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EXPERIMENTAL BEHAVIOR OF STRENGTHENED RC COLUMNS UNDER CYCLIC LOADING

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ABSTRACT

In this study, four scaled circular-shaped bridge columns were established, three of which were retrofitted using three different strengthening methods to wrap or confine the columns. Specimens were subjected to a constant axial load and a cyclically reversed horizontal force. Results of the investigation on experimental phenomena and data, showed that the three reinforcement materials served a significant function in confining the core concrete of columns for strength improvement of core concrete, thus resulting in enhanced ductility compared with an unstrengthened column. Among the three strengthening materials, the column is strengthened by Aramid fiber-reinforced polymer (AFRP) exhibited the best performance in seismic events.

Keywords: Displacement ductility ratio (DDR); dissipated energy; hysteretic curve; reinforced concrete (RC) column; strengthening methods.

1. INTRODUCTION

In the seismic design of the reinforced concrete (RC) columns of building and bridge substructures, the potential plastic hinge regions have to be carefully detailed for ductility to ensure that the shaking induced by large earthquakes will not cause collapse [1]. A sufficient deformation capacity for RC columns can be achieved by providing adequate confining reinforcement at a potential plastic hinge region [2]. A primary concern in the retrofitting of bridge columns is the lack of adequate confinement in columns designed in North America before the 1971 San Fernando earthquake. The behavior of these columns is characterized by rapid strength degradation under cyclic loadings [3]. However, most bridges built several decades ago were designed to withstand mainly gravity and vehicle loads or were constructed according to outdated seismic rules. Therefore, most bridge columns most likely yield to the formation of local hinges under seismic events.

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Most existing bridge columns designed and built using the old seismic design code are inadequately strong to resist major earthquakes and thus require retrofitting. Therefore, seismic retrofitting of bridge columns is an important issue. To improve the strength and ductility of under-designed RC columns, external confinement systems employing fiber-reinforced polymer (FRP) materials have appeared as a promising alternative to traditional strengthening techniques, such as steel and concrete jacketing. The growing interest in FRP materials is motivated by not only the incremental number of practical applications, but also by the progress of some national and international codes involved in this area, such as the ACI440 in the US; the fib Bulletin No.14 in Europe; and the DT200 edited by the national research council in Italy [4].

So far, the literature on FRP confined RC columns are vast, but it has mainly regarded the study of results rectangular columns retrofitted by FRP with high axial compressive ratio subjected to cyclic loading[4-11].

An investigation was conducted on the flexural behavior of earthquake-damaged RC columns repaired with prefabricated FRP wraps. Four column specimens were tested until failure under reversed inelastic cyclic loading to a level that can be considered higher than that in a severe earthquake. The results indicate that the proposed repair technique is highly effective. Both the flexural strength and displacement ductility of repaired columns were higher than those of the original columns.

A relatively limited number of experimental studies have been performed on FRP and external steel-hoop confined RC columns subjected to axial loading and cyclic loading, particularly axial loading calculated from the low axial compressive ratio. The quasi-static loading test (QST) [12, 13] adopted in this experiment is widely used in the study of anti-seismic structure. The background of the experimental specimen was based on a 20m span bridge column of the Chinese Bridge Codes [14, 15]. Using full-scale model is more desirable because the test specimen scale significantly affects the behavior of strengthened RC columns. However, equipment capacity limitations make scale models a viable alternative. A representative scale model should satisfy the similitude relationship. We therefore adopted the Buckingham π-theorem [16] to develop the similitude relationship between the model and the prototype, given that the similarity of the $\sigma-\varepsilon$ curve of the concrete and steel in the original columns is an important parameter in building the experimental model. The transfer function of the model and the prototype was thereby established, and the proportionality coefficient was then determined at 1/10, with the parameter neglecting the length and diameter of the column. Therefore, the column specimen was confirmed to be 1400 mm in height and 280 mm in diameter.

The results enabled the assessment of the benefits introduced by strengthening systems, considering strength and ductility, using various relevant parameters, such as dissipated energy, displacement ductility ratio, and bearing capacity.

The effect of the three strengthening methods on the crack pattern and failure mode of test specimens was also investigated.

2. EXPERIMENTAL STUDY

2.1 Test specimens and strengthening systems

Four scaled circular-shaped RC columns were tested at the Structural Laboratory of the Chang'an University of China under a constant axial load and cyclically reversed horizontal force.

The specimens have a diameter of 280 mm, a length of 1400 mm, and a concrete foundation of dimensions 1000 mm × 600 mm × 400 mm. To load the lateral force uniformly, the top zone of the column was designed to be a 300 mm × 300 mm × 400 mm cuboid. Fig. 1 illustrates the specimen geometry and reinforcements.

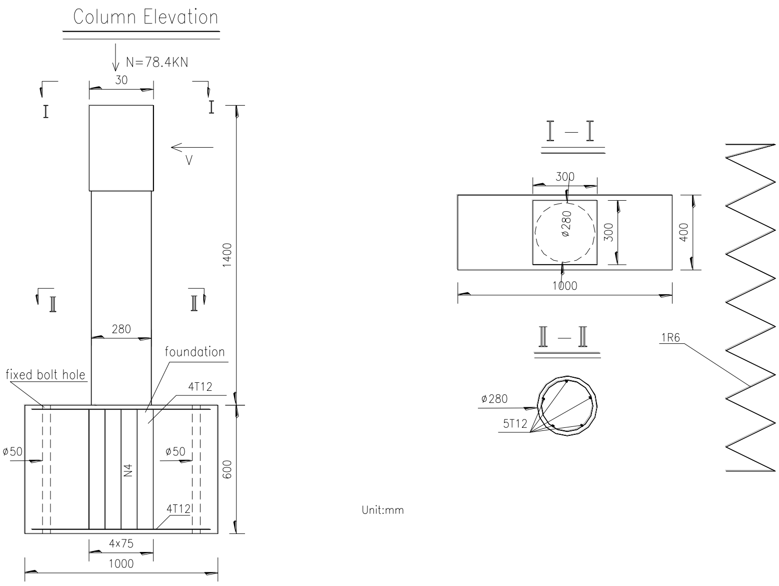

Figure 1. Schematic of concrete columns with steel rebars

Four circular-shaped RC bridge columns were produced according to the Chinese Bridge Standard and the proportionality coefficient. Research has shown that closely spaced transverse reinforcement in the potential plastic hinge zone of concrete bridge columns substantially increases the compressive strength and effective ultimate compressive strain in the core concrete [17]. Therefore, three of the specimens were retrofitted using different strengthening methods in the potential plastic hinge zone of columns. The details are listed in Table 1.

Table 1: Method of retrofitting of column specimens

Specimens	**Longitudinal Steel Rebar**	**Stirrup**	**Axial Compressive Ratio**	**Method of Retrofitting**
AZ1	5T12	1R6	0.1	Control
AZ2				GFRP
AZ3				AFRP
AZ4				Hoop Stirrup

Note: GFRP and AFRP are Glass and Aramid Fiber Reinforced Polymer, respectively.

Fig. 2 shows the systems used for strengthening the test specimens.

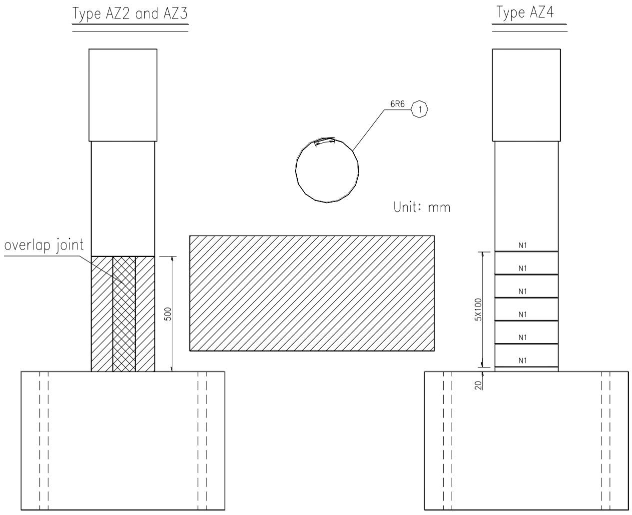

Figure 2. strengthening systems

Type AZ2 and Type AZ3 specimens were passively restricted through warping with unidirectional glass [18, 19] and aramid [20] fiber, respectively, starting from the column base to the 500 mm height of the column. To prevent fiber connecting failure at the joint, the width of the overlapping joint should be 100 mm. Type AZ4 was confined by hoop stirrup with 100 mm spacing, which provided confinement stress to the column the by screwing the bolt welded at both ends of hoop stirrup. Table 2 shows the strengthening material mechanical properties.

Table 2: Strengthening material mechanical properties

Material Type	**Tensile Strength(Mpa)**	**Young's Modulus (Mpa)**	**Thickness (mm/layer)**
GFRP	600	$2.25\text{x}10^4$	1
AFRP	2060	$1.18\text{x}10^5$	0.286
Hoop Stirrup(R6)	487	$2.1\text{x}10^5$	

2.2 Test setup and instrumentation

Fig. 3 shows the test setup. The foundations of the columns were fixed to the laboratory floor by the bolt through the base. Columns were installed vertically and tested in displacement control under a combined constant axial load and cyclically reversed horizontal force. The axial load (78.4 kN) calculated from axial compressive ratio was applied with a 500 kN vertical load pressure stabilizing system placed at the top of the column, which kept the vertical load constant during every test. The horizontal loading system was the displacement control with variable amplitude and uniform amplitude, as shown in Fig. 4. In particular, an increment of the enforced horizontal displacement was applied every three cycles to assess the strength and stiffness degradation at repeated lateral load reversals. In addition, the controlling requirement of the loading point displacement was an increase of 3 mm to 6 mm at every stage, and the testing was stopped when the horizontal load decreased dramatically.

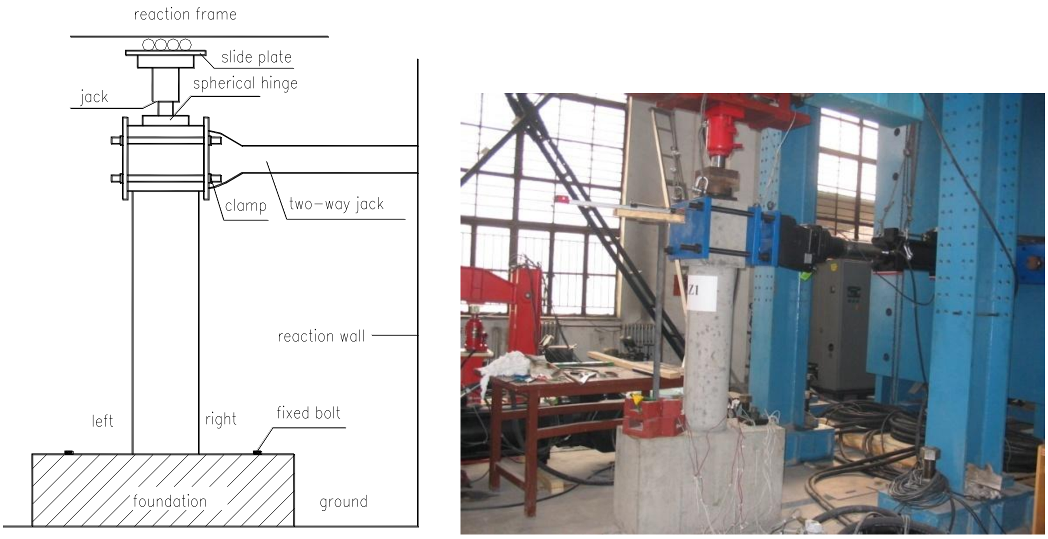

Figure 3. The illustration of experimental setup

For each specimen, the aim of measurement under every loading stage is as follows:
(a) determine the hysteretic curve (V-△) of the top of the column;
(b) measure the strain of longitudinal steel, FRP, hoop stirrup, and internal stirrup;
(c) use LVDTs to measure the displacement of the foundation.

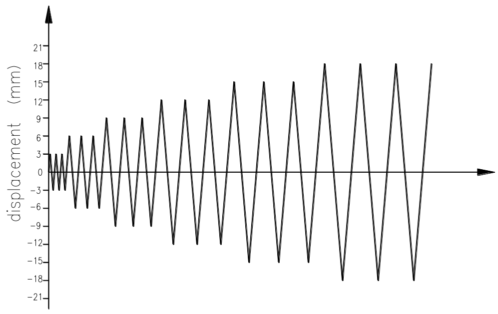

Figure 4. load-displacement history [21]

3. RESULTS AND DISCUSSION

3.1 Test results and failure modes

Table 3 summarizes the data and results on the four specimens tested in this study. It indicates that F^{+}_{max} and F^{-}_{max} are the maximum horizontal push and pull load, respectively. Fig. 5 shows the failure modes of each column.

Table 3: Details of the Tested Specimens; Test Results and Failure modes

Specimens	Retrofitting Method	f_{cm} (MPa)	F^{+}_{max} (kN)	F^{-}_{max} (kN)	Absolute Mean (kN)	Failure Mode
AZ1	Control	39.14	37.5	26.8	32.15	Concrete spalling
AZ2	GFRP	38.15	36.9	32.6	34.75	GFRP fracture close to column base, concrete crush
AZ3	AFRP	36.43	36.7	38.1	37.4	AFRP fracture close to column base, shear cracks out of the FRP wrapping
AZ4	Hoop Stirrup	37.25	31.7	34.7	33.2	Concrete crush at column base

AZ1(unstrengthened) AZ2(GFRP) AZ3(AFRP) AZ4(Hoop Stirrup)

Figure 5. Failure mode of each column

As shown in Table 3, there is not obvious regular of the maximum positive or negative horizontal forces, which may be explained that the arrangement of longitudinal steel was not installed uniformly in the columns. But from the absolute mean values, the maximum horizontal loads of AZ2 strengthened with GFRP and AZ4 strengthened with hoop stirrup are slightly greater than control column. However, the maximum force of AZ3 strengthened with AFRP shows a greatest value 37.4kN, which the increment of the force is 16.3% compared to control one. Fig. 5 displays the failure patterns of the four specimens. At the ultimate loading , the failure of unstrengthened column showed that concrete of 230 mm distance to column base was spalled; the two FRP strengthened columns have a common point that the failures happened FRP fracture close to the column base and the bottom concrete of the columns was crushed; the failure pattern of the specimen AZ4 presented the concrete near the column base also was crushed. Therefore, due to the action of FRP or hoop stirrup confining concrete, the failure of the strengthened specimens just involved in the connection of columns and bases at the ultimate loading which showed FRP fracture or concrete crushed.

3.2 Load-displacement cyclic curves and envelopes

Fig. 6 shows the lateral force-column top displacement cyclic curves relative to specimens with unstrengthened or strengthened columns and subjected to the low axial compressive ratio (0.1). The hysteretic curves of the four columns indicated that the shapes were similar, and the curves in small displacement stages showed an “arch” shape, although no existing significant “pinching phenomenon” was observed. However, the hysteretic curves exhibited an “arch” or “reverse S” shape only in the middle and later periods. Being close to failure, the strength and stiffness of columns degenerated severely, and the ductility of energy dissipation worsened in the failure stage. As illustrated in the hysteretic curves, lateral deformations of the three strengthened columns were larger than that in the control column, particularly in terms of the decline of curves. Therefore, GFRP, AFRP, and hoop stirrup can improve the compressive strength of concrete because they confined the concrete of columns effectively, which consequently increased ductility. The same results can be obtained from the load-displacement envelopes in Fig. 7.

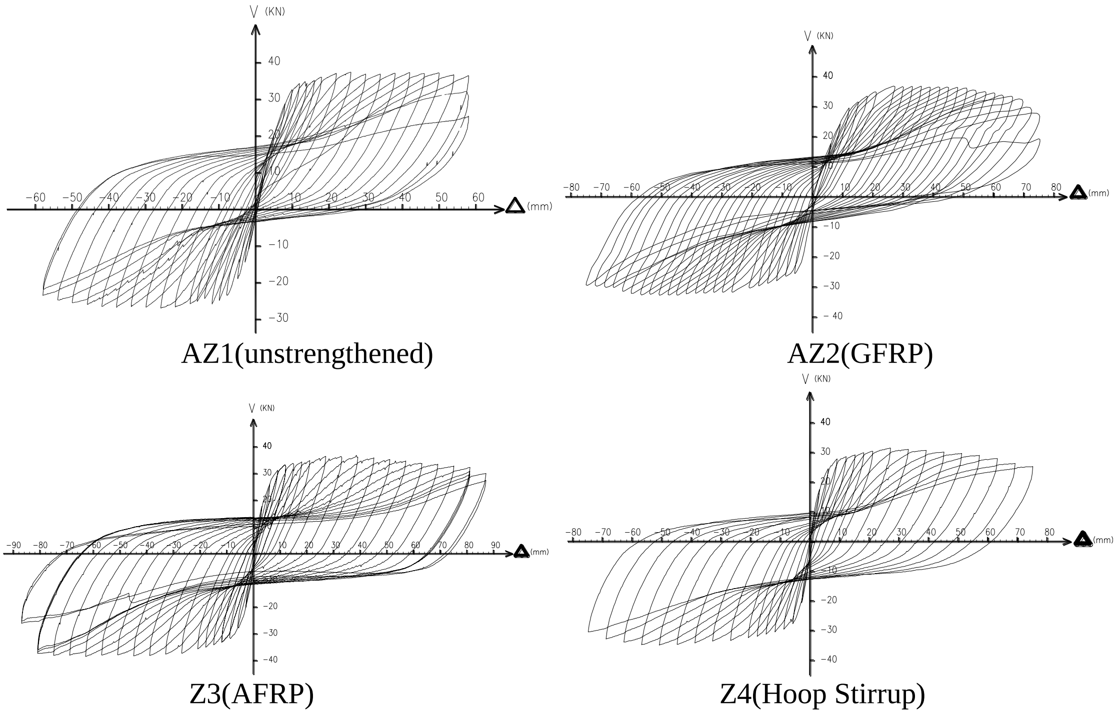

Figure 6. Load-displacement curves

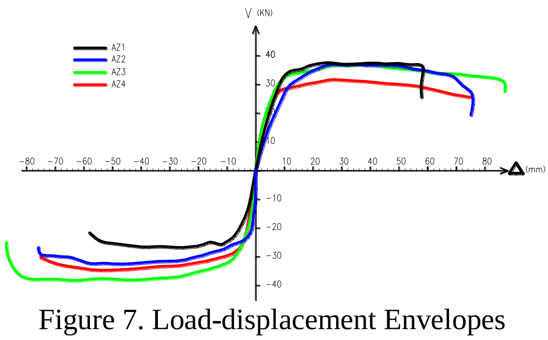

Figure 7. Load-displacement Envelopes

3.3 Comparative analysis of displacement ductility ratio (DDR)

DDR is an important parameter for the evaluation of the seismic performance of columns. The specimens were applied horizontally by cyclic loading, such that the mean of yield displacement Δ_y and ultimate displacement Δ_u in the pull and push directions are employed to form DDR μ_Δ [22], which is given by

$$\mu_\Delta = \frac{|+\Delta_u| + |-\Delta_u|}{|+\Delta_y| + |-\Delta_y|} \tag{1}$$

where “+” and “-” indicate the pull and push directions, respectively.

The displacement ductility ratio and other parameters are listed in Table 4, according to the experiment results and Formula (1).

Table 4: Comparison of the four columns using DDR and other parameters

Specimen	**AZ1**	**AZ2**	**AZ3**	**AZ4**
DDR	6.79	8.11	9.12	7.50
Yield Displacement（mm）	8.45	9.21	9.39	9.57
Yield Force （kN）	27.39	28.12	31.63	28.60
Ultimate Displacement（mm）	57.33	74.66	85.67	71.82
Ultimate Force （kN）	27.33	29.54	31.80	28.2

Table 4 indicates that the strengthened columns increased the ultimate bearing capacity, which verified that the column retrofitted by AFRP showed the best behavior, whereas hoop stirrup exhibited the poorest behavior. Furthermore, the DDR of strengthened columns was improved compared with the control column. In particular, the AFRP method obtained the best DDR result, whereas both GFRP and hoop stirrup strengthening methods enhanced the DDR of columns closely. The three strengthening methods collectively provided a significant contribution to the increase in the DDR of columns. Figs. 8 and 9 show the comparative results of DDR.

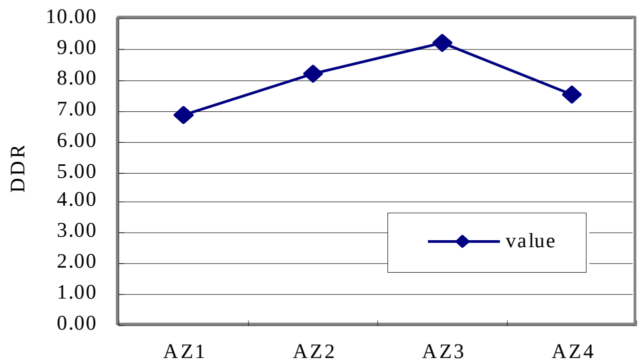

Figure 8. Comparison of DDR

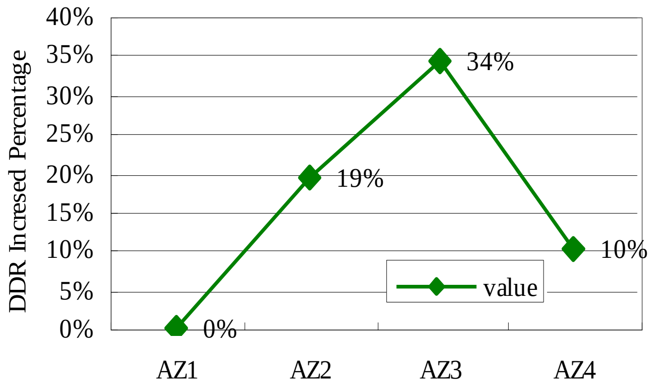

Figure 9. Comparison of DDR Increased Percentage

The above two figures indicate that the DDR increased percentages of AZ2, AZ3, and AZ4 strengthened columns compared with AZ1 by 19%, 34%, and 10%, respectively. These three methods exhibited the same characteristics when reinforcement material was applied to wrap the columns to confine the core concrete of columns, such that the stirrup reinforcement ratio and strength of concrete improved to some extent, which consequently raised the ductility and seismic capacity of columns.

3.4 Dissipated energy of columns

Fig. 10 depicts the relationship between the dissipated energy (E) and the cycle after yield. Dissipated energy and cycle values were obtained from the hysteretic curves in Fig. 6. The following findings can be observed based on the figure: In all cases, the dissipated energy of columns strengthened with GFRP, AFRP, and hoop stirrup is significantly higher than that for the unstrengthened column in the middle and later cycles. At the beginning of the cycle, the dissipated energy was at the same level for AZ2, AZ3, and AZ4 strengthened columns. Nevertheless, a significant difference was investigated in the later cycle, which reveals that the AZ3 column wrapped by AFRP produced significantly higher dissipated energy than AZ2 and AZ4 strengthened by GFRP and hoop stirrup, respectively. However, the value for AZ4 is slightly higher than that for AZ2. In sum, strengthening columns using these three different materials improved the seismic capacity of columns after column yield.

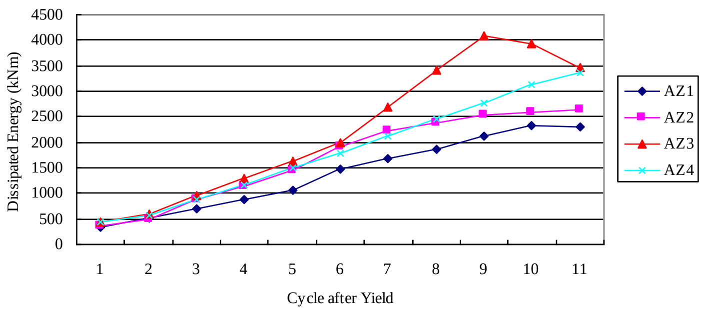

Figure 10. Comparison of Dissipated Energy

4.SUMMARY AND CONCLUSIONS

The experimental results from cyclic tests performed on scaled strengthened and unstrengthened RC bridge columns were presented and discussed. The experimental columns were designed according to the Buckingham π -theorem, and the specimens were obtained by using one unstrengthened column and three columns strengthened by GFRP, AFRP, and hoop stirrup. Columns were installed vertically and tested in displacement control under combined constant axial load and cyclically reversed horizontal force.

The primary conclusions derived from the experimental results can be summarized as follows:

1. In all cases, columns strengthened by the three methods show an increase in ductility, with DDRs of 9.12, 8.11, and 7.5 for columns strengthened by AFRP, GFRP, and hoop stirrup, respectively; the increased percentages of DDR are 34%, 19%, and 10%, respectively. In particular, the column strengthened by AFRP exhibited the best performance.
2. From the above summary, we can deduce that the three reinforcement materials served a significant function in confining the core concrete of columns to improve the strength of core concrete, which provided better column ductility compared with unstrengthened columns.
3. The relationship between dissipated energy (E) and the cycle after column yield was discussed. In the later period of the cycle, the three strengthened columns produced higher dissipated energy than the unstrengthened column. In particular, the column strengthened by AFRP exhibited the highest dissipated energy. Overall, strengthening columns using these three materials improved the seismic capacity of columns after the columns yield.

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