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Experimental Investigations on Strengthened Reinforced Concrete Columns under Monotonic Axial Loading

S. Sirimontree[a], S. Keawsawasvong[a], C. Thongchom[a], P. Jongvivatsakul[b], E. Noroozinejad Farsangi*[c]

[a] *Department of Civil Engineering, Thammasat School of Engineering, Thammasat University, Pathumthani, Thailand*
[b] *Innovative Construction Materials Research Unit, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand*
[c] *Faculty of Civil and Surveying Engineering, Graduate University of Advanced Technology, Kerman, Iran*

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ABSTRACT

Strengthening of the existing reinforced concrete (RC) column is nessesary to enhance their axial load-carrying capacity or ductility. This paper presents the results of an experimental study relating to the performance of reinforced concrete columns strengthened with different techniques such as the steel angle, steel straps, and ferro-cement under pure axial load. A total of six square short reinforced concrete columns were constructed. The cross-section and height of tested columns are 150×150 mm and 1.2 m, respectively. Two specimens were set as the control columns (without strengthening). The other four reinforced concrete columns were strengthened with different techniques. Two columns are strengthened with four steel angles at each corner of the column confined with prestressed steel straps. Another two columns are also strengthened with four steel angles confined with prestressed steel straps and ferro-cement. The experimental results are reported in terms of the load-deformation curves as well as the failure modes. A significant enhancement of the maximum axial load-carrying capacity and the ductility is observed for the strengthened reinforced concrete columns. Finally, the discussion of the use of different strengthening techniques is also carried out in this paper.

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1. INTRODUCTION

There are several effective approaches that can be used to enhance the axial load-carrying capacity and the ductility of RC structures. For instance, many researchers in the past have employed ferro-cement [1-5], fiber-reinforced materials [6-12], or steel angle/strips [13-15], to strengthen the reinforced concrete structures. Previous works by Mourad and Shannag [1], Kaish et al. [2], and Sirimontree et al. [3] employed the ferro-cement jacketing to strengthen RC column. The ferro-cement jacketing was utilized to repair concrete beams by Jongvivatsakul et al. [4-5]. In addition to ferro-cement jacketing, the fiber-reinforced materials is one of the strengthening composites widely used to increase the capacity of several RC structures (e.g., Kianoush and Esfahani [7], Maghsoudi et al. [8], Nateghi and Khazaei-Poul [9], Rahmanzadeh and Tariverdilo [10], Al-Akhras [11], Shadmand et al. [12]). The use of steel jackets is also a simple procedure to strengthen various types of RC structures, where its good performance was demonstrated by Abdel-Hay and Fawzy [13], Ma et al. [14], and Tarabia and Albakry [15].

The main elements supporting a building structure are the columns. The failure in columns can lead to the progressive collapse of the whole building. Thus, column strengthening is an essential issue in the seismic retrofitting of a building structure. To enhance the axial load-carrying capacity, the stiffness, or the ductility of the reinforced concrete columns, several researchers have used steel angles, steel jackets, or ferro-cement jackets to experimentally investigate the strengthening of

*Corresponding Author Institutional Email: noroozinejad@kgut.ac.ir (E. Noroozinejad Farsangi)

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reinforced concrete columns by employing these composites. For previous works considering steel angles, Adam et al. [16] performed the laboratory tests of RC columns retrofitted with steel angles and steel strips under axial static loading. These results of laboratory tests were then used to develop numerical models, the nonlinearity of the materials between different materials is taken into account. Tarabia and Albakry [15] carried out a study on the performance of the reinforced concrete square columns strengthened with steel angles and steel strips. They found that the confinement effects significantly dependent on several factors such as the strip spacing, the size of the steel angles, and the connection between the steel angles and steel strips to the head of the specimen. Campione [17] also proposed a design procedure for designing RC columns strengthened with steel angles and battens. The proposed procedure was validated with the experimental results to ensure the performance of the design process. The behaviors of reinforced concrete columns strengthened with steel jackets were also studied by Belal et al. [18] and Abdel-Hay and Fawzy [19]. For previous studies relating the use of ferro-cement jackets to strengthen reinforced concrete columns, Takiguchi [20] demonstrated that the use of external confinement to cover the entire length of the reinforced concrete columns can significantly increase the ductility of the reinforced concrete columns. By using a nonlinear finite element software, Elsayed and Elsayed [21] investigated the performance of the reinforced concrete columns wrapped by ferro-cement jackets under biaxial loading. More details on the performance of steel angles, steel jackets, and ferro-cement jackets can be found in the state-of-the-art review by Raza et al. [22] and Kaish et al. [23]. Recently, the uses of fibrous jackets, textile-reinforced concrete jackets, and prestressed steel jackets to strengthen RC structures were demonstrated by Jassim and Chassib [24], Ngo et al. [25], and Sirimontree et al. [26], respectively, The performance of RC circular and square columns under cyclic loading were examined by Ahmed et. al. [27]. The information of the framework to quantify the absolute permeability of water in a porous structure can be found in literature [28]. Besides, more information on the sustainability assessment in housing buildings can be found in literature [29].

This paper studies the behavior of strengthened reinforced concrete columns subjected to axial load. A total of six reinforced concrete square columns were investigated. Different techniques for strengthening the existing reinforced concrete columns were used such as the steel angle, steel straps, and ferro-cement. All columns are tested under static load. The load-displacement relationship and the failure modes of tested columns are presented and discussed in this paper.

The following is the structure of the paper. The details of all test specimens as well as the preparation processes are first presented to give the information of all considered factors in this study. The test setup and instrumentations are later shown in the same section. The experimental results of all columns are presented in the form of load-displacement curves to demonstrate the performance of all tested columns. The modes of failures showing the column collapses are also presented to portray the failure patterns of all columns. The conclusion of this paper is given lastly to summarize this work.

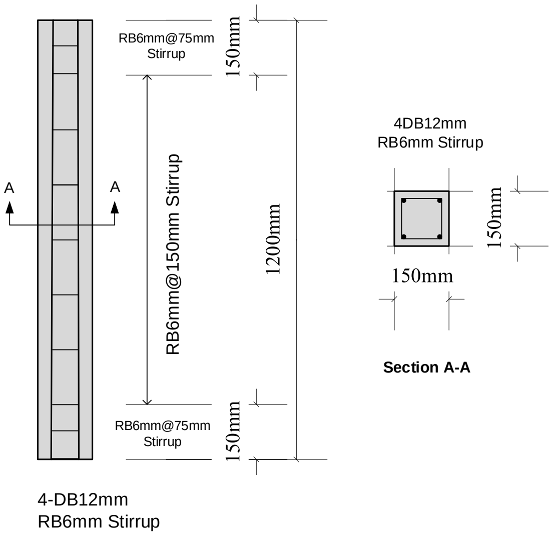
The innovation of this paper is to investigate the increasing axial load-carrying capacity and ductility of columns strengthened with steel angles confined with prestressed steel straps. Besides, a similar investigation on the use of ferro-cement confined around the reinforced concrete column is also carried out in this study.

2. EXPERIMENTAL PROGRAM

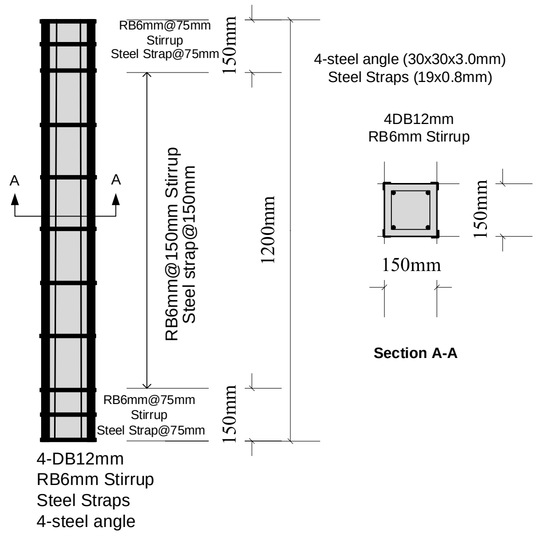
2. 1. Tested Specimens In the present study, a total of six reinforced concrete columns were cast. The cross-section of all columns was 150×150 mm and the height was 1.20 m. The ratio between column height and width was eight which was a short column. The columns were reinforced with four longitudinal bars with a diameter of 12 mm (DB12) and transverse bars with a diameter of 6 mm (RB6) that had a spacing of 150 mm. The area of longitudinal bars was 2.0 percent of cross-sectional area. The clear concrete covering was considered as 20 mm. Two columns were set as the control specimens (Columns CC-1 and CC-2), as shown in Figure 1(a). The other four reinforced concrete columns were strengthened with different techniques.

For strengthened reinforced concrete columns, two columns (CSA-1 and CSA-2) were strengthened with four steel angles at each corner of the columns and then confined with prestressed steel straps that had a spacing of 150 mm, as shown in Figure 1(b). The cross-section and thickness of steel angle were 30×30 mm and 3.0 mm, respectively. An injection plaster was employed in order to fill the gap between the steel jacket and concrete for the strengthened columns.

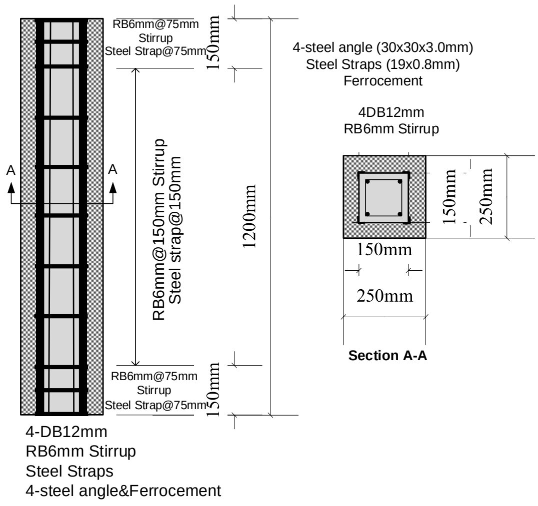
Another two columns (CSAF-1 and CSAF-2) were also strengthened with four steel angles at each corner of the columns and then confined with prestressed steel straps that had a spacing of 150 mm. After that, the ferro-cement was used to confine the columns at the last step. The square welded wire mesh was used to wrap around the existing column and the cement mortar was applied. A cross-dimension of 250×250 mm was controlled. Figure 1(c) shows the detail of columns CSAF-1 and CSAF-2.



(a) Columns CC-1 and CC-2 (References)



(b) Columns CAS-1 and CAS-2



(c) Columns CASF-1 and CASF-2

Figure 1. Details of tested specimens

2. 2. Specimens Descriptions In this experimental work, ordinary Portland cement was used for both mortar and concrete. The water-to-cement ratio (w/c) was set to 0.45. The average compressive strength of mortar and concrete obtained from the test of three samples (Ø150×300 mm) at 28 days was 23 MPa.

Two diameters of steel reinforcement were used. The average yield strength and the ultimate strength of 12-mm diameter (deformed bar, DB) obtained from the test of three samples were 586 and 717 MPa, respectively. The average yield strength and ultimate strength of 6-mm diameter (round bar, RB) obtained from the test of three samples were 423 and 538 MPa, respectively. The steel with equal angle was used. The cross-section and thickness of steel angle were 30×30 mm and 3.0 mm, respectively. The norminal yeild strength was 240 MPa.

For the steel strap, the width and the thickness were 19 and 0.8 mm, respectively. The average yield and ultimate strengths obtained from the test of three samples of the steel straps were 466 and 520 MPa, respectively.

2. 3. Specimens Preparation Figure 2 presents the flowchart of the experimental program. All specimens were cast from the same concrete batch. All columns were remolded after 24 hours and then were cured using plastic wrap. After 28 days, the columns (CSA-1, CSA-2, CSAF-1, and CSAF-2) were strengthened with four steel angles at each corner of the column and then confined with prestressed steel straps with a spacing of 150 mm. A steel strap was prestressed using a steel strap hand tool, as shown in Figure 3. The elongation of steel straps was controlled to be 2.0 mm or 4.2 kN. After that, the steel strap was locked by the steel grip. An injection plaster was carried out in order to fill the gap between the concrete surface and the steel jacket. The ferro-cement was applied for columns CSAF-1 and CSAF-2. The square welded wire mesh was used to wrap around the column and the cement mortar was installed. The controlled cross-dimension was 250×250 mm. After ferro-cement was applied, the plastic wrap was used to cure for another 28 days. Figure 4. shows the plastic curing for column CSAF-1 and CSAF-2.

2. 4. Test Setup and Instrumentations A typical test setup for all tested specimens is demonstrated in Figure 5. The static load was gradually applied in the vertical direction at the top of the tested columns by using a hydraulic jack. The load cell with a capacity of 5000 kN was set-up on top of tested columns. Two linear variable differential transformers (LVDT-1 and LVDT-2) were also set-up at two opposite sides of the columns to measure the vertical displacements. To ensure a uniform loading taking place at the top and bottom of the specimens, capping was used. during the specimens testing procedure, the load and displacements were automatically recorded by using the data logger. The failure modes of the tested columns were observed.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3. 1. Load and Displacement Curve The relationships between axial load and displacement for all tested columns are represented in Figure 6. Table 1

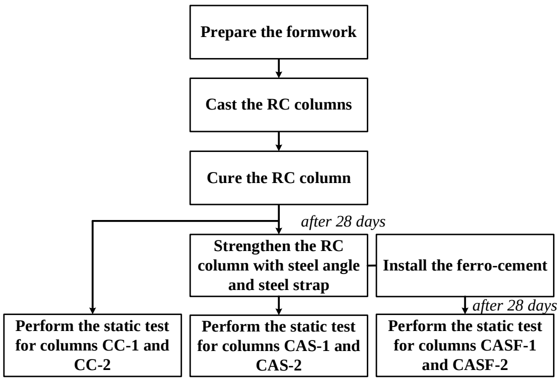


Figure 2. Flow chart of the experimental program

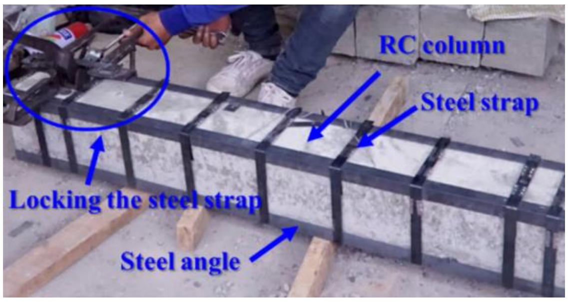


Figure 3. Strengthened column

Figure 4. Plastic curing for column CSAF

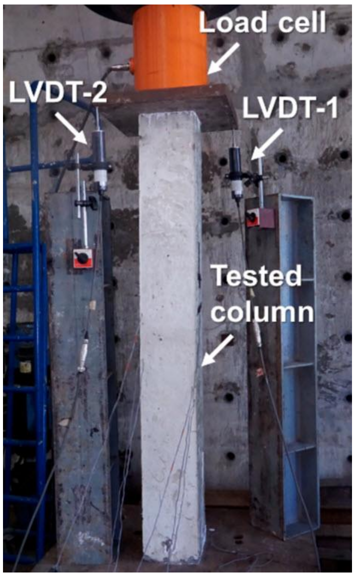


Figure 5. Test setup of a tested column

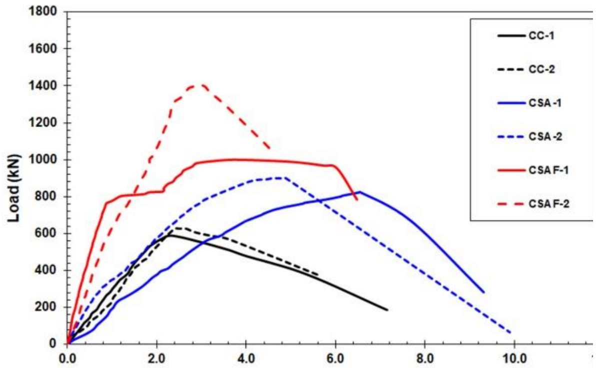


Figure 6. Load-displacement curves of tested columns

TABLE 1. The experimental results of all columns

Specimen Model	Steel Strap	Steel Angle	Ferro-Cement	Maximum Load (kN)	The Displacement* (mm)
CC-1	No	No	No	600	2.22
CC-2	No	No	No	630	2.46
CSA-1	Yes	Yes	No	825	6.55
CSA-2	Yes	Yes	No	900	4.89
CSAF-1	Yes	Yes	Yes	1000	3.97
CSAF-2	Yes	Yes	Yes	1400	3.04

* The displacement corresponding to the maximum load

summarizes the maximum axial load carrying capacity and the corresponding displacements of all tested columns in this research work.

For unstrengthened columns, the maximum axial load-carrying capacity of columns CC-1 and CC-2 were

600 and 630 kN, respectively, which yield an average of 615 kN. The axial displacements correspond to the maximum axial load-carrying capacity of columns CC-1 and CC-2 were 2.22 and 2.46 mm, respectively, which reach an average of 2.34 mm.

For columns CSA-1 and CSA-2, the maximum axial load-carrying capacities were 825 and 900 kN, respectively, which yield an average of 863 kN. The axial displacements corresponding to the maximum axial load carrying capacity of columns CSA-1 and CSA-2 were 6.55 and 4.89 mm, respectively, which yield an average of 5.72mm.

For columns CSAF-1 and CSAF-2 (larger cross-section area), the maximum axial load-carrying capacities were 1000 and 1400 kN, respectively, which reach an average of 1200 kN. The axial displacements corresponding to the maximum axial load carrying capacity of columns CSAF-1 and CSAF-2 were 3.97 and 3.04 mm, respectively, which reach an average of 3.51 mm.

Based on these observed results, the maximum axial load capacity and corresponding displacement of reinforced concrete columns strengthened with steel angle confined by prestressed steel straps (Column CSA) increased by 40% and 144%, respectively, compared to the control columns (Column CC). Using the ferro-cement as the confinement, the maximum axial load capacity and corresponding displacement of column CSAF increased by 95% and 50%, respectively, compared to the control column. In addition to the strength and ductility enhancement, the ferro-cement can improve the stiffness due to the cross-sectional expansion compared to the control column as depicted in Figure 6. All strengthened columns have more ductile behavior compared to the control specimen.

3. 2. Modes of Failure The modes of failure of tested columns are demonstrated hereafter in Figures 7 to 9. For the unstrengthened columns (Columns CC-1 and CC-2), the concrete crushing near the top of the columns was observed for the case of Columns CC-1 (see Figure 7a) and the propagated crushing towards the middle position of the column was observed for the case of Columns CC-2 (see Figure 7b). The buckling of the longitudinal steel bar was found after the concrete cover spalled off, which can be observed in Figure 7.

In the case of the reinforced concrete columns strengthened by steel angles (Columns CSA-1 and CSA-2), the failure has been the steel angles bucking followed by the steel strap rupture. The failure at the connected steel straps was not observed. After that, the concrete was crushed at one end of the column. Figures 8(a) and 8(b) depict the failure modes for columns CSA-1 and CSA-2, respectively. By comparing with the previous work by Sirimontree et al. [26], we found that the mode of failure is in the similar way as presented in the work by Sirimontree et al. [26].

In the case of the reinforced concrete columns strengthened by steel angles and then confined with

(a) Column CC-1

(b) Column CC-2

Figure 7. Failure modes of Columns CC


(a) Column CSA-1


(b) Column CSA-2

Figure 8. Failure modes of Columns CSA

ferro-cement (Columns CSAF-1 and CSAF-2), the crack initiated at the top of the column. A large vertical crack of the concrete was observed for column CSAF-2. Figures 9(a) and 9(b) show the failure modes for columns CSAF-1 and CSAF-2, respectively.


(a) Column CSAF-1


(b) Column CSAF-2

Figure 9. Failure modes of Columns CSAF

4. CONCLUSION

This paper demonstrates the performance of strengthened reinforced concrete columns that were evaluated under the axial load test. A total of six square RC columns were investigated. The original cross-section has been 150×150 mm with a height of 1.2 m. The main objective of this research is to investigate the axial behavior of RC columns strengthened with steel angles with and without ferro-cement. The following conclusions based on the experimental works can be reported:

- The reinforced concrete columns strengthened with steel angles confined with prestressed steel straps enhanced the maximum axial load-carrying capacity and the ductility up to 40% and 144%, respectively, compared to the un-strengthened reinforced concrete columns.
- Using ferro-cement confined around the reinforced concrete column strengthened with steel angle confined with prestressed steel straps, the maximum axial load carrying capacity and ductility increased by 95% and 50%, respectively, compared to the un-strengthened reinforced concrete columns.

5. ACKNOWLEDGMENTS

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Persian Abstract

چکیده

مقاوم سازی ستون های بتن مسلح موجود به منظور بالابردن ظرفیت باربری محوری و همچنین شکل پذیری آنها ضروری به نظر می رسد. در این مطالعه روش های مختلف مقاوم سازی ستونهای بتن مسلح با کمک نبشی، تسمه فلزی و *ferrocement* به صورت آزمایشگاهی مورد بررسی قرار گرفته است. در کل ۶ نمونه ستون بتن مسلح برای آزمایش ها ساخته شد. مقطع تمامی ستونها ۱۵۰ در ۱۵۰ میلی متر و ارتفاع همه ۱/۲ متر در نظر گرفته شد. دو نمونه به عنوان نمونه مرجع در نظر گرفته شد و سایر نمونه ها با روشهای پیشنهادی در این مطالعه مقاوم سازی گردیدند. دو نمونه با کمک نبشی و تسمه فلزی و دو نمونه دیگر با کمک نبشی و تسمه فلزی و *ferrocement* مقاوم سازی گردیدند. نتایج مطالعات آزمایشگاهی در قالب دیاگرام های نیرو-تغییرمکان و مدهای خرابی ارائه و با یکدیگر مقایسه گردیدند. نتایج بیانگر ارتقا قابل توجه عملکرد سازه ای ستونهای تقویت شده بوده است. در نهایت بحث بر روی روشهای پیشنهادی صورت گرفت.