Experimental and numerical investigation on the axial behavior of solid and hollow SIFCON columns

Shahad S. Khamees¹ · Mohammed M. Kadhum¹ · Nameer A. Alwash¹

Received: 3 February 2020 / Accepted: 13 May 2020 / Published online: 18 May 2020
© Springer Nature Switzerland AG 2020

Abstract

This paper looks at the effect of fibers shape, hollow ratio and cross sectional shape on the behavior of solid and hollow slurry infiltrated fiber concrete (SIFCON) columns. Two shape of steel fiber were used in the present study, straight micro fiber and hooked end fiber. Therefore, this study comprised of casting and testing two groups of SIFCON column specimens; columns group reinforced by hybrid fibers (3% straight micro fiber + 3% hooked end fiber) and columns group reinforced by 6% hooked end fibers. Each group comprises of six column specimens, 3 of them are circular and the others are square. Each circular column has an equivalent square column with the same cross-sectional area. These six columns have different hollow ratios ($\beta = 0, 25\%$ and 50%). Non-linear finite element analysis of axially loaded SIFCON columns has been done by using ABAQUS computer program. Analytical predictions of load carrying capacity, axial displacement, ductility and energy absorption capacity are compared with experimentally observed results of SIFCON columns, and the results shown a good agreement between them. The results illustrated that despite the small cross-sectional area and presence of longitudinal hole in columns, SIFCON columns were shown dazzling performance in terms of load carrying capacity, ductility and energy absorption capacity especially for columns reinforced by hybrid fiber. On the other hand, column performance deteriorates with increased hollow ratio. The results also demonstrated that the performance of circular columns exceeded that of square columns for the same cross-sectional area.

Keywords SIFCON columns · FEM · Hollow ratio · Fiber shape · Ductility · Energy absorption capacity

1 Introduction

In civil engineering, the primary element of most infrastructure is concrete, which is widely used for this purpose. With growing of modern civil engineering and structural design requirements especially in high-rise building columns that require high-strength materials, causes imperative need to evolve higher-performance engineering materials owning high strength, durability, toughness and energy absorption [1–4]. Today, the most significant requirements of concrete are the ductility. Attempts to disband the brittleness problem of concrete have been made by using high volume of fibers with absence of course

aggregate, this provide stress-hardening property and boost the ductility of the structural ingredient [5, 6]. But owing to the placing and mixing difficulties juttred from the interlocking effect of high volume of the fibers, there was an urgent need to develop special production methodologies. Therefore, slurry infiltrated fibrous concrete (SIFCON) was created [7–9]. Where the fiber is per-packing in the mould to its full capacity and then the cementitious slurry is infiltrated through the fiber with low pressure [6, 10]. This special manufacturing technique contains volume fraction of fiber ranging from (5 to 20%) [11]. In the literature, the effect of using discontinuous, short fibers which is randomly distributed in concrete gives improved

✉ Shahad S. Khamees, shahad93c@gmail.com; Mohammed M. Kadhum, Eng.mohammed.mansour@uobabylon.edu.iq; Nameer A. Alwash, namer_alwash@yahoo.com | ¹College of Engineering / Civil Engineering Department, University of Babylon, Babylon, Iraq.

strength, postcracking capacity, stiffness, impact resistance and energy absorption capacity as well as increase of the tensile and flexural strength. On the other hand, the incorporation of long and short fiber in concrete as hybrid fiber increase the ductility and gave better softening behavior compared to the concretes with one single type of fibre [12, 13]. Different type of steel fiber can be used in production of SIFCON concrete such as straight, hooked, deformed and crimped fibers [14, 15]. (Ali 2018) [14] investigated on the effect of fiber type on properties of SIFCON concrete. Specimens with micro steel fiber were prepared and compared the results with hooked end and hybrid (micro fiber + hooked end fiber) specimens. The test result shows that specimens casted by micro steel fiber have outstanding performance in term of compressive strength, tensile strength, impact resistance, energy, and lower strength loss after freeze thaw cycles as compared with the hooked end and hybrid specimens.

Nowadays, the present of a longitudinal hole in concrete members has many important advantages in construction: minimize the self-weight of concrete members results in reduced the foundation cost of concrete also resist the high moment and shear demands, embed PVC pipes for water supply, electricity wires, and air-conditioning [16–20]. Zacob [21], undertaken research on short columns with different hollow ratio (0%, 3.63%, 7.95%, 12.50% and 20.28%) with 150 mm × 150 mm cross sections. The test result show that with 60 mm load eccentricity and compered with solid column, the hollow column with hollow ratio up to 20.28% shown a decrease in maximum capacity and stiffness to 11.9% and 53.88% respectively. (Supriyadi 1997) [22], examined the varies hole ratio effect of on the strongly reinforced concrete column boundaries experimentally and numerically. The hole's ratio was (0%, 3.8%, 5.62% and 9.43%) with a size of cross-section 120 mm × 120 mm. The experimental concluded results that up to a hole ratio of 9.43%, the columns demonstrate relatively similar stiffness at the same level of eccentricity, and that no buckling failure was shown up to the limit of the column. Columns to hole ratio 5.62% experimental capacity still exhibit greater than the capacity of numerical results. While numerical result shows that the effect of holes on load carrying capacity of column decreases with increasing of the eccentricity. Only Kamath and Shilpa [23], investigated numerically SIFCON columns by using ANSYS program to simulate the behavior of combined SIFCON columns with reinforced concrete (RC-SIFCON). Where they investigated on the nonlinear behavior of (RC-SIFCON) with different percentages of SIFCON (0, 100, 20, 30, 40, 50) % with corresponding reinforced concrete (100, 0, 80, 70, 60, 50) %. The columns are solid square with dimension 100 mm × 100 mm × 1000 mm. The result show that when the proportion of SIFCON ranges

between 0 to 100%, for 40% SIFCON column, the critical buckling load is maximum for different slenderness ratio and maximum deflection was seen at the 100% SIFCON column for increase in the load when compared to the other percentages of the SIFCON column.

2 Research significance

Since SIFCON is a relatively new construction material, there is a lack of information on SIFCON columns. From this point of view, to increase knowledge in this area, this investigation seeks to get information that will assist tackle these study gaps. On the other hand, to highlight the benefit of using ultra-high-performance material like SIFCON in columns and the possibility of reducing the columns size, where small cross-section hollow columns were chosen for this purpose, this offers interesting opportunities to achieve high-performance hollow columns with fulfill architectural and service demands mentioned earlier. The behavior of SIFCON columns was investigated experimentally and numerically by employing ABAQUS computer program. The main experimental parameters were: shape of steel fiber, hollow ratio and cross sectional shape of columns.

3 Experimental investigation

3.1 Constituent materials and mix proportion

In the present investigation, following materials were used in preparing the SIFCON slurry as shown in Table 1: ordinary Portland cement type I. Fine sand of size passing through (1.18 mm sieve) to segregate the coarser particles is used. As a cementitious material, micro silica fume was added which conform with the requirements of [24]. It was utilized in this investigation as a partial replacement (10%) by weight of cement. Modified polycarboxylic polymers were used as a high-range-water-reducing- admixture (superplasticizer) compliant with [25] requirements. Only

Table 1 SIFCON optimal mixing proportions for 1 m³

Cement (kg/m ³)	872.1
Sand (kg/m ³)	969
Silica fume kg/m ³ 10% rep.	96.9
Steel fiber %	6
w/b ratio	0.33
SP (by wt.of binder) %	3.7
Mini-slump flow (mm)	364
V-funnel time (s)	11

steel fibers were used with two shapes, the first shape was straight steel fiber (micro steel fiber) with (0.2) mm diameter, (13) mm length, and (65) aspect ratio (l/d). The second shape was hooked end steel fibers with diameter of (0.5) mm, length of (30 mm) and (60) aspect ratio, see Fig. 1. Many trial mixes were done to prepare suitable slurry that has desirable fresh properties to satisfy the demands of SIFCON slurry with respect to fluidity, viscosity and filling ability without segregation or pore pockets in the fibers network by performing a mini-slump flow test and V-funnel test on SIFCON slurry only. Proportions of cement and sand for creating SIFCON slurry was 1:1. The mini-slump flow test was measured at 364 mm in order to assess the workability of SIFCON slurry. And to evaluate the viscosity of the slurry, the V-funnel test has been used and the slurry mix time was 11 s. SIFCON is a new material and there are no guidelines for SIFCON yet, however, several trial mixes have been done to choose a suitable fiber percentage that gives high strength and appropriate cost. It found that the percentage of 6% is appropriate for this study. Table 2 present some mechanical properties of SIFCON.

3.2 Test specimens

Twelve tested column specimens were divided into two groups in conformity with shape of fibers, once as hybrid fibers with 6% fiber volume fraction (3% micro steel fiber +3% hook end steel fiber) and the other as straight micro steel fibers with 6% fiber volume fraction, and thereupon these groups are subdivided into two subgroups in conformity with of cross section shape (circular and square), where each circular column has an equivalent square column with the same cross-sectional area, and finally, they are divided according to the columns hollow ratio (β), which is the ratio of the inner dimension to outer dimension of columns ($\beta=0, 25\%$, and 50%). These groups were browsed in Table 3. The height of all columns is 1000 mm and the dimensions are illustrated in Fig. 2.

Fig. 1 Shape of fibers were used in this research

Table 2 Some mechanical properties of SIFCON

Shape of steel fibers	Compressive strength (MPa)	Static modulus of elasticity (GPa)	Splitting tensile strength (MPa)
Hybrid fibers	71	26.8	17.2
Hooked end fibers	65.5	25.4	14.1

4 Casting procedure of SIFCON specimens

In this research, the casting of circular and square columns was done vertically see Fig. 3 by using iron molds of height 1000 mm. Each mold was divided vertically into two parts: the first vertical part is one-piece length of 1000 mm, while the second vertical part is divided horizontally into three pieces to control the casting process. To fill the hole of hollow columns, plastic water pipes were used in circular molds, whilst in the square molds, the wood was used. The slurry mixing mechanism was accomplished by a rotary horizontal mixer with a capacity of 0.09 m^3 . The mixing process and the time required for each step were exemplified in Fig. 4. The technique utilized to cast SIFCON columns is multiple layer-technique, which includes pre-placed of fiber in the mold with a thickness layer of 10 cm through sprinkled by hand in the mold to avoid balling (i.e. randomly-oriented) (Fig. 3b, c), followed by subsequent pouring the slurry over the resulting fiber network with compaction by steel rod with a pointed tip (Fig. 3d, e). This rod allows the slurry to penetrate between the fibers and to ensure that there are no voids in the fibers network.

5 Setup and testing procedures

All SIFCON columns were screened until failure at the age of 56 days by using a calibrated electrohydraulic test machine which have a maximum capacity of 2500 kN in the structural laboratory of the University of Babylon. By using load control, the load was applied with loading rate of 1 kN/s.

Table 3 Nomenclature and details of columns

Type of column	Shape of column	Column symbol	Cross section (mm)	Hollow ratio (β) %
Columns with hybrid fibers	Circular	HyC-0%	100	0
		HyC-25%	100	25
		HyC-50%	100	50
	Square	HyS-0%	90	0
		HyS-25%	90	25
		HyS-50%	90	50
Columns with hooked end fibers	Circular	HC-0%	100	0
		HC-25%	100	25
		HC-50%	100	50
	Square	HS-0%	90	0
		HS-25%	90	25
		HS-50%	90	50

Fig. 2 Cross section shape, hollow ratio (β) % and dimension of SIFCON column specimens

The axial displacement (Δu) of the specimens was recorded using deflectometers dial gauges with an accuracy of 0.001 mm per division and a capacity of 20 mm and a maximum sensor length of 50 mm. The dial gauge for exercised to measure the axial displacement of each column was set on the top surface of machine piston as visualise in Fig. 5. Small cameras were used to monitor the value of dial gage. This method provides protection for workers from explosion and fragmentation of SIFCON column, see Fig. 5, B. These cameras are linked to a computer to record the values of dial gauges, and the computer records them as a video for viewing after the test is completed.

6 Finite element analysis (FEA)

In this research, model of finite element is implemented by using ABAQUS/2019. This model seeks to simulate and prediction the behavior of SIFCON columns with different parameters and to validate the above-mentioned experimental analysis. Three-dimensional solid with eight-node brick elements (C3D8R) were applied to model the SIFCON columns.

Fig. 3 Procedure of casting SIFCON specimen

Fig. 4 Mixing procedure for SIFCON slurry

Fig. 5 Arrangement of dial gauges and cameras within the test device

6.1 Material modelling

In order to simulate the reinforced concrete constructions numerically, Lubliner et al. [26] and Lee et al. [27] cooperated to develop an effective and reliable model named concrete damaged plasticity model. This model has an essential fundamental ingredient of any numerical analysis in software systems such as ABAQUS program. In this model, the concrete deterioration is estimated on the basis the fracture energy that will be used to produce micro cracks depending on the theory of coupled damage plasticity as can be seen in Fig. 6. This model deem the decline of the material's tension and compression features during the analysis. To obtain reliable and accurate results, [3] recommended using the materials mechanical properties acquired during laboratory testing for the numerical model as an input data. Accordingly, the compression stress strain curves and modulus of elasticity of SIFCON calculated during performing the investigative process were integrated into

Fig. 6 Surface yield in plane stress produced by (Lee and Fenves, 1998)

the finite element model. While SIFCON's tensile stress–strain was calculated using an approach proposed by [28], Fig. 7, as follows:

For ascending branch:

$$\sigma = \sigma_{max} \left[\left(1 - \frac{\epsilon}{\epsilon_{max}} \right) \right]^A \quad (1)$$

where σ_{max} = maximum stress, ϵ_{max} = the corresponding strain, E_0 = elastic modulus of the material, and A is a parameter given by:

$$A = E_0 \frac{\epsilon_{max}}{\sigma_{max}}$$

For the descending branch:

$$\sigma = \sigma_{max} \left(1 - k \frac{2\delta}{\ell} \right)^2 \quad (2)$$

Fig. 7 Schematic representation of the stress-elongation curve of SIFCON in tension suggested by (Naaman et al., 1993)

where l = length of fiber, δ = crack opening.

6.2 Boundary conditions and mesh of FE model

It was noted that the level of complexity of the analysis and the time spent in the processing depends mainly on the mesh density. Therefore, a prior analysis of various densities of mesh was performed to determine the suitable density of mesh that gives the required accuracy. The size of the 10 mm element was therefore chosen for the mesh density. In the analysis of all SIFCON columns, the boundary conditions implemented were the displacement restricted in bottom side of column in all directions (X, Y and Z) axis. While the restrained to displacement was only in X and Z axis and free displacement was presumed in the direction of the longitudinal axis of the column (Y-axis). The columns were loaded at the same locations in the experimental work for all columns specimens as a uniformly applied pressure, see Fig. 8.

7 Result and dissociation

7.1 Load carrying capacity (failure load) of columns (Pu)

The experimental and numerical results are tabulated in Table 4. The analytical model has been shown to predict,

Fig. 8 Mesh, load and boundary condition of SIFCON columns

with fairly well agreement with experimental results that all the theoretical values of ultimate load of the column specimens exceed the experimental values by a margin ranging between (3.5 and 8.9%) with a standard deviation (0.0154). Figure 9 demonstrates a comparison between laboratory and theoretical outcomes and their convergence. This indicates that the proposed model is consistent and can be used with confidence.

7.1.1 Effect of steel fibre shape

As described previously, the tested column specimens were casted with two shape of steel fibre (hook end steel fibre and hybrid fibre). The test results showed that the use of hybrid steel fibre to reinforce SIFCON columns gives higher load carrying capacity than hook end steel fibre by (31 and 17.3) for square column with hollow ratio (0 and 50) % respectively, and by 11.2% for circular hollow column with $\beta = 25\%$. The most likely explanation is in hybrid case, the incorruption of micro fiber with higher aspect ratio increases the numbers of fibers per unit volume, in other words, minimizing the spaces between fibers, see

Table 4 The experimental and numerical summary of the results for SIFCON columns

Column symbol		Pu (kN)	Pu exp./ Pu num	Axial displacement Δu (mm)	$\Delta u_{exp.}/\Delta u_{num.}$
HyC-0%	F.E.M	602	0.93	14.9	1.064
	EXP.	562		15.86	
HyC-25%	F.E.M	561	0.94	13.1	1.122
	EXP.	525		14.7	
HyC-50%	F.E.M	512	0.92	12.14	1.071
	EXP.	471		13	
HyS-0%	F.E.M	590	0.93	14.4	1.083
	EXP.	551		15.6	
HyS-25%	F.E.M	558	0.93	12.42	1.171
	EXP.	519		14.54	
HyS-50%	F.E.M	486	0.95	12	1.063
	EXP.	460		12.75	
HC-0%	F.E.M	536	0.97	13.15	1.125
	EXP.	518		14.8	
HC-25%	F.E.M	512	0.92	12.15	1.099
	EXP.	472		13.35	
HC-50%	F.E.M	431	0.95	11	1.018
	EXP.	408		11.2	
HS-0%	F.E.M	512	0.95	13.11	1.068
	EXP.	488		14	
HS-25%	F.E.M	486	0.94	12.14	1.071
	EXP.	455		13	
HS-50%	F.E.M	427	0.92	10.36	1.052
	EXP.	392		10.9

Fig. 9 The comparison between ultimate load of experimental tests and finite element analysis of square SIFCON columns

Fig. 10. On the other hand, the mixing of hooked end shape with straight micro fiber increase the mechanical interlock both between fiber and matrix and between the fibers themselves which causes increase in the strength of specimens. Also [29] found that there was an increase in the compressive strength values as the aspect ratio increased, probability of heterogeneous distribution and flocculation of fibers in concrete mix is increased by increasing l/d ratios [30–34]. The beneficial effect of hybrid fibers is owing to that short fibers are efficient in minimizing number of defect including macro cracks, which develops in the initial phases of tensile loading, whilst long fiber is more effective in bridging larger macro cracks, that

grow later after the the microcracks have been propagation widening [13, 34].

Research found that casting cylinders of SIFCON expose to phenomenon known as edge effects which may adversely effect on SIFCON properties. Its occur at the interface of SIFCON and the mould leaving voids in this area and the fiber density becomes low compared to the central region which characterized by high fiber density [35] see Fig. 10, A. Since the microstructure around hybrid fibers is quite different than that of hooked end fibers, where it is characterized by a dense transition zone due to the present of micro fiber, thus eliminating the edge effect phenomenon in the packing of hybrid fiber, i.e. reduces the spaces between fibers as can be seen in Fig. 10b [36] and Fig. 11. Where the edge phenomenon shows clearly through the spalling on the surface of columns especially in columns reinforced by hooked end fibers as illustrated in Fig. 11. That figure also shows the cracks on the surface of hybrid columns having more number of fibres across a crack and smaller than the cracks on the surface of hook columns, could be due to a larger number of fibre results in a larger surface area of the fibre in contact with the slurry and therefore a great cohesion between fibres and slurry.

7.1.2 Effect of hollow ratio (β)

The behavior of hollow columns differs from the behavior of solid columns owing to the existence of the internal hole [37]. However, the strength of these elements is affected by reduction of the cross sectional area and other factors, such as concrete strength and reinforcement ratios

Fig. 10 Edge effect phenomenon and number of fibers per unit volume for SIFCON reinforced with: **a** hooked end fibers (Gilani 2007), **b** hybrid fibers

Fig. 11 Deterioration, spalling and cracks on the surface of SIFCON columns

[19]. Figure 12 presents the percentage reduction in load carrying capacity of SIFCON columns due to the presence of an inner hole. Where the hole has a major effect on load carrying capacity and every solid column resisted more load than its counterpart hollow one. For square column with hybrid fiber, the load carrying capacity reduced by 5.8% when $\beta = 25\%$ and 16.5% for $\beta = 50\%$. The effect of hollow ratio is greater when using hook end steel fiber due to less number of fiber across the cracks and the fiber density is low especially at the edge, where the load carrying capacity of circular column reduced by 8.9% and 21.2% for hollow ratio 25% and 50% respectively. The decrease in column carrying capacity is possibly caused

by the decrease in the area of the column, and the larger the diameter of the hole, the less the column thickness, therefore, the less the load carrying capacity. The load-carrying capacity in HyC-0% and HyC-50% only 16% difference; however, there is 25% in section area, i.e. SIFCON columns are less affected by the hollow ratio. This is because the uniform and randomly dispersed of fiber throughout the SIFCON matrix provide better distribution of both internal and external stresses owing to the creation of a three-dimensional reinforcing network [38]. In contrast to the normal columns in which the reinforcement is concentrated on the outer face of the column and thus the inner face of hollow columns is exposed to

Fig. 12 The percentage reduction in load carrying capacity of SIFCON columns due to the presence of an inner hole

cracking and weakens the bearing tolerance of the column [18], see Fig. 13.

7.1.3 Effect of cross sectional shape of columns

The researchers conducted that the circular columns are suitable for seismic zones that need high strength and ductility in all directions [39]. The results of this study proved that the circular columns give enhanced performance than the square columns for equivalent cross-sectional area. For hybrid SIFCON column, the load carrying capacity of circular cross section was higher by (2 and 2.4) % than square column for hollow ratio (0 and 50) % respectively. Higher concrete stresses are supported by the circular sections than the comparable square sections, owing to the stress-intensity concentrated in the folds of square columns which represent the points of weakness that may lead to failures [37]. In contrast, the load was uniformly distributed in circular cross section also it has a maximum radius of gyration and higher equivalent cross-section area [37].

7.2 Load–displacement relationships

The vertical displacement of SIFCON columns was recorded immediately after the application of the load. The effect of different shape of steel fibre were presented in Fig. 14 where for the same level of load, columns with hooked end steel fibre exhibit higher axial displacement than columns with hybrid steel fibre due to the higher deformation of SIFCON columns reinforced by hooked end steel fibre. This indicates a high stiffness for SIFCON reinforced with hybrid fiber. But for the final magnitude, columns with hybrid steel fibre display greater axial displacement than columns with hook end steel fibre maybe due to the load carrying capacity was higher in hybrid columns. For hollow column, the findings show that the

axial displacement of the hollow columns increased with regard to the rate of the applied load relative to the solid columns as illustrate in Fig. 15. This shape also shows that the stiffness of the columns reduces with an increase in the hollow ratio. For the same area, the difference between the axial displacement of square and circular columns was unnoticeable.

Furthermore, the information in Table 4 indicate little difference between computed experimental axial displacement and predicted numerical findings obtained from finite element analysis (FEA), and the standard deviation is marginally insignificant (0.0401). As can be seen from Fig. 16, that the numerical load–displacement curves offer a stiffer behavior relative to the outcomes of the experimental work. The most probable explanations of adverse consequence are the presence of micro cracks which are generated by drying shrinkage and during fabricating the columns specimens, this will reduce the stiffness of these

Fig. 14 The effect of fibres shape on load–displacement curve for solid SIFCON column

Fig. 13 The reinforcement in both normal strength concrete column and SIFCON columns

Fig. 15 The effect of hollow ratio on load–displacement curve of circular SIFCON column with hybrid fibre

specimens, while these micro-cracks are missing from the the FE model. Additionally, in all directions of the model, the FE analysis presumed that concrete is a homogeneous material, whereas concrete is a heterogeneous material in the real situation. In addition, precise modeling of support condition in the F.E evaluation resulting to significantly greater outcomes.

7.3 Ductility of SIFCON column specimens

The ductility of a structure defines as the ability to undergo deformation beyond the initial yield deformation, while still sustaining load. The ductility of the tested columns was estimated using the approach proposed by [40]. They determined the displacement ductility as the ratio between the displacement at ultimate load (Δ_u), and the notional yield displacement (Δ_y), as shown in Fig. 17.

Where (Δ_y), is described as the junction of the two straight lines correlated with the load displacement curves at the elastic and post elastic stages respectively. The equation below was used to calculated the ductility index:

$$\text{The displacement ductility index } (\mu_\Delta) = \frac{\Delta_u}{\Delta_y} \quad (3)$$

The ductility index computed from the numerical and experimental analysis are summarized in Table 5. It can be concluded from this table that the shape of steel fibre is the most crucial parameter which affects the behaviour of SIFCON columns with respect to ductility. Figure 18 illustrate the the positive effect of mixing different shape of steel fiber, where it gave much higher ductility compliance with hook steel fiber. The reason of this superiority is owing to the ability of hybrid fiber to bridging the crack. Also, the ductility is considerably enhanced as a function

Fig. 17 Determination procedures of displacement ductility index

Fig. 16 Effect of hollow ratio and fiber shape on load–displacement curve of square columns for both Experimental and theoretical data

Table 5 The experimental and numerical results of ductility and energy absorption capacity for SIFCON columns

Column symbol		Displacement ductility index (μ_{Δ})		Energy absorption capacity E (kN.mm)	E exp./E num
HyC-0%	F.E.M	5.46	0.98	6404.1	0.97
	EXP.	5.37		6273.1	
HyC-25%	F.E.M	4.51	0.96	5359.2	0.98
	EXP.	4.33		5267.2	
HyC-50%	F.E.M	3.3	0.97	4254	0.94
	EXP.	3.21		4029	
HyS-0%	F.E.M	5.4	0.97	6106.8	0.97
	EXP.	5.27		5971.1	
HyS-25%	F.E.M	4.36	0.96	5122.9	0.99
	EXP.	4.2		5075.9	
HyS-50%	F.E.M	3.13	0.95	3852.8	0.98
	EXP.	2.98		3820.1	
HC-0%	F.E.M	4.42	0.96	5156.7	0.98
	EXP.	4.27		5096.2	
HC-25%	F.E.M	3.42	0.98	4375.3	0.94
	EXP.	3.36		4130.1	
HC-50%	F.E.M	2.76	0.95	2943.4	0.97
	EXP.	2.62		2857.3	
HS-0%	F.E.M	4.36	0.93	4887.8	0.94
	EXP.	4.06		4604.2	
HS-25%	F.E.M	3.41	0.95	4137.3	0.93
	EXP.	3.25		3886	
HS-50%	F.E.M	2.64	0.95	2859.2	0.93
	EXP.	2.51		2667.7	

of the increase of aspect ratios of the fibres used resulting to improve both the strength and ductility of SIFCON columns [36, 41].

Due to the presence of an inner hole, the ductility of the hollow columns differs from the ductility of the solid columns. However, the bigger the hole, the lower the ductility value, perhaps owing to a reduction in the area and wall thickness of the column. It is clear that the ductility of the circular cross-sections outperforms that of the square cross-sections for the same area, possibly due to circular shape have maximum radius of gyration and the distribution of the load being more regular in the circular columns due to the absence of rims. Also, the moment of inertia of circular is 1.6 times the moment of inertia of square cross-section. Member stress is inversely proportional to the moment of inertia. Therefore, stress on square columns will be more like compare to stress on circular column for the same quantity of loading as square has less moment of inertia. Thus, it could be the reason that make circular cross section have higher load carrying capacity and ductility compared with square cross section [42].

7.4 Energy absorption capacity (E) of SIFCON column specimens

The concrete column's energy absorption capacity described as the area enclosed by the load displacement curve until the maximum load was reached, which represents the energy absorption of concrete column which could sustain before indicating a substantial decrease in load carrying capacity [43, 44].

The test results in Table 5 revealed that SIFCON columns have extraordinary ability to absorb energy especially for hybrid fibers SIFCON column where its higher than hooked end column, see Fig. 19. The reason for this is believed to be due to that the effective toughness increases as the aspect ratio increases and due to addition of short fiber [12, 45, 46]. On the other hand, Homrich and Naaman [31] noticed that fiber length and aspect ratio affect the possible volume fraction of fibers that may be placed in molds, where a higher aspect ratio is reflected by a higher absolute number of fibers in the mixture which lead to more energy absorption and better crack control. It is also illustrated that for hollow columns, the energy absorption decrease with increasing in hole diameter. The comparison

Fig. 18 The effect of fiber shape, hollow ratio and cross-section shape on the ductility of SIFCON column specimens

Fig. 19 The effect of fiber shape and hollow ratio on the energy absorption capacity of circular SIFCON column

between the experimental and numerical outcomes showed a reasonable agreement with standard deviation (0.0225).

8 Conclusions

The effect of fiber shape, cross-section shape and the hollow ratio of SIFCON columns was investigated experimentally and these result compared with analytical predictions from ABAQUS program. The experimental and analytical results demonstrated that SIFCON columns have high performance in term of load carrying capacity, ductility and energy absorption capacity. This is an indication of the possibility of using SIFCON columns in structural buildings. Also, the incorruption of two shape of steel fiber as hybrid fiber in SIFCON enhance the performance of SIFCON columns.

The hollow ratio of columns has major effect of columns performance. Where each solid column has better performance than the same cross section hollow columns. For load carrying capacity, the decreasing percentages were (5.8% and 16.5%) in square hollow hybrid SIFCON column with ($\beta = 25\%$ and 50%) respectively. The high ductility of SIFCON columns shown by the results clearly signalize that SIFCON columns have the capability to deform plastically under load exhibit ultimately better performance when compared to NSC columns. In addition, SIFCON columns have superior energy absorption capacity than normal strength concrete columns. The hollow columns showed lower energy absorption capacity than similar solid columns, and decrease with increasing in hollow ratio of columns. Where compared with solid columns, the percentage decrease was (23.39 and 78.25) % for circular hooked end columns with hollow ratio ($\beta = 25\%$ and 50%) % respectively. More work can be carried out on the

possibility of using SIFCON concrete in bridge columns and other constructions, in particular in seismic areas, as a result of reduced column size and increased space. It is important to research the convergence area between the SIFCON column and the NSC beam and to evaluate the possibility of compatibility between the two concrete types in this field.

Acknowledgements This paper is part of the requirements of the master's degree in Civil Engineering, so I would like to thank the supervisors of this research, professor Mohammed M. Kadhum and professor Nameer A. Alwash. I also give special thanks to the officials of the laboratories of Civil Engineering College at the University of Babylon to provide all facilities.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability All data, models, and code generated or used during the study appear in the submitted article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Farnam Y, Moosavi M, Shekarchi M, Babanajad S, Bagherzadeh A (2010) Behaviour of slurry infiltrated fibre concrete (SIFCON) under triaxial compression. *Cem Concr Res* 40(11):1571–1581
- Jayashree S, Rakul B, Helen S (2013) Flexural behavior of SIFCON beams. *Int J Eng Res Technol* 2(2):1–7
- Abdulraheem MS, Kadhum MM (2018) Experimental and numerical study on post-fire behaviour of concentrically loaded reinforced reactive powder concrete columns. *Constr Build Mater* 168:877–892
- Kadhum M, Essa M, Fawzi N (2011) Behaviour of fire exposed reinforced concrete columns. *J Eng* 17(3):412–429
- Ipek M, Aksu M, Yilmaz K, Uysal M (2014) The effect of pre-setting pressure on the flexural strength and fracture toughness of SIFCON during the setting phase. *Constr Build Mater* 66:515–521
- Chidambaram RS, Agarwal P (2015) Seismic behavior of hybrid fiber reinforced cementitious composite beam–column joints. *Mater Des* 86:771–781
- Beglarigale A, Yalçinkaya Ç, Yiğiter H, Yazıcı H (2016) Flexural performance of SIFCON composites subjected to high temperature. *Constr Build Mater* 104:99–108
- Rao HS, Ramana N (2005) Behaviour of slurry infiltrated fibrous concrete (SIFCON) simply supported two-way slabs in flexure. *NISCAIR-CSIR*
- C ACI 544 (2002) State of the art report on fiber reinforced concrete reported (ACI 544.1 R-96 Reapproved 2002). *ACI Structural Journal* 96:66
- Elavarasi D, Mohan KSR (2018) On low-velocity impact response of SIFCON slabs under drop hammer impact loading. *Constr Build Mater* 160:127–135
- Pannem RMR (2017) Punching strength and impact resistance study of sifcon with different fibres. *Int J Civ Eng Technol* 8(4)
- Parra-Montesinos GJ, Reinhardt HW (2012) High performance fiber reinforced cement composites 6: HPFRCC 6, vol 2. Springer, Berlin
- Marković I (2006) High-performance hybrid-fibre concrete: development and utilisation. IOS Press
- Ali M (2018) Properties of slurry infiltrated fiber concrete (SIFCON). Ph.D. Thesis, University Of Technology, Baghdad
- Deepesh P, Jayant K (2016) Study of mechanical and durability properties of SIFCON by partial replacement of cement with fly ash as defined by an experimental based approach. *Int J Innov Res Sci Technol* 5(5):2349–6010
- Nuryanti P, Sulityo D, Suhendro B (2018) Non-linear analysis of hollow reinforced concrete column quare cross-section with various load eccentricity and concrete strength. *Langkau betang: jurnal arsitektur* 5(1):33–44
- Lignola GP, Prota A, Manfredi G, Cosenza E (2008) Unified theory for confinement of RC solid and hollow circular columns. *Compos B Eng* 39(7–8):1151–1160
- Han T, Lim N, Han S, Park J, Kang YJ (2008) Nonlinear concrete model for an internally confined hollow reinforced concrete column. *Mag Concrete Res* 60(6):429–440
- Kassim MM, Ahmad SA (2018) Strength evaluation of concrete columns with cross-sectional holes. *Pract Periodical Struct Des Constr* 23(4):04018027
- Gilliam T, Yamamoto Y, Poston R, Breen J (1983) Verification of analysis programs for solid and hollow concrete bridge piers. *Res Rep No 254 1*
- Zacoeb A (2003) Flexural capacity of reinforced concrete short column with variations hole. Gadjah Mada University, Yogyakarta, Graduate Program
- Supriyadi (1997) The effect of holes on strongly reinforced concrete column boundaries. Graduate program. Gadjah Mada University, Yogyakarta
- Kamath R, Shilpa S (2017) Nonlinear buckling analysis of Rcsifcon column subjected to lateral and axial loading. *Int Res J Eng Technol* 4(9)
- ASTM C1240 (2015) Standard Specification for Silica Fume Used in Cementitious Mixtures
- ASTM C494/C494M (2017) Standard specification for chemical admixtures for concrete
- Lubliner J, Oliver J, Oller S, Oñate E (1989) A plastic-damage model for concrete. *Int J Solids Struct* 25(3):299–326
- Lee J, Fenves GL (1998) Plastic-damage model for cyclic loading of concrete structures. *J Eng Mech* 124(8):892–900
- Naaman A, Reinhardt H, Fritz C, Alwan J (1993) Non-linear analysis of RC beams using a SIFCON matrix. *Mater Struct* 26(9):522–531
- Soylu N, Bingöl AF (2019) Research on effect of the quantity and aspect ratio of steel fibers on compressive and flexural strength of SIFCON. *Chall J Struct Mech* 5(1):29–34
- Yazıcı Ş, İnan G, Tabak V (2007) Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. *Constr Build Mater* 21(6):1250–1253
- Homrich JR, Naaman AE (1988) Stress-strain properties of SIFCON in uniaxial compression and tension. Michigan univ Ann Arbor Dept of Civil Engineering
- Shi C, Mo Y-L (2008) High-performance construction materials: science and applications, vol 1. World Scientific, Singapore
- Drdlová M, Řídký R, Čechmánek R (2016) Influence of fibre type and fibre volume fraction on dynamic properties of slurry

- infiltrated fibre concrete. In: Materials science forum, 2016. Trans Tech Publ, pp 135–140
34. Bentur A, Mindess S (2006) Fibre reinforced cementitious composites. CRC Press, London
 35. Wang M, Maji A (1994) Shear properties of slurry-infiltrated fibre concrete (SIFCON). *Constr Build Mater* 8(3):161–168
 36. Naaman AE, Reinhardt HW (1995) High performance fiber reinforced cement composites 2 (HPFRCC2). Published by E & FN Spon, an imprint of Chapman & Hall, London SE1 8HN, UK
 37. Hadi MN, Jameel MT, Sheikh MN (2017) Behavior of circularized hollow RC columns under different loading conditions. *J Compos Constr* 21(5):04017025
 38. Ganesan N, Indira P, Sabeena M (2014) Behaviour of hybrid fibre reinforced concrete beam–column joints under reverse cyclic loads. *Mater Des* 1980–2015(54):686–693. <https://doi.org/10.1016/j.matdes.2013.08.076>
 39. Anwar N, Najam FA (2016) Structural cross sections: analysis and design. Butterworth-Heinemann, Oxford
 40. Azizinamini A, Darwin D, Eligehausen R, Pavel R, Ghosh SK (1999) Proposed modifications to ACI 318-95 tension development and lap splice for high-strength concrete. In: 1999. American Concrete Institute,
 41. Nawy EG (2008) Concrete construction engineering handbook, 2nd edn. CRC Press, New Brunswick
 42. G. Ganotra (2018). <https://www.quora.com/Between-a-circular-and-a-square-which-column-section-has-more-load-bearing-capacity>
 43. Barros J, Pereira E, Santos S (2007) Lightweight panels of steel fiber-reinforced self-compacting concrete. *J Mater Civ Eng* 19(4):295–304
 44. Abdulraheem MS (2017) Effect of fire exposed on the behavior of reactive powder concrete columns under concentric compression loading. University of Babylon
 45. Wang Z, Wu J, Wang J (2010) Experimental and numerical analysis on effect of fibre aspect ratio on mechanical properties of SRFC. *Constr Build Mater* 24(4):559–565
 46. Sovják R, Máca P, Imlauf T (2016) Effect of fibre aspect ratio and fibre volume fraction on the effective fracture energy of ultra-high-performance fibre-reinforced concrete. *Acta Polytech* 56(4):319–327
- Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.