Flexural behavior of hybrid ultra-high-performance concrete

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Abstract. Ultra-high performance fiber reinforced concrete has superior mechanical and structural properties but the major drawback of this new construction material is its high cost. This research presents an experimental study to investigate the flexural behavior of hybrid ultra-high-performance concrete with different steel fibers’ volume fractions, cast in full and partial depths of specimen’s cross sections to exploit the advantages of steel fibers in optimal way. The variables studied included the percentages of steel fibers used (0, 1, 2 and 3) % and the fraction of depth containing the steel fibers (0.25, 0.5, 0.75 and 1). Experimental results show that the failure load increases with the increase in the fraction of depth where the steel fibers were distributed. This increase was more significant as the fraction of depth increases from 0.25 to 0.5 and 0.75. As it reached the 0.75 the increase was none pronounced, and the failure load was almost similar to that of full depth. Therefore, it can be concluded that the maximum effective fraction of depth would be 0.75. It was noted that the different distribution of the same amount of the steel fibers within the depth of the section greatly affects the specimen load capacity and using the steel fibers in the tension zone effectively enhances the flexural performance of UHPFRC. The results also indicate that increasing the steel fiber volumetric ratio from 0% to 1%, 2% and 3% the percentages of increase in the failure load \((P_f)\) with respect to the control specimen were 156%, 261% and 389%, respectively.

1. Introduction:
Ultra-high performance concrete, UHPC, was introduced in the construction industry in the last decade of the past century [1]. This type of concrete showed enhancement in both tensile and compressive strength characteristics which made the (UHPC) a suitable material for important structures such as highways, bridges, skyscrapers, nuclear facilities, military engineering, etc. Therefore, both academic and engineering sides were interested in doing research on UHPC [2].

The addition of steel fibers to concrete (with high tensile strength and ductility) contributes in improving the load carrying capacity and deformation of the elements constructed with such material; it also improves the tensile cracking resistance, post cracking strength, ductility and energy absorption capacity [3, 4].

Adding steel fibers to UHPC, led to the production of a new strong material called Ultra-High Performance Fiber Reinforced Concretes (UHPFRC); this material is promising in structures and belongs to the group of High Performance Fiber Reinforced Cement Composites (HPFRCC) that produce strain-hardening under uniaxial tension [1], as shown in Figure 1.
The steel fibers, high cement content, elimination of coarse aggregate and using special materials are the factors that elevate the cost of UHPFRC [5]. Design criteria of hybrid elements is based on the concept that the use of the materials of improved performance (such as HSC, HPC and UHPC), which are relatively expensive materials, should be limited to parts in the structure subjected to severe environmental conditions and/or when stiffness or resistance of the structural element must be increased without increasing the dead weight or at points of concentrated load application, while other parts of the structure consist of conventional concrete [1, 6].

Figure 1. High Performance Fiber Reinforced Cement Composites (HPFRCC) [1].

2. Aim of Research:
With all superior properties of UHPFRC the major drawback is that the material by itself is very expensive. Therefore, in this study it is proposed to investigate the use of steel fibers in full and partial depths of element cross sections to exploit the advantages of steel fibers in optimal way by casting the HC element in two layers; the top layer is UHPC without steel fibers while the bottom layer containing steel fibers representing UHPFRC through the depth of the specimen.

3. Experimental Work:
Twenty six specimens 100 mm × 100 mm × 500 mm (the average of two specimens for each mix was recorded) were cast for this investigation. The variables studied included: the volumetric ratio of the steel fiber used (0, 1, 2 and 3) %, and the fraction of depth where the steel fibers were distributed (0.25, 0.5, 0.75 and 1). Eight of them were cast with different volumetric ratios of the steel fiber, (0, 1, 2 and 3) % cast in full depth of the specimens were used to act as control specimens. The remaining eighteen were cast as hybrid specimens constituting of two layers of UHPC at the top and UHPFRC at the bottom. Figure (2) illustrates cross-sections of hybrid specimens.
3.1. Designation of Specimens:
Specimen designation included three categories, the first category referred to the type of specimen; C for control specimens, H for hybrid concrete Specimens. The second category referred to the volumetric ratios of the steel fiber used (0, 1, 2 and 3) %. The third category referred to the fraction of depth for which the steel fibers were distributed (0.25, 0.5 and 0.75).

For example, the specimen (H-1-0.5) refers to a hybrid concrete specimen with 1% volumetric ratio of steel fiber distributed in 0.5 the depth of the specimen. The specimen (C-2-1) refers to a control specimen with 2% volumetric ratio of steel fiber distributed in full depth of the specimen. Table 1 shows the details of Specimens Studied in Present Research.

### Table 1. Details of Specimens Studied.

| No. | Specimen designation | Fraction of depth (h) | % V_f | Variables          |
|-----|----------------------|-----------------------|-------|-------------------|
| 1   | C-0-1                | 1                     | 0     |                   |
| 2   | C-1-1                | 1                     | 1     |                   |
| 3   | C-2-1                | 1                     | 2     |                   |
| 4   | C-3-1                | 1                     | 3     |                   |
| 5   | H-1-0.75             | 0.75                  | 1     | Fraction of Depth |
| 6   | H-1-0.5              | 0.5                   | 1     | (%h)              |
| 7   | H-1-0.25             | 0.25                  | 2     |                     |
| 8   | H-2-0.75             | 0.75                  | 2     | Fraction of Depth |
| 9   | H-2-0.5              | 0.5                   | 2     | (%h)              |
| 10  | H-2-0.25             | 0.25                  | 2     |                     |
| 11  | H-3-0.75             | 0.75                  | 3     |                     |
| 12  | H-3-0.5              | 0.5                   | 3     |                    |
| 13  | H-3-0.25             | 0.25                  | 3     |                    |

3.2 Properties of Materials Used:
Four batches were involved in this research, one batch to produce the UHPC (without steel fibers) and three batches to produce the UHPFRC with different steel fibers volumetric ratios (1%, 2% and 3%). UHPFRC was prepared using ordinary Portland cement (Type I), natural fine sand with maximum size 600µm, densified silica fume, Ultra High Performance Superplasticiser manufactured and supplied by Sika® company under the commercial name Sika® ViscoCrete®-5930, and straight steel fibers as...
shown in figure 3. The properties of the used steel fibers are presented in Table 2, while the constituents of the mixes are shown in table 3.

![Figure 3. Straight steel fibers.](image)

**Table 2. Properties of steel fibers.**

| Description | Length, mm | Diameter, mm | Tensile strength, MPa | Density, kg/m³ | Aspect ratio |
|-------------|------------|--------------|----------------------|----------------|-------------|
| Straight    | 13         | 0.2          | 2400                 | 7800           | 65          |

**Table 3. Mixes produced in the present study.**

| Type of Concrete | Specimen designation | Cement (kg/m³) | Sand (kg/m³) | Silica Fume (kg/m³) | V_f % | V_f (kg/m³) | w/c Ratio | SP |
|------------------|-----------------------|----------------|--------------|---------------------|-------|-------------|-----------|----|
| UHPC             | C-0-1                 | 750            | 1000         | 250                 | 0     | -           | 0.2       | 6.0%|
|                  | C-1-1                 | 750            | 1000         | 250                 | 1     | 78          | 0.2       | 6.1%|
| UHPFRC           | C-2-1                 | 750            | 1000         | 250                 | 2     | 156         | 0.2       | 6.3%|
|                  | C-3-1                 | 750            | 1000         | 250                 | 3     | 234         | 0.2       | 6.3%|

3.3 Mixing, Casting and Curing Procedures:
All specimens were cast in horizontal steel molds with the dimensions of (100×100×500) mm. Both UHPC and UHPFRC mixes were prepared earlier using a rotary mixer of 0.1 m³. The mixing of one batch required approximately 15 minutes, from the addition of water till the attaining of reasonable fluidity.

Sufficient mixing is necessary to achieve the desirable concrete performance and homogeneity. In UHPC and UHPFRC mixes, extending mixing time is necessary to fully disperse the silica fume, breaking up any agglomerated particles and to allow the full potential development of the superplasticizing agent.

All HC specimens were cast in two layers. The casting was performed in two stages, the first stage was pouring the UHPFRC into the molds up to the fraction of depth required, then stage two starts by pouring the UHPC up to the top of the mold. Each layer was compacted by an external table vibrator.
to minimize the air voids as well as to get a well-compacted concrete. The top surface was then leveled and the specimens were covered with polythene sheets to prevent loss of moisture.

After 24 hours, all specimens were stripped, marked and placed in curing tanks for 28 days. After curing, the specimens were removed from the curing tanks and left to dry at room temperature for a week then they were ready for testing.

3.4. Testing of specimens:
Cylindrical specimens (100×200 mm) were used to determine the compressive strength according to ASTM-C39 [7] using a digital testing machine of 2000 kN capacity. The average of three specimens was adopted for each mix.

The flexural test was performed on (100×100×500 mm) specimens. Each specimen was tested as a simple beam of span length 300 mm under third-point loading according to ASTM-C78 [8] and the average of two specimens for each mix was recorded. Figure 4 shows some photos of the tested specimens.

![Specimens after flexural test.](image)

**Figure 4.** Specimens after flexural test.

4. Test results:
Experimental test results of all specimens are listed in table 4. From these results and based on the variables studied, the following effects were concluded:
Table 4. Test results.

| Specimens | Vf % | Fraction of depth (h) | $f'_c$ (MPa) | Failure load $P_f$(kN) |
|-----------|------|-----------------------|--------------|-----------------------|
| C-0-1     | 0    | 1                     | 99           | 18.35                 |
| C-1-1     | 1    | 1                     | 107          | 45.76                 |
| C-2-1     | 2    | 1                     | 122          | 65.34                 |
| C-3-1     | 3    | 1                     | 133          | 87.73                 |
| H-1-0.75  | 1    | 0.75                  | 107          | 44.26                 |
| H-2-0.75  | 2    | 0.75                  | 99           | 122                   | 61.02 |
| H-3-0.75  | 3    | 0.75                  | 133          | 83.96                 |
| H-1-0.5   | 1    | 0.5                   | 107          | 31.62                 |
| H-2-0.5   | 2    | 0.5                   | 99           | 122                   | 51.44 |
| H-3-0.5   | 3    | 0.5                   | 133          | 72.86                 |
| H-1-0.25  | 1    | 0.25                  | 107          | 18.23                 |
| H-2-0.25  | 2    | 0.25                  | 99           | 122                   | 27.54 |
| H-3-0.25  | 3    | 0.25                  | 133          | 40.61                 |

4.1. Effect of Fraction of Depth (h) on the Failure Load:

The main variable studied in this paper was the distribution of the steel fibers within the depth of the specimen, three fractions of depth were studied, 0.25, 0.5 and 0.75 as well as the distribution within the full depth of the specimen.

Test results showed that for each volumetric ratio of the steel fiber used, the failure load increases with the increase in the fraction of depth. This increase was more significant as the fraction of depth increased from 0.25 to 0.5 and 0.75. As it reached the 0.75 the increase was none pronounced and the failure load was almost similar to that of full depth. Therefore, it can be concluded that the maximum effective fraction of depth would be 0.75, which gave almost the same results as distributing the steel fibers within the full depth of the specimen. For example, for 1% volumetric ratio of steel fibers, as the fraction of depth increased from 0.25 to 0.5, 0.75 and 1, the percentages of increase recorded were 78, 38 and 5, respectively, as shown in Table 5. The same behavior was observed for the other volumetric ratios used throughout this research work. The effects for all volumetric ratios are shown in figure 5.

When comparing the load capacity of the two specimens C-1-1 and H-2-0.5, which have the same amount of steel fibers, it was found that the hybrid specimen H-2-0.5 shows an increase in the failure load with percentage increase of 11% as compared to C-1-1 specimen. While specimen H-3-0.5 with less amount of steel fibers compared to C-2-1 shows an increase in the failure load with percentage increase of 12%. From these results it can be concluded that the distribution of the steel fibers within the depth of the section greatly affects the specimen load capacity and using the steel fibers in the tension zone effectively enhances the flexural performance of UHPFRC.

Table 5. Effect of increasing the fractional depth of 1% steel fibers on the failure load.

| Specimens | Vf % | %h | Pf (kN) | % Increase |
|-----------|------|----|--------|------------|
| H-1-0.25  | 1    | 0.25 | 18 | -    |
| H-1-0.5   | 1    | 0.5  | 32 | 78    |
4.2. Effect of Volumetric Ratio of Steel Fibers on the Failure Load:
The other variable studied in this paper was the volumetric ratio of steel fibers used; three volumetric ratios were studied 1%, 2% and 3% as well as the specimen without steel fibers.

The most significant effect for increasing the volumetric ratio was the increase in the failure load \( (P_f) \) of the specimens studied. The percentages of increase in \( P_f \) with respect to the control specimen, C-0-1, was 156%, 261% and 389%. While the percentages of increase in the compressive strength, \( f'_c \), with respect to the control specimen, C-0-1 was 8%, 23% and 34% as shown in table 6.

Table 6. The effect of steel fibers volumetric ratio on the failure load for the full depth specimen.

| Specimens | Vf % | %h | \( f'_c \) MPa | \( P_f \) (kN) | % Increase in \( f'_c \) | % Increase in \( P_f \) |
|-----------|------|----|----------------|--------------|-------------------|-------------------|
| C-0-1     | 0    | 1  | 99             | 18           | -                 | -                 |
| C-1-1     | 1    | 1  | 107            | 46           | 8                 | 156               |
| C-2-1     | 2    | 1  | 122            | 65           | 23                | 261               |
| C-3-1     | 3    | 1  | 133            | 88           | 34                | 389               |

Test results showed that, for each fraction of depth used, the failure load increases with the increase of the volumetric ratio. The steel fiber effects for all volumetric ratios are shown in figure 6.
5. Conclusions:
Based on the experimental work performed in the present research, the following conclusions can be drawn:

1. For each volumetric ratio (1%, 2% and 3%) of the steel fiber used, the failure load increases with the increase in the fraction of depth. This increase was more significant as the fraction of depth increases from 0.25 to 0.5 and 0.75. As it reached the 0.75 the increase was none pronounced and the failure load was almost similar to that of full depth.

2. The maximum effective fraction of depth would be 0.75, which gave almost the same results as distributing the steel fibers within the full depth of the specimen.

3. It has been found that the different distribution of the same amount of the steel fibers within the depth of the section greatly affects the specimen load capacity. The results also revealed that hybrid specimen with less amount of steel fibers showed an increase in the failure load with percentage of 12% compared to full depth specimen, so it can be concluded that using the steel fibers in the tension zone effectively enhances the flexural performance of UHPFRC.

4. The most significant effect for increasing the steel fibers volumetric ratio from 0% to 1%, 2% and 3% was the increase in the failure load ($P_f$) of the specimens studied. The percentage of increase in the $P_f$ with respect to the control specimen was 156%, 261% and 389%. While the percentages of increase in the compressive strength, $f'_c$, with respect to the control specimen was 8%, 23% and 34%, respectively.

6. References:
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