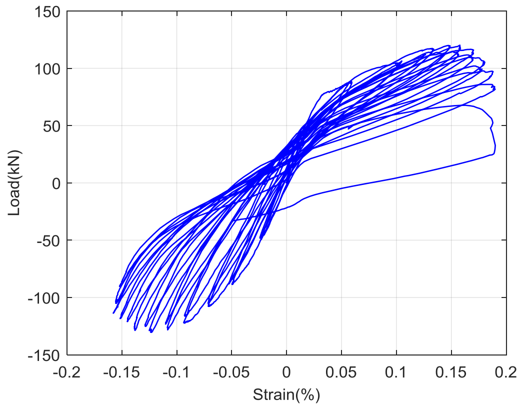

(d)

Figure 9. Curves of lateral load and strain of longitudinal reinforcement bars: (a) NON-C(L-1), (b) PO-A(L-1), (c) PG-A(L-1), (d) PG-E(L-4)

3.4. Shear Strength Provided by Composite Polyurea

The shear strength obtained through composite strengthening can be predicted based on the shear strength of FRP sheets as per ATC-40 [23]. The total shear strength of a strengthened RC column is given by the following superposition equation:

$$V_T = V_{RC} + V_F \tag{1}$$

Where V_T denotes the total shear strength of the strengthened RC column, V_{RC} is the shear strength of the RC column, and V_F is the additional shear strength provided by the composites.

ATC-40 specifies the shear strength of an RC column as follows:

$$V_{RC} = k\left[\frac{6\sqrt{f_c'}}{\frac{a}{d}}\sqrt{1+\frac{P}{6\sqrt{f_c'}}}(0.8A_g) + \frac{A_{st}f_{yt}d}{s}\right] \tag{2}$$

where k is the shear degradation coefficient; f_c' is the compressive strength of concrete; a and d are the shear span and effective depth of the section, respectively; P is the axial load; A_g is the gross area of the section; A_{st} is the area of transverse reinforcements; and s is the center-to-center spacing of the transverse reinforcements.

The equation for the shear strength provided by the composites in ATC-40 is modified as follows:

$$^{*}\ \upsilon = \frac{1.639\left(0.403-1.053\frac{P}{Agf_c'}+0.176\frac{a}{h}\right)}{\sqrt{\lambda_f+1.207}},\ \lambda_f = \frac{2A_{cf}}{bs}\frac{f_{cf}}{f_t},$$

Where f_{cf} denotes the tensile strength of CFRP, and A_{cf} is the area of strengthened CFRP.

$$V_F = \upsilon\lambda_f f_t bd \tag{3}$$

Where $\upsilon = \frac{1.5\left(0.403-1.053\frac{P}{Agf_c'}+0.176\frac{l_f}{h}\right)}{\sqrt{\lambda_f+1.207}}$ and $\lambda_f = \frac{t_f b_f}{bs}\frac{f_f}{f_t}$ are the modified forms of the equations given by ATC-40. Here, b denotes the width of the section; h is the column height; t_f and b_f denote the thickness and width of the sprayed composites, respectively; f_f is the tensile strength of polyurea or GFRPU; l_f is the spraying length; and f_t is the flexural tensile strength of the concrete.

Table 1 compares the shear strengths, V_T, of the RC columns reinforced by composites. It is assumed that the shear strength of the unstrengthened RC column given by Equation 2, V_{RC}, coincides with the shear strength of NON-C. The shear strengths of the PG-E, PO-A, and PG-A specimens treated with composites are 10.0, 10.6, and 11.2 kN, respectively. It is observed that Equation 3, which is used to estimate the shear strength provided by the composites, can appropriately describe the actual shear strength. An increase in the tensile strength of the polyurea or GFRPU composites will result in a greater enhancement in the load-carrying capacity, as shown in Equation 3. Moreover, it is expected that PG-A will provide greater strength enhancement than PO-A. By using polyurea in accordance with the manufacturer's test report, better strength enhancement can be achieved.

4. Conclusion

This study evaluated the structural retrofitting of RC columns using composites such as polyurea and GFRPU. An experiment was performed to evaluate the parameters of the strengthening materials and coating areas. Under loading, the specimens failed through uncontrollable diagonal shear cracks beyond the potential plastic hinge regions at both ends. The partial or complete strengthening achieved with polyurea or GFRPU was related to the degree of lateral confinement of the unstrengthened columns. Complete strengthening with polyurea or GFRPU may provide a more definite shear-resistance capacity, ductility, and dissipated energy. The specimen strengthened with GFRPU exhibited higher strength and dissipated energy than the specimen strengthened with polyurea. This study presented a modified form of ATC-40 for estimating the shear capacity provided by the composites. This can be used to design composite strengthening schemes. The study of GFRPU strengthening remains in its early stages. It is necessary to evaluate its efficiency through more experiments and research.

5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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