Behavior of Slurry Infiltrated Fibrous Concrete (SIFCON) Deep Beams: With and Without Openings

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Abstract: Due to the absence of study deals with the effect of SIFCON on deep beams, this study was conducted. The mechanical properties; compressive, tensile, flexural and shear strength were tested. The second aspect was the study of behavior of SIFCON deep beams with and without openings. The study was divided into two groups. The first group was prepared to cover the following cases: variation in SIFCON ratio, the effect of shear span to depth ratio, removing of vertical steel and removing of mesh reinforcement. While, the second group was prepared to study the following cases: variation in SIFCON ratio, openings reinforcement effect and effect of opening shape. The increase of SIFCON ratio by (6% to 9%) gave increasing in the cracking and ultimate load compared with a deep beam of conventional concrete. In addition, it was removed either vertical reinforcement or all reinforcement, it showed an increase in ultimate load for solid deep beams with SIFCON of (9%) increased than the conventional concrete. The results showed that the ultimate load was increased with decreasing the effective shear span to depth ratio. The SIFCON deep beam with inclined reinforcement around the openings gave increasing in the ultimate load than the conventional concrete deep beam with inclined reinforcement. Also, the SIFCON deep beam with circular opening gave high cracking and ultimate loads than square and triangular openings. The toughness and ductility were increased for all SIFCON deep beams.

1. Introduction
Reinforced concrete deep beams are exceedingly used in civil engineering for parking or storage facility, bridge, wall footings, transfer girders, , foundation pile caps, shear walls floor and diaphragms [1]. In some multi-storey buildings, one of the important structural requirements is to make the lower floor devoid of columns, so these structural elements (deep beams) may be designed as beams spanning along with the column-free space. The ACI 318M-14 code [2] defines deep beams as structural elements loaded from one side and supported from the opposite side such that struts-like the compression elements can be developed between loads and supports. The deep beam should satisfy a or b:
a) Clear span does not exceed four times the overall depth h.
b) Concentrated load exists within a distance 2h from the face of the support.

According to Eurocode 2 (EC2) [3], concrete beams are classified as deep beams when the width of the beam to its depth is smaller than three (L/h ≤ 3). Canadian standard associated (CSA) A23.3-04 [4] states that flexural members should be designed as deep elements when the width to depth ratio is smaller than two and should be designed by strut and tie method and take into a count nonlinear distribution of strain. Researches have shown that deep beams strength is usually determined by shear resistance rather than flexural resistance [5]. When designing deep beams, it should consider the non-linear distribution of longitudinal strains for the entire depth of the beam [2]. The strut-and-tie model is a rational method for the analysis and design of the reinforced concrete beams especially the deep beams, it was pioneered by Ritter [6] and Morsch [7]. The strut and tie
method (STM) is a lower-bound solution for the capacity that is recognized as an important issue for designing of the non-slender beams since it considers member capacity as a function of a/d [8,9]. Slurry infiltrated fibrous concrete (SIFCON) was explored by Lankard (1984) [10]. Lankard limited percentage of volume fiber between (5-20) % and he said it was possible to casting slurry into substrate bed of fiber. ACI defined SIFCON is a modern type of reinforced concrete with fibers, which fill their molds before casting with steel fibers randomly distributed, intertwined with each other and the fiber network depends on the cement mixture. Infiltration is usually accomplished by the gravity flow aided by the light vibration, or by pressure grouting. SIFCON composites differ from conventional steel fiber reinforcement concrete (SFRC) in at least two respects: The first is that it contains a larger volume of the steel fibers (usually 8-20% as a volume ratio), and they used a matrix consisting of very fine particles (absence of the coarse aggregates in SIFCON). As such, they can be made to simultaneously exhibit outstanding strength and ductility [11]. Furthermore, SIFCON mix contains a high percentage of cement and water compared to the traditional concrete mixture [10]. All steel fiber types namely straight, hooked and crimped can be used. SIFCON possess Excellent energy absorption, durability, abrasion and impact resistance and toughness [11]. The modulus of elasticity (Ec) values of the SIFCON specimens are higher than these of the plain concrete, also SIFCON exhibits a high ductility.

2. Materials Used

2.1 Cement

Ordinary Portland cement (type I) was used during this work, named as Karasta. It was stored in a dry place to avoid exposure to undesirable atmospheric conditions. The initial and final time setting were found as 2 and 3.5 hr respectively.

2.2 Admixture

The plasticizer used in the mixing process is commercially known as Flocrete PC 260, it conforms to ASTM C494-99 [12] type A&G.

2.3 Fine and coarse aggregates

Natural fine sand was used in concrete mixes in this work. Sulfate content of fine sand was 0.13%. The fineness modulus of fine sand was 2.3. Crushed gravel (passing sieve 12mm) was used for the preparation of the normal mix.

2.4 Fibers

Throughout this work, two types of hooked-end steel wire fibers were used as shown in Figures 1 and 2. This type of steel fiber is manufactured by Dramix® Company, imported from Turkey, according to ASTM-A820 [13]. This type of steel fiber is classified as (Type II). Program of work consists of casting (3 cubes, 3 cylinders, 3 prisms and 3 double L Shape specimens) for each aspect ratio of mixes to show the appropriated type for this work. The ultimate tensile strength of steel fiber was 1150 MPa and 1345 MPa for type 1 and type 2 respectively.

Figure 1. Steel Fiber (L = 30mm)  
Figure 2. Steel Fiber (L = 60mm)
2.5 Silica Fume
A grey densified (grade 920 D), a material made of silicon or ferro silicon, imported from Al Khaimah in the UAE, was used.

3. Casting Procedure
All molds, which made from steel plate, were cleaned and their inner surfaces were oiled to prevent adhesion of the concrete after hardening. The process of preparing and mixing samples is illustrated in the following steps:

- Before mixing all the quantities, were weighed and saved in plastic containers and molds were oiled the day before the casting process as shown in Figure 3.
- Reinforcement steel cages were placed in their proper places to provide adequate concrete cover by placing spacers between the sides of the molds.
- For all mixing processes, cement and silica were mixed in a dry condition for 5 minutes in order the silica disperses between the cement granules, then sand was added. The mixing was continued for another 10 minutes as presented in Figure 4. Then, the superplasticizer was dissolved in water, and then the solution of the water and the superplasticizer was added to the rotary mixer and the mixing was continued for an adequate period. Then the mixer was stopped and mixing was continued manually, especially as some quantities had not been reached by the mixer blades. The mixer then was operated for 5 minutes to attain reasonable fluidity (mixture become slurry). Then, to obtain a homogenous specimen, the mixture into the mold in three layers. Firstly, the fibers were placed as random distribution in the mold about one-third of the depth. Then, the concrete slurry was poured over a bed layer of steel fiber to infiltrate inside of network fiber. This process was then repeated to the other layers until the required depth was achieved, as shown in Figure 5.

![Figure 3. The material of all Deep Beams at Container](image1)

(a)  
(b)

![Figure 4. Silica Fume Mix with Cement (a), Silica Fume and Cement Mix with Sand (b).](image2)
4. Curing of Specimens

All specimens were demolded after 24 hours, and then they were cured at a water bath and left until the end of water curing at 28 days as shown in Figure 6.

5. Mechanical Properties Results

Four trail mixes were selected to confirm the perfect mix to cast the SIFCON deep beam. Table 1 shows the mix proportions of selected mixes to test SIFCON mechanical properties. The results of compressive strength, tensile strength, flexural strength and shear strength for all trail mixes are summarized in Table 2. It can be seen from Table 2 that the best results are for trail 3, so this mix was later used in casting deep beams.
Table 1 Mix Proportions.

| Items | Compressive strength (MPa) | Tensile strength (MPa) | Flexural strength (MPa) | Shear strength (MPa) |
|-------|----------------------------|------------------------|-------------------------|---------------------|
| Trail 1 | 61                          | 13.3                   | 30.4                    | 37.3                |
| Trail 2 | 64.4                        | 15.6                   | 38                      | 45.1                |
| Trail 3 | 81.1                        | 18.5                   | 55.5                    | 61.8                |
| Trail 4 | 43.4                        | 2.8                    | 5.9                     | 6.9                 |

Table 2 Properties Results of Mixes

| items | Trail 1 | Trail 2 | Trail 3 | Trail 4 |
|-------|---------|---------|---------|---------|
| Cement Kg/m³ | 1000 | 1000 | 1000 | 1000 |
| Fine Sand Kg/m² | 1000 | 1000 | 1000 | 1000 |
| Silica fume % from cement | 10 | 15 | 20 | - |
| Water Kg/m³ | 300 | 350 | 400 | 400 |
| Hyper plasticizer pc260 % from cement | 5 | 5 | 5 | - |
| Steel fiber Kg/m³ | 6% | 7.5% | 9% | - |
| Gravel Kg/m³ | - | - | - | 1100 |

Table 3 Loads at first crack and ultimate loads for (experimental) solid deep beams.

| Group No. | Deep Beam No. | Cracking Load (kN) | Ultimate Load (kN) | Max Mid Span Deflection (mm) |
|-----------|---------------|---------------------|---------------------|-------------------------------|
| G1        | NA1           | 160                 | 330                 | 2.8                           |
|           | SB1           | 600                 | 977                 | 8.4                           |
|           | SB2           | 690                 | 1010                | 11.7                          |
|           | SB3           | 740                 | 1120                | 14.4                          |
|           | SC1           | 505                 | 1030                | 12.6                          |
|           | SD1           | 550                 | 1050                | 16.4                          |
|           | SD2           | 880                 | 1400                | 7.1                           |
|           | SE1           | 523                 | 922                 | 15.1                          |

6. Results and Discussion

6.1 Load – deflection curve and crack pattern of solid deep beams

The experimental load-deflection curves for all tested solid specimens are shown in Figures 1 to 4, while Figures 11 to 17 depict the specimens after failure. Table 3 shows a summary of the details of the test results.
Figure 7. Load - deflection relation of (G1NA1, G1SB1, G1SB2 and G1SB3) specimens.

Figure 8. Load - deflection relation of (G1NA1, G1SB3 and G1SC1) specimens.

Figure 9. Load - deflection relation of (G1SB3, G1SD1 and G1SD2) specimens.
Figure 10. Load - deflection relation of (G1SB3, G1SD1 and G1SD2) specimens

Figure 11. Deep beam G1NA1 (0%SF) after failure.

Figure 12. Deep beam G1SB1 (6%SF) after failure.

Figure 13. Deep beam G1SB2 (7.5%SF) after failure.

Figure 14. Deep beam G1SB3 (9%SF) after failure.

Figure 15. Deep Beam G1SD1 (9%SF) after Failure.

Figure 16. Deep Beam G1SD2 (9%SF) after Failure.
As can be seen from these figures, all load-deflection curves have a different trend. For deep beam (G1SB1), flexural crack and another diagonal crack appeared. Cracks in top strut between two point loads appeared in advanced stages of loading. The flexural failure occurred at ultimate load. For deep beam (G1SB2), a combination of flexural and shear cracks appeared. Flexural failure accrued at ultimate load. In Deep beam (G1SB3) very fine crack in tension zone began to form when the load was applied. Also, one diagonal crack in top strut appears but flexural failure is occurred. In deep beam (G1SC1), the deflection is linearly proportional to the applied load. The difference in load-deflection behavior between deep beam (G1SD1) and (G1SD2) due to change in location of the load. In general, the relationship is approximately linear in the deep beam (G1SE1) prior to failure, it can be observed that the removal of mesh reinforcement caused increasing in deflection and ductility.

### 6.2 Load – deflection curve and crack pattern of deep beams with openings

The experimental load-deflection curves for all tested specimens tested are shown in Figures 18 to 20. Specimens after failure are shown in Figure 21-28. In deep beams (G2NA1, G2SB1, G2SB2 and G2SB3) linear relationship of load-deflection curves is marked. It can be noted that for deep beam G2NC1 the deflection values decreased when inclined reinforcement, was added with as a result of restricting the crack width in the shear zone reverse deep beam (G2SC2). The deep beams (G2SD1 and G2SD2) with square and triangular openings respectively, showed a difference in both load and deflection compared with the beams with circular openings. This might be due to more concentration of stress at corners zone of the square and triangular openings. Table 4 shows a summary of the details of the test results.
Figure 19. Load - Deflection Relation of (G2NA1, G2SB3, G2SC2 and G2NC1) Specimens.

Figure 20. Load - Deflection Relation of (G2SB3, G2SD1 and G2SD2) Specimens.

Figure 21. Deep beam G2NA1 after failure

Figure 22. Deep beam G2SB1 after failure.
Figure 23. Deep beam G2SB2 after failure.  
Figure 24. Deep beam G2SB3 after failure.  
Figure 25. Deep beam G2NC1 after failure.  
Figure 26. Deep beam G2SC2 after failure.  
Figure 27. Deep beam G2SD1 after failure.  
Figure 28. Deep beam G2SD2 after failure.  

Table 4. Loads at first crack and ultimate loads for (experimental) solid deep beams.

| Group No. | Deep Beam No. | Cracking Load (kN) | Ultimate Load (kN) | Max Mid Span Deflection (mm) |
|-----------|---------------|-------------------|-------------------|----------------------------|
|           |               | $P_c$ (Exp.)      | $P_u$ (Exp.)      | $\delta_{Exp.}$           |
| G2        | NA1           | 125               | 210               | 2.9                        |
|           | SB1           | 200               | 680               | 9.4                        |
|           | SB2           | 300               | 720               | 12.1                       |
|           | SB3           | 420               | 860               | 14.9                       |
|           | NC1           | 150               | 281               | 2.05                       |
|           | SC2           | 456               | 940               | 13.5                       |
|           | SD1           | 280               | 667               | 15.3                       |
|           | SD2           | 302               | 740               | 13.55                      |

7. Toughness
In the science of materials, toughness is the ability of the material to plastic deform and absorb the applied energy without fracturing [14]. Toughness is also known as the amount of energy per volume unit that the material can absorb. The toughness was calculated from the load-deflection curve [14]. Tables 5 and 6 listed the calculated expended toughness of solid deep beams with opening respectively. Rupturing is also called by (energy absorption) [14]. Figures 29 and 30 show variation of SIFCON ratio with toughness for group one and two:

**Table 5** Toughness of solid deep beams

| Specimen | Experimental Toughness (kN.mm) |
|----------|--------------------------------|
| G1NA1    | 543.9                          |
| G1SB1    | 4678.5                         |
| G1SB2    | 6527                           |
| G1SR3    | 6925.1                         |
| G1SC1    | 6338.3                         |
| G1SD1    | 7558                           |
| G1SD2    | 4265.5                         |
| G1SE1    | 5981.5                         |

**Table 6** Toughness of deep beams with openings.

| Items    | Experimental Toughness KN.mm |
|----------|------------------------------|
| G2NA1    | 302.45                       |
| G2SB1    | 2989                         |
| G2SB2    | 4143.7                       |
| G2SR3    | 5746                         |
| G2SC1    | 271.14                       |
| G2SC2    | 4818.2                       |
| G2SD1    | 4580.8                       |
| G2SD2    | 4278.5                       |

**Figure 29.** Variation of Toughness solid deep beams.

**Figure 30.** Variation of Toughness deep beams with the opening.

8. Ductility

Ductility is the long-term ability to undergo plastic deformities before rupture. It can be defined as the elongation ratio in tensile testing [18]. Tables 7 and 8 give the experimental ductility of specimens group of the first and
second group, respectively. A good match between the experimental ductility results in the present work was achieved. Figures 31 and 32 show variation of SIFCON ratio with ductility for group one and two.

**Table 7** Ductility of Solid Deep Beams.

| Items | Max Experimental Ductility % |
|-------|-----------------------------|
| G2NA1 | 0.78                        |
| G2SB1 | 1.93                        |
| G2SB2 | 3.5                         |
| G2SB3 | 3.92                        |
| G2NC1 | 0.25                        |
| G2SC2 | 2.434                       |
| G2SD1 | 5.01                        |
| G2SD2 | 4.376                       |

**Table 8** Ductility of Deep Beams with Openings.

| Specimen | Max Experimental Ductility |
|----------|-----------------------------|
| G1NA1    | 0.5                         |
| G1SB1    | 1.6                         |
| G1SB2    | 2.4                         |
| G1SB3    | 3.1                         |
| G1SC1    | 2.9                         |
| G1SD1    | 4.31                        |
| G1SD2    | 0.8                         |
| G1SE1    | 4.6                         |

**Figure 31.** Variation of ductility with SIFCON ratio of group one.
9. Conclusions

9.1 Conclusions for solid SIFCON deep beams

Based on the experimental test results, the following conclusions are drawn:

- The increase, of SIFCON ratio by (6%, 7.5% and 9%) gave a significant improvement in the behaviour of the RC beams subjected to two-point loads. The increase, in the cracking and, ultimate loads were about (275% and 196%), (331.25% and 206%) and (362.5% and 239.4%) for each SIFCON ratios, respectively when compared with conventional concrete beams.

- Removal of vertical reinforcement for SIFCON solid deep beams gave decreasing in the ultimate and cracking loads about of (8%) and (31.7%) than the deep beam with SIFCON (9%) respectively. While appeared increasing in the ultimate and cracking loads about of (212.1%) and (215.6%) respectively than the conventional concrete deep beam.

- The ultimate load was increased with decreasing of the effective shear span to depth (a/d) ratio. The ultimate load for the ratio of (a/d = 0.727) was increased about of 25% than the reference ratio (a/d = 0.9), while decreased about of 6.25% than the reference ratio for the ratio of (a/d =1.08).

- Removing of reinforcement mesh for SIFCON solid deep beams gave decreasing in the ultimate and cracking loads about of (17.6%) and (29.3%) than the deep beam with SIFCON (9%) respectively. While appeared increasing in the ultimate and cracking loads about of (165.3%) and (226.9%) respectively than the conventional concrete deep beam.

- When the SIFCON ratios were increased from (6% to 9%) the toughness was increased by (760% to 1173%) respectively.

- The toughness decreased with removing of vertical reinforcement, the ratio a/d = 1.08 and removing of reinforcement mesh about of 8.5%, 38.4% and 13.62% respectively.

- The toughness increased about 9.14% with the ratio (a/d = 0.727) than the reference ratio.

- The increasing of SIFCON ratios from (6% to 9%) caused increasing in ductility about (220% to 520%) respectively.

- The ductility decreased with removing of vertical reinforcement and the ratio (a/d = 1.08) about 6.45% and 74.2% respectively.

- The ductility increased for the ratio (a/d = 0.727) and the absence of reinforcement mesh about 39 % and 48.4% respectively.

9.2 Structural Behavior Conclusions for SIFCON Deep Beams with Openings

Based on the experimental test results and numerical analysis, the following conclusions are drawn:
The increase of SIFCON ratio by (6%, 7.5% and 9%) gave a significant improvement in the behaviour of the RC beams subjected to two-point load and the increasing in the cracking and ultimate loads were about of (60% and 223.8%) and, (140% and 242.85%) and (236% and 309.52%) for each SIFCON ratios respectively, when compared with conventional concrete beams.

- The conventional concrete deep beam with inclined reinforcement around the openings gave increasing in the ultimate load about of 33.8% than the conventional concrete deep beam without inclined reinforcement.
- The SIFCON deep beam with inclined reinforcement around the openings gave increasing in the ultimate load about of 234.5% than the conventional concrete deep beam with inclined reinforcement.
- The SIFCON deep beam with circular openings gave high cracking and ultimate loads than square and triangular openings. The reduction in the ultimate loads for square and triangular openings was about of 22.44% and 13.9% respectively.
- When the SIFCON ratios were increased from (6% to 9%) the toughness was increased about of (888.26% to 1799.8%) respectively.
- The conventional concrete deep beam with inclined reinforcement around the openings gave decreasing in the toughness about of 10.4% than the conventional concrete deep beam without additional inclined reinforcement.
- The SIFCON deep beam with inclined reinforcement around the openings gave increasing in the toughness about 1677% than the conventional concrete deep beam with inclined reinforcement.
- The SIFCON deep beam with circular openings gave high toughness than square and triangular openings. The increase in the toughness for the circular openings was about 20.3% than the square openings and 25.5% than the triangular openings.
- The SIFCON deep beam with circular openings gave high toughness than square and triangular openings. The increase in the toughness for the circular openings was about 20.3% than the square openings and 25.5% than the triangular openings.
- When the SIFCON ratios were increased from (6% to 9%) the ductility was increased by about (147.43% to 402.56%) respectively.
- The conventional concrete deep beam with inclined reinforcement around the openings gave decreasing in the ductility about 67.9% than the conventional concrete deep beam without additional inclined reinforcement.
- The SIFCON deep beam with inclined reinforcement around the openings gave increasing in the ductility about of 873.6% than the conventional concrete deep beam with inclined reinforcement.
- Square and triangular openings ductility values showed increasing if compared with SIFCON deep beam (9%) by about 27.8% and 11.6% respectively.

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