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Efficient use of steel fiber in high-strength reinforced concrete columns

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Abstract

The inclusion of steel fibers has been widely used in column members due to its effectiveness in enhancing strength, ductility, and delaying concrete cover spalling failure. Reinforced concrete columns are recently included steel fibers to enhance their structural performance and control the strain in concrete. In this study, partially-fibered and fully-fibered high-strength concrete (HSC) columns were investigated and compared to non-fibered HSC columns. The partially-fibered columns were examined here to eliminate the extra use of steel fibers through the confined core of the columns. The experimental work included different study parameters: percentage of steel fiber content, columns' length, and internal reinforcement details. The columns were tested under concentric axial loads. The results were analyzed in terms of improvement in the ultimate load, displacement ductility, and energy absorption. The test results determined the impact of using steel fibers in enhancing the axial ultimate load capacities of HSC columns between 14% to 80% of that in non-fibered columns and controlling the concrete cover spalling failure. As well, the test results showed that the increase in steel fiber content improved both the ductility displacement index by 29% to 66% of that in the non-fibered column and the energy absorption index by 1.5 to 3.2 of that in the non-fibered column.

Keywords

Steel fiber, High-strength concrete, Columns, Axial compression, Ultimate load, Failure.

1.Introduction

Reinforced concrete (RC) columns are the main structural elements in most infrastructural systems. High-strength concrete (HSC) columns have recently been used to improve the mechanical and durability performances of RC columns. However, a low confinement effect was detected [1] and a brittle failure of concrete columns was observed [2]. To overcome these problems, steel fibers were included in a mixture of HSC columns. Much experimental research has investigated the influence of the addition of steel fiber to HSC columns. Some research works have inspected the performance of steel-fiber HSC columns under concentric and eccentric compression loads [1−6].

The experimental results concluded the effect of the addition of steel fiber on arresting concrete cover spalling and increasing the ultimate load and ductility of the corresponding columns. The test results showed that the inclusion of steel fiber improved the ductility of HSC columns by altering the descending portion of the stress-strain curves.

As well, the deformability of HSC columns was developed by increasing both the strain at peak stress and the ultimate compressive strain at failure. The positive effect of steel fibers was observed through the experimental tests by bridging action across microcracks in the concrete mixture which was eliminated the cracks and reduced the crack opening [7]. Based on that, this study is to examine the structural behavior of non-fibered and fiber-reinforced HSC columns. This paper presents an experimental testing of circular medium-scale HSC columns under concentric compressive loading.

As the concrete cover spalling is observed for the outer columns' shell where the inside columns' core is confined by internal transverse reinforcement, the idea of this work is to include the steel fibers on the outer shell of HSC columns. Therefore, the experimental work included some columns with steel fibers provided on the outer shell of RC columns

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(partially-fibered columns) and other columns with steel fibers distributed on the entire cross-section area of the columns (fully-fibered columns). This study aims to dig into the structural performance of partially-fibered columns in comparison with fully-fibered columns and verify the possibility of using steel fibers only on the outer shell of HSC columns instead of using steel fibers through the entire cross-section area of HSC columns. The work paper is organized to involve an introduction section in the first section. A literature review for previous works and findings in the second section. Description of the used materials and their mechanical properties, method of casting the partially-fibered and fully fibered HSC columns, and the testing process and instrumentations are presented in the third section. The experimental test results and discussion of the study parameters are analyzed in the fourth and fifth section, and finally the conclusion and future works have been discussed.

2.Literature review

Several experimental studies that have been conducted to determine the influence of the inclusion of steel fibers into HSC column mixtures are presented here.

Tokgoz [8] examined the effects of steel fiber inclusion on the structural behavior of 14 short and slender HSC columns subjected to biaxial bending and short-term axial load.

Hadi [9] explored the effect of adding steel fiber to HSC columns only through the concrete cover area. The experimental axial testing on the columns showed an insignificant increase in the ultimate load by the addition of 1, 1.5, and 2% steel fiber content, respectively. However, the ductility increased in the columns having steel fiber content in the outer concrete cover only than for fully-fibered columns.

Paultre et al. [10] experimentally examined the effect of steel-fiber content on the structural performance of square fully-scale HSC columns under axial compression loads. The finding results demonstrated that the inclusion of steel fibers was enhanced the confinement action of the columns by preventing the concrete cover spalling failure as well as the columns' strength and ductility was increased.

On the same path, Mohammadi [11] directed a comprehensive research program to study the axial behavior of high-strength and ultra-high-strength RC columns having steel fibers. Twenty-three fully-scaled columns were experienced axial compression loads. The test results confirmed the improvement in the column behavior in terms of enhancements in the core confinement and cover behavior by the addition of steel fibers to the concrete mixtures. Also, the test results showed that the steel fibers can permit partial replacement of transverse reinforcement to resist shear stresses.

Perceka et al. [12] determined the effectiveness of steel fibers in HSC columns that were confined with internal lateral reinforcement and steel fibers analytically and experimentally. The experimental testing included sixteen square columns in different sizes under axial compression load. The steel fiber' volume fraction was differed by 0.75%, 1%, and 1.5%, and the transverse reinforcement was varied between 0% and 7.92%. The experimental results proved the influence of transverse reinforcement spacing on the performance of steel fibers in concrete. As the transverse reinforcement spacing enlarged, the efficiency of steel fibers increased. Another study conducted on the influence of hybrid steel fibers on the structural performance of circular HSC columns was reported [13].

Hybrid steel fibers were included a combination of macro steel fibers and micro steel fibers. Four different loading tests were investigated central load, eccentric loads, and four-point loads. The experimental results revealed the ability of hybrid steel fibers on improving significantly strength, ductility, and axial and lateral deformability.

Hung and Hu [14] experimentally studied the behavior of ten HSC slim columns reinforced with steel fibers under central axial loads. The results for slim columns with 0.75% steel fiber's volume fraction and more were restricted the spalling and crushing in concrete and transferring the failure mode to multiple narrow cracks. Furthermore, the full replacement of lateral steel reinforcement by 1.5% volume fraction of steel fiber enabled the columns to reach the compatible results of that in the control column.

Moreover, Wu et al. [15] experimentally deliberated the axial performance of hybrid concrete columns. The hybrid columns consisted of a shell with 20 mm thickness of ultra-high performance concrete with steel fibers and a core with normal strength concrete. The axial performance of hybrid concrete columns in terms of cracking, initial stiffness, ultimate load, displacement ductility, and energy absorption were improved concerning an increase in the steel fiber content or an increase in the lateral reinforcement. In addition, the test results revealed that the hybrid concrete columns behaved with fully-composite action on the initial loading stage and then to non-composite action when the reinforcing bars reached the buckling failure.

Al-Taan and AlDoski [16] examined twenty HSC columns with steel fibers in a square shape that were exposed to axial and biaxial compression loading. The steel fiber's weight was differed by (0, 1.2, 2.4, and 3.6 percentages) and the eccentricity was varied as (0, 16, 32, 48, and 64 mm). The experimental results showed the predominant effect of steel fibers in reducing the strain in the concrete and steel reinforcement as well as to the other advantage obtained in previous research works.

Usman et al. [17] also investigated the axial performance of HSC columns confined with steel fiber and fiber-reinforced polymers. The combined use of steel fiber and fiber-reinforced polymer confinement were enormously enhanced the axial compression behavior of HSC columns. As well, the failure mode turned from a brittle to ductile failure mode.

Gorgis et al. [18] explored the performance of square short HSC columns with and without steel fiber when subjected to concentric compression force. The experimental study was conducted for two different aspect ratios of steel fibers, L/d was equal to 60 and 100. The volume fraction of steel fiber was taken as 0, 0.5, and 0.75%. The test results showed that the strength and ductility of HSC columns were improved as the aspect ratio or the volume fraction of steel fibers increased.

On the other hand, Perceka and Liao [19] studied the shear behavior of HSC columns with steel fibers. The study included testing eight large-scale columns. The experimental results showed that the increase in the shear strength of the columns' specimen under low axial load level was more distinguished than for other columns'specimensn under high axial load level as the steel fiber' volume fraction increased.

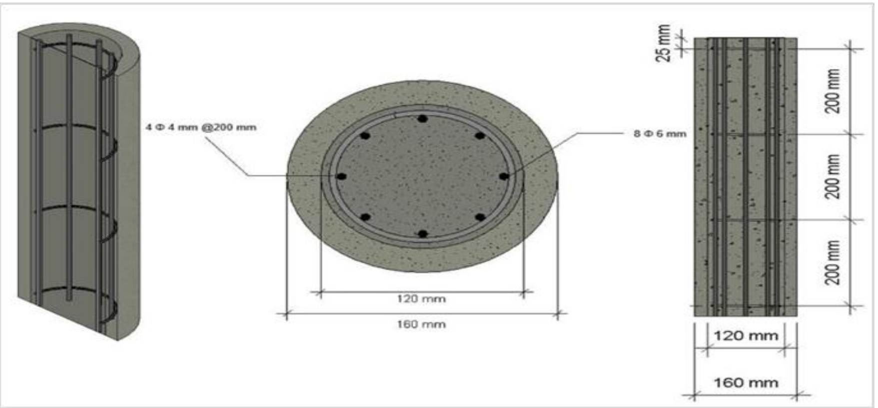
Suda and Rao [20] conducted a laboratory study of the ternary columns with steel fibers under axial compression loading. The study program included steel fiber with different ratios of volume fractions as 0.5%, 1%, 1.5%, and 2%. The test results determined that the steel-fibered columns observed better structural performance in terms of their ultimate load capacities, energy absorption, and ductility index in comparison with the conventional concrete columns and ternary columns.

As stated here, the steel fibers can enhance the strength and ductility of HSC columns and develop the confinement action. However, the addition of steel fibers through the entire cross-section area of columns present inefficient use of the materials when the inner concrete core is already restricted by the internal lateral reinforcement. Therefore, the idea of this study is to partially use the steel fibers at the outer shell of the columns. In such a case, the steel fiber will confine the outer cover of HSC columns while the inner core of HSC columns is still confined by the internal lateral reinforcement. A comparison between reinforced HSC columns with steel fiber through the entire cross-section (fully-fibered) and reinforced HSC columns with steel fiber at the outer cover (partially-fibered) was demonstrated to evaluate the performance of partially-fibered HSC columns. The experimental variables included partially-fibered and fully-fibered HSC columns with different percentages of steel fiber inclusion, columns' length, and impact of steel fibers as lateral reinforcement. The current work considered the performance of HSC columns subjected to an axial compression load in terms of the ultimate load capacities, axial displacement, energy absorption, and displacement ductility. Also, the failure mode of each columns' specimens was announced during the test.

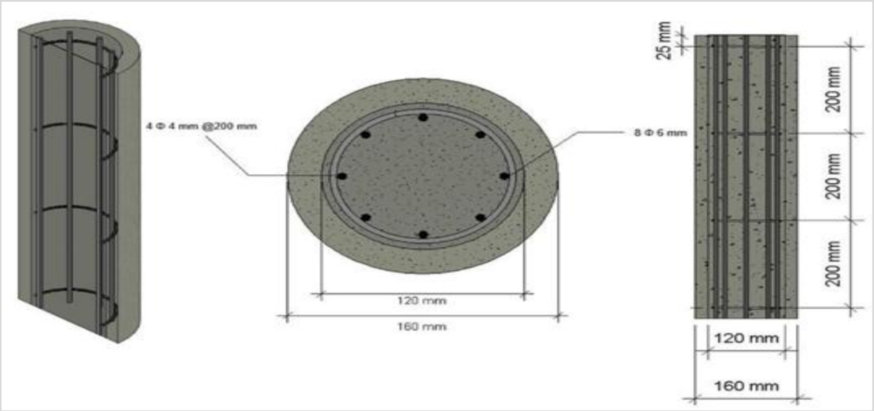
3.Materials and methods

3.1Description of columns

The experimental work of this research included testing eight circular-scaled columns subjected to monotonically concentric axial compression. One column was fabricated without steel fiber (control column). Five columns were partially reinforced with steel fiber (at the outer cover). Four columns had an overall height of 650 mm while the fifth column had a 1000 mm height. The other two columns were fully reinforced with steel fibers. Seven of the columns were reinforced with 8-Ø6 internal longitudinal reinforcement and Ø4@200 mm internal lateral reinforcement. However, two columns had no internal reinforcement to examine the function of steel fibers as internal lateral reinforcement. The test matrix is presented in *Table 1*. Columns' specimens were identified by the letter C and numbers from one to eight. The column's specimen (C1) referred to the control column with no fiber content. The other columns' specimens from (C2 to C8) referred to columns with either partially or fully fiber content. The partially-fibered columns' specimens were represented by the letter P and numbers based on steel fiber content in percentage as P0.8, P1.4, and P2. As well, the fully-fibered columns' specimens were represented by the letter F and number based on steel fiber content in percentage as F1.4. The geometries of the columns are presented in *Figure 1(a)-(b)*. All of the columns' specimens had a circular cross-section of 160 mm diameter. In fully-fibered HSC columns, the whole cross-sectional area (concrete core and cover) of the specimens contained an addition of steel fiber. While in the partially-fibered specimens, only the concrete cover with 40 mm thickness had an addition of steel fiber. The addition of discrete steel fiber was ranged from 0% to 2%, as detailed in *Table 1*. The addition of steel fibers was chosen based on recommendations of previous studies [21, 22]. These studies determined a decrease in the concrete compression strength when the volume fraction of steel fiber was exceeded 2%.



(a)Columns with 650 mm length



(b)Columns with 1000 mm length

Figure 1 Columns' cross-sectional and reinforcement details

Table 1 Columns' reinforcement details

Column ID	The volume of fraction for steel fibre, (%)	Steel fiber content	Column length, mm	Steel reinforcement	
				Long.rein.	Tie rein.
				No. & size (mm)	size & spacing (mm)
C1-Control	0	N0 fibre	65	8Ø6	Ø4@200
C2-P0.8	0.8	Partially fibered	65	8Ø6	Ø4@200
C3-P1.4	1.4	Partially fibered	65	-	-
C4-P1.4	1.4	Partially fibered	65	8Ø6	Ø4@200
C5-P1.4	1.4	Partially fibered	100	8Ø6	Ø4@200
C6-P2	2	Partially fibered	65	8Ø6	Ø4@200

Column ID	**The volume of fraction for steel fibre, (%)**	**Steel fiber content**	**Column length, mm**	**Steel reinforcement**	
				Long.rein.	**Tie rein.**
				No. & size (mm)	**size & spacing (mm)**
C7-F1.4	1.4	Fully fibered	65	-	-
C8-F1.4	1.4	Fully fibered	65	8Ø6	Ø4@200

3.2Columns' fabrication

The columns' specimens were prepared for vertical casting using two different diameters of steel tubes that were cut to the required height of the columns. In fully-fibered specimens, only one steel tube with 160 mm diameter was fabricated to mold the specimens. While for partially-fibered specimens, two steel tubes were used. The exterior tube had a cylinder diameter of 160 mm and the interior tube had a cylinder diameter of 120 mm, as presented in *Figure 2a*. The purpose of these two tubes was to isolate the concrete mixture that contained steel fiber from the one with no steel fiber.

The base of the molds was made from a plywood panel which has square dimensions of 300 mm * 300 mm. A circular hole with 120 mm diameter and 10 mm depth was prepared using a machine to position the interior tube so the constant cover was achieved from all sides. All the required tubes were cut vertically and then hooks were welded to the tubes to connect the tubes with the base plate. Small steel parts were welded at the top of the interior tube to maintain equal thickness between the exterior and interior tubes, as presented in *Figure 2(a).* In addition, a handle was welded at the top of the interior tube to facilitate the pulling out after casting. Two holes were made in the base plate to fix the vertical exterior tube with base by screws, as presented in *Figure 2(a).*

For reinforced HSC specimens, 8 holes were made around the center of the base precisely at the positions of the longitudinal bars to hold the bars in place and prevent their movement during casting, as presented in *Figure 2(b).* The steel tubes were fixed to the base of the mold, as presented in *Figure 2(c).* Finally, the concrete mixtures were poured to full the whole cross-section of the columns' molds, as presented in *Figure 2(d).* The slump was controlled by adding the superplasticizer to maintain the workability of the concrete without changing the water/cement ratio.


(a)Column mold formwork


(b)Fixing steel cage to the base plate


(c)Steel cage inside the mold

(c)RC column

Figure 2 Columns' fabrication

3.3Materials' properties

The columns were prepared using HSC with partially or fully fiber content. The mixed proportions of high-strength concrete are summarized in *Table 2*. The constituents included ordinary Portland cement (Type I), silica fume, sand, superplasticizer, water, and steel fibres. The steel fibers in a needle shape had a length ranging between (12 mm–14 mm) and a diameter ranging between (0.2 mm-0.25 mm) with an aspect ratio of 100 and a density of 7800 Kg/m3. The steel fiber's tensile strength was 2,850 MPa and its' elastic modulus was 201 GPa. The HSC material contained a 0%, 0.8%, 1.4%, and 2% volume fraction of steel fibers (Vf). Deformed steel reinforcing bars with 6 mm and 4 mm sizes were used as longitudinal and lateral reinforcement; respectively. The tensile testing of reinforcement was performed according to American society for testing and materials (ASTM) A370 [23]. *Table 3* summarizes the tensile test results of steel reinforcement.

Table 2 Mix proportions of HSC

Type I portland cement (kg/m^3)	Silica fume (kg/m^3)	Sand (kg/m^3)	Water/cement ratio	Super plasticizer	Fibers (by volume)
1000	250	1000	0.2	2	0, 0.8%, 1.4%, or 2%

Table 3 Tensile properties of steel bars

Bar diameter (mm)	Bar area (mm^2)	Yieldingstrength (Mpa)	Ultimate strength(Mpa)	Strain at ultimate trength (%)
6	28.29	420	532	7
4	12.57	379	480	10.2

3.4Mechanical properties of concrete mixtures

For the concrete tests, three cubes having dimensions of (100 mm x 100 mm x 100 mm) and three cylinders having dimensions of (100 mm x 200 mm) were prepared and tested for each batch of concrete mixtures. The compressive strength of concrete was performed based on BS EN 12390-3 [24] for cubic samples while the splitting tensile test was performed based on ASTM C496 [25] for cylindrical samples.

The compressive strength and splitting tensile strength of concrete mixtures were specified at 28 days, as presented in *Table 4*. The addition of steel fibers in partially-fibered columns and fully-fibered columns did not significantly impact the compressive strength of tested specimens. However, the steel fibers were bridged the concrete cracks to sustain higher tensile loads.

Table 4 Mechanical properties of concrete mixtures

Concrete mixtures	Volume fraction of steel fiber, V_f, (%)	Avg. compressive strength, f_{cu}, (MPa)	Splitting tensile strength, f_{sp}, (MPa)	Corrected compressive strength, $f'c$, (MPa)
Mix#1	0	70..0	2.1	56.0
Mix#2	0.8	71.5	4.4	57.2
Mix#3	1.4	72.0	4.8	57.6
Mix#4	2	70.4	5.4	56.3

3.5Test instrumentation

All columns' specimens were tested in the civil engineering department laboratory at Al-Nahrain university by using a hydraulic universal testing machine of 2000 kN ultimate capacity, as presented in *Figure 3*. The hydraulic jack of the testing machine was established based on displacement control applied to the specimens with a rate of 0.1 mm/sec. The displacement rate was controlled by two parts of an electronic system, human-machine interface, (HMI) and programmable automation control (PAC). The axial displacement measurement of the columns' specimens was measured by linear variable displacement transducers (LVDT). The columns' specimens were stabled in the machine with two steel plates having dimensions of (250 mm x 250 mm x 30 mm) from both the top and bottom faces, as presented in *Figure 3*. These steel plates were used to distribute the applied load uniformly over the cross-sectional area of the columns' specimens.

Figure 3 Test set-up of column specimen

4.Experimental results

4.1General observation

The axially applied load-axial displacement relations for all columns in comparison with that for the control column are shown in *Figure 4*. All the partially-fibered and fully-fibered columns observed an improvement in their ultimate loads and ultimate axial displacements in comparison with that in the control column. *Table 5* and *Table 6* presents the test results summary for ultimate load, ultimate axial displacement, the percentage improvement in the ultimate loads, displacement ductility index, and energy absorption index of columns' specimens corresponding to that of the control specimen. The improvement in the ultimate loads ranged between 14% and 81%. The displacement ductility index was represented as a percentage increase in the ultimate displacement of the partially-fibered and fully-fibered columns' specimens corresponding to that of the control specimen. The fibered columns' specimens revealed displacement ductility indices ranging between 29% and 66% enhancement in comparison to that of the control specimen, as presented in *Table 6*. It should be noted that the inclusion of steel fibers in partially-fibered columns and fully-fibered columns did not significantly impact the compressive strength of tested specimens; however, it has a great potential in enhancing the ultimate load capacity of the tested specimens.

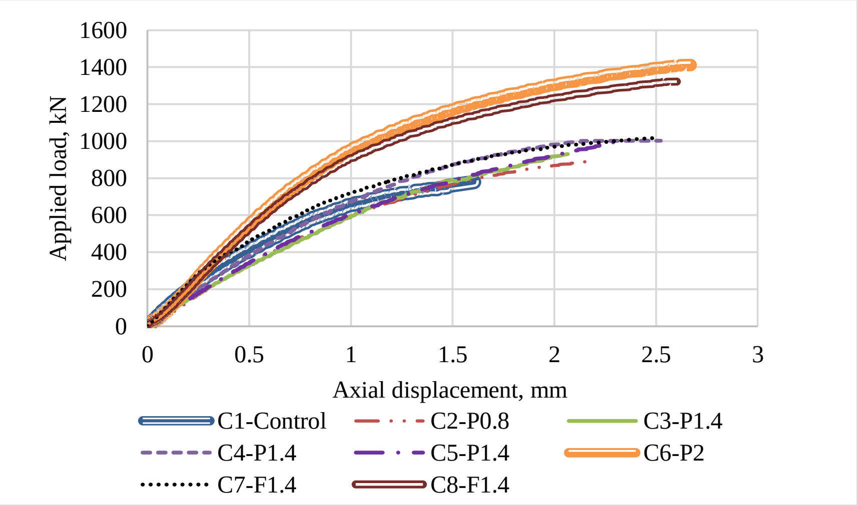


Figure 4 Load- axial displacement relation

Table 5 Summary of load results

Column ID	f'c (MPa)	Ultimate load Pu, kN	% improvement in Pu
C1-Control	56.0	780.38	
C2-P0.8	57.2	891.68	14
C3-P1.4	57.6	930.32	19
C4-P1.4	57.6	1002.43	28
C5-P1.4	57.6	1002.81	29
C6-P2	56.3	1411.69	81
C7-F1.4	57.6	1037.73	33
C8-F1.4	57.6	1322.05	69

Table 6 Summary of displacement results

Column ID	Ultimate dis., Δu mm	Displacement ductility index	Energy absorption index
C1-Control	1.60	NA	NA
C2-P0.8	2.20	37	1.7
C3-P1.4	2.07	29	1.5
C4-P1.4	2.52	57	2.1
C5-P1.4	2.33	45	1.8
C6-P2	2.67	66	3.2
C7-F1.4	2.50	56	2.2
C8-F1.4	2.60	62	3

4.2Influence of steel fiber inclusion

The inclusion of steel fiber in partially-fibered columns indicated a dramatic increase in both ultimate loads and axial displacements as the steel fiber volume fraction increased (*Figure 5*). The comparison between columns' specimens (C4-P1.4 and C8-F1.4) having the same steel fiber volume fraction (V_f=1.4%) determined that the fully-fibered column's specimen provided better axial performance than the partially-fibered column's specimen. However, increasing the steel fiber volume fraction from (V_f=1.4% to 2%) in the partially-fibered column's specimen enhanced its axial performance in comparison to that of the fully-fibered column's specimen with (V_f=1.4%). Thus, the steel fiber can be arranged through the concrete cover only with a high dose instead of spreading it through the enter-cross sectional area of the columns.

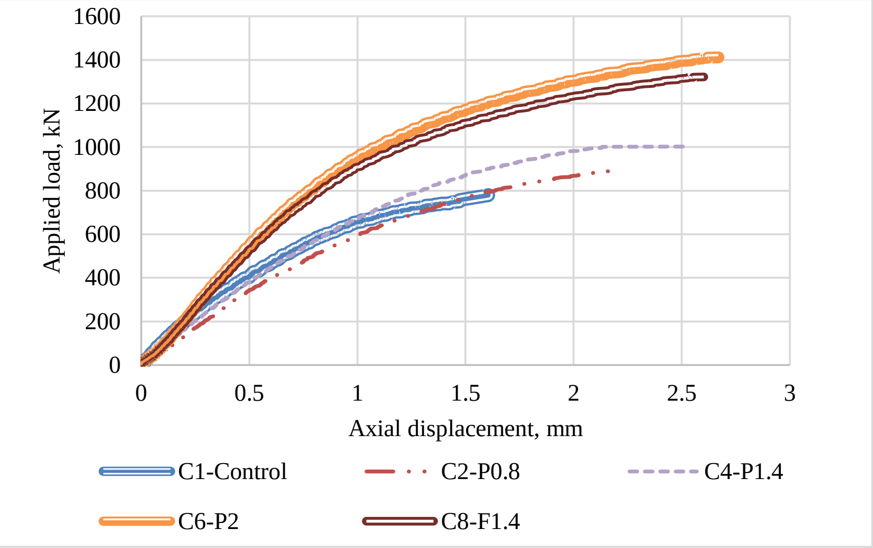


Figure 5 Comparison between axial performance for non-fibered and fibered columns

4.3Impact of steel fiber as a lateral reinforcement

Figure 6 showed the relation between test results of the columns' specimens with and without internal reinforcement. For columns' specimens that were partially reinforced with steel fibers, the difference in their ultimate loads was not significant, the column' specimen (C3-P1.4) failed at an ultimate load of 930 kN while the column' specimen (C4-P1.4) failed at an ultimate load of 1002 kN. However, the column' specimen with no internal steel reinforcement (C3-P1.4) having steel fibers in concrete cover only presented a lower axial displacement in comparison to that of the column' specimen with internal steel reinforcement (C4-P1.4). On contract, for columns' specimens that were fully reinforced with steel fibers, the difference in their ultimate loads was substantial, the column' specimen (C7-F1.4) failed at an ultimate load of 1037 kN while the column' specimen (C8-F1.4) failed at an ultimate load of 1322 kN. Though both columns observed the same axial displacement at failure. Thus, the steel fiber can function as a lateral reinforcement when it is distributed through the entire cross-sectional area of the column's specimen.

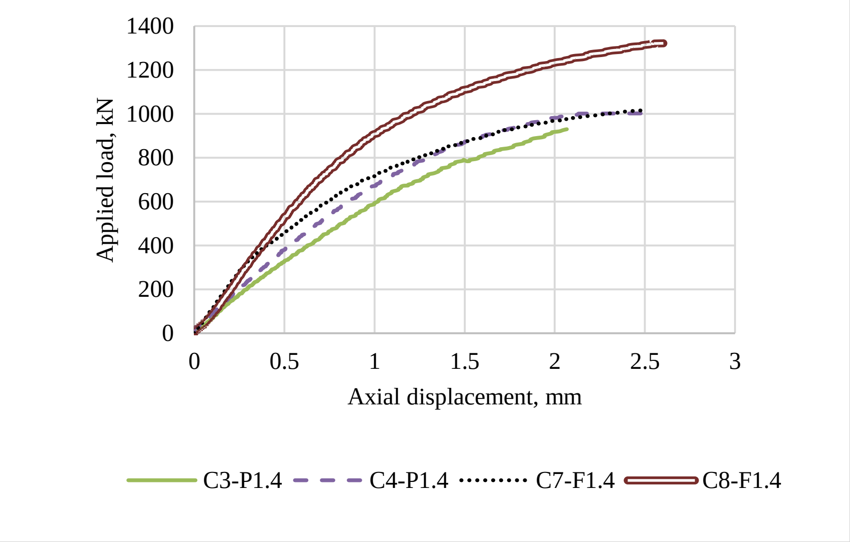


Figure 6 Comparison between the axial performance of columns with and without internal lateral reinforcement

4.4Columns' specimen length effect

The load–axial displacement relations of two columns that tested under the same conditions except that having a different length (column' specimen with 650 mm length (C4-P1.4) and column' specimen with 1000 mm length (C5-P1.4) are presented in *Figure 7*. The test results showed that both columns have almost the same axial performance in terms of reaching the same ultimate loads with slight variation in their axial displacements.

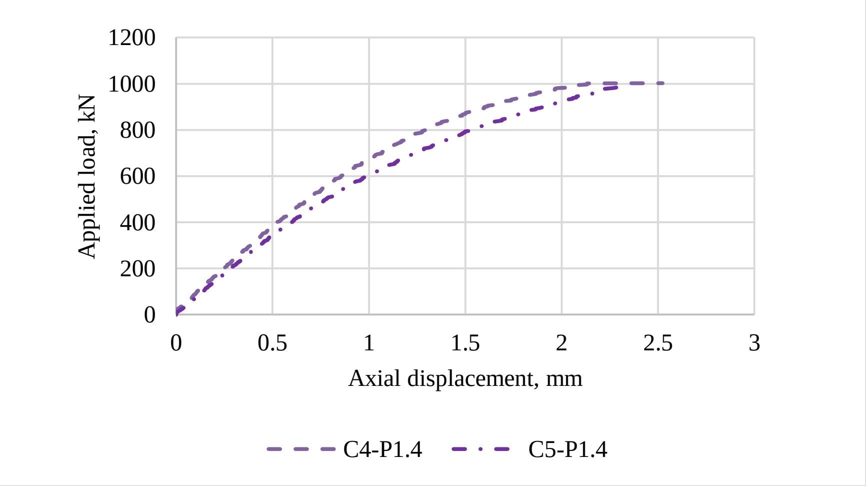


Figure 7 Comparison between the axial performance of different columns' length

4.5Energy absorption

The energy absorption of each tested column' specimen was defined as the area under the curve of the load-axial displacement relation. The energy absorption index was represented by the energy absorption index of the partially-fibered or fully-fibered columns over the energy absorption index of the non-fibered column (*Table 6*). The higher energy absorption index was observed in the partially-fibered column' specimen with V_f=2% and the fully-fibered column' specimen with V_f=1.4%. While the energy absorption indices were slightly various between 1.5 to 2.2 for the other tested columns' specimens. The column' specimen (C3-P1.4) observed a lower energy absorption index than that of the column' specimen (C4-P1.4). The column' specimen (C4-P1.4) has the same energy absorption index as that in column' specimen (C7-F1.4). Therefore, it can be concluded that the full replacement of steel fibers to the internal lateral reinforcement is essential to ensure proper energy absorption before failure.

4.6Failure mode

The failure mode for each tested columns' specimen was identified during the progress of the loading test. The column' specimen (C1-control) exhibited a brittle unconfined failure of the column core, as presented in *Figure 8(a)*. The partially-fibered columns' specimens (C2-P0.8, C4-P1.4, C5-P1.4, and C6-P2) experienced a concrete cover spalling with a significant delay as the steel fiber content increased (*Figure 8*(*b*), *(d)*, *(e)*, and *(f)*). However, the column' specimen (C3-P1.4) exhibited a concrete crushing failure mechanism in the absence of internal steel reinforcement (*Figure 8(c)*). On the other hand, the fully-fibered columns' specimens also observed different failure modes based on the existence or absence of internal steel reinforcement. The column' specimen (C7-F1.4) was failed due to punching shear mode, as presented in *Figure 8(g)*. While the column' specimen (C8-F1.4) revealed a high resistance to failure and a substantial delay in its concrete cover spalling (*Figure 8(h)*). A complete list of abbreviations is shown in *Appendix I*.

(a)C1-control (b)C2-P0.8 (c)C3-P1.4 (d)C4-P1.4

(e) C5-P1.4 (f) C6-P2 (g) C7-F1.4 (h) C8-F1.4

Figure 8 Failure patterns of the columns' specimens

5.Discussion

The experimental work results revealed the impact of steel fibers on improving the structural performance of HSC columns. The ultimate load capacities of partially-fibered columns were significantly enhanced by 14%, 28%, and 81% with an increase in the volume fraction of steel fiber from 0.8%, 1.4%, and 2%, respectively. The partially-fibered columns can provide the same structural performance as fully-fibered columns by increasing the steel fiber volume fraction from 1.4% in the fully-fibered column to 2% in the partially-fibered column. Thus, the study idea of adding steel fiber to the external column shell is proved. The fully-fibered column with internal lateral reinforcement, having a steel fiber volume fraction of 1.4%, reached more than the double ultimate load capacity of that fully-fibered column with no internal lateral reinforcement. So, the study determined that the addition of steel fiber to the entire cross-sectional area of the column is required in case of the absence internal lateral reinforcement in order to achieve optimum confinement. As well, the fully-fibered column with internal lateral reinforcement, having a steel fiber volume fraction of 1.4%, reached more than the double ultimate load capacity of that partially-fibered column. However, the displacement ductility and energy absorption were slightly different. In addition, the increase in the column length from 650 mm to 1000 mm did not affect the ultimate load capacity, the displacement ductility or the energy absorption of the partially-fibered columns. Thus, the study concluded the addition of steel fiber to the entire cross-section area of the column provided higher structural performance than the addition of steel fiber to the column 'shell only. But, increasing the steel fiber content into the column shell can compromise the results.

6.Conclusion and future work

This work studied the impact of steel fibers on the axial performance of HSC columns under concentric loads. The finding results exhibited that the partially-fibered and fully-fibered columns improved the axial strength, axial displacement, energy absorption, and delayed the concrete cover spalling concerning that non-fibered column. As well, the main conclusion points are listed here:

- The axial performance of HSC columns was incredibly developed by increasing the steel fiber volume fraction from 0.8% to 2%.
- The partial inclusion of steel fibers in columns can provide compatible axial performance results to those columns with fully-fibered content.
- The inclusion of steel fibers into the entire cross-sectional area of columns is essential in case of no lateral reinforcement is available.

- The ductility and energy absorptions were improved with rising in the steel fiber volume fraction for partially-fibered columns.
- The variation in the columns' length did not reveal a significant difference in the axial performance of the two compared columns.
- The concrete cover spalling was delayed concerning with rising in the steel fiber volume fraction.
- The HSC columns with no internal reinforcement observed a very severe brittle failure in the concrete core. However, the partially-fibered and fully-fibered columns with internal reinforcement exhibited a less intense brittle failure with a delay in the concrete cover spalling.

Based on this work, there are some suggestions for future works, as follows:

- Experimental investigation on reactive powder concrete columns containing steel fiber of various degrees of reinforcement under the effect of eccentric loading.
- Performance of reactive powder concrete columns strengthened by steel fiber at the external layers under the effect of repeated loading.
- A comparison between the concrete columns strengthened by steel fiber or glass fiber at the external layers.
- The effect of elevated temperatures on the external fiber-reinforced HSC columns.
- The behavior of external fiber-reinforced HSC columns under seismic loading.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Authors contributions statement

Zena R. Aljazaeri: Progressed the idea of the work, supervision, interpretation of results, and paper writing. **Hussein K Al-Qabbani**: Performed the experimental work including the fabrication and testing of the columns' specimens, data collection. **Laith Khalid Al-Hadithy:** Placed the study plan with the other authors, supervised the experimental work by providing the way of fabricating the required mold of casting two different concrete material types, and reviewed the written paperwork.

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Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Society for Testing and Materials
2	HMI	Human-Machine Interface, HMI
3	HSC	High-Strength Concrete
4	LVDT	linear Variable Displacement Transducers
5	PAC	Programmable Automation Control
6	RC	Reinforced Concrete