Static and Dynamic Behavior of Circularized Reinforced Concrete Columns Strengthened with Hybrid CFRP

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Abstract-In this study, three strengthening techniques, near-surface mounted NSM-CRFP, NSM-CFRP with externally bonding EB-CFRP, and hybrid CFRP with circularization were studied to increase the seismic performance of existing RC slender columns under lateral loads. Experimentally, 1:3 scale RC models were studied and subjected to both lateral static load and seismic excitation. In the dynamic test, a model was subjected to El Centro 1940 NS earthquake excitation by using a shaking table. According to the test results, the strengthening techniques showed a significant increase in load carrying capacity, of about 86.6%, and 46.6%, for circularization and NSM-CFRP respectively, of the reference unstrengthened columns. On the other hand, columns strengthened with hybrid NSM-CFRP and EB-CFRP showed a different failure mode. Dynamically, the lateral drift was decreased by about 75%, 47%, and 49% for earthquake amplitudes of 0.05g, 0.15g, and 0.32g respectively. Finally, it was concluded, depending on the static and dynamic analyses, that the circularization process showed a significant increase in lateral load-bearing capacity.

Keywords-circularization; strengthening; CFRP; NSM; dynamic; slender column

I. INTRODUCTION

Most structures in Iraq were built exclusively for gravity loads only, posing a significant problem when minimizing earthquake hazards is concerned. Improved design standards and procedures can keep the damage to newer buildings to a manageable level in the event of a moderate to severe earthquake [1]. In this work, three strengthening techniques, externally bonding EB-CFRP, near-surface mounted NSM-CRFP, and hybrid CFRP with circularization were studied to increase the seismic performance of existing RC slender columns under lateral loads. After reviewing the literature regarding the CFRP strengthening techniques, and to the best of our knowledge, there is no previous work that studied the strengthening of slender columns under seismic excitation with the use of a circularization technique. Therefore, the main aims of this study are: (i) to understand the behavior of several types of strengthened Reinforced Concrete (RC) slender columns being subjected to different amplitudes of the El-Centro 1940 earthquake, and (ii) assessing the efficacy of the strengthening techniques after exposure to seismic excitation.

Prior to the '70s, the majority of structures were built to withstand gravity stresses. While these structures did well under such pressures, their performance under seismic loads was doubtful. Due to the ever-aging infrastructure and losses caused by significant catastrophic events worldwide, there is an increasing demand for the introduction of inexpensive and speedier retrofitting approaches. Due to their increased strength, light weight, durability, corrosion resistance, and aesthetic appeal, Carbon Fiber Reinforced Polymers (CFRPs) are being used more and more for strengthening and retrofitting RC structures [3]. Many strengthening techniques have been developed and used to repair and rehabilitate earthquake-damaged and seismically deficient structures. The identification of an effective rehabilitation method is directly related to the outcome of a seismic evaluation of the structure and is based on the consideration of many factors, including the type of structure, its rehabilitation objective, strengthening scheme effectiveness, constructability, and cost. It is possible to employ FRP materials and systems to enhance the overall seismic performance of a structure by modifying individual components. There are many advantages of using FRP reinforcement strengthening to effectively decrease brittle failure mechanisms at the component level. Shear failure of unconfined beam-column junctions, shear failure of beams, columns, or both, and lap splice failure are all possible. FRP strengthening may also be used to raise the inelastic rotational capacity of reinforced concrete members, as well as:

- To increase the flexural capacity of RC members and prevent flexural steel bars from buckling.
- To improve the overall behavior of reinforced concrete structures exposed to seismic events by increasing the structure's global displacement and energy dissipation capabilities.

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FRP shear strengthening and confinement have a minor impact on the structure's stiffness or mass. A reevaluation of the seismic demand after strengthening is usually not necessary in such circumstances. FRP strengthening of local components may be combined with other typical global upgrading approaches when structural stiffness has to be enhanced [4].

Many columns have a rectangular or square cross-section because it is simpler and less expensive to construct. Some columns have non-regular cross-sections, such as hexagons and other shapes. As a consequence, the goal of this research is to investigate the process of converting existing non-circular columns to circular ones and then wrapping the changed circular elements with sheet reinforcement. Modifying rectangular or square members into circular columns may be done in various ways. These approaches may essentially be divided into two categories

- A circular mold is used to encircle the non-circular compression element. After that, a rich concrete mix is poured to fill the gaps between the mold and the non-circular compression parts.
- To generate a circular cross-section, adhesives are used to adhere previously cast and cured concrete segments to the faces of the non-circular compression component (or column) [5].

Furthermore, authors in [6] found that using the circularization technique to change the form of square (non-circular) compression members to a circular shape eliminates stress concentration zones that appear at the corners of externally constrained square compression members.

II. EXPERIMENTAL PROCEDURE

A. Methodolgy

In the experimental work, 8 square concrete columns were casted for laboratory experiments with length and width of 130×130mm and height of 1500mm. The experimental tests are categorized into two main groups, each group with 4 columns (Figure 1):

- 4 specimens were tested statically.
- 4 specimens were tested dynamically.

All column specimens were designed with a normal concrete strength of fc = 30MPa. For the circularization process, plain concrete was used with concrete strength of fc = 30MPa.

B. Concrete Casting

Self-Compacting Concrete (SCC) with a compressive strength of 30MPa was used to cast the square columns due to the small cross-section of the column and the difficulty of using a vibration [7]. SCC is more workable and its production makes less noise [8]. Figure 5 shows the models after casting. Table I lists the details of the concrete mix.

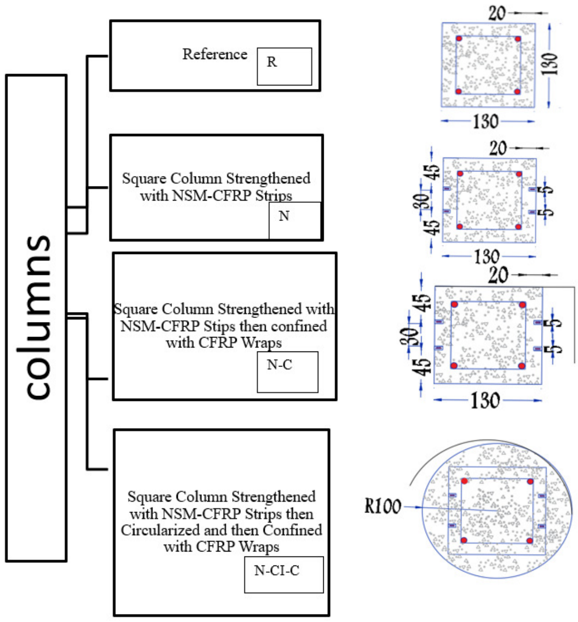

Fig. 1. Experimental matrix.

TABLE I. DETAILS OF MIX DESIGN

Materials	Final mix (kg, m^3)
Cement: Sand: Gravel (ratio by weight)	1:1.25:1.25
Water/Cementitious materials ratio	0.4125
Water	165
Cement	400
Sand	500
Gravel	500
Viscocrete 5930 IQ	8 ml / kg of cement
Rapid-1	2.6ml / kg of cement

C. Strengthening Methods

1) NSM CFRP Strengthening Method

The grooves were formed by a diamond blade cutter. The groove size is about 10mm in depth and 5mm in width. The longitudinal distance of the groove is 1250mm with an embedded length of 300mm, so the grooves were extended below the top face of the foundation block by 300mm by drilling holes along the grooves at the foundation, and the spacing between the two grooves was 30mm. The dimensions of the grooves were calculated according to ACI-440.2R-17. Figures 2-4 show the columns' specifications. The grooves were filled with the adhesive material, Sikadur 30LP, after mixing the epoxy adhesive according to supplier recommendations; components A (white) and B (black) were mixed in (3:1) proportion with an electric mixer until the color became a uniform grey.

The CFRP strip was inserted into the middle of the groove and was pressed gently so that it was completely covered by epoxy, and then the surface was leveled and pressed well by hand [9]. Finally, the columns were cured for 7 days according to the product datasheet before being tested to achieve the maximum strengthening level, as shown in Figure 6.

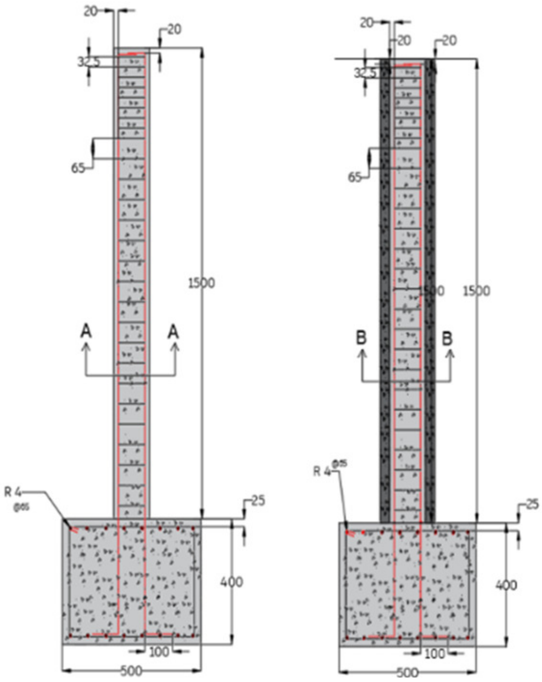

Fig. 2. The column models. All dimensions in mm.

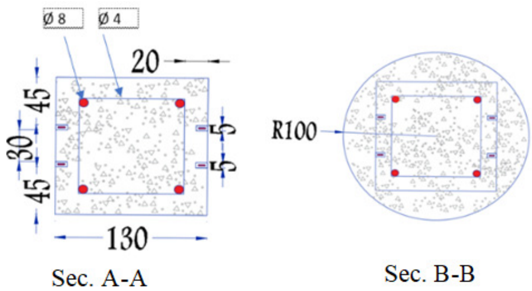

Fig. 3. The column sections. All dimensions in mm.

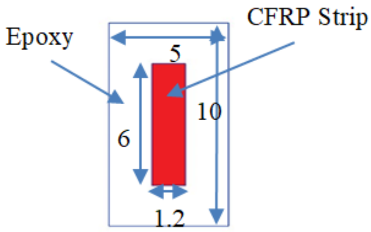

Fig. 4. Groove details. All dimensions in mm.

Fig. 5. The column models after casting.

Fig. 6. NSM-CFRP technique procedure.

2) *Strengthening Technique with Circularization*

Cylindrical formworks were used to change the shape of the square columns from a square cross-sectional into a circular cross-sectional shape. The molds had dimensions of 20cm diameter and 150cm height. For this study, the direct circularization method was used. In this method, the square columns were cast first. After sufficient time had passed, the cylindrical molds were put outside the square columns to perform the shape modification process. Finally, it should be noted that, like the square members, the casting of circularization concrete was done vertically. The advantage of applying the direct circularization method is that the surface of final circularized columns is almost a perfect cylinder with no discontinuities or distortions. Square columns that are circularized by the direct circularization method are shown in Figure 7.

Fig. 7. Circularization and CFRP-EB technique.

3) *Strengthening with External Confinement Technique*

The dry layup technique was used to wrap the columns using epoxy resin. First, the epoxy resin (Sikadur 330) was prepared by mixing the two components of the product, A and B, in 1:4 proportions. After putting components A and B of the epoxy in one container following the proportions recommended by the product datasheet, slow mixing rate was applied by hand with a spatula. When applying the epoxy resin to the surface, the resin was spread evenly throughout the model's surface with a tiny brush. After that, one layer of CFRP was applied to the specimens' surface. A small, serrated roller was utilized to ensure good resin impregnation inside the CFRP layer and to prevent any air bubbles from forming or get trapped inside the epoxy. Furthermore, the development length for CFRP wraps is mandated by ACI-440.2R-17, and is equal to 73mm [10]. A 100mm overlap was adopted for every single layer to ensure more confinement effectiveness. They were additionally arranged around the specimens like hoops. In order to prevent any air bubbles from being caught, the serrated roller spun in the fibers' direction, the EB process is shown in Figure 7. Additionally, according to the product datasheet, it should be noted that CFRP wraps were left for 7 days to develop full bonding strength [11]. Figure 8 shows the final shape of the models.

Fig. 8. Final shape of column models.

III. STATIC TEST

To study the performance of the RC columns before and after strengthening, all columns, which included 1 column reference column and 3 strengthened columns, were loaded up to failure by applying incremental monotonic static load horizontally over the tipping point of the column where the steel cap was put to prevent local crushing. The load was measured by the testing machine's load cell, and displacement data were recorded by an LVDT placed in the free end of the column. All specimens were tested in the structural laboratory of the Department of Civil Engineering, University of Baghdad.

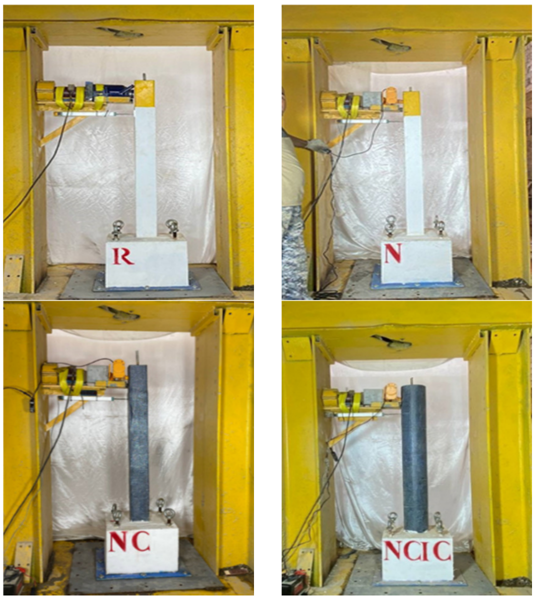

Fig. 9. Static test.

For each specimen, the base was screwed on all sides with a steel plate which was fixed on the frame floor by welding to avoid uplifting. An electric control jack applied the lateral load with a capacity of 40kN, which was connected to a load cell with a 200kN capacity. Figure 9 shows the static test.

A. *Static Results*

Table II lists the results of the models after being subjected to static lateral force. Figures 10-11 show the load-displacement curve of the models and the comparison with the reference model.

TABLE II. STATIC TEST RESULTS

Column code	Ultimate load *Pu* (kN)	Load *Pu* (kN) at 60mm	Δ*u* (mm)	% Increase in load at 60mm
R	4.11	3.15	124	/
N	4.67	4.62	72.9	46.6
N-C	3.66	3.42	203.8	8.57
N-CI-C	6.52	5.88	100.5	86.6

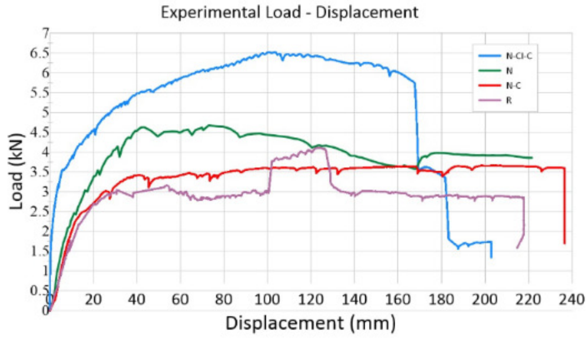

Fig. 10. Load displacement of models.

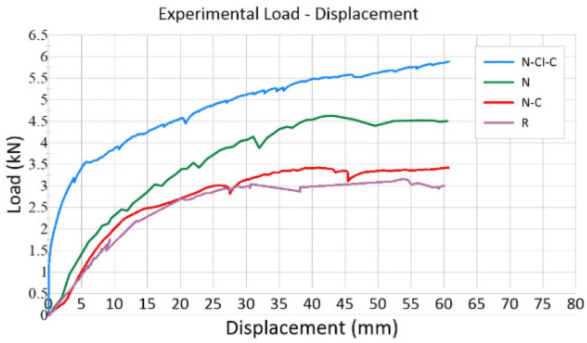

Fig. 11. Load displacement of models at 60mm displacement.

B. *Static Test Results and Discussion*

Table II and Figures 10-11 lead to the conclusion that a major increase in the load-bearing capacity was detected by the column N-CI-C due to the circularization technique that provided more rigidity in comparison to the column R. Column N also showed a significant increase in the load-bearing capacity but less than column N-CI-C. In contrast, the column N-C showed a different failure mode, in which it doesn't increase the load-bearing capacity. Figure 11 shows the load displacement of the models for 60mm displacement due to the serviceability limit [12].

IV. DYNAMIC TEST

One column from each group was tested using the shaking table developed in [13], utilizing the time history analysis method to simulate the seismic excitation. Two LVDTs were put at the top and the base of the columns to assess the displacement after the seismic excitation with 3 amplitudes, 0.05g, 0.15g, and 0.32g, to study the behavior of the columns that were strengthened with different techniques, as shown in Figure 12, In this study, an additional mass was used to similitude the loads subjected to the column, so it was assumed that the load on the prototype is 2543kg, and the weight of the mass model is 282.6kg, according to [14]. For mass similitude, additional weight was added in the form of steel plates at the free end of the column models, which were made up for the weight deficiency of 22mm thickness and 15kg weight each.

Fig. 12. Dynamic test.

1) Dynamic Test Results and Discussions

Table III lists the results of the 4 models after being subjected to El Centro seismic excitation. Each column was subjected to three amplitudes, 0.05g, 0.15g, and 0.32g. Figures 13 to 21 show the displacement-time curve of all models and the comparison with the reference model.

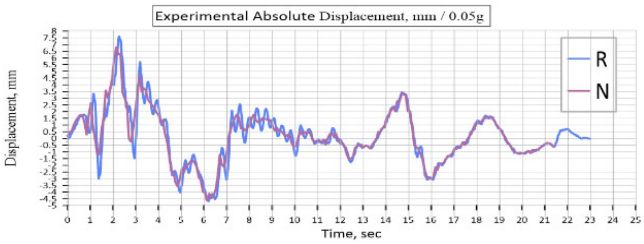

Fig. 13. Time-displacement of R and N models with 0.05g excitation.

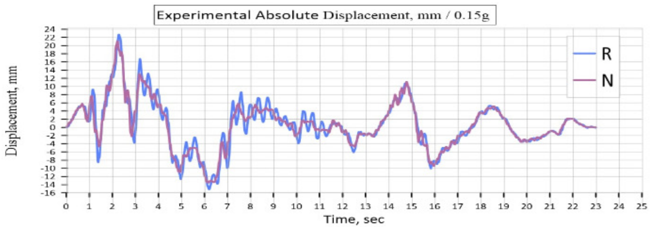

Fig. 14. Time-displacement of R and N models with 0.15g excitation.

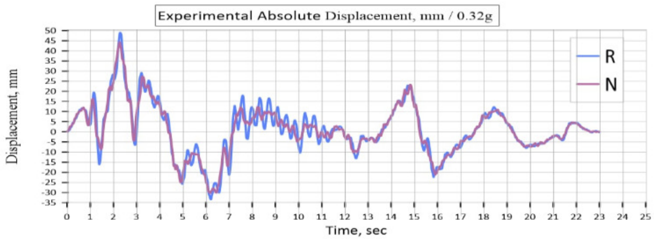

Fig. 15. Time-displacement of R and N models with 0.32g excitation.

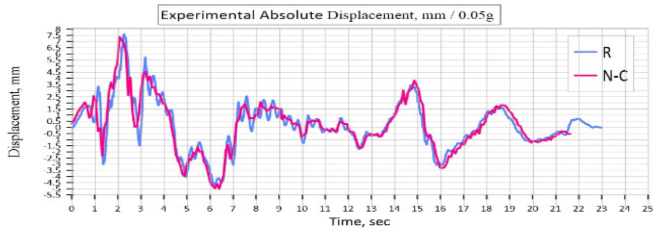

Fig. 16. Time-displacement of R and N-C models with 0.05g excitation.

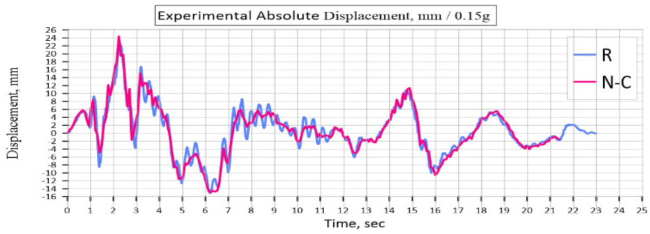

Fig. 17. Time-displacement of R and N-C models with 0.15g excitation.

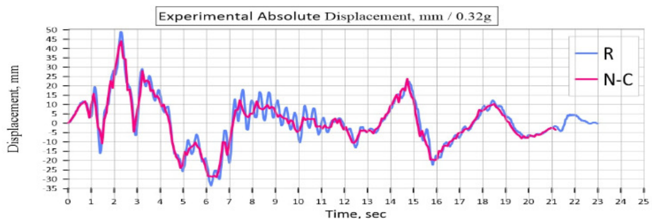

Fig. 18. Time-displacement of R and N-C models with 0.32g excitation.

Fig. 19. Time-displacement of R and N-CI-C models with 0.05g excitation.

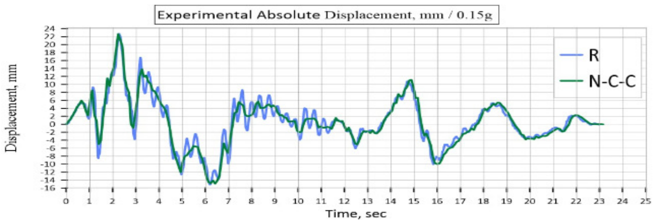

Fig. 20. Time-displacement of R and N-CI-C models with 0.15g excitation.

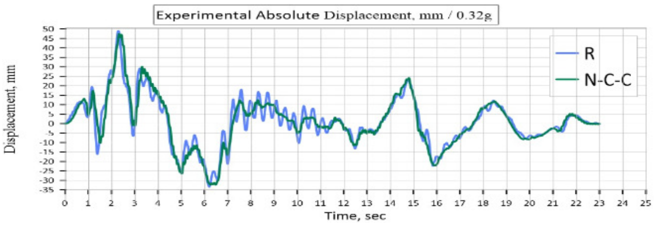

Fig. 21. Time-displacement of R and N-CI-C models with 0.32g excitation.

TABLE III. DYNAMIC TEST RESULTS

Column code	Earthquake amplitude (g)	Absolute displacement (mm)		Relative displacement (mm)	
		Max.	Min.	Max.	Min.
R	0.05	7.607	-4.685	2.059	-2.289
	0.15	22.69	-15.12	5.127	-5.968
	0.32	48.96	-33.41	5.801	-7.821
N	0.05	6.909	-4.621	0.973	-0.911
	0.15	21.08	-13.51	2.233	-3.882
	0.32	44.33	-30.31	3.901	-6.019
N-C	0.05	7.384	-5.117	0.924	-1.807
	0.15	24.4	-14.93	3.912	-3.187
	0.32	43.9	-28.9	4.115	-6.501
N-CI-C	0.05	7.352	-4.8	0.413	-0.551
	0.15	22.63	-14.8	3.11	-2.54
	0.32	46.05	-32.3	2.322	-3.924

Table III and Figures 13-21 showed that a major reduction in the displacement was detected by the column N-CI-C due to the circularization technique that provided more rigidity compared to the column R. Column N also showed a significant reduction in the displacement, but less than N-CI-C. In contrast, the column N-C showed a different failure mode, which doesn't enhance the dynamic response.

V. CONCLUSIONS

In this study, the behavior of slender columns strengthened with strengthening techniques was studied. Two approaches were adopted. In the dynamic test approach, a column model was subjected to El Centro 1940 NS earthquake excitation by using a shaking table. In the static test approach, a column model was subjected to a lateral load and tested up to failure. Depending on the experimental test results the main conclusions can be summarized as:

In the static test, the strengthening techniques showed significant increase in load carrying capacity, of about 86.6%, and 46.6%, for circularization with NSM-CFRP and NSM-CFRP respectively, of the reference unstrengthened columns.

In the dynamic test, columns that were strengthened with hybrid NSM-CFRP and EB-CFRP showed a different failure mode. Dynamically, the lateral drift was decreased by about 75%, 47%, and 49% for earthquake amplitudes of 0.05g, 0.15g, and 0.32g respectively.

The circularization process effectively avoided stress concentration zones that would otherwise occur when a non-circular column was wrapped in CFRP. As a result, the load-carrying capacity and dynamic response improved.

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