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Experimental Study on the Behavior of Axially Loaded Reinforced Concrete Square Columns Strengthened with SIFCON Shell

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Abstract. Slurry infiltrated fiber concrete (SIFCON) is an advanced generation of fiber-reinforced concrete (FRC) with higher fiber content. SIFCON offers excellent potential for use in areas that require high ductility and impact resistance, particularly when designing seismic retrofits and repairing or strengthening structural reinforced concrete members. This study investigated the behavior of square normal strength concrete (NSC) columns of grade M35 strengthened with SIFCON shell and compared them with unstrengthen NSC. The effect of different SIFCON shell thicknesses (2 and 3) cm, fiber type and volume fraction (4 and 6%), and tie spacing (8 and 16) cm were studied. The fiber types employed were polypropylene and hooked-end steel fiber. Eleven columns were cast and tested for the current investigation in two groups, where the first group (control specimens) consists of two unstrengthen NSC columns and one square NSC column strengthened with a 2 cm SIFCON shell with a 6% steel fiber ratio. The second group comprises eight NSC columns strengthened with a hybrid fiber SIFCON shell. The NSC square columns had dimensions of (8x8x80) cm. 3 cm SIFCON shell thickness was observed to evolve the strengthen columns' load-carrying capacity and energy absorption. The maximum load achieved is about 223% as compared with unstrengthened NSC columns. The energy absorption was about 16 times that of the control. At the same time, the stiffness of strengthened columns is less than that of NSC columns.

Keywords: Column strengthening; SIFCON; hybrid fiber; energy absorption; stiffness.

1. INTRODUCTION

Most concrete buildings consist of different structural members. Column is the most important and dangerous structural member. Therefore, any damage to it may lead to failure and possibly collapse of the building because the column is subject to compression load that moves vertically through it to the soil. The nature of the damage done in the reinforced concrete column can be in the form of cracks without damaging the steel reinforcement except for serious cracks, steel reinforcement buckled, ties ruptured, and concrete crushed. According to the degree of damage caused, the appropriate method of strengthening is used [1]. The structure requires development for several reasons: changes in its function, different design requirements, and natural disasters such as earthquakes and floods. Several methods have been used to strengthen reinforced concrete structures, such as “fiber-reinforced polymer, steel bracing, external post-tensioning, steel plate bonding, adding new structural elements, etc.” There is no ideal way. Each method has its own downsides. For example, when using a steel plate, it does not resist fires and may exposed to corrosion, while when using concrete jackets, the dimensions and dead load will increase [2]. In the last decades, researchers developed a type of concrete called SIFCON, which showed suitability for use in several applications, such as strengthening and repairing reinforced concrete members, pavement overlays, and structures designed against earthquakes [3].

Previous research studied the strengthening of various reinforced concrete members with SIFCON; Sisupalan studied the strengthening of a beam of ordinary reinforced concrete and another from FRC using precast layers of SIFCON. These layers are glued with epoxy to the bottom of the beam and on its sides under the influence of a 2-point load test. It was used hooked end steel fibers by (5, 7, 9, and 11%). The ratio of 5% gave the highest results. The results showed that strengthening FRC and RC beams with SIFCON gave a noticeable increase in improving the load capacity [4].

Dalya studied the bending strength, toughness, and ductility of prisms made of ordinary concrete reinforced with layers of SIFCON. Prisms coated only from the bottom, from above, and from all sides with different thicknesses (3.5, 2.5, and 1.5) cm and used steel fiber by (6, 7.5, and 9%). The results showed that increasing the thickness of the SIFCON layer and its proportion of steel fiber leads to an improvement in "load bearing capacity, toughness, ductility" where the highest results were obtained when the prism fully strengthened with SIFCON, where it was 23 times higher than control prism [5].

There have been numerous studies on strengthening NSC columns. Still, according to the author's knowledge, only one experimental study has investigated the behavior of NSC columns strengthened with a SIFCON shell by Roller. He investigated the circular column's residual axial load-carrying capacity when subjected to explosive loads and reinforced with abrasive materials such as polymer concrete, SIFCON, ductile concrete (DUCON), and ultra-high-performance concrete (UHPC). The SIFCON layer strengthened the cross-section locally in the probable damaged location with more than 5% steel fiber ratio [6]. Therefore, the current investigation's objective is to study the behavior of square NSC columns strengthened with SIFCON shells subjected to concentric loading to provide valuable information and a better understanding of their behavior.

In addition, it studies the effect of various parameters such as SIFCON shell thickness, fiber type and volume fraction, and spaces between columns ties and compares its behavior with strengthened NSC columns. Since SIFCON comprises fiber and slurry, the variables will either be in mixing ratios or fiber. The researchers used various fiber types in different volume fractions to know their effect on the behavior of NSC columns strengthened with SIFCON at different thicknesses in order to determine whether or not the strengthening of the column increases as the thickness increases. The researchers also studied the effect of reducing the number of ties if there is an error in the design or implementation.

2. EXPERIMENTAL INVESTIGATION

2.1 Materials

Ordinary Portland cement (CEM I-42.5) was used to make the SIFCON columns. SIFCON slurry was made using only fine sand that had been sieved through (0.6 mm sieve) to remove the larger particles. Additionally, SIFCON slurry contains densified micro silica fume that complies with the requirement of (ASTM C1240, 2015)[7]. In this study, an original carboxylic ether polymer with long lateral chains was used as a range-reducing admixture (superplasticizer) compliant with (ASTM C-494 Type F& G BS EN 934-2) which is called commercially (Glenium 54). This investigation used polypropylene and steel fibers with a hooked end. Polypropylene fibers were chosen for SIFCON because of their low density, which reduces dead weight. They were also chosen because they are less expensive than steel fiber and prevent corrosion. Table 1 and Figure 1 display the properties and shape of fibers.

Figure 1: Hooked end steel fiber and polypropylene.

Table 1: Properties of fiber.

Property	Hooked fiber	Polypropylene
Description	Deformed shape Hooked end	Deformed shape
Appearance	Bright and clean wire	White straight fibers
Length (mm), L	35	60
Diameter (mm), D	0.5	0.85
Aspect ratio L/D	70	71.42
Density (kg/m^3)	7800	910
Tensile strength (MPa)	1100	430

2.2 MIX PROPORTION of SIFCON and NSC

Numerous trial mixes were conducted to create a slurry that meets the requirements of SIFCON slurry for fluidity, viscosity, and filling ability without segregation or Honeycombing in the fiber network. Cement and sand were blended in a 1:1 ratio to create SIFCON slurry. For the mini-slump flow test, the SIFCON slurry's workability was evaluated at a measurement of 245 mm. The v-funnel test and a 10-second slurry mix time were also performed to assess the slurry's viscosity. According to the American mix design process, the normal strength concrete (NSC) mix was created (ACI 211.1, 1991) [8]. The mix proportion of SIFCON and NSC are shown in Table 2. The type of fiber affects the w/b ratio because polypropylene fiber has a larger absorption as compared with steel fiber.

Table 2: Mix proportions of SIFCON and NSC for 1 m^3.

Mix type	Mix proportion						
	Blended cement (kg/m^3	Sand (kg/m^3)	Silica fume (kg/m^3)10 % rep.	Gravel (kg/m^3)	Fiber (%) ratio	w/b or w/c ratio	SP (by wt. Of binder) (%)
SIFCON	872.1	969	96.9	—	and 6 4	0.28	2.4
NSC	518	1129	—	704	-----	0.61	—

2.3 Test Specimens

The experimental program was designed to investigate the effects of four parameters on the behavior of NSC columns strengthened with SIFCON shell, which are volume fraction of fiber (4 and 6%), ties spacing (8 and 16) cm, and thickness of SIFCON shell (2 and 3) cm. Since SIFCON hasn't received a standard specification yet. The fiber content used in this study is based on previous studies [9,10]. There were 11 columns of specimens, where in Figure 2, the method for identifying the samples is represented. All columns that were examined had a length of 800 mm. Each of the NSC columns was reinforced with 4Ø6 mm of longitudinal reinforcement, which has yield stress (fy) of 560 MPa, and Ø4 mm bars were used with yielding stress (fy) of 555 MPa as transverse reinforcement (ties), which design according to ACI code. Figure 3 illustrates how steel reinforcement is fixed and organized in square columns. The fibers were used as hybrid fibers, with a 6% fiber volume fraction (4% hooked-end steel fiber and 2% polypropylene). In comparison, the 4% fiber ratio is (2% hooked-end steel fiber and 2% polypropylene) and steel fiber only has a 6% fiber ratio.

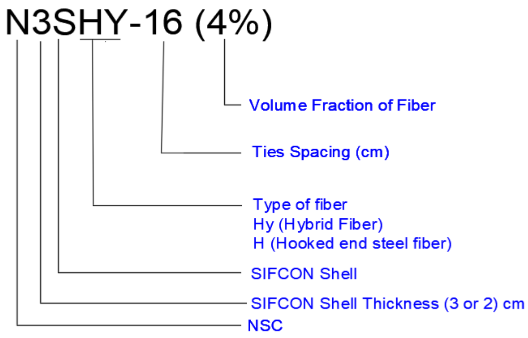

Figure 2: The procedure for identifying column specimens.

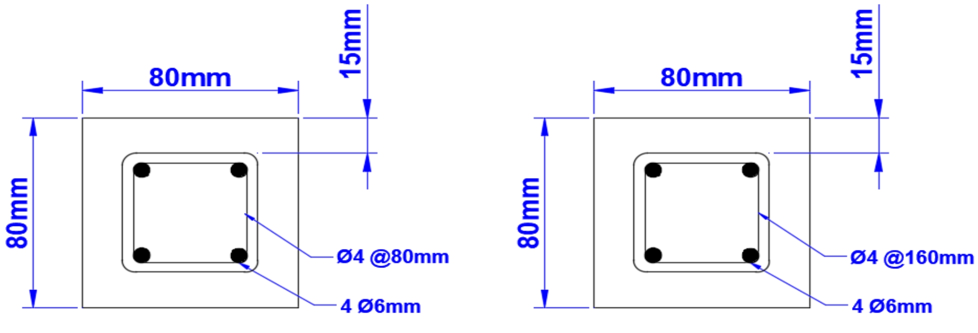

Figure 3: Cross-section of reinforcing steel in square NSC columns.

2.4 Mixing Procedure of SIFCON Specimens

The mixing procedure consists of several steps, which are:

- Prior to mixing, the mixer cleared any lingering fresh or dried components (from previous combinations).
- For about 0.5 minutes, the entire amount of HRWR was mixed separately with (1/3) of mixing water.
- To create the SIFCON slurry, the cement and silica fume (SF) binder material first mixed for one minute in a mixer to distribute the SF particles throughout the cement particles. Then, sand was added, and the mixture continued for two more minutes.
- The revolving drum was then filled with (2/3) of mixing water, which was then blended for 1 minute. After adding 1/3 of the mixing water, HRWR (high-range water reducer) was fed into the mixer and blended for 3 minutes.
- The mixer then halted, and hand mixing was carried out for the area the mixer blades could not reach.
- The mortar components are then blended for an additional (1) minute to get the desired smoothness.

2.5 Casting Procedure of SIFCON Specimens

The square columns used in this study are cast vertically. The iron molds are divided vertically into two sections with a height of 800 mm; the first vertical portion is an 800 mm length that is one piece, and the second vertical section is divided horizontally into three pieces to regulate the casting process, as shown in Figure 4. The square molds for (2 and 3) cm thickness have a cross-section of (12x12) cm and (14x14) cm. The sample dimensions were chosen based on the permitted dimensions of the device used to test the columns.

The following phases are outlined in the casting process:

- Cast NSC columns, and for 28 days of curing, leave the square NSC columns in the water.
- After 28 days, the NSC columns are removed, left to dry, and then roughed the surface to increase the bonding between normal and SIFCON concrete.
- Cleaning the iron molds, painting their internal sides with a light layer of oil, placing the molds on flat ground, and adjusting them horizontally and vertically.
- Mixing materials to form slurry by horizontal rotary mixer according to the earlier mixing steps.
- To prevent the NSC columns from shifting while the SIFCON shell was poured and to provide good bonding between SIFCON and NSC concrete, epoxy should have been applied to the base and all sides of each column before placing it in the center of the iron mold and allowing it to cure.
- Pour the SIFCON shell based on the multi-layer technology, where each layer is poured 10 cm thick by distributing the fiber randomly, then pouring the slurry over it with a metal rod to give the concrete compacting and prevent gaps or segregation.
- After giving the columns a 24-hour rest, remove the molds and put the columns in a water tank to cure for 56 days at a temperature of (23±2 °C).

Figure 4: Square and circular iron molds.

2.6 Setup and Procedures of Testing

Using a standardized electro-hydraulic testing device with a maximum capacity of 600 kN in the structural lab of the University of Babylon, all SIFCON columns tested up failed at 56 days. On the test stand, the columns are positioned so that the boundary conditions at the column ends are fixedly supported while ensuring that the columns are vertical. For the axially loaded columns, the load is applied through a bearing plate, and for the line load simulation, through a cylindrical roller attached to the top of the bearing plates. Using load control, the load was applied at a rate of 1 kN/s, and readings were taken every 10.0 kN load until failure. The load was constant between each increment until the necessary measurements were taken and recorded. Testing went on until the column's load capacity decreased as deformation increased. Utilizing dial gauges with an accuracy of 0.001 mm per division, a capacity of 30 mm, and a maximum sensor length of 50 mm, the specimens' axial and mid-high lateral displacement were measured. These dial gauges were installed at mid-height along the vertical midline side of each column to measure the lateral deflection. As shown in Figure 5 and Figure 6, a dial gauge is used to measure each column's axial displacement while being fixed on the top surface of the machine piston. Small cameras connected to the laptop record the screen used to monitor the dial gauge's value. This technique protects workers from the SIFCON column's explosion and fragmentation.

Figure 5: Electro hydraulic testing device of columns.

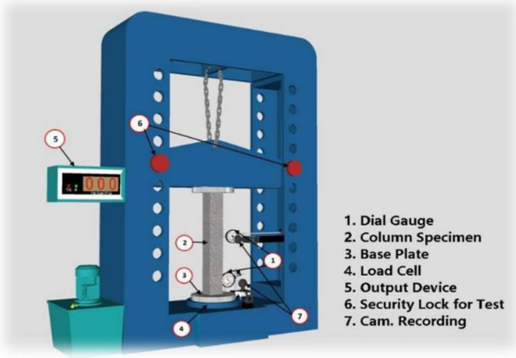

Figure 6: 3D drawing of the columns test device.

3. RESULTS AND DISCUSSION

3.1 Load Carrying Capacity

To compare NCS columns with columns that had been strengthened by SIFCON, two NCS column specimens were cast and put to the test. As shown in Figure 7, strengthened square columns significantly outperform NSC columns by a significant margin in terms of load-carrying capacity. The max increase in load achieved is 223% for the N3SSHy16-4% column strengthened with SIFCON shell of 3 cm and 4% hybrid fiber ratio, while the maximum load for NSC columns strengthened with SIFCON shell of 2 cm was 115% for N2SSHy16-4% column as a compared with NSC columns. It was observed that columns of the same reinforcement and fiber ratio strengthened with SIFCON shell of steel fiber only have higher load-bearing capacity than that of hybrid fiber by about 19%. The 3 cm SIFCON shell has a large percentage of fibers due to the 3 cm thickness increases in cross-sectional area. When steel fibers cross diagonal cracks in a concrete mass, they are excellent at preventing cracks from spreading and containing their growth [11-13]. In addition, polypropylene fiber's ability to bridge gaps results in stronger mechanical bonds. Compared to ordinary concrete, SIFCON has higher fiber to slurry adhesion and a more uniform, finer grain size [14].

However, "a number of phenomena occur in NSC columns that are damaged in the following order: yielding of longitudinal steel reinforcement, spalling and crushing of concrete cover, buckling of longitudinal steel reinforcement, and compression failure of core concrete that does not happen in SIFCON shell" [15]. All of these events could be the reason why strengthened columns outperformed NSC columns in terms of performance. According to the results, SIFCON shell-strengthened NSC columns have a larger improvement in load-carrying capacity with a 4% fiber ratio due to remarkable edge effects, which happen at the SIFCON and mold interface. Fibers cannot randomly organize themselves at this interface as they can in places farther from the edges. Observations show that the fiber density is less dense near the specimen's edge than it is in the center. Mostly, fiber ends or fibers that have been pushed into a vertical alignment fill this edge area. As a result, the vertical fiber at the edge spalls off under compressive load and, therefore, does not contribute to the compressive strength [16]. In this study, fiber orientation is random because the square section has sharp edges, making it challenging for the fibers to reach the corners and edges unless they are spread vertically or horizontally. Due to the difficulties of fiber distribution in a horizontal or vertical direction when the fiber ratio is increasing within a tiny thickness in a square section, the edges' contribution to load bearing capability became unnoticeable. Because of this, square columns perform better when the fiber volume fraction is 4% rather than 6%.

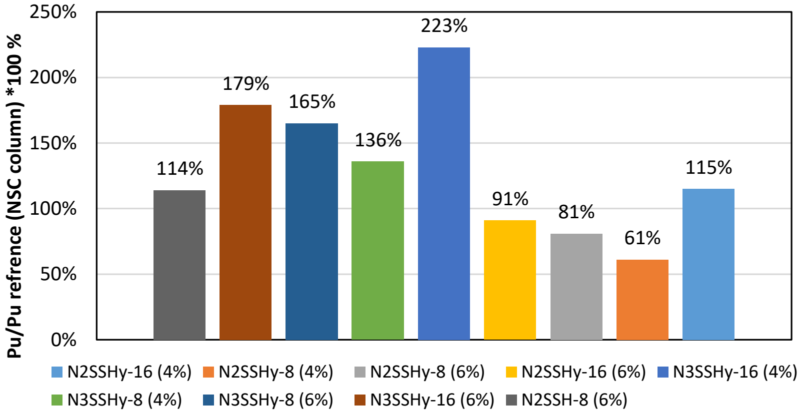

Figure 7: Ratio of increasing load-bearing capacity of strengthened columns to strengthened columns (NSC columns) * 100%.

3.2 Column Specimen Load-Displacement Relationships

The vertical displacement and the mid-height lateral displacement of these columns were recorded immediately after the load was applied in order to be able to study the behavior of strengthened SIFCON columns with various parameters and to determine the deformation properties of strengthened with SIFCON and NSC columns. These characteristics are significant in introducing concrete columns' stiffness and energy dissipation characteristics. The columns' ultimate displacements and lateral displacements at mid-height are shown in Table 3. The test results revealed that columns strengthened with SIFCON have a much higher ultimate axial displacement than NSC columns.

It also demonstrated that the NSC specimens' ascending portion of the curve is linear, whereas its descending part rapidly drops within a small deformation range. Figure 8 shows that the curves, unlike NSC columns, do not descend once they reach their maximum strength as compared with NSC columns. It is also evident from the experiment results that the strengthened SIFCON columns' ultimate mid-height lateral displacement is higher than that of the NSC columns. This may be because of the high deformation of the strengthened SIFCON columns prior to failure [17].

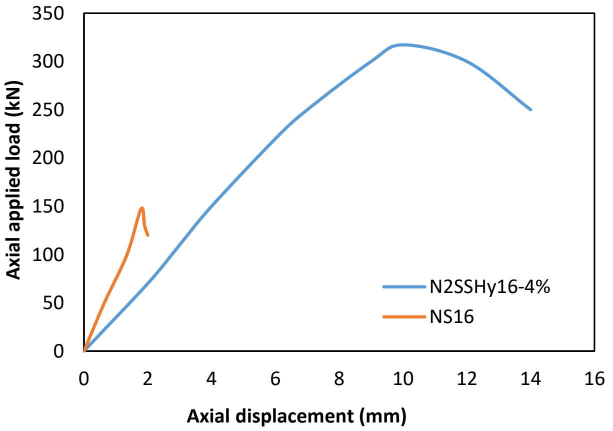

Figure 8: An example of the load-displacement relationship of NSC column and strengthened with SIFCON column.

3.3 Initial Column Specimen Stiffness

Initial stiffness testing, which Sullivan developed to evaluate the stiffness of concrete columns (K_{in}). This was measured using a straightforward method, in which a secant was extended to meet the horizontal line at (Pu) after passing through a location on the load-displacement envelope where 70% of the maximum applied force to the specimen was located (0.7 Pu) [18]. Table 4 contains a summary of the column stiffness test results. The stiffness of strengthened SIFCON columns is lower than that of NSC columns. That may be because the calculations of initial stiffness depend on yielding displacement, where the initial stiffness decreases with increasing yielding displacement. Strengthened columns have higher yielding displacement than NSC columns because their calculations depend on axial displacement at ultimate load. Axial displacement of strengthened with SIFCON columns is much higher than NSC columns for the same reasons mentioned previously. Therefore, the Initial stiffness of NSC columns was higher. The highest percentage of decrease in column stiffness was approximately 54% for N2SSHy16-4% square column, as shown in Figure 9.

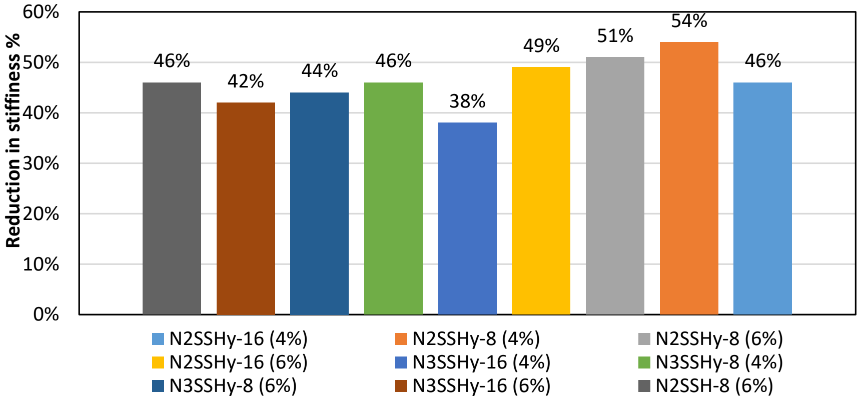

Figure 9: Percentage of reduction in stiffness of NSC columns after strengthening with SIFCON shell compared to NSC columns.

3.4 Energy Absorption Capacity of Column Specimens

The area enclosed by the load-displacement curve up until the maximum load is utilized to describe the concrete column's energy absorption capacity. This area represents the maximum energy a concrete column could absorb before significantly reducing its capacity to carry loads [19, 20]. The energy absorption capacity for strengthened with SIFCON and NSC columns was measured, and the results are given in Table 4. From that table, it can be observed that the energy absorption capacity is constantly rising and reaching a maximum increase of around 16 times for strengthened with SIFCON column (N3SSHy16-6%) as compared with NSC column of the same characteristics as shown in Figure 10, due to the SIFCON shell's high fiber content and fibers' ability to transfer loads across broken sections concrete's ability to absorb energy in a hardened condition [21]. On the other hand, SIFCON columns have a larger energy absorption capacity due to their high fiber/matrix bonding [22].

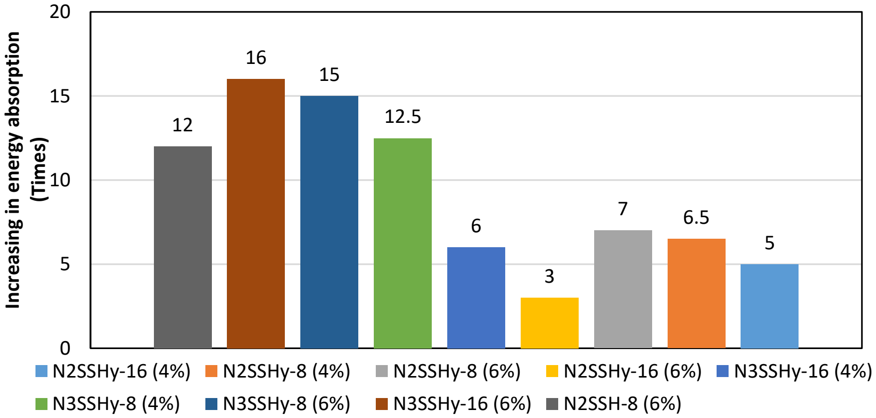

Figure 10: Percentage of increase in energy absorption of NSC columns after strengthening with SIFCON shell compared to NSC columns.

Table 3: Experimental test results of column specimens.

Type of Concrete of column	Columns Symbol	Ultimate Load Pu (kN)	Axial displacement (mm)	Mid-height Lateral Displacement (mm)
NSC	N8	152.21	1.79	0.168
	N16	147.33	1.98	0.158
NSC Strengthened with SIFCON shell	N2SH8-6%	327.14	9.81	0.482
	N2SHy16-4%	317.24	9.47	0.466
	N2SHy8-4%	244.88	5.78	0.203
	N2SHy8-6%	274.86	7.74	0.361
	N2SHy16-6%	282.3	7.23	0.368
	N3SHy16-4%	475.86	12.16	0.705
	N3SHy8-4%	359.19	10.24	0.576
	N3SHy8-6%	402.81	11.28	0.648
	N3SHy16-6%	410.45	11.41	0.667

Table 4: Test results of initial stiffness and energy absorption of columns.

Columns Symbol	Initial Stiffness			Energy absorption capacity (kN.mm)
	Pu (kN)	$y\Delta$	K_{in} (kN/mm)	
N8	152.21	1.611	94.482	110.345
N16	147.33	1.574	93.602	260.823
N2SH8-6%	327.14	6.43	50.89	1349.87
N2SHy16-4%	317.24	6.273	50.572	1281.321
N2SHy8-4%	244.88	5.657	43.288	723.763
N2SHy8-6%	274.86	5.969	46.048	785.682
N2SHy16-6%	282.3	5.933	47.581	883.310
N3SHy16-4%	475.86	8.171	58.238	1563.920
N3SHy8-4%	359.19	7.042	51.007	1378.560
N3SHy8--6%	402.81	7.641	52.717	1476.080
N3SHy16-6%	410.45	7.846	54.011	1496.080

3.5 Discussions on the Column Failure Process

During the testing process, the failure mode for all NSC columns was gradual, starting with a large piece of concrete falling, and the steel reinforcement started to appear until a localized failure occurred. For NSC columns, spalling the cover happened. While strengthened with SIFCON, columns do not have a noticeable spalling on the surface due to great cohesion and interlock between fibers. During the testing process, small multiple cracks and deterioration appeared on the surface of strengthened SIFCON columns. Visible cracks at approximately 65% of the ultimate load were strengthened with SIFCON columns compared to 35% for NSC columns. A huge explosion that occurs at failure accompanied by a loud voice is one of the most common things that distinguish the strengthened with SIFCON columns from NSC columns. The reason for the explosion is that the SIFCON shell absorbed enormous energy. Figure 11 shows the failure pattern of columns.

Figure 11: Failure Pattern of (left) NSC column strengthened with SIFCON shell, (right) NSC column.

4. CONCLUSIONS

The effect of different SIFCON shell thicknesses, fiber volume fraction, fiber type, and distance between ties of NSC columns strengthened with SIFCON shell compared to NSC columns was experimentally investigated. The following conclusions are drawn:

- The performance of strengthened SIFCON shell columns is significantly superior to NSC columns in load-carrying and energy absorption capacity.
- Classical test results indicate that the stiffness of strengthened SIFCON columns was much lower than that of corresponding NSC columns, where the highest decrease in column stiffness was approximately 54%.
- Strengthened with SIFCON shell columns absorb more energy than the NSC columns. The maximum energy absorption achieved is 16 times the number of NSC columns. The high energy absorption of SIFCON concrete increases the possibility of employing this concrete in bridge columns and other constructions, particularly in seismic areas.
- Using hybrid fiber (hooked-end steel fiber and polypropylene) with 4% and 6% fiber volume fraction in mortar significantly impacts by providing a perfect spread of fiber crossing the SIFCON section, reducing dead weight and preventing corrosion.
- With a reduced number of NSC column ties, the load-bearing capacity is reduced slightly.
- Thicker SIFCON shell shows higher load carrying capacity as compared with NSC columns, where the max increase in load achieved is 223% for NSC column strengthened with SIFCON shell of 3cm while for 2cm SIFCON shell, the maximum load was 115%.
- Columns strengthened with a SIFCON shell of steel fiber show a higher load-bearing capacity increase by about 19% than hybrid fibers.
- The 4% hybrid fiber ratio shows higher load-bearing capacity than 6%.
- The cost of using SIFCON in strengthening is high compared to other methods of strengthening because the raw materials are unavailable locally. Its industry requires experience and highly skilled labor, but its unique mechanical properties compared to its cost make it worth using.

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