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Structural Behavior of Hybrid Reinforced Concrete Short Columns Under Uniaxial Load

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Abstract: Columns are essential part of several civil engineering applications that relocate the weight of the superstructure and the other loads to the soil. Usually, columns are subjected to eccentric compressive loads. Sometimes, it is required to increase the cross-sectional area of columns to gain additional load capacity. This paper investigates the behavior of reinforced concrete columns under uniaxial loading. Five specimens of 0.2 × 0.2 × 1 m were fabricated to study the effect of type of concrete and near surface mounted NSM strengthening technique on the structural behavior of the columns. All columns were tested under uniaxial loads of 50 mm offset with simply supported ends. The presented strengthening techniques are flexible and effective. The experimental results showed that using of steel fiber concrete SFC of 1% volume fraction raised the ultimate load by 200% while increasing of concrete strength by 42.1% achieved just 36.4% additional load capacity. Also, strengthening of columns using NSM steel and carbon fiber reinforced polymer bars increased the load carrying capacity by 54.5 to 136.4%. Furthermore, the stiffness criteria increased by 105.3, 29.3, and 90% for the specimens with higher compressive strength, SFC, and strengthened with NSM steel bars owing to the additional stiffness provided. However, the brittle weakness nature of FRP composites in compression decreased the stiffness criteria by 14.6%.

Keywords: Concrete columns, Steel fiber concrete, Near surface mounted, Uniaxial loads

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1. Introduction

The design of columns should receive highly importance because the failure of them result collapse of the structure. In modern construction, columns are mainly constructed by concrete and steel. Sometimes strengthening of reinforced concrete columns is required to transmit additional loads or dominating unexpected layout and material snags. Several techniques can be implemented for strengthening, selection of any method depends on the amount of load, existence of additional column area, cost, etc [1].

Julio et al. (2003) suggested a bonding agent instead of roughness for reinforced concrete columns rehabilitated using steel jacketing. Also, a uniform distribution for the additional reinforcement must be provided. Furthermore, the new concrete used must be self-compacted with high strength and durability [2].

The behavior of circular reinforced concrete columns confined using fiber reinforced polymer FRP composites was investigated by Benzaid et al. (2008) [3]. A twenty-one prisms of 100 × 100 × 300 mm were tested, they concluded that external confinement increased significantly the strength specimens subjected to axial loads.

Near-surface mounted NSM fiber reinforced polymers has been utilized by Sarafraz and Danesh (2012) to improve the flexural capacity of reinforced concrete columns under bending and compression. Seven reinforced concrete columns subjected to axial and lateral cyclic loading were used. The test results showed that the capacity and energy dissipation of the reinforced concrete columns was effectively increased [4].

Islam and Hoque (2015) reviewed the strengthening techniques of reinforced Concrete columns using steel jacket. The review focused on the effect of strengthening configurations like strip size, thickness, and spacing on load capacity, ductility, and lateral flexural strength and. It was found that steel jacketing could increase the axial strength from 18.65% to 109% [5].

The behavior reinforced concrete columns confined by glass fiber reinforced polymer GFRP was studied by Sudhakar and Partheeban (2017). Nine columns of 150 × 150 × 800 mm warped by GFRP mat subjected to axial load were tested. The results showed that the strength of columns was increased by 15.31 to 31.35% when compared with the control column. In addition, the decrease of deflection was 53.5% to 64.68% [6,7].

Tayeh et al. (2019) investigated the efficiency of repairing damaged concrete columns using thin concrete jacketing. A total of 36 identical columns of 100 × 100 × 300 mm were cast, damaged with approximately 90% of their ultimate axial load capacities, repaired, strengthened by applying normal strength or ultrahigh performance concrete UHPC with steel reinforcement of 25 or 35 mm thickness on all sides, and then retested. The experimental results showed that specimens strengthened by normal concrete jacketing experienced ultimate loads 200% higher than the unjacketed reference columns while the increase reached to 300% for columns jacketed with UHPC [8].

The behavior of reinforced concrete columns repaired using concrete jackets, steel jackets, and carbon fiber reinforced polymer CFRP sheets were studied by El-Kashif et al. (2020). The experimental study involved testing of 16 repaired columns of dimensions 150 × 150 × 800 mm under concentric and eccentric loads up to failure. The results showed that all of the strengthening techniques improved the ultimate loads. Also, CFRP wrapping experienced high ductility for both cases of loading [9].

Naji et al. (2021) reviewed the rehabilitation and strengthening techniques for reinforced concrete columns. Steel jacketing, concrete jacketing, ferrocement jacketing, CFRP jacketing and GFRP jacketing which have been used for rehabilitation of RC columns was reviewed with emphasis on its performance, advantages, disadvantages, application details, and factors that influence the design and scope of applicability. They indicated that Steel jackets provide a confined pressure, similar to the internal transverse reinforcement, especially under the effect of axial load. Also, concrete jackets that enclosed the existing member improved the column axial, shear, flexural strength and stiffness. The bond between the old and new concrete should be enhanced beforehand by roughening the surface of the original member. Finally, carbon fiber reinforced polymers CFRPs and GFRPs are great composites for strengthening RC columns. They have shown excellent performance, time saving and durability [10,11].

Many researches have been studied the behavior of reinforced concrete columns strengthened or rehabilitated by steel jacketing, concrete jacketing, and FRP composites. However, it still needs more investigations. On the other hand, axially loaded columns are rarely exist due to the bending moments developed from gravity and lateral loads Afefy and El-Tony (2016) [12]. So, the current study will focus on several strengthening techniques like using steel fiber concrete instead of normal strength concrete. In addition, initial strengthening of columns by NSM steel or carbon fiber reinforced polymer CFRP bars will be utilized. The suggested techniques will be investigated under uniaxial loading. It is expected that such techniques will improve the behavior of the strengthened columns.

2. Experimental work

2.1. Specimens

Five columns of 0.2×0.2×1 m is prepared to investigate the effect of the studied parameters as illustrated in Figure 1. The first column C_1 is cast with normal strength concrete NSC (Mix M_1), another mix M_2 is used to increase the compressive strength of concrete in specimen C_2 while SFC of 1% volume fraction and Mix M_3 is used instead of NSC in column C_3. On the other hand, both of columns C_4 and C_5 are cast with NSC (M_1) but they strengthened using 2 near surface mounted NSM Ø 8 mm steel and Ø 6 mm CFRP bars, respectively as shown in Figure 2. Table 1 provides the details of all columns used in this study.

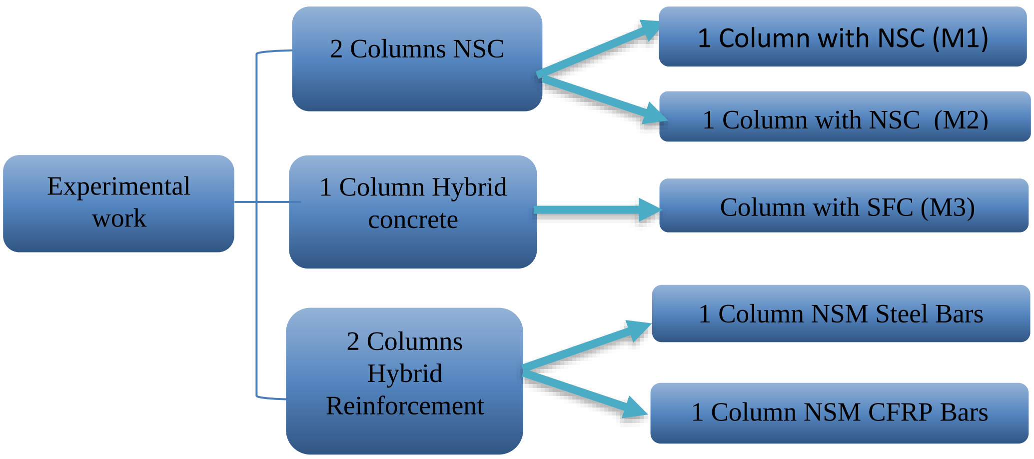

Figure 1. Description for the experimental work

Table 1. Details of the tested columns

Column symbol	Reinforcement		Type of Concrete	NSM Reinforcement
	Longitudinal	Transverse		
C_1	4 Ø 12 mm	Ø 10 mm	NSC, M_1	-
C_2		@ 300 mm c/c	NSC, M_2	-
C_3			SFC, M_3	-
C_4			NSC, M_1	2 Ø 8 mm steel bars
C_5			NSC, M_1	2 Ø 6 mm CFRP bars

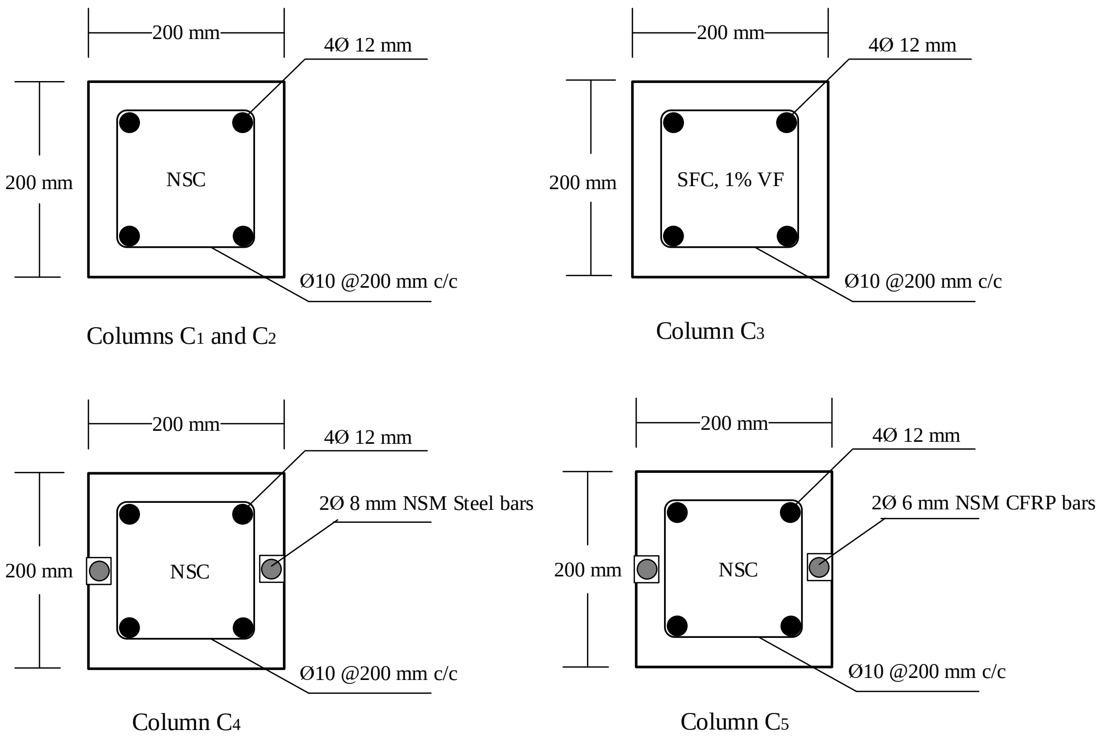

Figure 2. Details of the columns cross sections

2.2. Materials used and casting process

Two diameters of steel reinforcing bars were used in this work. Longitudinal reinforcement of size φ 12 mm and transverse reinforcement (ties) size φ 10 mm. Samples of steel bars were tested according to ASTM A615/A615M-15a (2015). The yield stress of the steel bars used were 387 and 423 MPa [13].

Concrete with a mix proportion of (1 cement: 1.8 sand: 2.75 gravel) and a water cement ratio of 0.4 was used for columns with normal strength concrete NSC. Compaction was used to expel the trapped air inside the concrete to achieve the highest possible density of the compacted mass. To increase the compressive strength of concrete, mix proportions of (1 cement: 2.2 sand: 2.7 gravel) were used with water cement ratio equal to 0.3. Master Glenium 54 supper plasticizer was added to the mixing water with a rate of 1 liter per each 100 kg of cement.

For steel fiber concrete, mix proportions of (1 cement: 1.1 sand: 1.375 gravel) were used with water cement ratio w/c equal to 0.45. Steel fibers with aspect ratio equal to 75 were used in this work by volume fraction of 1% Yazıcı et al. (2007) [14]. During casting, three 150×150×150 mm cubes were sampled for each concrete mix to evaluate the compressive strength of the concrete, the average compressive strength for each type of concrete is given in Table 2. After casting, all columns were cured for 28 days using wet burlaps.

Table 2. Concrete compressive strength

Type of concrete	Average compressive strength (MPa.)
NSC, M_1	33.7
NSC, M_2	47.9
SFC, M_3	40.3

2.3. Application of NSM steel and CFRP bars

Steel bars of 8 mm diameter and carbon fiber reinforced polymer CFRP bars of diameter 6 mm are used for strengthening one of the reinforced concrete columns. The yield stress of steel bars was 492 MPa whereas the ultimate stress of CFRP bars supplied by the manufacture is 2241 MPa. In addition, quickmast (epoxy adhesive) of two parts (the resin A and the hardener B) is also used to achieve the required bond between the steel and CFRP bars and concrete surfaces.

As shown in Figure 3, two opposite grooves of 15×15×1000 mm are made; one at each column side using hand machine so the steel and CFRP bars could be placed and filled later. To avoid debonding, the concrete surfaces are roughened and cleaned from any unsound materials before instillation. After preparing the concrete surfaces, the two parts of quick mast epoxy adhesives A and B are mixed by (1:1) till the color be homogeneous, epoxy is applied to the column with a thickness of 1 to 2 mm. CFRP or steel bars are put on the grooves which coated by epoxy, then, all grooves are completely immersed by the mixed resin using a roller to assure a sufficient bond between the bars and concrete ACI Committee 440 (2007). At least 24 hours curing time are specified for the mixed resin prior to test [15].

a. Column with groove b. Bars in coated groove

Figure 3. Application of NSM steel and CFRP bars

2.4. Test setup

All columns were painted and labeled prior to test under uniaxial loads with simply supported ends and 50 mm eccentricity. The length of each column is 1 m. A hydraulic actuator of 1000 ton capacity loading frame is used for testing. Two dial gages of 25 mm and 0.01 mm accuracy was used to measure small displacements at mid-length and under the applied load. Figure 4 shows test setup.

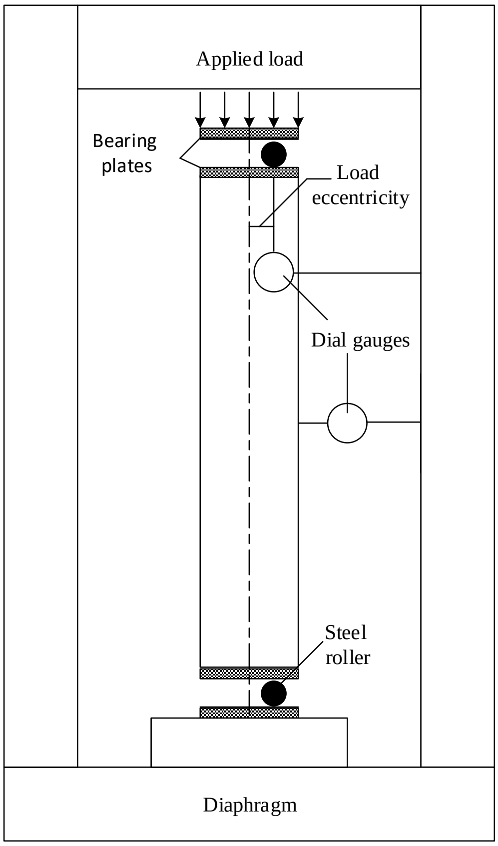

Fig.4 Specimen preparation and casting process

3. Results and discussion

3.1. General

All columns were tested under uniaxial load till failure. During test, the displacements were recorded at each load increment. Table 3 gives a summary of the test results of the columns.

Table 3. Summary of test results

Column symbol	Ultimate load (kN)	Failure mode
C_1	220	Splitting of concrete at ends
C_2	300	Splitting of concrete at ends
C_3	660	Splitting of concrete at ends
C_4	520	Splitting of concrete at ends
C_5	340	Splitting of concrete at ends

The results showed that increasing of compressive strength of concrete by 42.1% increased the ultimate loads by 36.4% while the increase is 200% when SFC is used instead of NSC because of the ability of steel fibers added to withstand additional loads by bridging the cracks, redistribute internal stresses, and provide more stiffness and ductility.

In addition, the columns strengthened by NSM steel and CFRP bars experienced load carrying capacity higher by 136.4 and 54.5%, respectively if compared with the non-strengthened normal concrete column owing to the additional stiffness provided by the steel and CFRP bars through all loading stages up to failure.

3.2. Load displacement curves

During test, the lateral mid-height and longitudinal displacements were recorded. The load lateral displacement curves of the tested columns are shown in Figure 5. The effect of compressive strength of concrete, NSM steel, and NSM-

CFRP bars on the stiffness of the columns through the reduced displacements is clear. Also, the ductility provided by steel fiber concrete is the main reason of the highest load carrying capacity of column C_3.

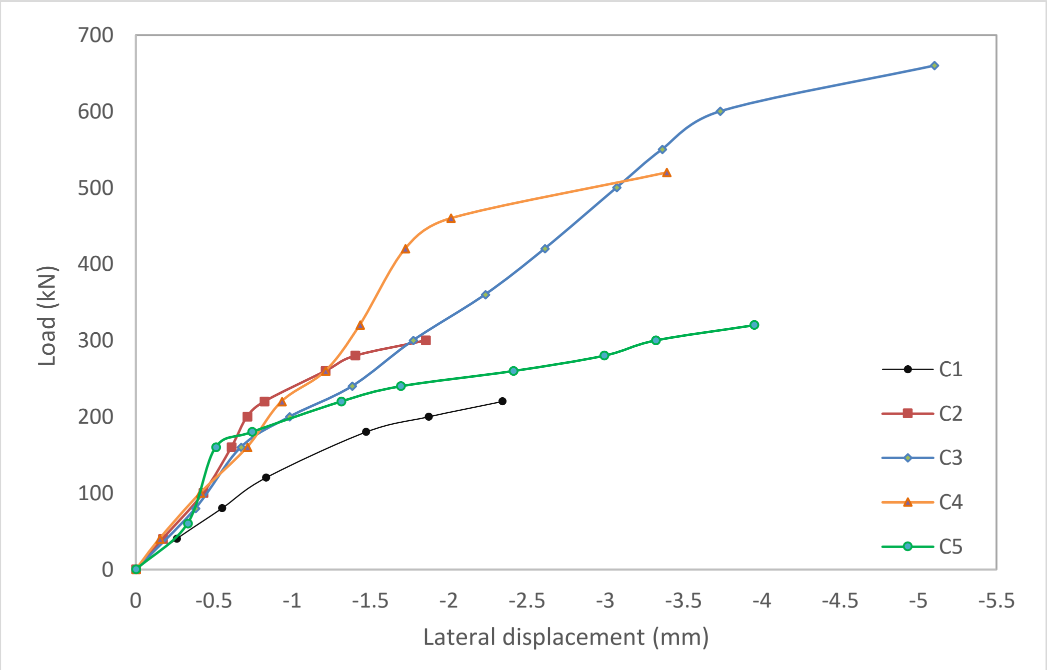

Figure 5. Load lateral displacement curves of the tested columns

For longitudinal displacement along axis of loading, column C_3 with steel fiber concrete and column C4 strengthened by NSM steel bars experienced the lowest displacements especially in the plastic zone as shown in Figure 6. The steel fibers and NSM steel bars contribution in compression is better than flexural due to the equiponderant load distribution between them and the surrounding concrete. Increasing of compressive strength in column C_2 showed a slight improvement that the load eccentricity led to a stress concentration while the brittle nature of CFRP bars used in column C_5 under compression produced similar tendency to column C_1 despite of the additional load capacity.

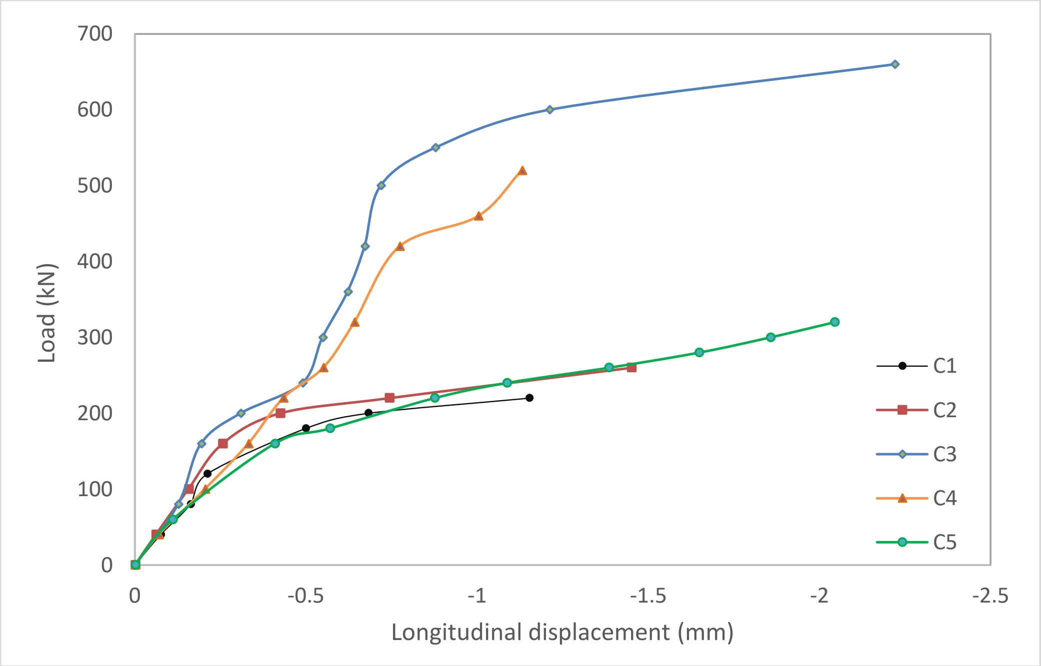

Figure 6. Load longitudinal displacement curves of the tested columns

3.3. Stiffness criteria

In the load deflection curve, the slope of the secant drawn at 0.75 of the ultimate load is called stiffness criteria Muthuswamy and Thirugnanam (2014) [16]. The stiffness criteria of the tested columns are given in Table 4.

Table 4. Stiffness criteria of the tested specimens.

Column symbol	75% of the ultimate load (kN)	Displacement at 75% of the ultimate load (mm)	Stiffness criteria (kN/mm)
C_1	165	1.31	125.95
C_2	225	0.87	258.62
C_3	495	3.04	162.83
C_4	390	1.63	239.26
C_5	255	2.37	107.59

The stiffness criteria of column C_2 increased by 105.3% if compared with column C_1 because of the stiffness added by the highly compressive strength, this increased lessened to 29.3% when steel fiber concrete is used that the steel fibers provide ductility and absorbed energy more than stiffness. In addition, strengthening of column C_4 by NSM steel bars increased significantly the stiffness criteria to about 90% if compared with the non-strengthened column of normal concrete owing to the stiffness provided by steel bars in tension or compression zones as shown in Figure 7. Despite of the high load capacity of column C_5 strengthened by NSM-CFRP bars, the fragility of FRP composites in compression decreased the stiffness criteria by 14.6%.

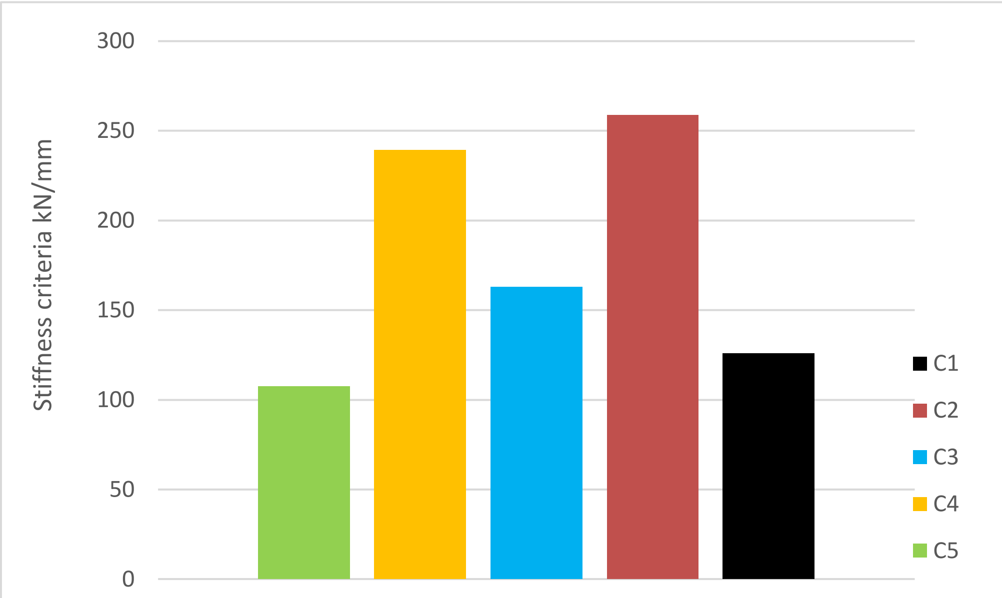

Figure 7. Stiffness criteria of the tested columns

3.4. Failure mode

As shown in Figure 8, the tested columns exhibited approximately similar failure modes at their ultimate loads, splitting of concrete at top end produced brittle failure due to the high compressive stresses which lead to transverse tensile stresses. Increasing of compressive strength, using of steel fiber concrete, and NSM steel and CFRP bars raised the first cracking and ultimate loads while steel fibers produced the highest ultimate load by bridging the cracks, providing ductility, and absorbing more energy up to failure.

a. Column C_1 b. Column C_2 c. Column C_3

d. Column C_4 e. Column C_5

Figure 8. Failure mode of the tested specimens

4. Conclusions

Based on the experimental results obtained, the following points can be concluded:

1. The suggested strengthening techniques in this paper are effective and can be implemented economically without any need to redesign or increase the cross sectional dimensions of the columns.
2. Using of high strength concrete instead of normal concrete increased the ultimate load and stiffness criteria by 36.4 and 105.3%, respectively due to the additional stiffness gained from the high compressive strength.
3. Steel fiber concrete experienced the highest load carrying capacity of the tested columns with an increase of 200% if compared with NSC and 153.8% if compared with HSC that the steel fibers bridge the formed cracks, absorb more energy, and provide ductility to the column till failure.
4. Strengthening of the RC columns by NSM steel bars of about 22% of the main longitudinal reinforcement increased the ultimate load capacity and stiffness criteria by 136.4 and 90%, respectively when compared with the non-strengthened column of NSC owing to the additional stiffness provided by the steel bars in the direction of loading.
5. Strengthening of the RC columns by 2 Ø 6 mm NSM CFRP bars increased the load carrying capacity by 54.5%. However, the stiffness criteria decreased by 14.6% if when compared with the non-strengthened column of NSC because of the brittle nature of the FRP composites especially in compression zones.

6. Despite of the high ultimate loads gained from the suggested techniques; the failure mode still rather brittle. Splitting of concrete at ends happened for all columns, these phenomena can be prevented or reduced through providing additional strengthening ties at both ends.

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Statements and Declarations

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