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Enhancing load capacity of reinforced concrete columns using high-strength concrete and fiber reinforcement

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Abstract

Strengthening of structural elements is sometimes necessary for architectural purposes to withstand additional loads without cross-section enlargement. This study evaluates the structural performance of reinforced concrete columns toughened using high-strength concrete, steel fiber concrete of 1% volume fraction, and near-surface mounted NSM steel or carbon fiber reinforced polymer CFRP bars. Five columns of 0.15×0.15×1 m were cast and axially loaded till failure. The investigational consequences revealed that a load-carrying capacity and stiffness augmented by 55.1 and 91.1% when the compressive strength is 1.5 times the normal with a ductility decrease of 28.2% whereas steel fiber concrete raised them by 34.3, 6.4, and 11.6%. In addition, NSM steel or CFRP bars exhibited ultimate loads and stiffness 13.6 to 29.7% and 17.2 to 21.7% higher than the non-strengthened column. However, the ductility decreased by 2.5 to 12.4%.

Keywords: Sustainability, Load capacity, Reinforced concrete columns, High-strength concrete, Fiber reinforcement

1. Introduction

Columns are an essential part of any structure that transmits the load to the foundations. Although many materials are available for columns, such as steel and timber, most traditional facilities columns are made from concrete due to its bearable strength and durability which make it an optimal choice for construction. Sometimes, a cross-sectional area for columns does not meet the target capacity so, it is necessary to obtain additional resistance without increasing the cross-sectional area [1].

The structural performance of reinforced concrete columns has been investigated by many researchers during the last decades. A bonding agent was suggested by Julio et al. as an alternative to the roughness of old concrete in strengthening with a reliable distribution for reinforcement [2]. After extensive review, steel jacketing could raise the axial strength of the renovated columns from 18 to 109% [3].

Benzaid et al. [4], concluded that concrete column confinement with fiber-reinforced polymer FRP reinforcement increased considerably the axial strength for tested specimens. Also, an intensification in the axial capacity of 15.31 to 31.35% with a decrease of 53.5 to 64.68% in the deflections was achieved [5].

Strengthening of reinforced columns by near-surface mounted NSM – FRP bars was employed by Sarafraz and Danesh [6], the proposed technique was effective in promoting capacity and energy dissipation for specimens under constant axial compression with lateral cyclic loads. Grooves made in concrete surfaces for bonding of CFRP composites delayed buckling which in turn led to a compelling rise in the load-carrying capacity of the strengthened columns [7].

Tayeh et al. [8] examined the effect of concrete jacketing for concrete columns damaged by loading to about 90% of their actual capacities. Normal and ultra-high performance concrete were used in jacketing. According to the experimental consequences, the ultimate loads increased by 186 to 300% when compared with the unjacketed columns. The efficiency of different techniques for repairing concrete columns was investigated by El-Kashif et al [9]. Specimens strengthened by steel, concrete jacketing, and CFRP sheets have been tested under centric and eccentric loads, the proposed techniques increased the axial capacity, but the FRP composites gained the highest ductility.

Concrete columns strengthened with steel plates, straps, and ferro-cement were evaluated by Sirimontreea et al. [10], under monotonic axial loads. The final load and ductility for strengthened specimens improved by 40% to 95% and 50% to 144%, respectively. Vivekanandan and Aarthi revealed that strengthening reinforced concrete columns with fiber-reinforced cementitious matrix combined with externally bonded FRP materials raised the capacity and enhanced the ductility of the strengthened columns [11].

A novel NSM configuration for strengthening of concrete columns through which horizontal NSM are connected with vertical NSM was investigated numerically by Gurunandan and Raghavendra [12], and the results showed that four horizontal NSMs are optimal for column specifications. Hamoda et al. [13], utilized different configurations for strengthening of columns with external stainless steel plates, a load capacity and absorbed energy increased by 26 to 112% and 34 to 190%.

Different techniques for strengthening have been studied by many researchers. However, the strengthening schemes still need more investigation. In addition, some configurations have not been investigated together yet. The present study will evaluate the employing of high-strength concrete, steel fiber concrete, NSM steel, and CFRP bars in strengthening concrete columns without an increase in the cross-sectional area. It is prospective that such methods will enhance the capacity and stiffness of strengthened columns.

2. Methodology

2.1. Specimens

In this study, five circular specimens of 150 mm diameter and 1000 mm height were prepared, cast, and then tested to evaluate the proposed parameters. The first column was cast with normal concrete without any strengthening scheme. High strength and steel fiber concrete of 1% volume fraction were used in the next two columns. The last two columns were cast with normal concrete as the first control specimen, but NSM steel and CFRP bars were used for strengthening, respectively [14]. Table 1 explains the particulars for columns while Figure 1 depicts a cross-section of each specimen.

Table 1. Details of the specimens

Column symbol	Reinforcement		Concrete type	Strengthening configuration
	Longitudinal	Transverse		
C1	4 Ø 10 mm	Ø 6 mm @ 10 mm c/c	Typical strength concrete NSC	-
C2			High strength concrete HSC	-
C3			Steel fiber concrete SFC	-
C4			Typical strength concrete NSC	4 Ø 10 mm steel bars
C5			Typical strength concrete NSC	4 Ø 6 mm CFRP bars

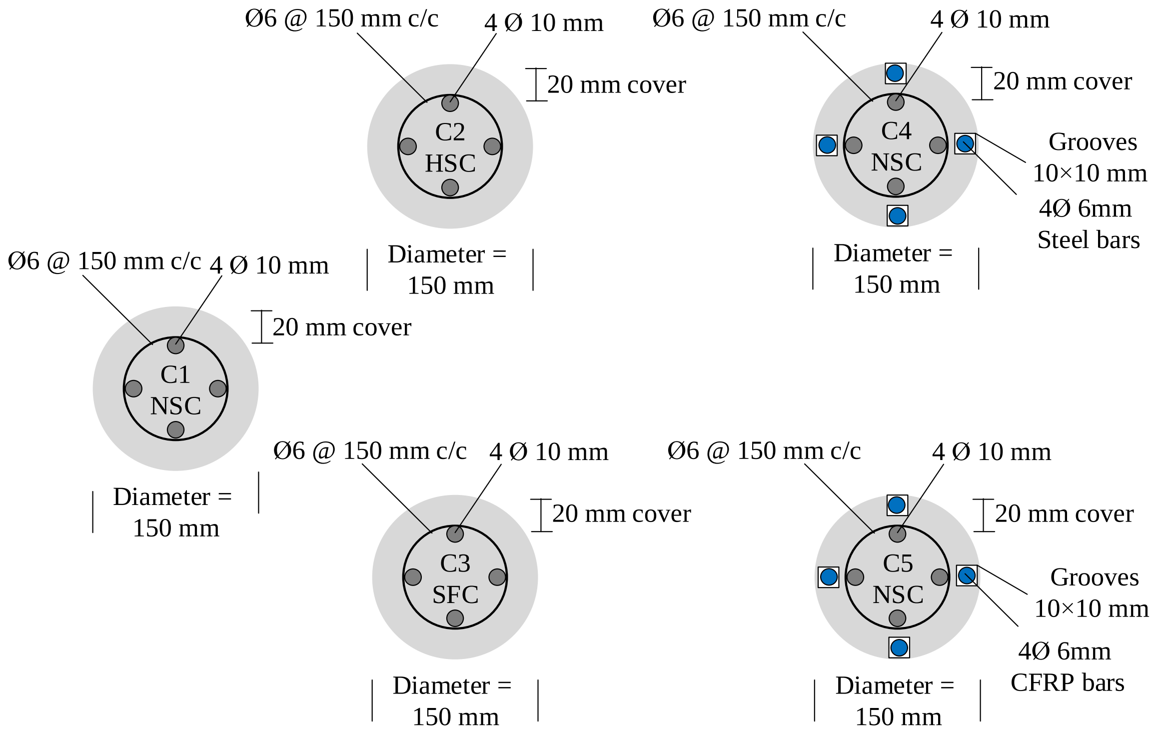

Figure 1. Cross sections of the tested columns

2.2. Materials and cast process

Steel reinforcing bars of 10 and 6 mm diameters were used for longitudinal, transverse reinforcement (ties), and strengthening of column C4, based on ASTM A615/A615M-15a, the yield strength was 577 and 623 MPa, respectively [15].

For this project, three different concrete mixes were used. M1 normal strength concrete with a water-to-cement ratio of 0.4 and a mix proportion of 1 cement to 1.8 sand to 2.75 gravel. In M2, a water-cement ratio of 0.35 and Master Glenium 54 superplasticizer at a rate of 1 liter per 100 kg of cement was utilized to increase the compressive strength of the concrete. The mix proportions utilized were 1 cement, 1.6 sand, and 1.73 gravel. The M3 steel fiber concrete mix is called for 1 part cement, 1.1 parts sand, and 1.375 parts gravel, with a water-to-cement ratio of 0.45. Connected knots One percent by volume of steel fibers with a 75 aspect ratio had been utilized [14].

The plan called for using normal-strength concrete to cast columns C1, C4, and C5, high-strength concrete to cast column C2, and steel fiber concrete to cast column C3, in that order. We measured the average compressive strength of concrete by sampling cubes and cylinders. For 28 days, all of the columns were treated using wet burlaps. It is possible to see the mean compressive strength of concrete in Table 2.

Table 2. Average compressive strength

Concrete mix	Average compressive strength (MPa)
NSC, M1	39.63
HSC, M2	59.39
SFC, M3	43.33

2.3. Strengthening of columns by NSM steel and CFRP bars

As illustrated in Table 1, column C4 was planned to be strengthened by 4 Ø 6 mm NSM steel bars. Similarly, four CFRP bars of 6 mm diameter were suggested for strengthening column C5. The rupture stress of the CFRP bars from the manufacturer was 2240 MPa. Firstly, four grooves of 10×10×1000 mm where the bars were placed were made using a hand machine. The grooves were rough and clean to ensure the best contact with concrete surfaces. A quick mast epoxy adhesive was used to cover the grooves surface then, the bars were placed into the grooves and filled with epoxy [16]. The strengthened columns were left for seven days for curing.

2.4. Test setup

Prior to the test, the specimens were painted and then labeled. The loading frame shown in Figure 2 with a hydraulic actuator of 10000 kN capacity and simply supported ends was used for testing. Dial gages of 0.01 mm accuracy were fixed at the bottom and mid-length to record the axial and lateral displacement at each load increment during the test.

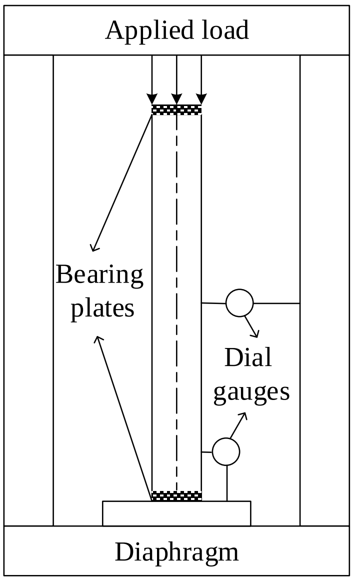

Figure 2. Test setup

3. Consequences and discussion

3.1. General

Everything was tried and tested until it broke. The displacements and cracks were carefully observed, documented, and marked throughout the test. A synopsis of the test results is provided in Table 3. Figure 3 shows the patterns of cracks that formed after the specimens failed.

Table 3. Summary of the test results

Column symbol	Concrete type	Strengthening configuration	First cracking load (kN)	Ultimate load (kN)	Failure mode
C1	NSC	-	223	236	End splitting
C2	HSC	-	357	366	End splitting
C3	SFC	-	309	317	Concrete crushing
C4	NSC	4 Ø 10 mm steel bars	288	306	End splitting
C5	NSC	4 Ø 6 mm CFRP bars	255	268	End splitting

The results revealed that column C2 with a compressive strength higher than NSC which was used in column C1 raised the cracking and ultimate load by 60.1% and 55.1% with a similar failure mode in consequence of the extra load gained from the increase of the compression resistance [17]. Also, the increase in column C3 was 38.6% and 34.3% despite steel fiber concrete SFC resistance close to NSC with a different failure mode (Concrete crushing) that the steel fibers used had the ability to redistribute the internal stresses, absorb more energy, and bridge the formed cracks till failure. Moreover, the strengthening of columns C4 and C5 by additional NSM steel or CFRP bars enhanced the load-carrying capacity by 13.6% to 29.7% due to the extra uniform stiffness supplied through the section.

Figure 3. Crack patterns (C1-C5)

3.2. Load deflection response

An axial and lateral displacement for the tested columns versus an applied load are shown in Figures 4 and 5, respectively. Column C2 exhibited the lowest axial displacement as a consequence of the additional axial stiffness provided by the highest compressive strength while the minimum lateral deflections have been noticed in columns C4 and C5, especially in the last loading stages that the location NSM steel and CFRP bars introduce buckling resistance more than axial stiffness.

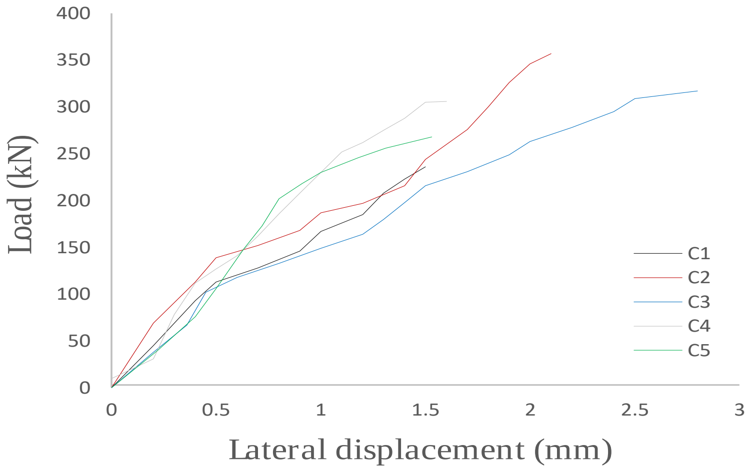

Figure 4. The lateral displacement for the tested columns

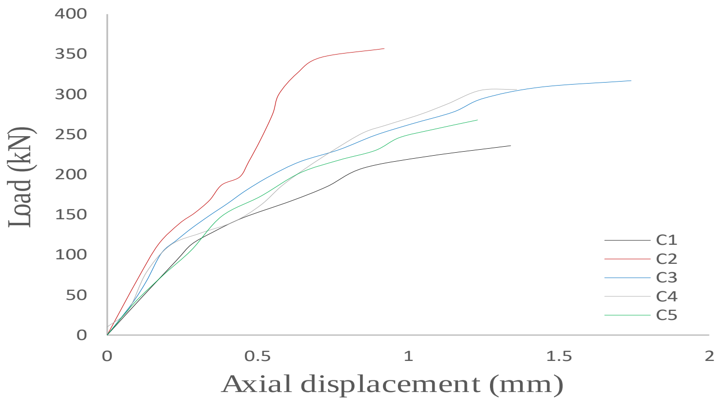

Figure 5. The axial displacement for the tested columns

3.3. Ductility index

Under externally applied loads, members exhibited displacements and rotations. When the slope of load-displacement polynomial decreases, the stiffness of the member is adversely affected so, the post-elastic deformations depend substantially on the member's ductility which can be theoretically determined by dividing the displacement at 95% of the ultimate load by that at 67% [15]. Based on the load-displacement curve, the ductility indices are given in Table 4.

Table 4. Axial ductility index for the tested columns

Column symbol	Displacement at 67% of peak load (mm)	Displacement at 95% of peak load (mm)	Ductility index
C1	0.542	1.095	2.02
C2	0.512	0.742	1.45
C3	0.620	1.333	2.15
C4	0.650	1.147	1.77
C5	0.539	1.062	1.97

Increasing compressive strength decreased the ductility index while steel fibers raised it [18]. Column C2 showed a ductility index lower than C1 by 28.2% but it was increased by 6.4% when steel fiber concrete was used. On the other hand, the strengthening of columns C4 and C5 by NSM steel and CFRP bars reduced the ductility index by 2.5 to 12.4%. It is striking that CFRP bars exhibited higher value when compared with steel bars due to the huge decrease of the CFRP bars in compression which led to large displacements.

3.4. Stiffness criteria

Any change to material or geometric properties of member cross-section affects negatively or positively to the stiffness. Theoretically, a slope for a line drawn from the origin intersects the load-displacement curve at 75% of the peak is called stiffness criteria. Table 5 provides the values of stiffness for the tested columns.

Table 4. Stiffness criteria for the investigated columns

Column symbol	75% of the peak load (kN)	Corresponding displacement (mm)	Stiffness criteria (kN/mm)
C1	177.0	0.677	261.45
C2	274.50	0.547	501.83
C3	237.75	0.815	291.72
C4	229.50	0.748	306.81
C5	201.0	0.631	318.54

As usual, increasing concrete strength introduced the highest stiffness. The stiffness of column C2 increased by 91.9% when compared with C1 and the difference between normal and high-strength concrete appears directly to the stiffness. Also, steel fiber concrete in column C3 enhanced the stiffness by 11.6% despite the convergent strength to the normal attributable to the ability of the distributed steel fibers to maintain a bond between the concrete matrix. On the other hand, the strengthening of columns C4 and C5 with NSM steel and CFRP bars improved the stiffness by 17.2% to 21.7% owing to a large modulus for elasticity of an added reinforcement which provides additional virtual cross-sectional area without geometrical changes.

4. Conclusions

The current study adopts some techniques to strengthen reinforced concrete columns under axial loads. After evaluation of the specimen's structural behavior based on the obtained experimental consequences, the following can be inferred:

- The proposed methods can be easily used before or after casting without the need to increase the cross-sectional area.
- Increasing the concrete compressive strength is the easiest way to improve the behavior of a column. The ultimate load and stiffness are raised by 55.1% and 91.1% when a compressive strength is augmented by about 50% so an additional strength gained will cover all of the cross-sectional area. However, the ductility decreased by 28.2% owing to the rather brittle nature of huge-strength concrete.
- Steel fiber concrete improved the behavior of columns with strength close to that of normal. The ultimate load, ductility, and stiffness increased by 34.3%, 6.4%, and 11.6% due to the ability of steel fibers to redistribute the stresses, bridge the micro cracks, and provide ductility to withstand additional loads.
- Strengthening of columns with NSM steel or bars raised an ultimate load and stiffness by 29.7 and 17.2% attributable to an added stiffness provided by the symmetric distribution of bars. However, the ductility decreased by 12.4%.
- The ultimate load and stiffness increased by 13.6% and 21.7% when CFRP bars were used for strengthening. However, the ductility decreased by 2.5% as a result of the brittle nature of FRP reinforcement.

Conflict of interest

The authors declare that they have no conflict of interest and all of the authors agree to publish this paper under academic ethics.

Author contributions

All the authors contributed equally to the manuscript.

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