Dynamic Response of Slender Reinforced Concrete Columns Strengthened by Using CFRP and Circularization Subjected to Seismic Excitation

Zena H. Abdulghafoor and Hayder A. Al-Baghdadi

Abstract This paper presents a numerical study comparing the drift of slender columns with different strengthening techniques subjected to different amplitude seismic with a pure axial compressive load. A total of three 1:3 scale square concrete column models were used throughout the study. The first column consisted of a square column without CFRP (carbon fiber reinforced polymer) strip confinement and shape modification; it was considered as a reference member. The second one consisted of a square column confined with CFRP strips using Near-Surface-Mounted (NSM) technique and then strengthened with CFRP wraps. The third column and last one consisted of a square column confined with CFRP strips, then circularized and confined with CFRP wrappings. All columns are tested using a time-compressed El Centro 1940 earthquake at different amplitudes (0.05 g, 0.15 g, 0.32 g). Numerical results showed that the displacement of columns, which strengthened with CFRP strips, the circularized and confined with CFRP wrappings technique, was decreased of about 89.14%, 88.33%, 88.71% at 0.05 g, at 0.15 g, and at 0.32 g, respectively, compared with the reference column.

Keywords Circularization · Slender Columns · Confinement · Drift · CFRP · NSM · Seismic

1 Introduction

Damage of (RC) (reinforced concrete) columns under seismic and in impact due to fire and explosion can prompt the whole RC structure's catastrophic failure. Columns are the primary member bearing loads in the structure and cannot go through extreme severe damages to stay in their function [1]. Through the earlier 90s, the major technique that was used to strengthen columns included expanding the segment

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M. O. Karkush and D. Choudhury (eds.), *Geotechnical Engineering and Sustainable Construction*, https://doi.org/10.1007/978-981-16-6277-5_38

by adding concrete cages or by injecting grout in steel jackets. The two methods are workers intensive and present challenges at the site [2]. “Fiber-reinforced polymer” (FRP) has been used effectually in current years as an alternate material for rehabilitate, strengthened damaged reinforced concrete structures according to its preferred tensile strength, corrosion resistance, durability, and lightweight property with comparison to steel jacketing. Many research types have proven that FRP wrapping of reinforced concrete columns is an effective method of increasing the column’s strength and ductility as it presents confinement to the concrete core [3]. External wrappings of RC columns is a high spread strengthening method that is accepted to cause gain in axial load and bending moment capacity and causing ductility improvement. The composition of CFRP sheets and longitudinal CFRP plates for slender columns is a system that can take the benefit of longitudinal stiffening members and transverse members with confinement and buckling support functions [4]. Many buildings in Iraq were designed only for gravity loading. These make structures attend a great difficulty for the persons caring with decreasing earthquake risk. However, the most building was established earlier to any particular specifications to design against earthquakes. Therefore, retrofit of these buildings was important. Results have displayed that columns wrapped by CFRP sheets enhance their strength, ductility, and energy dissipation capacity without adding stiffness to the members. The ease of installation makes the use of the CFRP sheet an effective alternative in the earthquake retrofit of existing structures [5].

Since Iraq is situated in the middle east, this is making it affected by earthquakes, and the building must be designed and constructed against seismic [6]. Most of the buildings are defective to withstand for future extensive earthquakes. Most of these buildings have common deficiencies such as insufficient reinforcing details, poor construction quality and part ratios of members was caused strong beams, weak columns, short columns, and soft stories. The concrete strength in existing structures is far less than the chosen strength values due to poor labor. The transverse confinement in members, especially near the potential plastic hinging regions is not enough. Studies on lapped bars subjected to the earthquake have shown that many of the bond mechanisms accessible through static loading of splices degrade with the number of cycles and deformations amplitude. Throughout the seismic load, confinement plays a significant part in the lapped splice strength. The reason is confinement controls the loss of mechanical connections after the enlargement of concrete [7]. One of the most effective ways to make efficient use of FRP in square columns is to modify the shape of the square sections before applying the FRP jacketing. The circularizing of a square column to change its shape is known as section circularization, and the resulting shape-modified column is known as a circularized square column [8].

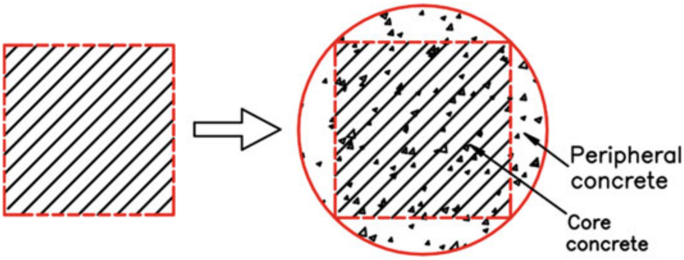

Fig. 1 Circularization for the square column

2 Circularization

Circularization is transforming non-circular concrete members into circular ones by changing their cross-sectional structure from non-circular to circular. This may be a rectangle, square, or another shape, as cited by [9]. Shape-modifications, or changing a rectangular or square column section into an elliptical, oval, or circular section, is one way to increase the usefulness of FRP-confined rectangular columns [10] (Fig. 1).

3 Methodology of Study

In this study, three reinforced concrete columns were analyzed numerically using the finite element software Abaqus (as a qualitative study to investigate the behavior of columns with different strengthening methods subjected to different amplitude 0.5 g, 0.15 g, 0.32 g El Centro 1940 earthquake before starting with the experimental study), include:

- Reference column (R): (unstrengthen square column 130 × 130 × 1500 mm) was analyzed under 0.5 g, 0.15 g, 0.32 g El Centro 1940 earthquake.
- Strengthened column (N–C): square column 130 × 130 × 1500 m was strengthened by four CFRP strips using (NSM) technique in the direction of seismic (*x* direction) then confined with CFRP wrapping was analyzed under El Centro 1940 earthquake with amplitudes of 0.5 g, 0.15 g, and 0.32 g.
- Strengthened column (N–CI–C): square column 130 × 130 × 1500 m was strengthened by four CFRP strips using (NSM) technique in the direction of seismic (x-direction) then circularized and confined with CFRP wrapping was analyzed under El Centro 1940 earthquake with amplitudes of 0.5 g, 0.15 g, and 0.32 g.
- The columns were designed using concrete strength of $fc' = 30$ MPa.
- The CFRP plate dimension is (1.2 × 6) mm with 1800 mm length, embedded in the base about 300 mm according to ACI 440.2R-17.

- The CFRP sheet thickness is 0.381 mm.

4 Material Properties

The geometry and materials properties used in the numerical modeling are given in Fig. 2 and Tables 1, 2 and 3.

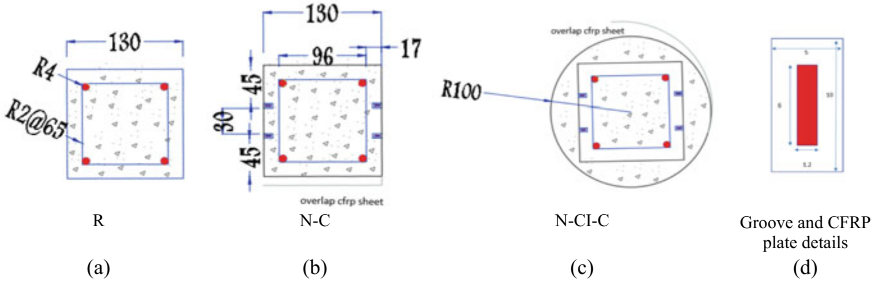

Fig. 2 Cross-section of column models (dimensions in mm)

Table 1 Sikadur 30 epoxy resin properties used with CFRP plates

Property	Value
Resin tensile strength	29 N/mm^2 (7 days at +35 °C)
Resin tensile modulus of elasticity	11,200 N/mm^2 (+23 °C)
Resin tensile adhesion strength	(>4 N/mm^2)
Resin density	1.65 ± 0.1 kg/l (component A + B mixed) (at +23 °C)

Table 2 Sikadur 330 epoxy resin properties used with CFRP sheets

Property	Value
Resin tensile strength	30 N/mm^2 (7 days at +23 °C)
Resin tensile modulus of elasticity	4500 N/mm2 (23 °C)
Resin elongation at break	0.9% (7 days at +23 °C)
Resin tensile adhesion strength	(>4 N/mm^2)
Resin density	1.3 ± 0.1 kg/l (component A + B mixed) (at +23 °C)

Table 3 Properties of CFRP plates and sheets

Property	Value	
	Plates	Sheets
Dry fiber tensile strength	3100 N/mm^2	3450 N/mm^2
Dry fiber tensile modulus of elasticity	165,000 N/mm^2	230 000 N/mm^2
Dry fiber strain at break	1.7%	1.5%
Dry fiber density	1.6 g/cm^3	1.8 g/cm^3

5 Numerical Modeling

- In this study, the mass, column, and the base of the column, circularized column, CFRP strips, epoxy resin was modeled of C3D8R: (An 8-node linear brick, reduced integration), steel reinforcement was modeled of T3D2: (A 2-node linear 3-D truss), CFRP wrap was modeled of S4R: (A 4-node doubly curved thin or thick shell, reduced integration).
- (CDPM) concrete damage plasticity model, the dynamic, implicit method was used for analyzing the models.
- Steel mass with a dimension of 0.3 × 0.3 × 0.4 m was applied on the top of the column.
- The seismic amplitudes were applied in x-direction, and the bottom block reinforced concrete (base with a dimension of 0.5 × 0.5 × 0.4 m) was assumed to be fixed and given no degree of freedom.
- For interactions between epoxy resin and concrete, between the epoxy resin and CFRP strips, and between concrete and CFRP wrapping, tie constraint was modeled. With this constraint, the members attached together and stay tied during the analysis. The constraints of concrete with steel reinforcement were modeled using the embedded region constraint. To ensure that both have the same degrees of freedom (Fig. 3).

6 Test Results and Discussion

Each model was analyzed three times using (0.05 g, 0.15 g, 0.32 g) El Centro 1940 earthquake. The max displacements were measured for each model, and for three earthquake amplitude, the numerical test results are summarized in Table 4. Figure 4 represents the displacement of the models under seismic excitation.

Figures 5, 6, 7, 8, 9 and 10 represent the displacement -time response for the models. The columns strengthened with CFRP strips, then circularized, and finally wrapped with CFRP have small displacement compared with reference column and column that strengthen with CFRP strips. Figures 11, 12 and 13 represent the displacement -time response for the same strengthening technique with the El Centro 1940 earthquake's different amplitude. It is observed that the (R) model under the

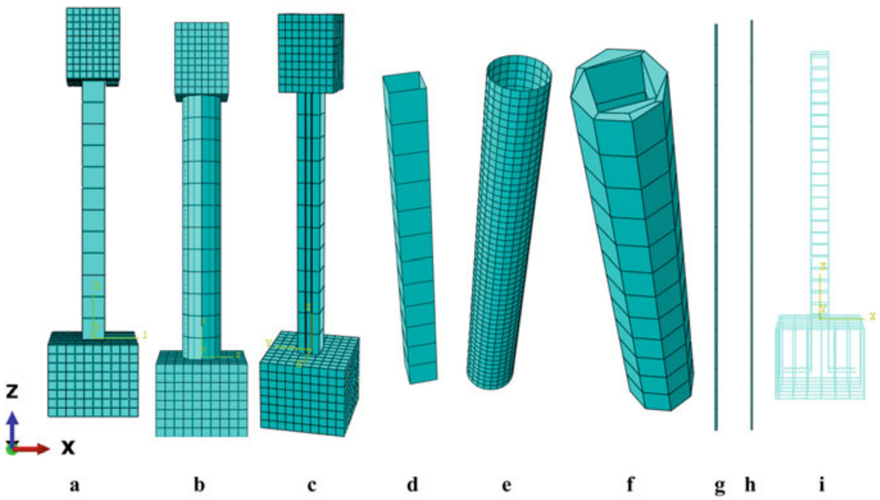

Fig. 3 Components of the numerical model: **a** R model, **b** N–CI–C model, **c** N–C model, **d**, **e** CFRP jacket, **f** circularized shape, **g** epoxy resin, **h** CFRP strip, **i** steel reinforcement

Table 4 Summary of the numerical test result

Column Type	Strengthening technique	Earthquake Amplitude (g)	Absolute Displacement (mm)		Relative Displacement (mm)	
			Max	Min	Max	Min
R	–	0.05	6.55034	−6.62044	6.329961	−6.3314
	–	0.15	19.9159	−19.7218	19.16798	−18.9763
	–	0.32	42.5623	−41.8167	37.87404	−39.7361
N–C	NSM strips with CFRP wrapping	0.05	3.38543	−2.34045	2.360752	−2.45694
		0.15	13.2692	−10.8587	5.06181	−4.85824
		0.32	24.9488	−19.8048	8.967478	−9.7981
N–CI–C	NSM strips with circularization then CFRP wrapping	0.05	3.20055	−2.86299	0.686956	−0.63808
		0.15	10.1474	−8.70042	2.236297	−2.27933
		0.32	21.7935	−17.0673	4.27452	−2.92976

different amplitude has the same behavior with different magnitudes. For the (N–C) and (N-CI-C) models under 0.15 g, 0.32 g amplitudes, also it has the same behavior with different magnitudes, but in 0.05 g the behavior is different.

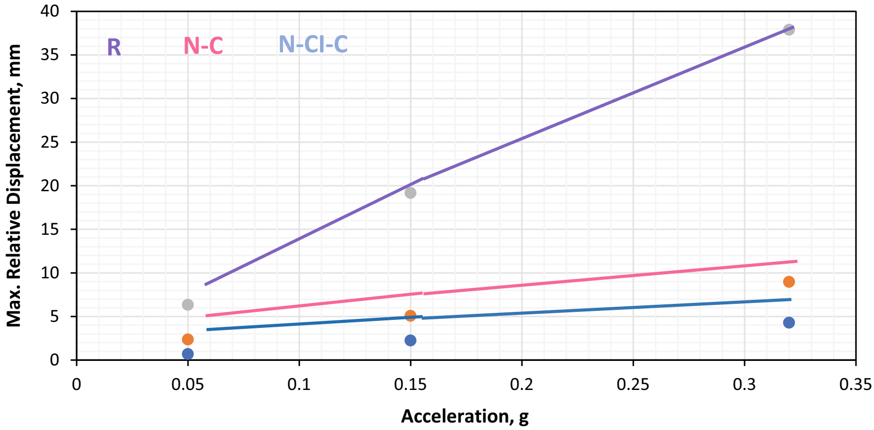

Fig. 4 Max. Relative displacement with different amplitudes earthquake to the three models

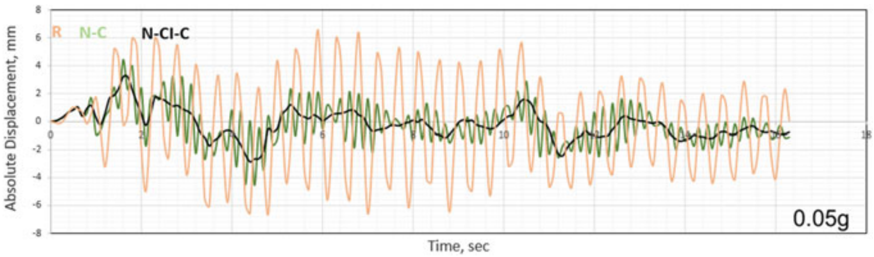

Fig. 5 Absolute displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.05 g

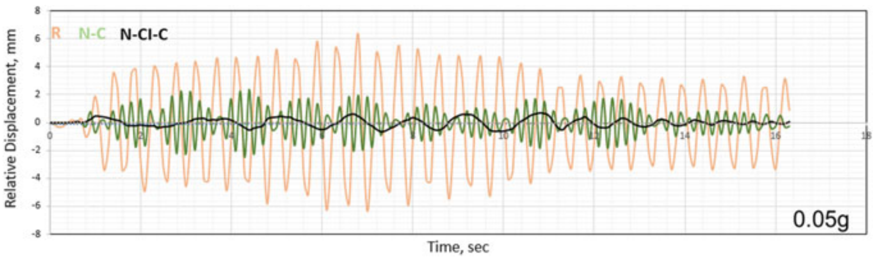

Fig. 6 Relative displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.05 g

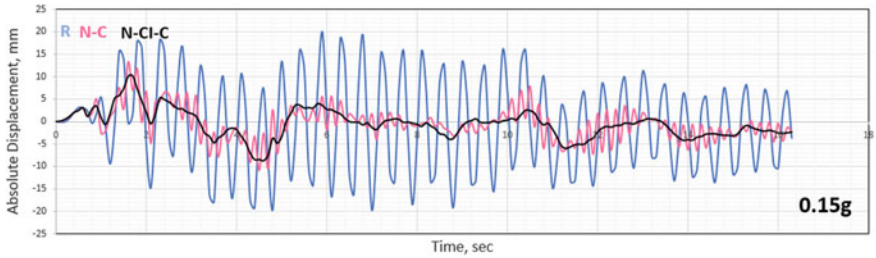

Fig. 7 Absolute displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.15 g

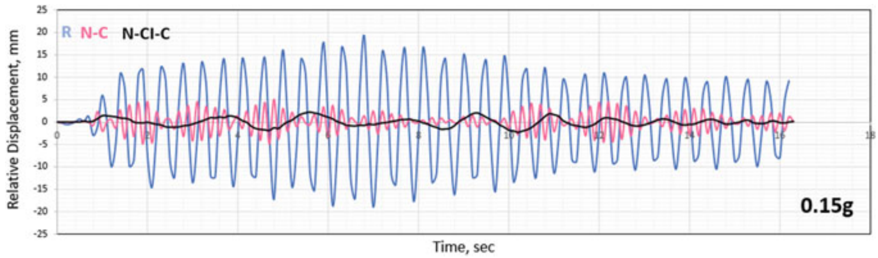

Fig. 8 Relative displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.15 g

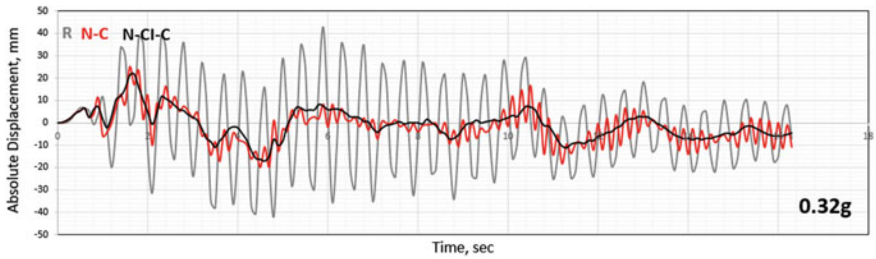

Fig. 9 Absolute displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.32 g

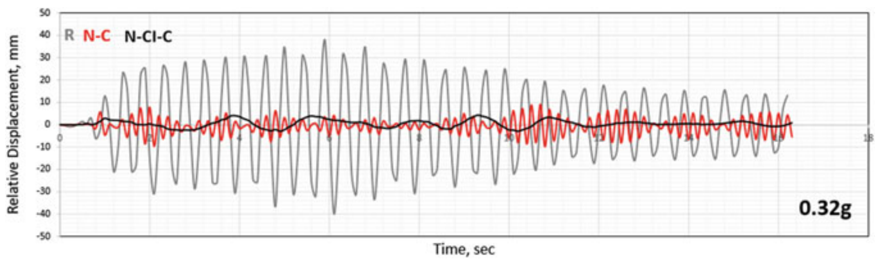

Fig. 10 Relative displacement–time response for inelastic behavior in the x-direction for acceleration amplitude 0.32 g

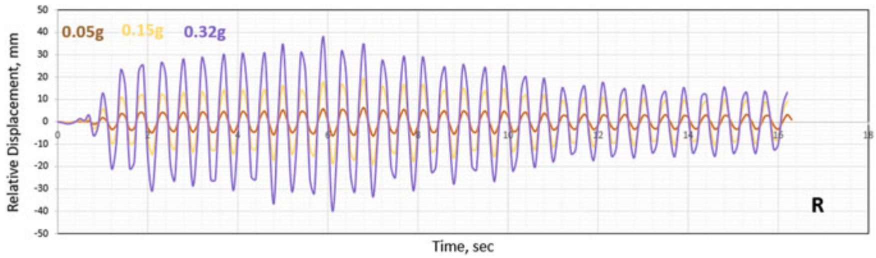

Fig. 11 Relative displacement–time response for inelastic behavior in the x-direction for R model

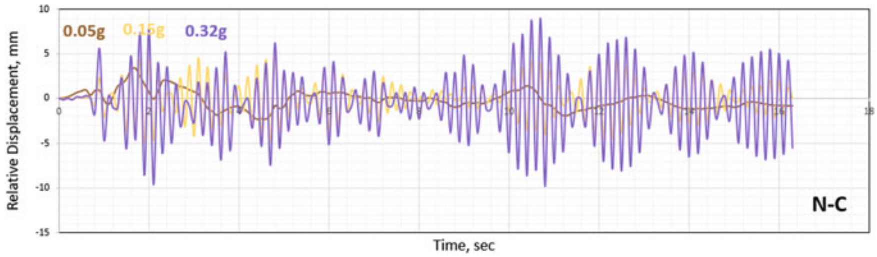

Fig. 12 Relative displacement–time response for inelastic behavior in the x-direction for N–C model

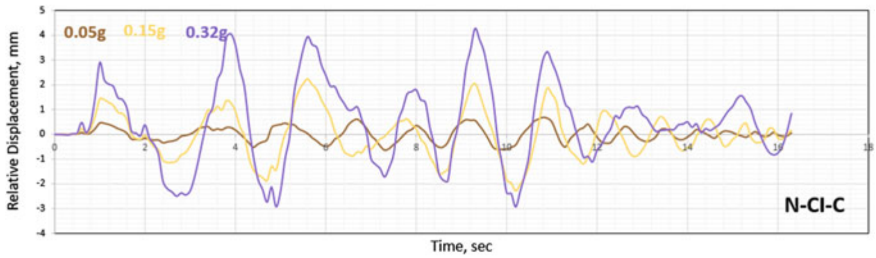

Fig. 13 Relative displacement–time response for inelastic behavior in the x-direction for N-CI-C model

7 Conclusions

A numerical study was conducted to investigate the reinforced concrete column's behavior strengthened with different techniques under different amplitude El Centro 1940 earthquake. The following conclusions were drawn.

- The circularization process essentially reduced tension accumulation areas that would otherwise exist when a non-circular column was covered in CFRP.

- Confinement with CFRP wrapping and circularization proved efficient in improving the structural performance of reinforced columns subjected to seismic excitation.
- The method of strengthening square columns using CFRP-NSM with the CFRP wrapping strengthening technique produced remarkably good results compared with the reference model. It was noticed that decreases the displacement of a column of about 62.7% of the reference model under (0.05 g), 73.59% under (0.15 g), and 76.32% under (0.32 g) and this means that the efficiency of this technique increased with increasing the earthquake amplitude.
- The method of strengthening square columns using the circularization technique and applying external confinement offered by CFRP wraps produced excellent results to reduce the displacement. For the NSM CFRP with circularization and CFRP wrapping, it is noticed that the displacement of the column is reduced about 89.14% of the reference model under (0.05 g), 88.33% under (0.15 g), and 88.71% under (0.32 g).
- The max. displacement in N–CI–C model is significantly less than the R and N–C models.
- In summary, it is possible to use these methods in Iraq for the efficiency and ease of work to strengthen the columns of buildings not designed according to the seismic load instead of "thinking about demolishing them".

Acknowledgements The authors would like to express special thanks of gratitude to the staff at the Department of Civil Engineering, College of Engineering, University of Baghdad for their support and help for making this project.

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