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AN EXPERIMENTAL AND FEASIBILITY STUDY ON FLEXURAL BEHAVIOR OF CONCRETE BEAMS REINFORCED WITH DISCRETE AND CONTINUOUS STEEL FIBERS

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A B S T R A C T

The random distribution of discrete steel fibers in concrete and their negative impact on workability limit their use in the concrete industry. This research presents a novel approach to concrete reinforcement using continuous steel fibers to overcome the above mentioned limitations. Three innovative composites were developed, namely, double inline-continuous steel fiber reinforced concrete (DI-CSFRC), single inline-continuous steel fiber reinforced concrete (SI-CSFRC), and single staggered-continuous steel fiber reinforced concrete (SS-CSFRC). Steel reinforced beam and discrete steel fibers reinforced concrete beam (DSFRC) beam were fabricated and considered as control specimens. The results showed that replacing discrete steel fibers with continuous steel fibers significantly enhanced the mechanical performance. At a constant fiber volume fraction (0.4%), the cracking and ultimate loads of DI-CSFRC beam were 145% and 105% higher than that of DSFRC beam, respectively. The implementation of continuous steel fibers also offered cost and weight benefits, making it a promising alternative for concrete reinforcement.

1. INTRODUCTION

Conventional reinforcement in concrete improves its structural behavior, but it is the most expensive part of the reinforced concrete, either in terms of material cost or cost of installation process. Discontinuous steel fibers were used in discrete form for reinforcing concrete, where a large number of previous investigations confirmed the reinforcing effect of fibers [1-2]. The interest in fiber reinforced concrete (FRC) began in the early 1960s [3]. Over the last few decades, a lot of literatures have been carried out to investigate the efficiency and benefits of FRC. Polyethylene fibers, steel fibers, glass fibers, polypropylene fibers, polyvinyl alcohol fibers, polyester fibers, basalt fibers, and natural fibers are some examples of discrete fibers used in literature [4-12]. Steel fiber is the most popular fiber utilized in the concrete manufacture. Discrete steel fibers were added to concrete in many forms such as hooked end, crimped, and round discrete steel fibers [13]. The important role of steel fibers is to decrease the developments of micro cracks [14].

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Despite the above mentioned benefits of fibers, there are several drawbacks associated with fibrous concrete which limit its use in many applications. The major drawback is the low workability of FRC, such that considering high levels of both fibers aspect ratio and fibers volume fraction in concrete leads to a significant decrease in its workability. Khaloo et al. [15] studied the relationship between of steel fibers volume fraction and the workability of self-compacted concrete (SCC). The effect of four volumetric ratios 0.5, 1, 1.5, and 2% of fibers were investigated. It was found that increasing the amount of fibers reduced the workability of SCC. Bajgirani et al. [16] investigated the influence of steel fiber aspect ratio on the concrete workability. Three levels of aspect ratios (50, 92, and 114%) were considered in the experimental program. They concluded that increasing steel aspect ratio led to a significant reduction in the concrete workability. Workability of FRC is, however, not the only technological requirement for application in concrete industry. The addition of steel fiber in concrete reduces its pumpability and sprayability, which limits its application in one of the largest application of concrete industry, i.e. the tunnel industry.

The random distribution of discrete steel fibers decreases the efficiency when compared to steel bars. Recent studies have been conducted on the fibers distribution in concrete to increase their benefits. The importance of fiber orientation in improving the mechanical behavior steel fiber reinforced concrete (SFRC) was emphasized. Better distribution of steel fibers results in a significant improvement in the concrete mechanical behavior [17, 26]. Various orientation processes for discontinuous fibers were reported in previous literature [27-31]. The majority of the suggested positioning approaches use either the pneumatic technology or the hydrodynamic to align discrete fibers. Converging jet flow and a modified papermaking techniques have been developed with positive results obtained.

1.1. Research Significance

While, numerous researches investigated the effect of discrete steel fiber (DSF) on concrete behavior, no literature has been found on using continuous steel fibers in concrete. Therefore, the objective of this research is to investigate reinforcing of concrete using continuous steel fibers to overcome the above mentioned limitations of DSF and to increase the efficiency of FRC. The specified purposes of the present work were set as follows:

1. To examine the performance of three innovative concrete-based composites namely, single staggered-continuous steel fiber reinforced concrete (SS-CSFRC), single inline-continuous steel fiber reinforced concrete (SI-CSFRC), and double inline-continuous steel fiber reinforced concrete (DI-CSFRC).
2. To investigate the feasibility of replacing DSF with continuous steel fibers.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

Silica fume (SF) and ordinary Portland cement (CEM I, 52.5 grade) complying with ES: 4756-1 [32] were used. Surface area of CEM I and SF were 0.37 and 2 m^2/g, respectively. Table 1 presents the physical and chemical characteristics of cement and SF. Sand complying with ASTM C33 [33] was used. Specific gravity and fineness modulus of sand were 2.65 and 2.75 respectively. Crushed dolomite stone of a maximum nominal aggregate size of 10 mm was considered. Viscocrete 3425 with a relative density of 1.13 was used to produce self-compacted concrete. Mild steel of 240 MPa yield strength was used for stirrups and longitudinal reinforcement of steel reinforced beam. Continuous and discrete round corrugated steel fibers of 210 GPa young's modulus and 1 GPa yield strength were purchased from Nassar Group, Egypt. A photo of the used continuous and discrete steel fibers is shown in Fig.1.

Table 1
Chemical analysis and surface areas of CEM I and SF

Oxide	CEM I	SF
SiO_2	21.2	96.1
Al_2O_3	4.53	0.5
Fe_2O_3	3.61	0.71
CaO	61.6	0.22
MgO	2.38	0.47
Na_2O	0.36	0.32
K_2O	0.22	0.48
SO_3	2.8	0.1

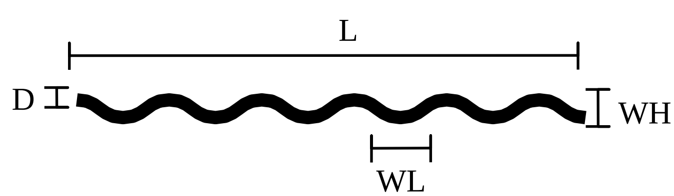

Fig. 1. Continuous steel fiber and discrete steel fibers.

Length (L): 30 mm (+/- 3 mm) for discrete steel fibers and 500 mm (+/- 3 mm) for continuous steel fibers, Diameter (D): 1 mm (+/- 0.05 mm), Wave Length (WL): 6 mm - 8 mm, Wave Height (WH): 1.5 mm - 2.0 mm

2.2. Mixing, concrete properties, and reinforcement details

The target compressive strength of concrete was 30 MPa. Self-compacted concrete (SCC) was considered throughout this work. The dry constituents (cement, silica fume, sand, and dolomite) were mixed in a concrete mixer for 2 minutes, then tap water and Viscocrete 3425 were added to the concrete mixer and mixed for another two minutes. Mix proportions of SCC are listed in Table 2.

Table 2

Mix Proportions

CIM I kg	SF kg	W/C ratio	Water kg	Dolomite kg	Sand kg	S.P. kg
475	25	0.4	200	590	1100	2

Beams of size 100 mm × 100 mm × 500 mm were used for flexural test. A total of five simply supported concrete beams were fabricated and tested, as shown in Fig. 2. Three beams were fabricated to examine the mechanical behavior of the newly developed composites namely, DI-CSFRC, SI-CSFRC and SS-CSFRC. In order to determine the feasibility of using these composites, DSFRC and steel reinforced beams were fabricated and considered as a control specimens.

2.3. Installation of continuous steel fibers

In the presented innovative technique, continuous steel fibers were fixed using two side wooden plates as shown in Fig. 3. A number of holes with a diameter of 3 mm is drilled through the wooden plates provided that the distance between the holes in the vertical and horizontal directions is 1.5 cm. Continuous steel fibers are passed through the opposite holes of the two wooden plates in the longitudinal direction of the concrete beam, with two continuous steel fibers for each hole. The continuous steel fibers are fixed to the wooden plates by screws before concrete is poured. The demolded SI-CSFRC beam is shown in Fig. 4.

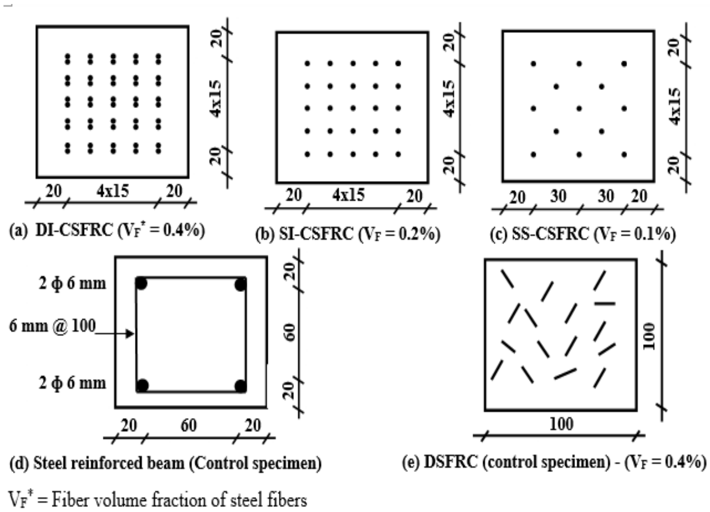

Fig. 2. Cross-sectional details of (a) Double Inline-Continuous Steel Fiber Reinforced Concrete (DI-CSFRC), (b) Single Inline-Continuous Steel Fiber Reinforced Concrete (SI-CSFRC), (c) Single Staggered-Continuous Steel Fiber Reinforced Concrete (SS-CSFRC), (d) Steel Reinforced Concrete, and (e) Discrete Steel Fiber Reinforced Concrete (DSFRC). All dimensions are in mm.

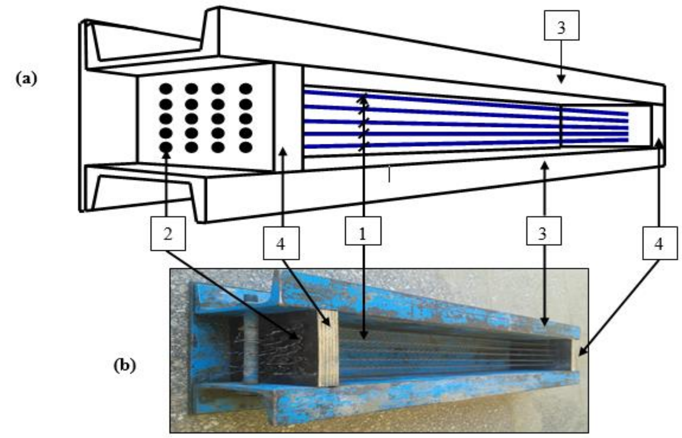

Fig. 3. (a) Sketch and (b) photo of installation of continuous steel fibers of SI-CSFRC beam. (1) Continuous steel fibers, (2): clamping screws, (3) steel mold, and (4) perforated wooden plate.

Fig. 4. Demolded single inline-continuous steel fiber reinforced concrete (SI-CSFRC) beam.

2.4. Testing technique and procedure

Flexural testing of all beams was carried out using ELE machine of 2000 kN maximum load. Test setup and instrumentation for flexural specimens are shown in Fig. 5.

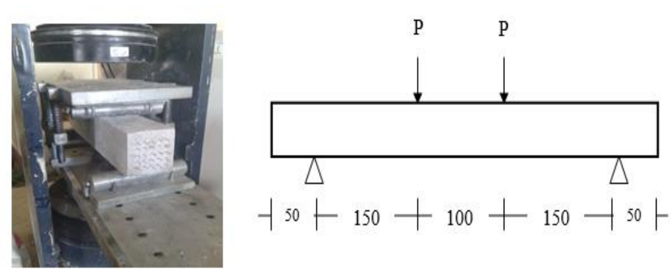

Fig. 5. Experimental set-up and two-point loading arrangement, all dimension in mm.

3. Results and Discussion

3.1. Load to mid-span deflection

The experimental load to mid-span deflection curves of DI-CSFRC, SI-CSFRC, SS-CSFRC, DSFRC, and steel reinforced beams are shown in Fig. 6. The values of cracking and ultimate loads of these beams are listed in Table 3. It can be concluded from Fig. 6 and Table 3 that the steel reinforced beam showed the highest ultimate loads, while the DSFRC beam showed the lowest ultimate loads. The ultimate loads of steel reinforced beam, DI-CSFRC, SI-CSFRC, SS-CSFRC, and DSFRC beams were found to be 20.5 kN, 19.5 kN, 15.4 kN, 12 kN, and 9.5 kN respectively. The ultimate loads were reduced by 5%, 25%, 41%, and 54% in case of DI-CSFRC, SI-CSFRC, SS-CSFRC, and DSFRC beams, respectively, compared to steel reinforced beam. On the other hand, it is clear from the results shown in Fig. 6 and Table 3 that, replacing discrete steel fibers with double inline continuous steel fibers (DI-CSF), single inline continuous steel fibers (SI-CSF), and single staggered continuous steel fibers (SS-CSF) increases the ultimate load by 105%, 62%, and 26%, respectively, compared to DSFRC beam.

Moreover, at ultimate load, steel reinforced beam and DSFRC beam showed the highest and the lowest mid-span deflections 11.2 mm and 4.6 mm, respectively, when compared with other beams. Mid-span deflection at ultimate load of DI-CSFRC, SI-CSFRC, SS-CSFRC, and DSFRC beams reached about 95%, 94%, 73%, and 41%, respectively, of the corresponding load of steel reinforced beam.

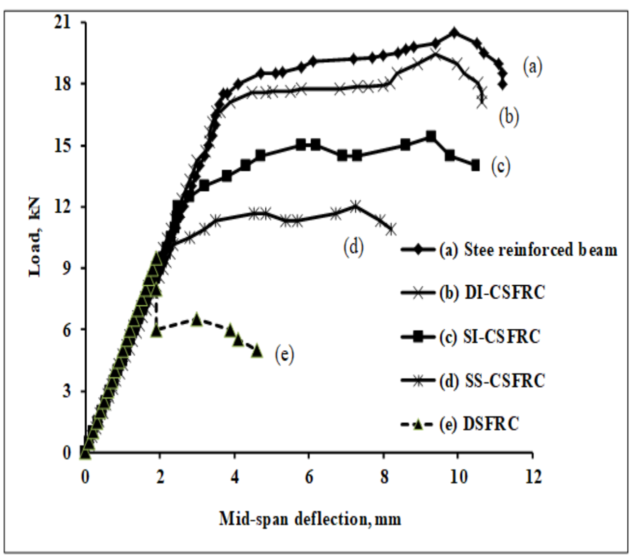

Fig. 6. Load – deflection behavior of (a) steel reinforced beams, (b) DI-CSFRC, (c) SI-CSFRC, (d) SS-CSFRC, and (e) DSFRC beams.

Table 3

Cracking and ultimate loads of all tested beams

Composite Type	Cracking Load (kN)	Ultimate Load (kN)
Steel reinforced beam	17.2	20.5
DI-CSFRC	16.4	19.5
SI-CSFRC	13.5	15.4
SS-CSFRC	8.5	12
DSFRC	6.7	9.5

3.2. Crack Pattern

Crack patterns of all tested beams are shown in Fig. 7. Overall, all beams failed in flexure. The failure began with vertical cracks near to the center of beams. For DSFRC beam, another inclined crack appeared near to the tension zone. As shown in Table 3, steel reinforced beam and DSFRC beam showed the highest and lowest cracking loads, respectively. Cracking loads of DI-CSFRC, SI-CSFRC, SS-CSFRC, and DSFRC beams reached about 90%, 74%, 47%, and 45%, respectively, of the corresponding load of steel reinforced beam. Using DI-CSF, SI-CSF, and SS-CSF increases the cracking load by 145%, 101% and 27%, respectively, compared to DSFRC beam. The improvement in the mechanical properties of DI-CSFRC, SI-CSFRC, SS-CSFRC beams when compared with DSFRC beam can be attributed to the replacement of discrete steel fiber with continuous steel fibers which solve the problem of random distribution of discrete steel fiber and hence increases its the efficiency in concrete.

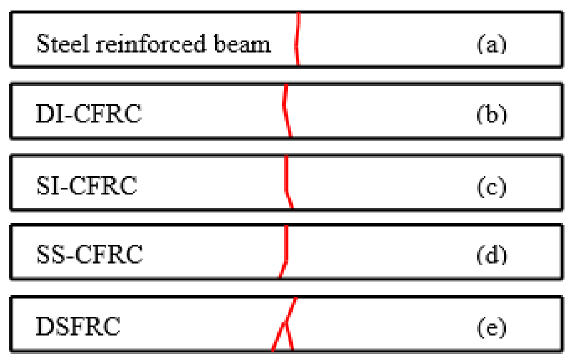

Fig. 7. Crack pattern of (a) steel reinforced beams, (b) DI-CSFRC, (c) SI-CSFRC, (d) SS-CSFRC, and (e) DSFRC beams.

3.3. Feasibility of the new developed composites

The results shown in Fig. 6 promote the DI-CSFRC to be used as a new technique for concrete reinforcement and therefore the feasibility of such technique is checked as follows. The ultimate load and weight and steel for the considered beams are listed in Table 4. Although the DI-CSFRC has an ultimate load of 19.5 kN, which is very close to that of the steel reinforced beam (20.5 kN), the weight of the continuous steel fibers used in DI-CSFRC is almost one-fifth of the weight of steel bars in the reinforced concrete beam, as shown in Table 4. Therefore replacing steel bars in reinforced concrete beam with continuous steel fibers saves money and reduces the own weight of fibers, resulting in a significant lower dead load.

Moreover, at a constant fiber volume fraction (0.4%), DI-CSFRC beam showed a better flexural behavior when compared with DSFRC beam. The ultimate loads of DI-CSFRC and DSFRC beams are 19.5 and 9.5 kN, respectively. So, it was generally concluded that using continuous steel fiber is a very promising technique for concrete reinforcement and concrete industry. Also, continuous steel fibers can be a good replacement of both discrete steel fibers and steel bars due to the following: (1) light weight, (2) cost, (3) corrosion resistance by electroplating of the fibers, (4) workability, (5) pumpability, and (6) applicability in narrow beams. Further research should be done to investigate the influence of fibers diameter, material, shape, and density on the strength of the concrete.

Table 4
Comparison between cost and weight of steel bars, continuous steel fibers, and discrete steel fibers

Type	Ultimate load (kN)	Fiber volume fraction (%)	Weight of steel (Kg)
Steel reinforced beam	20.5	-	0.77
DI-CSFRC	19.5	0.4	0.154
SI-CSFRC	15.4	0.2	0.077
SS-CSFRC	12	0.1	0.04
DSFRC	9.5	0.4	0.154

4. CONCLUSION

The major conclusions of the research can be outlined as follow:

1. Replacing DSF with double or single inline-continuous steel fibers improved in the mechanical behavior of concrete beams. The cracking and ultimate loads of DI-CSFRC beam increased by approximately 145% and 105%, respectively, compared to DSFRC beam. These values were about 101% and 62 % for SI-CSFRC.
2. In addition to the improvement in the flexural behavior DI-CSFRC beam but also the price and weight of continuous steel fibers are almost a quarter and one fifth, respectively of steel bars in reinforced concrete beam.
3. At a constant fiber volume fraction (0.4%), the cracking and ultimate loads of DI-CSFRC beam were 145% and 105% higher than that of DSFRC beam, respectively.
4. DI-CSFRC beam showed the lowest reduction in load carrying capacity (5%), followed by SI-CSFRC beam (25%), compared to the steel reinforced beam.
5. Mid-span deflection, at ultimate load, of DI-CSFRC, SI-CSFRC, SS-CSFRC, and DSFRC beams reached about 95%, 94%, 73%, and 41%, respectively, of the corresponding load of steel reinforced beam.
6. Replacing steel bars in reinforced concrete beam with continuous steel fibers saves money and reduces the own weight of fibers and therefore much less dead load.

List of abbreviations

DSFRC	Discrete steel fiber reinforced concrete
DSF	Discrete steel fiber
DI-CSFRC	Double inline-continuous steel fiber reinforced concrete
DI-CSF	Double inline-continuous steel fiber
SI-CSFRC	Single inline-continuous steel fiber reinforced concrete
SI-CSF	Single inline-continuous steel fiber
SS-CSFRC	Single staggered-continuous steel fiber reinforced concrete
SS-CSF	Single staggered-continuous steel fiber
FRC	Fiber reinforced concrete
SCC	Self-compacted concrete
SFRC	Steel fiber reinforced concrete
FRP	Fiber-reinforced polymer
CFRP	Carbon fiber-reinforced polymer
GFRP	Glass fiber-reinforced polymer
AFRP	Aramid fiber-reinforced polymer
BFRP	Basalt fiber-reinforced polymer
SF	Silica fume

Declarations

Available of data and materials

No data, models, or code were generated or used during the study.

Competing interest

The authors declare no conflict of interest.

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