Lateral Resistance Enhancement of Reinforced-Concrete Columns by RC Jacketing under Cyclic Loading

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ABSTRACT

The occurrence of earthquakes in Thailand significantly impacts building structures, resulting in damage to property and loss of life. Most buildings in Thailand are not designed to withstand earthquakes, making it necessary to strengthen their structural resistance against seismic forces. This research aimed at investigating the enhancement of the lateral resistance of RC columns through full-scale experimental testing. Ordinary RC columns and enhanced RC columns with RC jacketing were tested under cyclic lateral loading with constant axial loading. The ordinary RC column had a 325 x 325 mm cross-section with 20-DB16 reinforcement bars. The cross-sectional dimensions of the strengthened column was 425 x 425 mm with 32-DB16 reinforcement bars. The results indicated that the RC columns with the RC jacketing had been able to increase lateral resistance and stiffness against earthquakes by approximately two times. However, this enhancement was not able to significantly affect the ductility and energy dissipation capacity of the experimental columns.

Keywords: Lateral resistance enhancement, RC column, RC jacketing, Cyclic loading

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Introduction

In recent years, Thailand has experienced frequent earthquakes, resulting in extensive damage to buildings, as well as the loss of life and property in the northern region of the country. Most buildings have not been designed to withstand the forces generated by earthquakes, making it necessary to analyze their structural capacities and the demands of structures that are subjected to seismic forces in order to prevent future damage. Seismic hazard maps can be used to determine the severity of the earthquake-induced forces on buildings [1-2]. Many researchers have proposed seismic hazard maps for Thailand by using the methods of Deterministic Seismic Hazard Analysis (DSHA) and Probabilistic Seismic Hazard Analysis (PSHA). DSHA provides a conservative estimate based on a single, worst-case earthquake scenario and is primarily used for quick assessments or preliminary design purposes [3-4]. In contrast, PSHA offers a more comprehensive and realistic assessment by considering multiple earthquake scenarios with varying magnitudes, locations, and recurrence rates, which have been weighted by their probabilities [5-7]. Columns are crucial components of low-rise buildings and are most important in resisting seismic forces. If the columns are not capable of resisting lateral forces, it can lead to the collapse of the entire structure, resulting in a disaster. If the damage to columns exceeds the acceptable criteria [8-10], enhancing the building's resistance to prevent potential damage is necessary [11]. Various methods are available to strengthen the lateral resistance of structures, such as reinforced concrete (RC) jacketing, fiber-reinforced polymer (FRP) jacketing, and steel jacketing [18-19]. Each strengthening method has its advantages, weaknesses, and its own suitability. RC jacketing is an economical option that increases the strength and rigidity of a structure, but it also adds a large amount of weight and has aesthetic constraints [12-14]. The utilization of FRP jacketing is characterized by its lightweight and corrosion-resistant properties. However, it is limited in terms of fire resistance and incurs higher costs [15-17]. Steel jacketing has excellent levels of strength and stiffness, but it also adds a large amount of weight and is vulnerable to corrosion [18-19]. The suitability of each method depends upon certain factors, such as cost, weight constraints, desired strength improvements, aesthetics, and environmental conditions, requiring a thorough analysis in order to determine the most appropriate solution for a specific structure.

This study investigated the lateral enhancement of RC columns by using the RC jacketing method, which is a simple, cost-effective, and effective strengthening method. The study compared the behaviors of ordinary RC columns (OC) with those of RC columns, which had been strengthened with a reinforced concrete jacketing (EC). The OC had a cross-section of 325 x 325 mm, while the EC had a 425 x 425 mm cross-section. The increase in lateral load capacity, which was due to the strengthening, was evaluated by conducting cyclic lateral load tests. The study compared the lateral capacity, stiffness, energy dissipation, ductility, and stiffness degradation of the OC and EC under cyclic loading.

Experimental Specimens and Material Properties

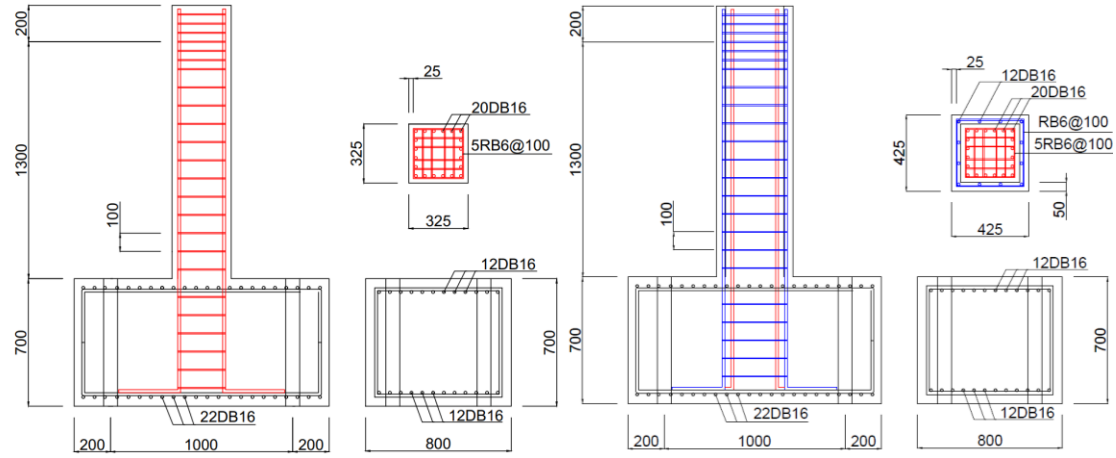
The experimental specimens used in this study consisted of both pre-strengthened and strengthened RC columns, as illustrated in Figure 1, and as detailed in Table 1. The ordinary column (OC) had a cross-sectional dimension of 325 x 325 mm or 1,056 cm^2. The longitudinal reinforcement consisted of 20-DB16 bars, with a total area of 40.22 cm^2 or a longitudinal reinforcement ratio of 3.81%. The transverse reinforcement was comprised of 5-RB6@100 mm stirrups with a volumetric ratio of 1.64%, as shown in Figure 1(a). The enhanced column (EC) was an RC column that had been enhanced using reinforced concrete jacketing (RCJ), which was composed of a concrete-filled steel tube column wrapped with additional reinforcement. The added reinforcement consisted of 12-DB16 mm longitudinal bars and RB6@100 mm stirrups at a transverse spacing of 100 mm. The cross-sectional dimensions of the strengthened column were 425 x 425 mm or 1,806 cm^2. The longitudinal reinforcement consisted of 32-DB16 bars, with a total area of 64.35 cm^2 or a longitudinal reinforcement ratio of 3.56%. The transverse reinforcement was comprised of 6-RB6@100 mm stirrups with a volumetric ratio of 1.18%, as shown in Figure 1(b). For the convenience of specimen preparation, the longitudinal reinforcement had been embedded within the footing. In practice, the application of concrete jacketing occurs after the establishment of the original structure, making it unfeasible to embed the longitudinal bars within the footing. Both columns were 1,300 mm in height and were tested under cyclic lateral loading with an axial load of 209 kN, which was applied at the top of the column. The columns had a concrete cover measuring 25 mm. The test specimens were made using Type 1 Portland cement, which after curing for 28 days, demonstrated an average cylinder compressive strength of 34.91 MPa. The properties of the reinforced steel bars are shown in Table 2. The longitudinal reinforcement was deformed bars (DB) with a diameter of 16 mm and with a tensile strength of 556 MPa at the yield point and 636 MPa at the ultimate point. The transverse reinforcements were round bars (RB) with a diameter of 6 mm and with a tensile strength of 365 MPa at the yield point and 513 MPa at the ultimate point.

Table 1 The details of the reinforced concrete column specimens

Specimens	Cross Sections (mm)	Column Heights (mm)	Axial Loads (kN)	Reinforcement Ratios (%)	Volumetric Ratios (%)	Coverings (mm)
OC	325 x 325	1300	209	3.81	1.64	25
EC	425 x 425	1300	209	3.56	1.18	25

Table 2 The properties of the reinforced steel bars

Reinforcements	Diameters (mm)	Yield Strengths (MPa)	Ultimate Strengths (MPa)
RB6	6	365	513
DB16	16	556	636



(a) OC specimen (b) EC specimen

Figure 1 The dimensions and reinforcement of the RC column specimens

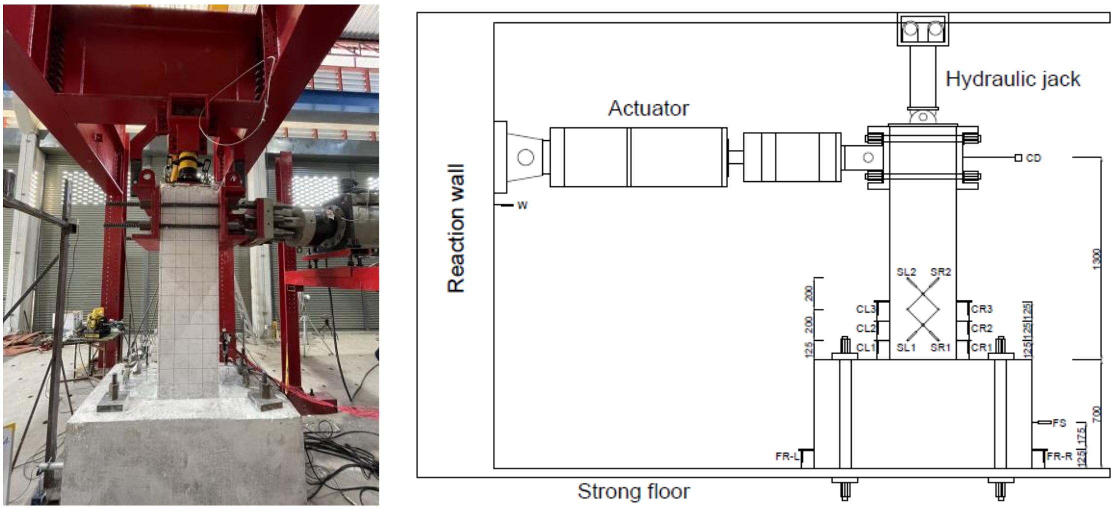
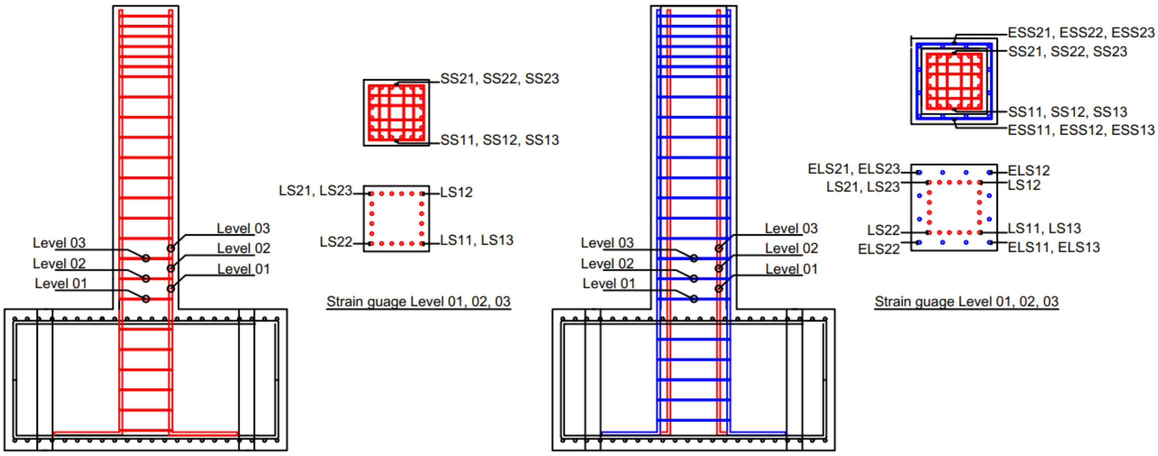


Figure 2 The Experimental setup

The Experimental Setup and Applied Loads

The experimental setup of the RC column specimen, as shown in Figure 2, was supported on the strong floor of the laboratory by using pre-stressing rods to provide a fixed support behavior, which would prevent movement or overturning due to the lateral loads. The test was conducted by using a 500 kN capacity actuator located 2,000 mm above the laboratory floor and applying a cyclic loading with an axial load of 209 kN. Fifteen LVDTs were installed to measure the displacement at various locations. One LVDT was installed to measure the lateral displacement at the point of applied lateral load. Six LVDTs were installed to measure the curvature in the non-linear region, and the vertical displacement was measured at three levels spaced at 125 mm intervals. Additionally, four LVDTs were installed to measure shear deformation, while three LVDTs measured the displacement and rotation, and one LVDT measured the wall displacement. Strain gauges were installed along the longitudinal and transverse reinforcement in the non-linear region, as shown in Figure 3. The data was collected using a data logger at a sampling frequency of 1 Hz for the subsequent analysis of the test results.



(a) The OC specimen (b) The EC specimen

Figure 3 The locations of the strain gauges

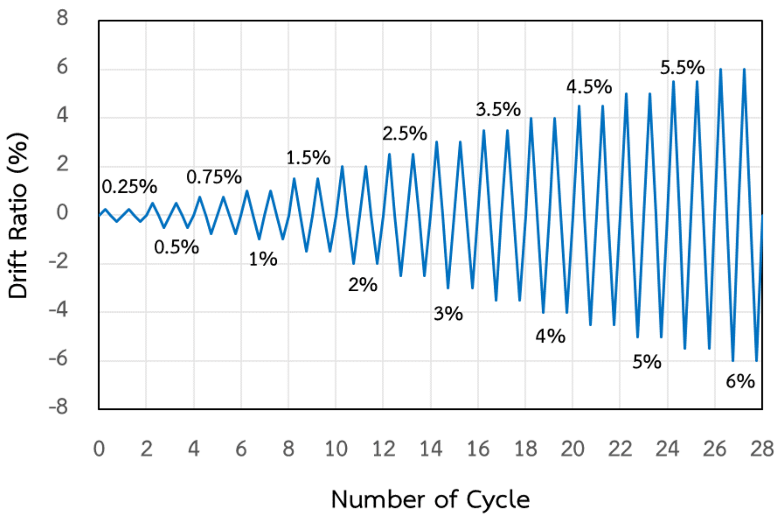


Figure 4 The displacement pattern of the lateral cyclic loading

The RC column specimens were tested under lateral cyclic loading by using a displacement control method. The displacement pattern is shown in Figure 4. The experiments involved applying lateral loads in a displacement-controlled manner using a sinusoidal pattern. The testing procedure began by applying an axial load of 209kN, which corresponded to an axial load ratio of 0.084 for the OC specimen and 0.049 for the EC specimen. The drift ratio was initiated at 0.25% in both the positive and negative directions for two cycles and was then followed by incremental increases of 0.25% until 1.00% was reached. Subsequently, the drift ratio was increased by 0.50% per cycle until the lateral resistance of the specimens had decreased to less than 80% of the maximum lateral resistance.

The Experimental Results

Modes of failure

According to the lateral cyclic loading test results under the controlled displacement, the tested OC and EC specimens exhibited crack patterns at different drift ratios, as shown in Figures 5 and 6, respectively. The cracking behaviors of both specimens showed similar characteristics at each drift ratio. However, during the initial testing stage, the EC specimen exhibited cracking behavior that was concentrated primarily in the region of the plastic hinge, which differed from the OC specimen, in which the cracking was distributed along the height of the column. In the OC specimen, the first crack appeared at a drift ratio of 0.24%. Following this at a drift ratio of 1.28%, the reinforcement bars in the column yielded, and the cracks that appeared on both sides of the column grew more observable and nearly converged. The column achieved its maximum lateral resistance at a drift ratio of 2.42%, in which the enlargement of the cracks and the crushing of the concrete were observed at the corners. Further increasing the drift ratio to 3.95% resulted in an increased crushing of the concrete and the occurrence of buckling in the longitudinal reinforcement bars. The ultimate point for the OC specimen occurred at the drift ratio of 4.58%, with the lateral resistance reaching 80% of the maximum lateral resistance. The Enhanced Column (EC) specimen displayed its first crack at a drift ratio of 0.17%. At a drift ratio of 1.49%, the column experienced cracks that expanded and merged on both sides, and there was the yielding of the reinforcing bars. The column reached its maximum lateral resistance at a drift ratio of 2.17%, with cracks growing larger and more apparent and with a slight crushing of the concrete, which took place in the corners. The EC specimen reached its ultimate point at a drift of 4.96%. It exhibited increased crushing of the concrete and longitudinal buckling of the reinforcement bar.

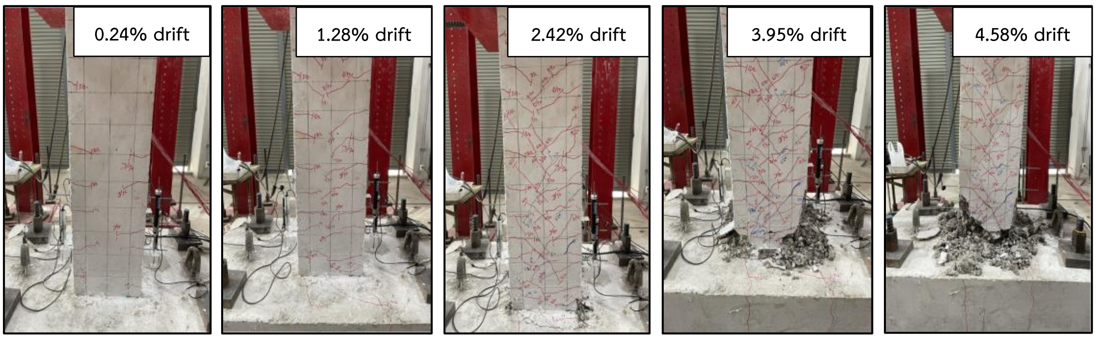


Figure 5 The crack patterns of the OC specimen

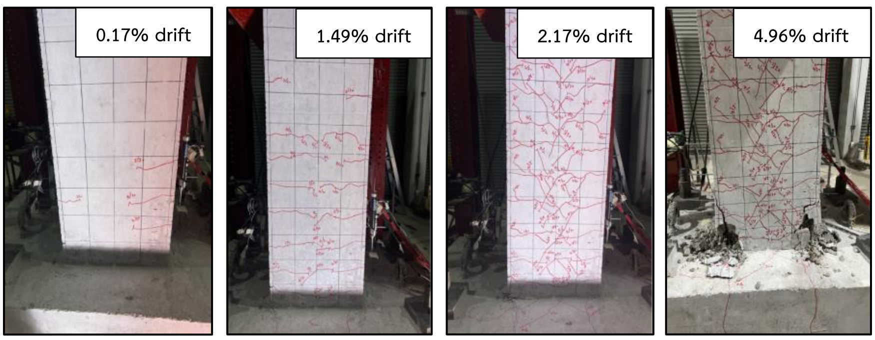


Figure 6 The crack patterns of the EC specimen

The relationship between the lateral resistance and the lateral displacement

The relationship between the lateral resistance and the lateral displacement and the test results of OC and EC specimens are illustrated in Figure 7 and Table 3, respectively. The lateral resistance at the yielding point of the OC specimen was found to be 191 kN at a lateral displacement of 16.67 mm, which resulted in a stiffness of 11.46 kN/mm. The maximum lateral resistance was 215 kN at a lateral displacement of 31.48 mm. At the drift ratio of 3.95, buckling of the reinforcement bar occurred with a lateral resistance of 202 kN. At the ultimate point when the lateral resistance had reached 80% of its maximum value, the displacement was 59.60 mm with a drift ratio of 4.58%. For the EC specimen, the lateral resistance at the yielding point increased by 410 kN at the lateral displacement of 19.33 mm, which resulted in a 21.21 kN/mm stiffness. The maximum lateral resistance was 447 kN at the lateral displacement of 28.21 mm. At the buckling of the reinforcement bar and the ultimate point, the lateral resistance was 375 kN with a displacement of 64.50 mm. It could be seen that the lateral resistance of the EC specimen had been approximately twice the value of the lateral resistance of the OC specimen under the same conditions.

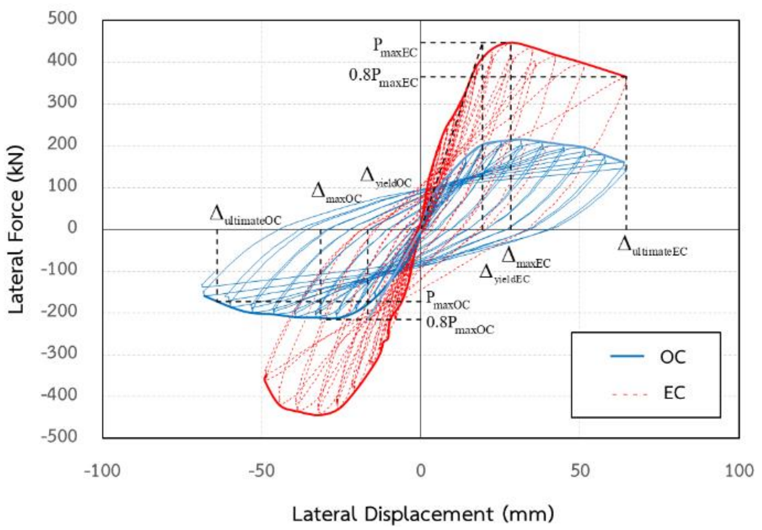


Figure 7 The relationship between the lateral resistance and the lateral displacement of the OC and EC specimens

Table 3 The experimental results of the OC and EC specimens

	OC			EC		
	Loads (kN)	Disp. (mm)	%Drift	Loads (kN)	Disp. (mm)	%Drift
First crack	73	3.13	0.24	109	2.17	0.17
First yield	191	16.67	1.28	410	19.33	1.49
Maximum Load	215	31.48	2.42	447	28.21	2.17
Buckling	202	51.36	3.95	357	64.50	4.96
Ultimate	167	59.60	4.58	357	64.50	4.96
Yielding Stiffness (kN/mm)		11.46			21.21	

Ductility

Ductility is the ability of a structure to maintain its shape without immediate failure under extreme loading conditions, which can be defined as the ratio of maximum deformation to the corresponding deformation at yield, which is also known as the ductility ratio. This ratio can be calculated by using Equation (1). As shown in Table 4, the ductility of the OC and EC specimens had been 3.57 and 3.34, respectively. The ductility values of the two specimens were close to each other, indicating that the RC columns enhanced with RCJ had not significantly increased ductility. However, it was observed that the RC columns, which had been enhanced with RCJ, led to a rapid decrease in resistance after reaching the maximum load. Therefore, using reinforced concrete jacketing to enhance the RC column may not effectively increase the ductility.

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

in which... μ_{Δ} is a ductility ratio, Δ_u is the maximum displacement at the lateral resistance decreased to 80% of the maximum lateral resistance, and Δ_y is the yielding displacement.

Table 4 The displacement and ductility ratio

Specimens	Yielding Displacements (mm)	Ultimate Displacements (mm)	Ductility Ratios
OC	16.67	59.60	3.57
EC	19.33	64.50	3.34

Energy dissipation

The energy dissipation was obtained by calculating the area under the curve of the lateral force versus the lateral displacement relationship for each cycle of experimental results using the Trapezoidal Rule numerical integration method. To calculate the energy dissipation for each cycle, the process involved applying an initial force in the direction of push at the point of zero displacement until the predetermined displacement had been reached. The force was applied in the opposite direction until the predetermined displacement had been reached again and returned to the zero displacement point, which constituted one testing cycle. The relationship between the energy dissipation and the drift ratio is plotted in Figure 8. It was observed that the energy dissipation of the OC and EC specimens had been fairly equal in the drift ratio range of 0% to 2% due to the linear behavior of the experiments. After reaching a drift ratio of greater than 2%, the amount of energy dissipated by the OC specimen had been greater than that of the EC specimen because the six longitudinal steel reinforcements in the OC specimen had yielded. In contrast, it was observed that only four longitudinal steel reinforcements had yielded in the EC specimen. Nevertheless, the RC columns, which were enhanced with RCJ, had not significantly affected the energy dissipation coefficient.

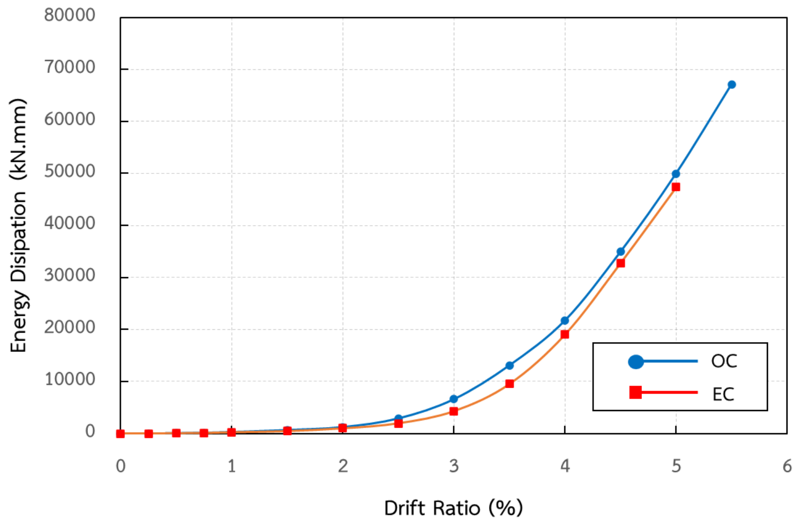


Figure 8 The relationship between energy dissipation and drift ratio of OC and EC specimens

Stiffness degradation

Figure 9 shows the relationship between the lateral stiffness and the drift ratio. In the linear range of column behavior, the EC specimen exhibited stiffness, which had been roughly twice that of the OC specimen. However, as the drift ratio increased, the stiffness of the EC test specimen declined more than that of the OC test specimen. This decrease in stiffness was due to the amplified displacement of the test specimen, which had ultimately caused its failure and had resulted in concrete catastrophe.

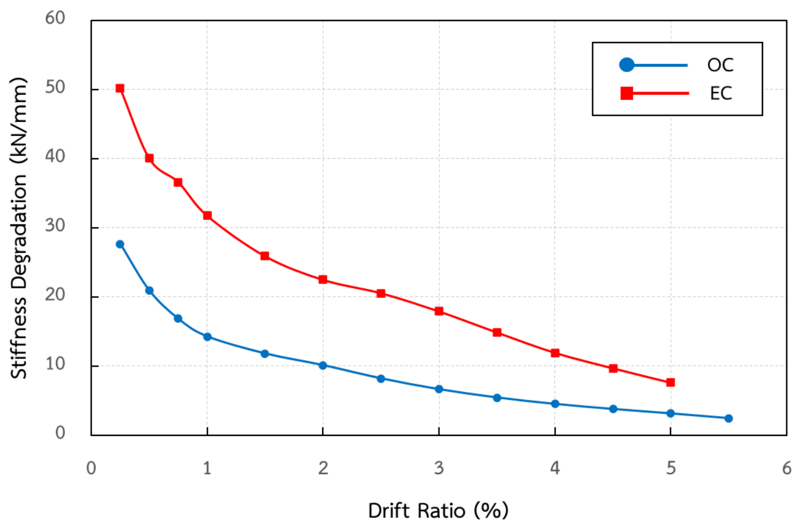


Figure 9 The relationship between the stiffness degradation and the drift ratio of the OC and EC specimens

Conclusions

The objective of the study was to investigate the response of maximum lateral resistance, ductility, energy dissipation, and stiffness degradation under lateral cyclic loading with a constant axial load for both regular RC columns and RC columns, which had been reinforced with a reinforced concrete jacketing. The experimental findings led to the following conclusions.

1. The experimental results showed that reinforcing the Enhanced Column (EC) using a jacketing method and increasing of the cross-sectional area of the longitudinal reinforcement from 40.22 cm² to 64.35 cm² had resulted in a 60% increase in the cross-sectional area. The EC specimen exhibited a maximum lateral resistance value of 447 kN, which was 108% higher than that of the Ordinary Column (OC) specimen with an original cross-sectional area of 215 kN. In addition, the stiffness of the EC specimen increased by 85%, from 11.46 kN/m for the OC specimen to 21.21 kN/m.

2. The addition of a reinforced concrete jacket to the EC specimen in this study had not resulted in a significant increase in stiffness when compared to the OC specimen. Both specimens exhibited similar energy dissipation capacities under the same drift ratio during the elastic range. However, during the nonlinear range, the EC specimen had shown a slightly higher energy dissipation capacity but did not show a significant difference. Furthermore, the EC specimen had demonstrated higher stiffness values than the OC specimen at all drift ratios, but the rate of stiffness reduction had been faster.

3. Reinforced concrete jacketing can improve a structure's ability to resist lateral forces and stiffness by up to two times, resulting in better seismic resistance. This desirable behavior helps the structure maintain its linear behavior when subjected to earthquakes. Nevertheless, while this technique is effective in improving a building's seismic performance, it does not significantly enhance the ductility and energy dissipation of the columns, both of which are equally critical factors in seismic resistance.

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