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Replacement of Stirrups by Steel Fibers in Shear Dominant UHPFRC Beams

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ABSTRACT

In the present study, the impacts of variety of fiber types and amounts on shear dominant Ultra High Performance Fiber Reinforced Concrete (UHPFRC) beams and the feasibility of fully replacement of stirrups by the steel fibers were investigated. Fifteen UHPFRC beams containing five different fiber types and three volume fractions were prepared without stirrup and were loaded under four-point loading. The influences of steel fiber were discussed in terms of the load-deflection behavior, cracking behavior, collapse modes, ultimate shear strength, nominal moment capacity and deflection ductility. The steel fiber use prominently increased the post-cracking stiffness and load capacity of the UHPFRC beams with the help of the fibers' crack-bridging ability. Conversely, the steel fibers in different types didn't have an importance on the collapse mode of the shear dominant UHPFRC beams. The use of straight steel fibers in the UHPFRC beams, even at very low volume fractions of 0.5 percent, changed the collapse condition from shear to flexure resulting in a ductile behavior. But the hooked fiber inclusion by 1.5 vol percent percent at least is needed to guarantee the flexural behavior regardless of hooked or multi hooked-end form.

Keywords: Ultra high performance fiber reinforced concrete, ultimate shear strength, moment capacity, fiber type, volume fraction.

1. INTRODUCTION

In recent years, the Ultra High Performance Fiber Reinforced Concrete (UHPFRC) has become one of the important products of concrete technology thanks to its many advantages. The UHPFRC use is a new option to fulfill the disadvantages of traditional normal strength

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reinforced concrete in design and practical applications through its excellent compressive strength and considerably improved post-cracking tensile behavior. As widely used in the literature, when the concrete compressive strength exceeds the threshold of 130 MPa - 150 MPa and the tensile strain-hardening characterization is ensured by sufficient steel fiber content, this kind of special concrete mixture can be defined as the UHPFRC [1-6]. The compressive and tensile properties of UHPFRC are improved with optimization of the standard cement, silica fume, grand granulated blast slag, quartz flour and particular admixtures such as superplasticizer, air-entraining agent [1,7-10]. In addition, the steel fibers can be randomly dispersed in the UHPFRC mixture, which may be in straight, single, double or triple end-hooked, wavy or twisted forms, significantly improves the strength, stiffness and ductility of structural members. Compared to normal or high strength fibrous concrete, the UHPFRC has high level of compressive / tensile deformation capacities and durability through its high-density matrix and special curing techniques [2, 11, 12]. Thus, the superior mechanical properties of UHPFRC allow more economic and long-life structures in comparison to the traditional normal or high strength concrete usas [7, 13]. The above-mentioned advantages of the UHPFRC become much more evident in design applications of reinforced concrete beams [7, 13, 14].

Regarding the shear dominant UHPFRC beams, as in well-known structural behavior for the normal or high strength concrete, when the principal tensile stress exceeds the tensile stress of concrete, the diagonal inclined shear crack develops through the member's web region and thus the brittle collapse occurs in adverse manner. Owing to the superior mechanical properties of the UHPFRC, the steel fibers randomly added to the concrete mixture have a noteworthy potential to fully replace or partially reduce the stirrups or shear reinforcements or shear links which may lead to reinforcement congestion in slender cross-section members [7]. In the meantime, the inclusion of steel fibers considerably restricts the formation and propagation of shear cracks.

In earlier studies, the shear behavior of UHPFRC members with and without stirrups have been intensively investigated under two topics. The first one is the impact of fiber type and amount on the shear strength and failure pattern, and the second one is the feasibility of use of steel fibers in place of the stirrups or shear reinforcements. Some research studies by others widely reported that the addition of steel fibers to the UHPFRC beams enhanced their ultimate shear strength through the concrete's post-cracking strength, depending also upon the fiber geometry and volume fraction, compressive strength, tensile reinforcement characteristics, shear span-to-depth ratio [7, 15-25]. In this sense, Voo et al. [26] pointed out that the fiber type and amount didn't have a notable effect on the first cracking load, but they had a particular influence on the failure load and crack propagation. Baby et al. [15] revealed that the shear strength of UHPFRC beam not only depended on the compressive and tensile strengths, but also the cross-section shape, dispersion characteristics of fibers, level of applied pre-stressing load. Yang et al. [21] stated that the shear strength of a pre-stressed UHPFRC beams were larger than that of non-pre-stressed beam under same fiber content. Ciprian et al. [23] studied the impacts of mono and hybrid fiber usages to the shear behavior on I-shaped UHPFRC beams. For the considered fiber amounts of 1.5 vol percent, 2.0 vol percent and 2.55 vol percent, the hybrid fiber use was more effective than the mono use in point of the ultimate strength and cracking parameters. El-Dieb et al. [16] also noted that the ultimate strength of a UHPFRC beam containing the steel fibers of 1.2 vol percent was greater than that of beams with the stirrups. Qi et al. [17] obtained similar outcomes with respect to these parameters in the shear dominant UHPFRC beams. They reported that the fiber type did not have a notable impact for same fiber volume fraction. At this point Yavas et al. [7] concluded that the steel fiber use in low volume fractions did not have significant effect on the first cracking levels regardless of fiber type. Nevertheless, the shear load exhibited an increasing trend for further fiber amounts. It was also noted that the UHPFRC members' collapse mode changed to flexure, indicating ductile behavior when the short-straight fibers of 1.5 vol percent were used. Lim and Hong [20] tested a series of rectangular shaped UHPFRC beams in shear. They reported for the cases with and without the shear reinforcement that the fiber use contributed positively to the shear strength and played an important role on restraining the cracks along with the shear reinforcement. It was also noted that the UHPFRC beams gained a significant strength even when the spacing of shear reinforcements was exceeded the stipulated limits in the ACI 318 design code. A similar study was conducted by Yavas and Goker [27] for four tensile reinforcement ratios ranging from 0.8 percent to 2.2 percent. Although the steel fibers were insufficient to prevent the shear failure at higher reinforcement ratios, the ultimate strength increased about 2 times in comparison to the non-fiber beam. However, the inclusion of hooked fibers to the concrete mixture changed the collapse mode to the ductile flexure failure for lower reinforcement ratios.

Another research issue for the shear dominant UHPFRC members is the feasibility of fully or partially replacement of stirrups by the steel fibers. Within this context, the partially use of steel fibers in place of the stirrups in the reinforced concrete members was included for the normal strength concrete in the ACI 318-19 [28]. But very limited information is available with regard to this challenge. Zagon et al. [29] studied the replacement of stirrups by steel fibers on the I-shaped UHPFRC beams exhibiting the shear behavior without steel fiber. They declared that the replacement of traditional stirrups by the steel fibers in particular volume fraction was feasible for moderate level of shear loads. The study recommended a combination of additional single diagonal rebar and steel fiber uses instead of fully stirrup use. Yoo et al. [30] investigated the elimination of minimum shear reinforcement in high-strength fibrous reinforced concrete beams. Based on the test results of five beams with and without the hooked fibers, the inclusion of steel fibers by 0.75 vol percent might correspond the minimum shear reinforcement stipulated in design codes. A similar outcome was presented in Lim and Hong [20] and they revealed that no shear reinforcement required for the UHPFRC beams including the fiber content of 1.5 vol percent. Qi et al. [17], on the other hand, recommended the use of moderate level stirrups to get better structural performance since the increasing fiber volume fraction did not ensure a notable contribution. Meszöly and Randl [31] discussed the importance of traditional stirrups and steel fiber usages on the shear behavior. The total of twenty I-shaped UHPFRC beams consisting of the non-fiber, short-straight fiber and different stirrup configurations was tested in the shear. The results showed that the steel fiber use, regardless of the volume fraction, provided notable contribution to the ultimate shear strength and ductility of UHPFRC beams compared to the configurations with the stirrup.

Various efforts were made on the shear response of UHPFRC beams, however, most of them focused on the short-straight fibers. In the existing studies, the feasibility of replacement of the stirrups in the reinforced concrete beams has not been examined for different fiber types. Thus, there is significant lack of knowledge about different fiber content (type and amount) on the shear behavior. In the experimental study presented here, the impact of various fiber contents on the shear dominant UHPFRC beams as well as the best fiber content allowing the availability of steel fibers in place of the stirrups were investigated. In this context, a total of fifteen UHPFRC beams with five fiber types and three volume fractions were prepared without stirrup and they were loaded until collapse failure. In addition, two non-fiber reference beams were produced with/without the stirrups to represent pure effectiveness of steel fibers. The structural behaviors relation to the test beams were discussed in terms of the load-deflection behavior, cracking behavior and failure pattern, ultimate shear strength, nominal moment capacity and deflection ductility by referencing the non-fiber configurations.

2. EXPERIMENTAL PROGRAM

2.1. Mixture Design and Mechanical Properties

In the experimental program, the UHPFRC and non-fiber mixture compositions, which were previously developed in other studies by the authors, were used [6, 7]. So, the minimum concrete compressive strengths of 130-140 MPa and 110-120 MPa were targeted for the fibrous and non-fiber mixtures, respectively. The binder part of mixtures consisted of the standard cement CEM-I/42.5-R (C), silica fume (SF) and ground granulated blast-furnace slag (GGBFS). The aggregates consisted of two sizes of quartz sands, the particle sizes in the range of up to 0.8 mm (QS-1) and 1.0 to 3.0 mm (QS-2). In proportion to the traditional concrete mixtures, the water-to-binder ratio (W/B) for the designed concrete mixture was significantly reduced to 0.18 with the help of polycarboxylate ether-based superplasticizer (SP) which could provide adequate viscosity and workability. When the impacts of different fiber contents were investigated, two types of short-straight and two types of hooked and multi hooked-end steel fibers were used in the UHPFRC mixtures. However, the considered volume fractions of 0.5 percent, 1.0 percent and 1.5 percent comprised of the fiber use by 0.75 vol percent in place of the minimum shear reinforcement in the ACI 318-19 design code [28]. The mixture components and proportions, fiber dimensions, type and volume fractions,

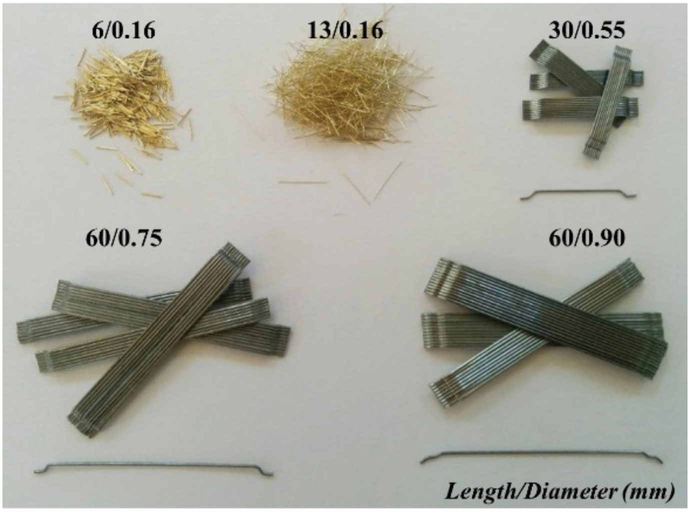


Figure 1 - The considered straight and hooked-end steel fiber types

characteristic strengths of tensile reinforcements are given in Figure 1 and Tables 1-2. The concrete compressive strength of each mixture was obtained from uniaxial compression tests using the cubic samples in the dimension of 100x100x100 mm^3 in accordance with the specifications of EN 12390-1 and EN 12390-3 [32-33]. Regarding the tensile strengths of mixtures, the dog bone-shaped samples having cross-sectional area of 30x30 mm^2 with the 68 mm overall width and 240 mm height were prepared. While the compression strengths of samples were measured by a hydraulic press with the 3000 kN loading capacity and rate of 1 MPa/s, the tensile strengths were determined through the universal testing machine with the displacement control by the loading speed of 0.1 mm/min. The samples were tested at 28 days.The average experimental strengths of cube and dog bone-shaped specimens corresponding to each beam configuration are summarized in Table 2. The test beams were coded by the fiber length, type and volume fraction (percent), respectively. Here, the *S*, *H* and *MH* denote the straight, hooked and multi hooked-end fibers, respectively. For instance, the code 13S_1.5 indicates the beam containing the straight fiber with the length of 13 mm by 1.5 vol percent (Table 2).

Table 1 - Material composition by weight (kg/m^3)

Mixture	Non-fiber	UHPFRC-1	UHPFRC-2	UHPFRC-3
C	690	690	690	690
SF	138	138	138	138
GGBFS	276	276	276	276
QS-1	542	535	530	525
QS-2	542	535	530	525
Water	199	199	199	199
SP	17.25	17.25	17.25	17.25
Steel fiber	-	0.5 vol percent	1.0 vol percent	1.5 vol percent

All UHPFRC mixtures showed higher compressive strength than the non-fiber mixture due its high-density matrix as well as the limitation of opening of micro cracks and further propagation by the steel fibers. Thus, the steel fiber use relatively improved the compressive strength in the percentages varying between 2 percent and 20 percent. It should be noted that the increases related to the mixtures containing the straight fibers of 13 mm were more apparent than those of other fiber types. However, the highest compressive strength was obtained for the mixture with 13 mm straight fiber by 1.5 vol percent. It can be deduced that, increasing fiber volume fraction enhanced the compressive strength, regardless of the fiber type, due to improvement in the mechanical bond strength, as shown in Table 2. Regarding this matter, the similar outcomes were pointed out in some research by others [6, 7, 9, 30, 34-36].

Table 2 - Steel fiber, reinforcement and concrete properties

Beam	Fiber					Rebar	Concrete	
	Type	L_f (mm)	L_f / D_f	f_t^{fib} (MPa)	percentvol	f_y and f_u (MPa)	f_c' (MPa)	f_t^{conc} (MPa)
NF	-	-	-	-	-	458 / 581	126	4.8
NF_OS							128	
6S_0.5	Straight	6	38	2500	0.5	466 / 570	132	5.8
6S_1.0					1.0		134	5.9
6S_1.5					1.5		139	7.9
13S_0.5	Straight	13	81	2500	0.5	469 / 593	144	5.9
13S_1.0					1.0		148	7.1
13S_1.5					1.5		152	10.2
30H_0.5	Hooked-end	30	55	1345	0.5	451 / 573	136	5.3
30H_1.0					1.0		142	5.6
30H_1.5					1.5		144	6.8
60H_0.5	Hooked-end	60	70	1225	0.5	484 / 597	131	4.7
60H_1.0					1.0		133	5.2
60H_1.5					1.5		137	6.1
60MH_0.5	Multi hooked-end	60	67	1500	0.5	488 / 607	130	4.3
60MH_1.0					1.0		132	6.4
60MH_1.5					1.5		135	7.7

L_f: fiber length, D_f: fiber diameter, f_t^{fib}: tensile strength of fiber, *percentvol* : fiber volume fraction,

f_y and f_u: yield and tensile strength, f_c': compressive strength, f_t^{conc}: tensile strength of concrete

As for the results of tensile strength, the inclusion of steel fibers ranged from 0.5 vol percent to 1.5 vol percent significantly improved the tensile strength by between 8 percent and 113 percent by depending also on the fiber geometry. It was also noted that when the fiber amount in the mixture increased from 0.5 vol percent to 1.0 vol percent, the tensile strength was more sensitively affected by the increase in fiber amount, as shown in Table 2. During the uniaxial sample tests, the brittle collapse occurred once the first cracking was observed on the non-fiber specimen, as expected. After this stage, the tensile strain-hardening behavior was achieved for the fibrous concrete mixtures above 1.0 vol percent except for the shortest straight fiber of 6 mm (Figure 2). This fiber type did not exhibit hardening response for the overall volume fractions since the fiber length could not build a bridge on both sides of cracks. Beyond the peak load level, the fibers began to slide out because of the growing of cracks in the tensile region. Thus, the strength drops launched on axial force - deflection relationships of the samples.

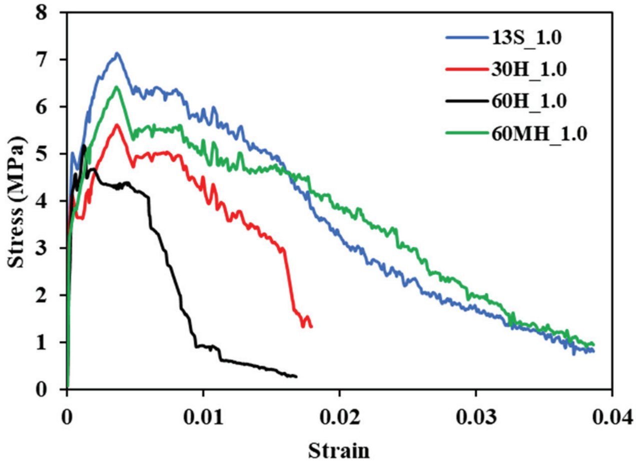


Figure 2 - Stress-strain relationships of specimens with fiber volume fraction of 1.0 percent showing strain hardening behavior

2.2. Preparation of UHPFRC Test Beams

In the framework of this study, a total of fifteen simply reinforced UHPFRC beams consisting of five fiber types were prepared for three volume fractions. In addition, two non-fiber reference beams were produced with (NF_OS) and without (NF) the stirrup to reveal the impacts of variety of fiber content (type and amount). The dimensions of the test beams are 100x150x1500 mm and clear span between the two supports is 1400 mm. The tensile reinforcement ratio was kept constant as 2.4 percent, which composed of two 14 mm steel rebars. Whereas the considered reinforcement ratio almost corresponds the upper limit (2.0 percent) in the Turkish Design Standard (TS 500) [37], the maximum ratio stipulated in the ACI 318 design code was modified by the strain equilibrium in the recent editions [28, 38, 39], in which the ratio was calculated as 6.3 percent.

The beam dimensions and reinforcement details are presented for a typical test beam in Figure 3. Three coupon samples related to the longitudinal reinforcements for each test group were tested under the direct tension. In this way, the average yield and tensile strengths of the samples are given in Table 2. The ends of longitudinal reinforcements were hooked to avoid the premature bond failure. Shear reinforcement was not provided in the shear span of UHPFRC beams to eliminate the influences of other components. While the beam NF was designed to fail by shear, the beam NF_OS was equipped with open stirrups with 8 mm diameter and the spacing of 65 mm, which almost corresponds to the minimum transverse spacing in the TS 500 and ACI 318-19 guidelines [37, 28], as shown in Figure 3. Overall, the preparation and casting procedures in regard to the test beams can be found in detail in Hasgul et al. and Yavas et al. [7, 13].

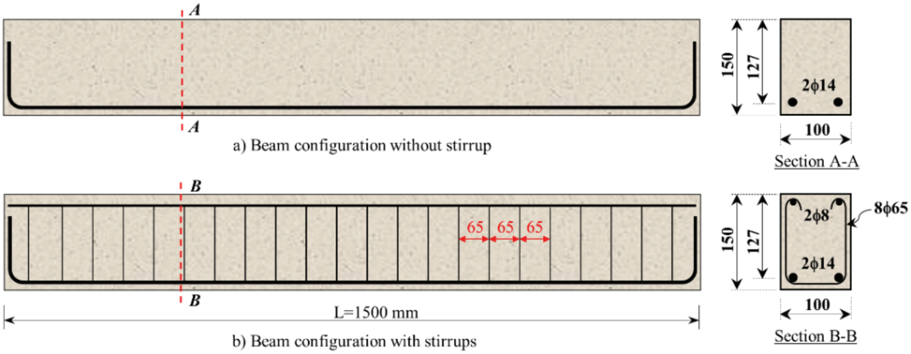


Figure 3 - Schematic representations of test beams

2.3. Test Setup

The four-point loading test setup is presented in Figure 4. In the study, the shear-span to depth ratio (a/d) was 3.9 for all beams, and the vertical loads were applied at a distance of 500 mm from both supports. Referring to Figure 4, a load cell was attached between the jack and spreader beam to measure the applied load. The load P was applied to the beams as two equal concentrated loads as $P/2$ and $P/2$ through a steel spreader beam. Later on, the load increments were monotonically applied to the beam by a hydraulic servo testing machine with the capacity of 500 kN. The whole tests were conducted under deflection control procedure at 0.2 mm/min.

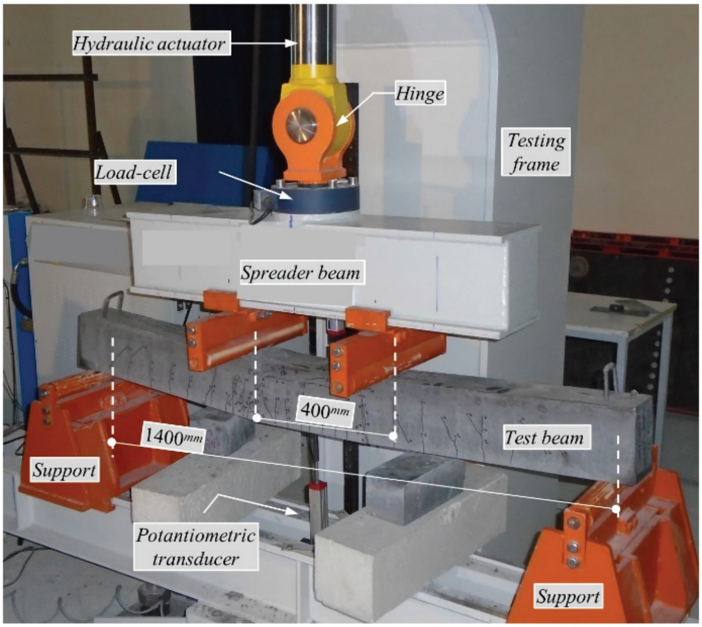


Figure 4 - The four-point loading system

It should be noted that the loading speed for the test beams changing to flexure was increased to 0.5 mm/min to reduce duration between the peak and ultimate deflections. A potentiometric transducer was mounted the bottom face of beam midpoint to measure vertical deflections. The applied load (*P*) and mid-span deflections (Δ) were recorded by use of 24-channel data acquisition system that had the data-recording frequency of 8 Hz per channel. At the certain deflection steps, the crack formations and propagations were highlighted over the test beams.

3. TEST RESULTS AND DISCUSSIONS

In the experimental program, the total of seventeen singly reinforced UHPFRC beams and non-fiber reference beams were loaded under the four-point loading scheme until collapse failure. Because of conducted various loadings, the parameters of *P*–Δ behavior, cracking pattern and collapse mode, ultimate shear strength, nominal moment capacity and deflection ductility were discussed by comparing them with the non-fiber reference configurations.

3.1. Load-Deflection Relationships

The test beams were subjected to the planned loading protocol until the collapse condition and their load (*P*) and mid-span deflection (Δ) behaviors were determined (Figure 5). The *P*–Δ relationships and corresponding crack patterns at the collapse conditions are given for each fiber type in Figure 5. In addition, the main quantitative features obtained from the loadings are summarized in Table 3. It should be noted at this point that the deflection and ductility responses beyond the peak load were determined for only the beams the structural behavior of which transformed from the shear to flexure after the steel fiber use. Firstly, the yield deflection Δ_y was calculated from the bi-linearized $P - \Delta$ relationship, which is one of the methods recommended in Park [40]. Here, the deflection point Δ_y corresponds to the deflection at the intersection of secant stiffness at the peak load P_p and $0.75P_p$ [2, 13]. Secondly, Park [40] also proposed some procedures to specify the ultimate deflection Δ_u of an experimental load-deflection relationship. One of these procedures, which is well-known as the load reduction method of 20 percent, was based on in the study [41-44].

Referring to Figure 5, all the *P*–Δ relationships showed linear elastic response until the first cracking point and stiffness degradations commenced on the beam responses. In the post cracking stage, the *P*-Δ relationships could be divided into two groups according to their collapse conditions as the shear or flexure. In the shear dominant beams, as shown in Figures 5c-5e, a dramatic load drop occurred without any significant increase in the deflection response as well as before the yielding of reinforcement.

When the stirrup or sufficient fiber content was provided, full flexural response was observed by reinforcement yielding following the deflection hardening as well as strength degradation after the peak load (Figures 5a-5e). The short-straight fibers considered each volume fraction prominently improved the post-cracking stiffness values and load-carrying capacities of the UHPFRC beams in comparison with the non-fiber configuration because of the crack-bridging ability of the fibers which allows smaller deflections even at higher load levels. In addition, the stiffness and load capacity showed an increasing trend with the increases in the fiber amount. While the hooked and multi hooked-end fibers provide ductile flexural behavior for only 1.5 percent volumetric ratio, they significantly improved the capacity with respected to the reference beam NF_OS, especially beams with long hooked-end fibers of 60H_1.5 and 60MH_1.5 (Figures 5c-5e). However, these beams were limited in terms of deflection capacity compared with the beam NF_OS. These results are very compatible with the previous studies in relation to the structural behavior of UHPFRC beams [2, 7, 13, 17, 45-48].

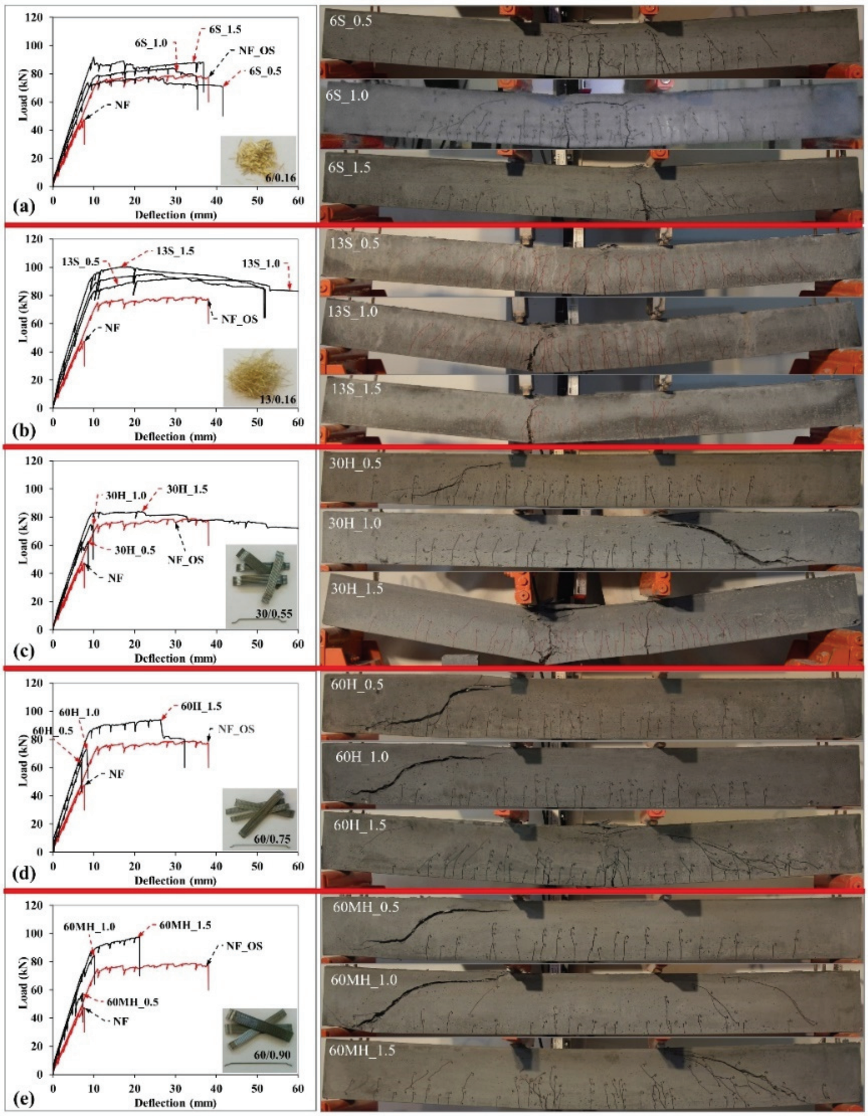


Figure 5 - P–Δ relationships and collapse modes of the test beams; a)6S, b)13S, c)30H, d)60H, e)60MH

Table 3 - Characteristic values of P–Δ relationships at various stages and collapse modes

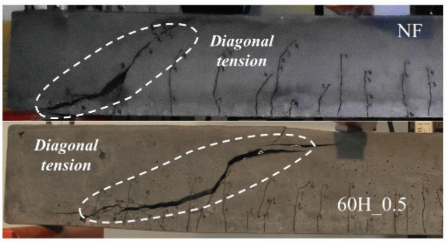
Beam	Δ_y (mm)	P_y (kN)	Δ_p (mm)	P_p (kN)	Δ_u (mm)	P_u (kN)	Ductility index		Collapse mode
							Δ_p/Δ_y	Δ_u/Δ_y	
NF	-	-	7.57	47.41	-	-	-	-	DT
NF_OS	11.23	71.36	34.28	78.84	38.1	77.37	3.05	3.39	CC
6S_0.5	8.57	73.31	24.72	78.19	41.54	70.38	2.88	4.85	CC
6S_1.0	10.41	78.19	29.22	83.85	35.32	74.62	2.81	3.39	CC
6S_1.5	9.53	88.21	9.95	91.87	36.86	87.05	1.04	3.87	CC
13S_0.5	10.54	82.84	32.76	92.35	51.65	84.75	3.11	4.90	CC
13S_1.0	10.22	88.15	23.37	95.11	72.01	76.09	2.29	7.05	RR
13S_1.5	9.58	92.87	18.16	100.32	51.94	84.23	1.90	5.42	RR
30H_0.5	-	-	8.62	62.76	-	-	-	-	DT
30H_1.0	-	-	9.26	74.58	-	-	-	-	DT
30H_1.5	9.00	80.25	20.88	84.08	66.74	67.24	2.32	7.42	CC
60H_0.5	-	-	6.99	63.62	-	-	-	-	DT
60H_1.0	-	-	8.26	72.90	-	-	-	-	DT
60H_1.5	9.40	84.56	26.27	93.81	32.25	79.80	2.79	3.43	CC
60MH_0.5	-	-	7.26	57.78	-	-	-	-	DT
60MH_1.0	-	-	10.19	84.37	-	-	-	-	DT
60MH_1.5	-	-	21.16	97.60	-	-	-	-	F+DT

P_y: yield load, P_p: peak load, P_u: ultimate load, Δ_y: yield deflection, Δ_p: peak deflection, Δ_u: ultimate deflection, DT: diagonal tension, CC: concrete crushing, RR: reinforcement rupture, F: Flexure

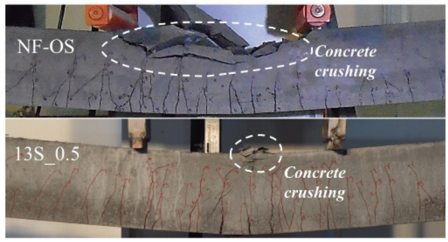
3.2. Cracking Behavior and Collapse Modes

The collapse conditions of UHPFRC beams with respect to the studied fiber types are presented for three volume fractions in Figure 5. At the beginning of load steps, the vertical flexural cracks vertically commenced at the lowermost faces in the constant moment zone of the beams. Thereafter, additional vertical cracks formed alongside the existing cracks with the increasing loads, but the crack widths remained in a well-restricted level for the UHPFRC beams because the steel fibers built a bridge between both sides of the cracks. But it is not easy to see these cracks with naked eyes until the peak load in the $P-\Delta$ relationship. These cracks can be only seen with the help of crack width magnifier. As the load increased further, the member behavior and collapse modes separated depending on the fibers type and amount as shown in Figure 5.

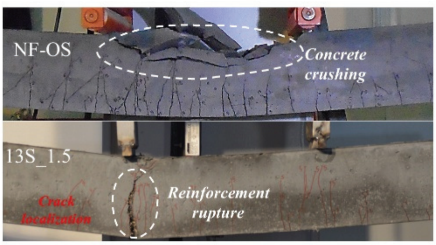
For the reference beam (NF) without the fiber and stirrup, when the principal tensile stress reached the tensile strength of concrete, as in the conventional normal strength concrete, the beam failed suddenly as a consequence of formation of diagonal single crack initiated in the shear span and propagated between the loading point and support, as shown in Figure 6a. This collapse mode points out the diagonal tension (DT) in the brittle manner. At this point, while the test beams containing the hooked or multi hooked-end fiber by 0.5 vol percent and 1.0 vol percent failed by the DT, the fibers significantly delayed the formation of shear cracks (Figure 6a). However, the beam 60MH_1.5 exhibited the flexure-shear failure by a splitting at the diagonal crack after the tensile reinforcement yielded. It can be deduced that the steel fiber type has an important influence on the collapse mode of the shear dominant UHPFRC beams.



a) Shear failure (*diagonal tension*)



b) Flexural failure (*concrete crushing*)



c) Flexural failure (*reinforcement rupture*)

Figure 6 - Typical collapse modes for the test beams

Whereas the reference beam NF was designed to fail by shear, the reference beam NF_OS, which had the minimum shear reinforcement ratio, exhibited full flexural behavior resulting the concrete crushing (CC) along a wide region at the constant moment zone, as shown in Figures 6b-6c. The catastrophic collapse with the CC occurred in the compression zone when the critical section of beam reached their flexural capacity. When it comes to the UHPFRC beams without stirrup having an adequate fiber content in the concrete matrix, the test beams showed well enough stable behavior from the beginning to the end of tests through the deformation ability provided by the steel fibers. In this regard, the fibers prevented the formation of diagonal cracks therefore, well-distributed flexural cracks propagated towards to the compression zone with further load increments, as shown in Figure 5.

The beams containing the straight fiber of 6 mm as well as the beams 13S_0.5, 30H_1.5 and 60H_1.5 failed by the concrete crushing (CC) as such in the reference beam NF_OS rather than the non-ductile shear failure (Figure 6b). While the CC occurred in the UHPFRC beams, the deformation stayed at a limited region since the steel fibers produced a kind of confinement effect in comparison with the NF_OS. For the beams 13S_1.0 and 13S_1.5, flexural behavior was terminated by the reinforcement rupture (RR). In the UHPFRC beams with flexural failure, a large crack formed at a single point adjacent to the beam midpoint. As shown in Figure 6c, the related crack width intensely enlarged as against others and dominated the beams' collapse mode. This response of UHPFRC is widely defined as the crack localization [44, 48-51]. It should be noted that even though the crack localization phenomenon occurred in all UHPFRC beams, only the beams 13S_1.0 and 1.5 failed by RR. This outcome indicates that the use of 13 mm straight steel fiber pointedly increased the compressive deformation capacity of the UHPFRC more than other fiber types. Despite the increased deformation, the concrete did not crush and eventually the RR occurred. Regarding the crack localization phenomenon, while the research by others [2, 13, 30, 45, 52] reported the RR for only the 13 mm straight fiber, Yoo and Yoon [46] declared that the rupturing failure was inevitable under low reinforcement ratio regardless of the fiber type. Sturm et al. [52] also pointed out that the reinforcement ratio had particular importance on the collapse condition. The authors' previous study [13] confirmed this outcome since very high strength and deformation capacity of the UHPFRC could allow the use of excessive tensile reinforcements.

It can be deduced from these tests that the use of short-straight fiber in the UHPFRC beams, even at very low volume fractions of 0.5 percent, changed the collapse mode to flexure resulting the ductile behavior without placing the stirrups. However, the hooked fiber inclusion by 1.5 vol percent at least is needed to guarantee the flexural behavior regardless of hooked or multi hooked-end form. The test results also revealed that the short-straight fibers showed much better performance in terms of the limitation of diagonal cracks as against the hooked fiber types. This is related to the fact that number of the hooked fibers in per unit volume is lower than the straight fibers due to their longer length. Beside this, the dispersion and orientation of longer fibers became poor because of the blocking effect of longitudinal reinforcement.

3.3. Deflection Ductilities

For the UHPFRC beams exhibiting the flexure behavior with the help of some fiber contents, the ductility responses were evaluated by the peak load deflection ductility $\mu_{\Delta p}$ and ultimate deflection ductility $\mu_{\Delta u}$. Firstly, the ductility corresponding to the peak load can be determined by proportioning the deflection at the peak load Δ_p to the yield deflection Δ_y. Secondly, the deflection ductility capacity can be calculated by considering the ultimate deflection Δ_u instead of the Δ_p for the beams continued to sustain loads well beyond the peak load, just as the UHPFRC beams. Both ductility indexes calculated for the corresponding UHPFRC beams as well as the reference NF_OS beam are compared in Figure 7. It can be noted that the test beams that failed by the shear were left out of the flexural assessments.

Referring the Figure 7 and Table 3, while the ductility levels at the peak loads of the beams 6S_0.5 and 13S_0.5 nearly corresponded to that of the reference beam NF_OS, regardless of the fiber length, the ductility level provided by the stirrups couldn't be ensured for higher fiber amounts. The reason of this is that as the fiber volume fraction increased in the concrete matrix, its restriction ability on the crack formations was enhanced. Thus, the beam deflections before the peak load decreased by a certain amount in comparison to the non-fiber stirrup configuration. This circumstance led to a decrease in the peak load ductility with the increase of fiber amounts. Figure 7 also allows to compare the effect of fiber length for

1.5 vol percent. Accordingly, longer fiber use slightly increased the deflection ductility due to fibers' low efficiency in the pre-peak area where the crack widths were too small.

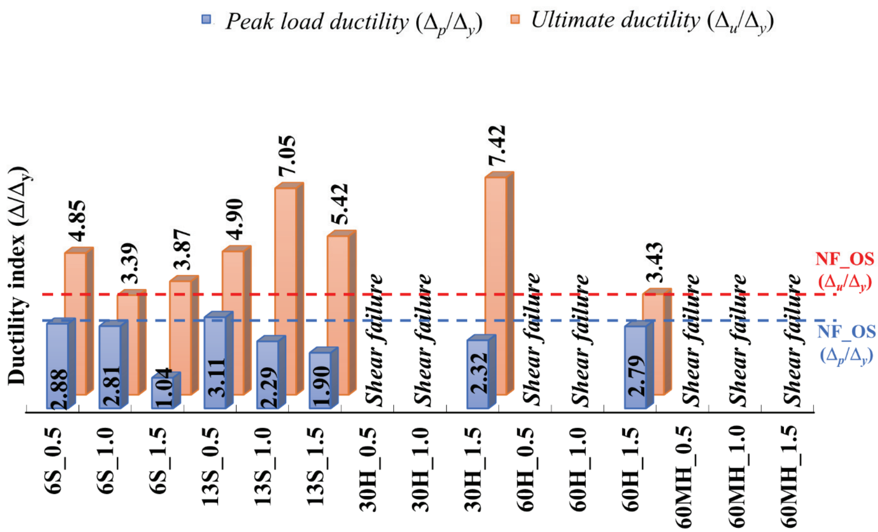


Figure 7 - Ductility indexes at the peak load and ultimate deflection

From the point of the ultimate deflection ductility $\mu_{\Delta u}$, as shown in Figure 7, fully replacement of stirrups by the straight fibers of 6 mm and 13 mm is feasible for the considered volume fractions. Moreover, these UHPFRC beams showed more ductile behavior up to 2.1 times compared to NF_OS. It can be pointed out that the minimum 1.5 vol percent needed to get the same ductility level by the hooked fiber (Figure 7). Here, the ductility performance of hooked-end fiber 30H was better than the 60H and 60DH. While the ductility ratio obtained for the beam 30H_1.5 was greater 2.2 times than that of the beam NF_OS, the beam 60H_1.5 exhibited the same ductility level. But the multi hooked-end fiber use, even at 1.5 vol percent, could not change the collapse condition to the flexure. However, there was no apparent trend between the considered fiber types and amounts from the point of the ultimate ductility (Figure 7). It can be also understood that while the fiber length relating to the straight fiber did not affect the ductility ratio for the lowest volume fraction, it became an important variable to be considered for additional volume ratios. Unfortunately, it is not easy to support this outcome for the UHPFRC beams with the hooked or multi hooked-end fiber types because the most of them failed by shear. Regarding this issue, Yoo and Yoon [48] and Singh et al. [45] reported that higher flexural ductility could be achieved as the fiber length increases in the UHPFRC matrix. From the point of ductility definitions, it can be clearly deduced that the most effective fiber type was the 13 mm straight fiber (Figure 7). This fiber type not only had a great potential to change the structural behavior of shear dominant UHPFRC beams, but also provided the stipulated ductility by means of the stirrups in design codes.

3.4. Shear and Flexural Capacities

In the shear dominant UHPFRC beams exhibiting the brittle failure even when higher amount of steel fiber was used for the certain fiber types, the ultimate shear strengths V_u of UHPFRC and non-fiber reference beam are presented together in Figure 8 in order to show how the fiber content influenced the behavior. It can be added that the test beams displaying flexural collapse were left out in the discussions related to the shear strengths.

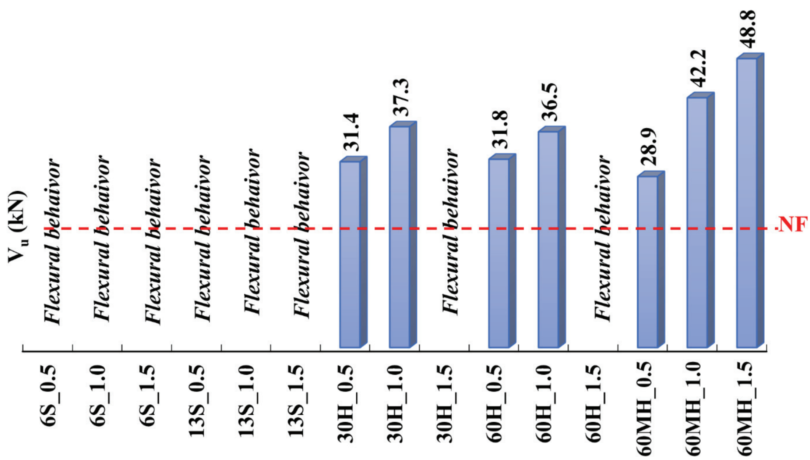


Figure 8 - Influences of fiber type and amount on the shear strength of UHPFRC beams

Referring the Figure 8 and Table 3, the strength of shear dominant beams were much higher than those of the non-fiber configuration. Besides, an increase in the volume fraction of fibers uniformly enhanced the shear strength, regardless of the fiber type for both 0.5 vol percent and 1.0 vol percent. However, the steel fibers increased the shear strength in ratios varying between 22 percent and 106 percent depending on whether the fiber type is hooked or multi hooked-end (Table 3). As a side note, an increment of 0.5 percent in the fiber amount gained significant strength varying between 15 percent and 46 percent.

While various investigations [7, 15-25] generally accepted the view that the steel fibers enhance the shear strength, the provided strength increase was more apparent for the fiber amounts higher than 1.0 vol percent according to Pansuk et al. [53] and Meszöly and Randl [31]. For the same fiber amount (1.0 vol percent), Meszöly and Randl [31] obtained roughly four times higher capacity than non-fiber condition. However, the authors' previous study [7] revealed that the fiber contribution on shear strength remained very limited below 0.5 vol percent for the straight, hooked and multi hooked-end fibers.

Figure 8 also indicates that the fiber type does not have an importance on the ultimate strength of shear dominant UHPFRC beams. Besides that, the choice of hooked or multi hooked-end fiber type did not affect the shear behavior distinctively. Although the largest capacity enhancement among the test beams was obtained for the beam 60DH_1.5, this fiber type could not transform the collapse mode to the flexure in contrast to other UHPFRC beams having 1.5 vol percent. On the other hand, the nominal moment capacities M_p corresponding to peak load of the experimental load-deflection relationships with respect to the UHPFRC beams transferring the flexure by steel fibers as well as the non-fiber beam with the minimum transverse reinforcement are presented for each volume fraction in Figure 9. Parallel to the shear strength, the test beams failed by shear were left out in the discussions. For the UHPFRC beams exhibiting flexural behavior, a small increment in the fiber amount provided notable contribution to the capacity in a positive manner. So, the moments were enhanced up to 27 percent depending on the fiber amount in the concrete matrix (Table 3). However, the fiber type had a particular influence on the moment capacity unlike the shear behavior. In this sense, longer fiber length resulted in an apparent capacity increase for the straight fiber type since the fibers' crack-bridging ability improved across the crack width. The moment capacities of beams 13S_0.5, 1.0 and 1.5 were greater by 18 percent, 13 percent and 9 percent than those of the 6S_0.5, 1.0 and 1.5, respectively.

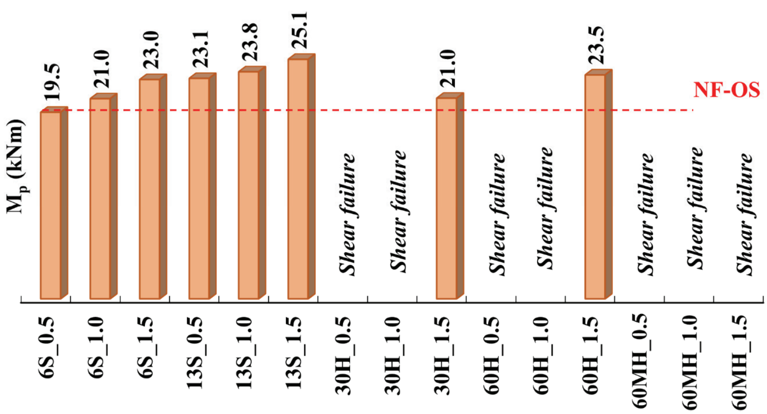


Figure 9 - Influences of fiber type and amount on the moment capacity of UHPFRC beams

Considering both straight fiber types, whereas the 0.5 vol percent for the fiber 6S almost corresponded to the minimum transverse reinforcement, as shown in Figure 9, the hooked fiber inclusion by 1.5 vol percent at least was required to guarantee the flexural behavior. For others, the 30 mm and 60 mm hooked fibers for the related fiber amount could improve the moment capacity by 7 percent and 19 percent when compared with NF_OS, respectively. As in the straight fibers, it is perceived that the variation of moment capacity will be in an increasing tendency as the length of hooked fiber increases to the further amounts such as 2.0 vol percent and 2.5 vol percent. The best performance from the point of the moment capacity was obtained once again for the beam 13S_1.5 (Figure 9). These results indicated that the use of straight fibers in place of the stirrups in UHPFRC beams not only transformed the collapse mode from the shear behavior, but also provided additional flexural capacity even for the lowest volume fraction considered (0.5 vol percent). It should be also noted that these findings are based on the considered UHPFRC matrix and steel fiber content used in this study. It is necessary to emphasize that this ratio is far below the ACI 318 criteria [28], in which the minimum amount of steel fiber by 0.75 vol percent is needed for the stirrup replacement in the structural members produced by the normal strength fibrous concrete.

4. CONCLUSIONS

In the present study, the impacts of different fiber contents on the shear dominant UHPFRC beams as well as the feasibility of fully replacement of stirrups by the steel fibers were investigated. In this framework, the total of fifteen UHPFRC beams containing five different fiber types and three volume ratios were prepared without transverse reinforcement and were loaded until collapse failure. The following findings can be drawn from the experimental investigations:

- All the *P*–Δ relationships of UHPFRC beams showed linear elastic response until the first cracking points. Beyond this level, all *P*–Δ relationships were divided into two groups according to their collapse modes as shear or flexure.
- Regarding UHPFRC beams that failed in the form of diagonal tension, the steel fiber use substantially increased the post-cracking stiffness and load capacity in comparison with the non-fiber reference configuration because of the crack-bridging ability which allowed smaller deflections even at higher load levels. However, the fiber type did not have an important influence on the shear failure. As in the existing shear investigations, the shear strengths of UHPFRC beams were much higher than that of the non-fiber configuration. However, an increase in the volume fraction of fibers uniformly enhanced the shear strength, regardless of the fiber type.
- On the other hand, the UHPFRC beams, in which an adequate fiber content was ensured without stirrup, showed well enough stable behavior through the deformation ability provided by the steel fibers. The fibers prevented the formation of diagonal cracks for further load increments and thus, well-disturbed vertical cracks propagated towards to the uppermost compression face. Accordingly, the test beams with the straight fiber of 6 mm as well as the 13S_0.5, 30H_1.5 and 60H_1.5 failed by the concrete crushing. Differently, the beams 13S_1.0 and 1.5 showed more deformation ability than other beams and failed by the reinforcement rupture due to the crack localization phenomenon.
- A small increase of the fiber amount provided notable contribution to the moment capacity in a positive manner. So, the moments increased up to 27 percent depending on the fiber amount in the concrete matrix. Unlike the shear behavior, the fiber type has also a particular influence on the moment capacity.
- It can be drawn from the conducted tests that the use of straight fiber in the UHPFRC beams, even at very low volume fraction of 0.5 percent, changed the collapse condition to flexure resulting the ductile behavior without placing the stirrups. It is important to note that this ratio is far below the ACI 318 requirements regarding stirrup replacement in the structural members. However, the hooked fiber inclusion by 1.5 vol percent at least is needed to guarantee the flexural behavior regardless of hooked or multi hooked-end form.
- Referring to the ultimate deflection ductility, the full replacement of stirrups by the straight fibers of 6 mm and 13 mm is feasible for fiber amounts by 0.5 percent-1.5 percent by volume. These beams showed more ductile behavior up to 2.1 times in proportion to the non-fiber configuration with the stirrups. But the 1.5 vol percent

at least is needed to get same ductility level by the hooked fiber because of less homogenous dispersion and less numbers per unit volume.

The primarily results of this study revealed that the fiber type and amount significantly affects the shear and flexural behaviors of the UHPFRC members. It should be also noted that these findings are based on the considered UHPFRC matrix and steel fiber content used in this study. Similar studies incorporating other parameters such as fiber contents, shear span-to-depth ratios, reinforcement ratios, and loading conditions, will play an important role on the preparing of specific code and standard regarding the UHPFRC.

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