Seismic Behavior Aspects of Fiber-Reinforced Concrete Structures

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Abstract: The application of fibers to enhance the mechanical properties of concrete continues to gain recognition among researchers and structural engineers. Significant research work has been carried out to study the application of fiber reinforced concrete (*FRC*) to reinforced concrete structural members. The main objective of this study is to investigate the suitability of reinforced concrete structures made of *FRC* in high and moderate seismicity areas. This is done through the study the effects of both fiber volume fraction (V_f) and the ratio of internal steel reinforcement on Secant stiffness, ductility and over-strength, as well as its ability to absorb (dissipate) energy of steel-reinforced *FRC* beams. Results of existing experimental investigations on flexural *UHPFRC* and *HSFRC* reported in literature are used. Design values for the tensile reinforcement ratio, volumetric fiber content that favorably affect the seismic resistance and seismic forces induced from earthquakes are reached.

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Keywords: Fiber content, FRC, HSFRC, UHPFRC, reinforcement ratio, ductility ratio, over-strength factor.

1. Introduction

The application of fibers to enhance the mechanical properties of concrete continues to gain recognition among researchers and structural engineers. Significant research work has been carried out to study the application of fiber reinforced concrete (*FRC*) to reinforced concrete structural members. The mechanical properties of *FRC* are influenced by the fiber material, its shape (hooked end or straight), the surface deformation, the aspect ratio (length/diameter), and the amount of fibers (fiber volume fraction, V_f). Normal strength concrete (*NSC*), high strength concrete (*HSC*) and ultra-high performance fiber-reinforced concrete (*UHPFRC*) are three classes of fiber-concrete that have been produced. Hooked fibers typically used in *NSC* and *HSC*, while on the other hand, straight, smooth, and short fibers often used to produce *UHPFRC*. Superplasticizers are generally used in *FRC* mixes to enhance its workability to achieve good compaction [1-5]

Since the pioneering work of Romualdi in the 1960s based on the idea on controlling cracking in concrete by fiber bridging [6], both fiber technology and knowledge of the interaction between fibers and matrix have constantly developed. The additional role of fibers in *UHPFRC*, in comparison to the role of fibers in ordinary and in high strength fiber-reinforced concrete (*HSFRC*), is to provide sufficient ductility to the material. This is achieved by choosing the appropriate type and amount of fibers [7-9].

Secant Stiffness, ductility ratio and over-strength factor are important parameters in determining the response and the seismic force level of concrete structures located in moderate and high seismic risk areas. Secant stiffness affects the natural period of vibration of the structure, *T*, which has a prime role in determining the design response spectrum, S_d, of the structure. High secant stiffness result in high response spectrum, S_d, which in turn increases the seismic design force demand. High ductility ratio allow the use of high response modification factor (force reduction factor), *R*, resulting in lower seismic force demand. Finally, over-strength is a measure of the increase of the system strength during the post-yield range of behavior over the design strength. The increase of over-strength factor increases the design shear force demand to avoid the possibility of brittle shear failure. Also, higher over-strength factors increase the length of the inelastic response regions at the ends of reinforced concrete members. Moreover, higher over-strength factors result in more stable hysteretic loops during the cyclic behavior. The last two effects are favorable since they increase the energy dissipation characteristics of structural members [10-13].

The main objective of this study is to investigate the suitability of reinforced concrete structures made of *FRC* in high and moderate seismicity areas. This is done through the study the effects of both fiber volume fraction (V_f) and the ratio of internal steel reinforcement on Secant stiffness, ductility and over-strength, as well as its ability to absorb (dissipate) energy of steel-reinforced *FRC* beams. Results of existing experimental investigations on *UHPFRC* and *HSFRC* beams reported in [14] and [15] respectively.

2. UHPFRC BEAMS

UHPFRC is distinguished between other *FRC*s as a material exhibiting strain hardening in tension. Other *FRC*s may exhibit a hardening behavior in flexure, while they show strain softening under tension. The increased compactness of the cement matrix has led to increased strength but also increased brittleness, where discontinuous fibers were added to overcome the unfavorable brittleness [8].

Shihab *et al.* [14] have investigated the flexural behavior of steel-reinforced UHPFRC beams. The steel-reinforcement ratio and the fiber content were the main study parameters. Concrete mixtures of steel fibers content of 0.0%, 1%, 2% and 3% are used to cast the tested beams. The mixtures fiber content, V_f, characteristic strength, f_{cu} and the balanced reinforcement as calculated from Equation (1) for the tested beams, are listed in Table 1.

$$\rho_b = \frac{0.85\beta_1 f_c'}{f_y}\left(\frac{600}{600+f_y}\right) \quad (1)$$

Table 1: Concrete mix properties for UHPFRC test beams

Fiber content	$V_f = 0$ %	$V_f = 1$ %	$V_f = 2$ %	$V_f = 3$ %
f_{cu} (Mpa)	169	174	177	180
Balanced Reinforcement ratio ρ_b	0.116	0.120	0.122	0.124

UHPFRC Tested Specimens

All tested beams are of 100 mm × 200 mm cross-sections, 1600 mm total length, and top (compression) reinforcement of two 10 mm. UHPFRC beams with different volume fractions of steel-fiber, 0, 1, 2 and 3 %, corresponding to the steel-fiber amount per volume with 0 kg/m^3, 78 kg/m^3, 156 kg/m^3, 234 kg/m^3 respectively. Dimensions and reinforcement of all tested beams are shown in Figure (1), for more information refer to Shihab et al.[14]. The beams are grouped in three groups as follows:

Group (A): All beams have bottom reinforcement of two 12 mm diameter bars, a tension reinforcement ratio, ρ = 1.33 % , where, $\rho = A_s/b.d$, with transverse reinforcement of 8 mm diameter stirrups at 110 mm centers with ratio ρ_v = 0.91 % , where, $\rho_v = A_v / s\, b$.

Group (B): Beams of this group have bottom reinforcement of four 12 mm diameter bars with ratio ρ = 2.83 %, and transverse reinforcement of 8 mm diameter stirrups at 110 mm centers with ratio ρ_v = 0.91 %.

Group (C): Beams of this group have bottom reinforcement of four 16 mm diameter bars of ratio ρ = 5.36 %. The transverse reinforcement of 8 mm diameter stirrups at 70 mm centers had a ratio ρ_v =1.44 %.

Test Results

The results of the four point flexure test of all *UHPFRC* beams as reported in Shihab et al. [14] are used directly or through some mathematical manipulations to obtain the secant stiffness, K_S, displacement ductility ratio, μ_Δ, the curvature ductility ratio, μ_ϕ, and the over-strength factor, Ω. Their values are listed in Table 2, in addition to corresponding net steel reinforcement ratio, ρ - ρ`, as a ratio of its balanced value, ρ_b. Table 2 also contains the depth of the neutral axis from the top compression fiber (*k.d*) at the yield moment, where *d* is the effective beam depth. Also it contains the depth of the neutral axis from the top compression fiber (*x*) at the ultimate moment resistance. From Table 2 fiber content has insignificant effect on secant stiffness, K_S, while the reinforcement ratio has substantial effect on it.

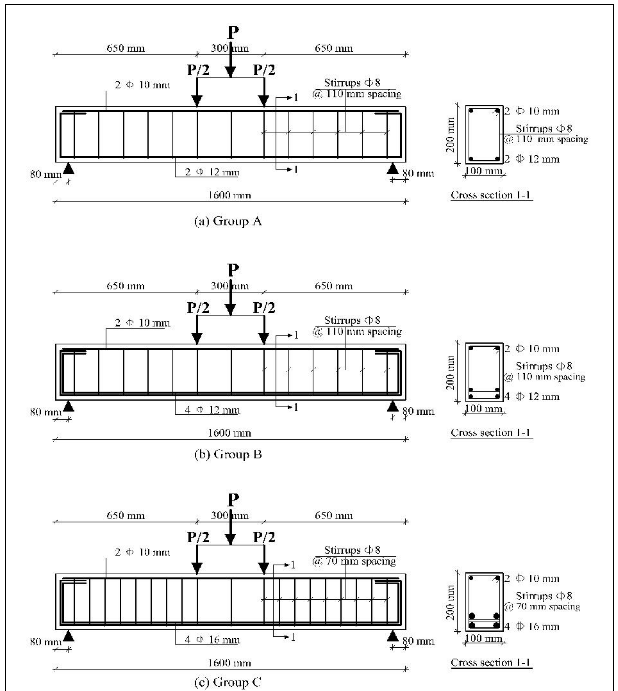

Figure (1): Dimensions and reinforcement of tested UHPFRC beams

Moreover, beams critical sections curvature at yield and ultimate points, ϕ_y and ϕ_u respectively, are also calculated and listed in Table 2.

The yield and ultimate curvatures are calculated as follows:

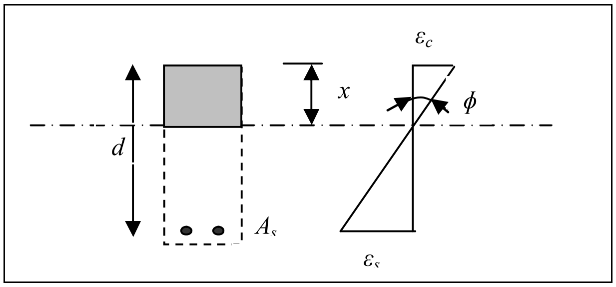

Figure (2): Curvatue definition of reinforced concrete beams

As shown in Figure (2), beam curvature can be defined below:

$$\phi = \frac{\epsilon_c}{d} = \frac{\epsilon_s}{d - x} \qquad (2)$$

The curvature at the yield point, ϕ_y , and at the ultimate point, ϕ_u , are calculated by using the strain measurments taken during the beam tests for the top fiber compression strain, ε_c, and the strain in tensile reinforcement, ε_s , into Equation (2), [10, 16 and 17].

Table 2: Stiffness, ductility ratios, over strength factor and reinforcement ratios of tested UHPFRC beams

Beam Specimen	Overall values				Critical section' values				
	$\frac{(\rho - \rho`)}{\rho_b}$	K_S (kN / mm)	Ω	μ_Δ	$k.d$ (mm)	$\phi_y \times 10^{-3}$ (rad.)	x (mm)	$\phi_u \times 10^{-3}$ (rad.)	μ_ϕ
A_o	0.035	4.57	1.19	1.98	54	0.17	10.35	2.03	11.9
A_1	0.034	4.62	1.23	2.07	54	0.17	12.40	2.26	13.3
A_2	0.034	4.85	1.30	2.25	54	0.17	14.20	2.46	14.5
A_3	0.033	5.10	1.33	2.49	54	0.17	15.70	2.74	16.1
B_o	0.159	11.0	1.14	1.57	61	0.25	19.20	1.35	5.4
B_1	0.150	11.4	1.17	1.97	61	0.25	22.60	1.55	6.2
B_2	0.148	11.7	1.18	2.17	61	0.25	24.40	1.80	7.2
B_3	0.145	12.0	1.21	2.29	61	0.25	26.90	2.01	8.04
C_0	0.368	24.6	1.11	1.24	75	0.32	39.50	0.75	2.34
C_1	0.356	25.6	1.12	1.51	75	0.32	38.60	0.91	2.84
C_2	0.350	26.2	1.14	1.77	75	0.32	42.90	1.07	3.34
C_3	0.345	26.5	1.17	2.07	75	0.32	46.20	1.21	3.78

Analysis of Results

Displacement ductility ratio and the curvature ductility ratio for the tested beams are drawn versus the volumetric fiber content, V_f, values in Figure (3) and Figure (4) respectively. Three curves are drawn on each figures, for three different tensile reinforcement ratios, ρ- ρ`. Namely, ρ- ρ` = 0.41%, ρ- ρ` = 1.85% and ρ- ρ` = 4.31%, for groups (A), (B) and (C) respectively. Observations on Figure (3) can be summarized as follows:

1. Adding fibers improves displacement ductility, the degree of improvements depends on the volumetric fibers content, V_f , as well as the net reinforcement ratio, ρ - ρ`. Displacement ductility improvements of 5%, 14 % and 26% for UHPFRC beams of fiber content, $V_f$ = 1%, 2% and 3%, respectively, for beams of ρ - ρ` = 0.41%. While, these improvements are higher for beams of ρ - ρ` = 4.31%: Namely, 22%, 43%, and 67% for V_f = 1%, 2% and 3%, respectively.
2. For beams of the highest reinforcement ratio (ρ - ρ` = 4.31%), adding fibres of 1 % or more is nessesary to change beam behavior from brittle to ductile ($\mu_\Delta > 1.5$), [10].

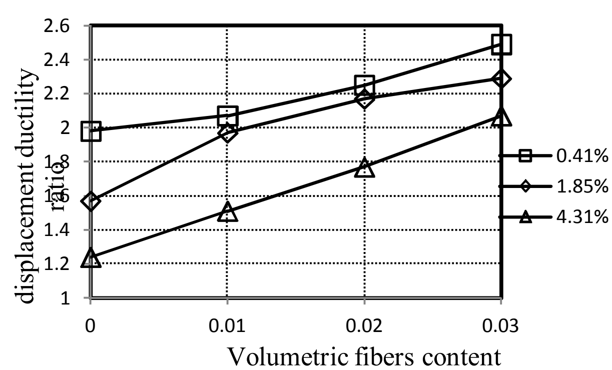

Figure (3): Displacement ductility ratio versus volumetric fiber content

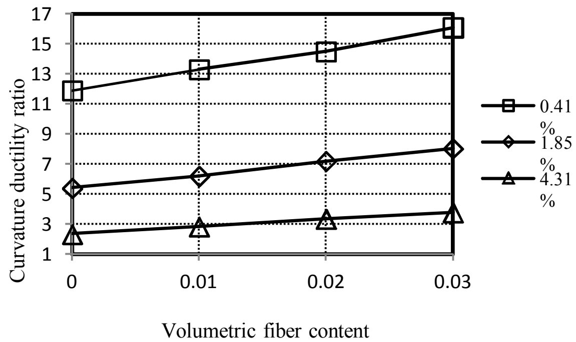

Figure (4): Curvature ductility ratio versus volumetric fiber content

From observation on Figure (4) the effects of the fiber content, V_f, and the net tensile reinforcement ratio, ρ – ρ\`, can be summarized as follows:

1. The higher the net steel reinforcement ratio, ρ – ρ\`, the lower the curvature ductility ratio.
2. The higher the volumetric fibers content, V_f, the higher the curvature ductility ratio.
3. Adding fibers increases the curvature ductility of beams, the increase depends on the volumetric fibers content, as well as the net reinforcement ratio. Increase of 11%, 21 % and 35% for V_f = 1%, 2% and 3%, respectively, for beams of ρ- ρ\` = 0.41%. While, these improvements are higher for beams of ρ- ρ\` = 4.31%: Namely, 22%, 43%, and 67% for V_f = 1%, 2% and 3%, respectively.
4. For beams of the highest reinforcement ratio (ρ- ρ\` = 4.31%), curvature ductility are very low (μ_ϕ < 3). Therefore adding adequate fibers content is necessary to change beam behavior from brittle to ductile [10].

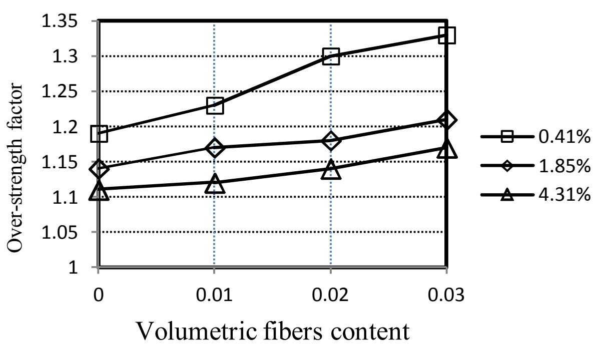

Figure (5): Over-strength factor versus volumetric fiber content

The over-strength factor of the tested *UHPFRC* beams are drawn versus the volumetric fiber content as shown in Figure (5). Three curves are drawn for the three values of net tensile reinforcement ratios, ρ - ρ\` = 0.41%, 1.85% and 4.31%. Observations on Figure (5) can be enumerated as follows:

1. The higher the volumetric fibers content, V_f, the higher the over-strength factor.
2. Adding fibers increases over-strength factor, ρ – ρ\`, the increase depends on the volumetric fibers content, as well as the reinforcement ratio. Increase of about 3%, 9 % and 12% for $V_f$ = 1%, 2% and 3%, respectively, for beams of ρ- ρ\` = 0.41%. While, the increase is insignificant for UHPFRC beams of ρ- ρ\` = 4.31%: Namely about, 1%, 3%, and 5% for V_f = 1%, 2% and 3%, respectively.

Design limits on the acceptable maximum reinforcement ratio to allow sufficient ductility in *UHPFRC* members for flexural design, are needed. Therefore, ductility ratios are re-drawn versus tensile reinforcement ratio as a fraction of the balanced reinforcement ratio, (ρ-ρ\`) / ρ_b , of *UHPFRC* beams in Figures (6-9).

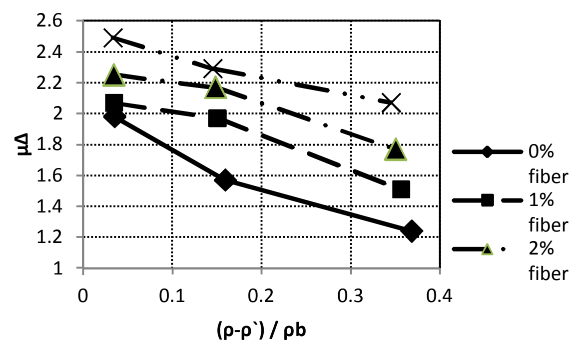

Figure (6): Displacement ductility ratio versus (ρ-ρ\`) / ρ_b

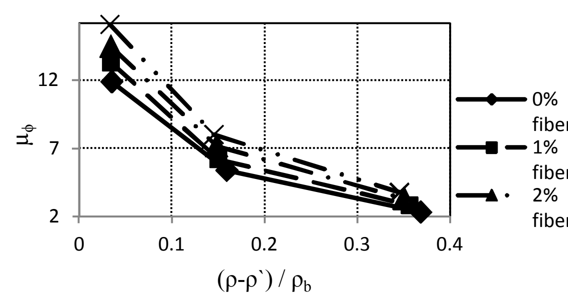

Figure (7): Curvature ductility ratio versus (ρ-ρ\`) / ρ_b

In Figure (6) to obtain μ_Δ > 1.5 maximum design tensile reinforcement ratio, (ρ-ρ\`) / ρ_b = 0.17 for beams without fibers. While this ratio can reach 0.37 for UHPFRC beams with V_f = 1%, and may reach the value of given by the ACI- 318 [15] for normal strength concrete, namely 0.5 for $V_f \geq$ 2%. On the other hand, in Figure (7) to obtain μ_ϕ > 3 maximum design tensile reinforcement ratio, (ρ-ρ\`) /

ρ_b = 0.25 for beams without fibers. While this ratio can reach 0.35 for UHPFRC beams with V_f = 3%.

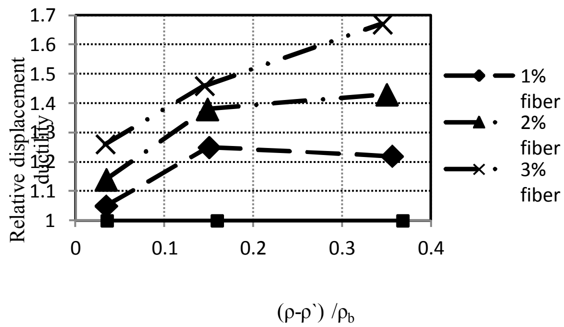

Figure (8): Relative displacement ductility versus (ρ-ρ`) / ρ_b

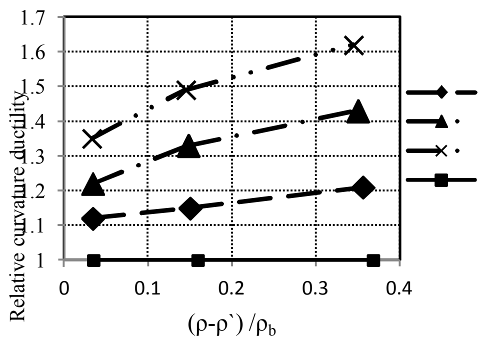

Figure (9): Relative curvature ductility versus (ρ-ρ`) / ρ_b

Figures (8 and 9) shows the relative displacement and curvature ductility ratios, respectively, versus the tensile reinforcement ratio (ρ-ρ`) / ρ_b. The relative ductility ratio is the ductility ratio of beams with fiber to the ductility ratio of beams without fibers, the use of this figures directly help in obtaining the gain in ductility due to the addition of fibers.

Both figures show that the effect of fibers on ductility is significant for UHPFRC beams with high reinforcement ratio, where ductility can be enhanced by 60% or more for fiber content V_f = 3%. While ductility enhancement is less significant, namely from 25 % to 35% for *UHPFRC* beams with lower reinforcement ratio.

3. HSFRC BEAMS

Sallam *et al.* [15] have carried out experimental investigation on the flexural and shear behavior of hybrid fiber-reinforced beams. Twelve different *HSFRC* beam specimens were cast and tested to study the flexural and shear behavior of *HSFRC* beams. Concrete mixtures are reinforced by the hybrid fiber (1% or 2% steel fibers + 0.1% polypropylene fibers) with different patterns. Five reinforced concrete beams (BF1, BF2, BF3, BF4 and BF5) including one beam (BF1) without fibers as a reference beam, designed to fail in flexure. On the other hand, seven beams (BS1, BS2, BS3, BS4, BS5, BS6 and BS7) including one beam (BS1) without fibers as a reference beam, were designed to fail in shear.

All the twelve beams have a rectangular cross-section of width, b = 150 mm, height t = 250 mm and an affective depth d = 219 mm. The length of the beam, L = 2500 mm with span of 2300 mm. Tensile steel reinforcement of two bars of 12 mm diameter is provided in all beams in the first group, and four bars of 16 mm diameter for all beams in the second group. Two bars of 10 mm diameter located at the top in compression zone, and 8 mm diameter steel stirrups are provided at spacing 75 mm center to center in the shear span.

The behavior of *HSFRC* beams BF1, BF2, BF4, BS1, BS2 and BS3 will be used during the current study, summary of their properties are listed in Table 3. The applied load – midspan deflection curves of beams, BF1, BF2 and BF4 are plotted in Figure (10). While on the other hand, load – midspan deflection curves of beams, BS1, BS2 and BS3 are plotted in Figure (11).

Table 2: Properties of HSFRC beams of reference[15]

Specimen	BF1	BF2	BF4	BS1	BS2	BS3
V_f	0 %	2 %	2 %	0 %	1 %	2 %
f_{cu} *(Mpa)*	75.5	111	97.8	79.8	87.6	97.7
ρ_b	0.063	0.090	0.081	0.066	0.072	0.081

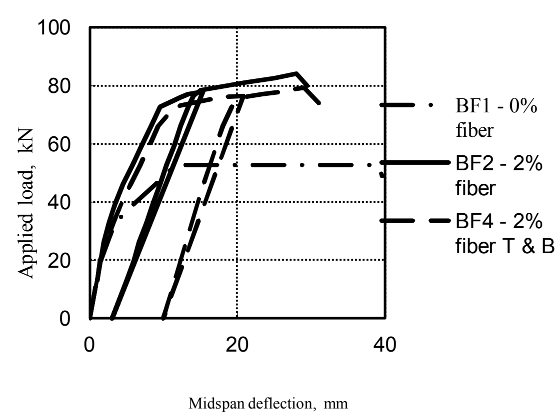

Figure (10): Applied load- Midspan deflections BF1, BF2 and BF4

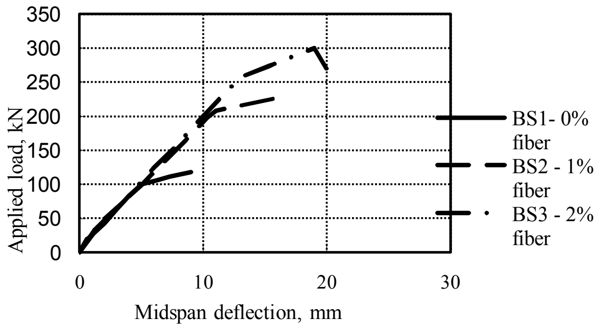

Figure (11): Applied load- Midspan deflections BS1, BS2 and BS3

From observations on Figure (10 and 11) show that the effect of fibers, where the of fiber content, increases the yield strength, ultimate strength as well as the secant stiffness, but reduces displacement ductility. However, high fiber content result in higher energy absorption and toughness. Calculations for the values of the net tension reinforcement ratio $(\rho - \rho`)$ as fraction of the balanced ratio, ρ_b, the over-strength factor, Ω, and the displacement ductility ratio, μ_Δ , and the secant stiffness, K_S are performed and results are shown in Table 4.

Table 3: Reinforcement ratios, over-strength, ductility and stiffness of HSFRC beams

Beam Specimen	$\frac{(\rho - \rho`)}{\rho_b}$	Ω	μ_Δ	K_S
BF1	0.032	1.0	3.36	4.55
BF2	0.022	1.16	2.95	7.64
BF4	0.025	1.09	2.52	6.31
BS1	0.350	1.19	1.80	19.8
BS2	0.320	1.09	1.45	18.9
BS3	0.290	1.16	1.46	19.8

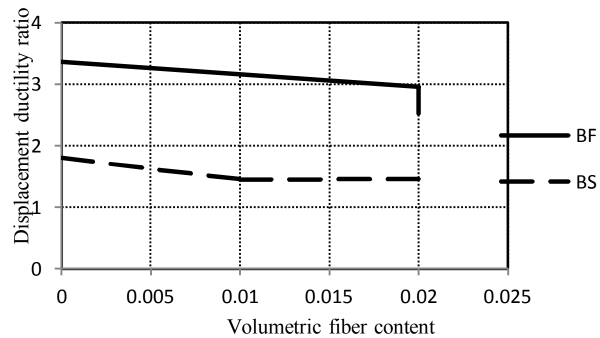

Figure (12): Displacement ductility ratio versus volumetric fiber content

From the data of Table 4 the value of the over-strength factor, Ω , is independent of both the volumetric fiber content and tensile steel reinforcement ratio, $(\rho - \rho`) / \rho_b$. The displacement ductility ratio and the secant stiffness are drawn in Figure (12) and Figure (13) respectively. The fiber content, V_f , has insignificant effects on both the displacement ductility ratio, μ_Δ , and the secant stiffness, K_S. On the contrary tensile steel reinforcement ratio, $(\rho - \rho`) / \rho_b$ has substantial effects on them. Observations on Figure (12) indicate that, the lower the reinforcement ratio, the higher the displacement ductility. While Figure (13) shows the lower the reinforcement ratio, the lower the secant stiffness, K_S.

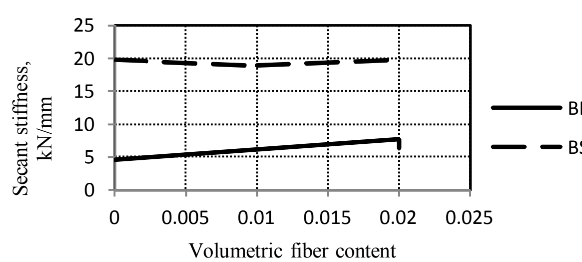

Figure (13): Secant stiffness versus the volumetric fiber content

4. Discussions

Based on the foregoing investigations and analysis the following point are highlighted:

1. The amount of fibers has affects the displacement ductility, the curvature ductility and the over-strength of *UHPFRC* beams, while its effect is insignificant on them for *HSFRC* beams. Also the fiber content has in significant effect on both *UHPFRC* and HSFRC beams.
2. The lower the tensile steel reinforcement ratio, the higher the displacement ductility, the curvature ductility and the over-strength of *UHPFRC* beams. However, it is indifferent for those of the *HSFRC* beams.

3. The higher the tensile steel reinforcement ratio, the higher the secant stiffness for both *UHPFRC* and *HSFRC* beams. While the fiber content has almost no effect on the secant stiffness both *UHPFRC* and *HSFRC* beams.
4. The maximum design reinforcement ratio required to give appropriate ductility (assumed to be inherent in concrete structures) shall be reduced for ultra-high strength concrete *UHSC* and ultra-high performance concrete *UHPC* from the value of $0.5\ \rho_b$ given for normal strength concrete [16, 17] to between $0.17\ \rho_b$. This value can be increased by adding fibers, where for fiber content of $V_f \geq 3\%$ it can be increased to $0.35\ \rho_b$.
5. The high fiber content, the higher energy absorption and toughness for both *HSCFC* and *UHPFRC*, energy absorption is very important in dissipation of seismic energy during ground excitations.
6. The addition of fibers to concrete result in less cracking and high integrity of the tension zone which contribute to the reinforced concrete ability to safely sustain many cycles of loading into the inelastic range which is expected during earthquakes.

5. Summary and Conclusions

High strength fiber reinforced concrete, ultra High strength fiber reinforced concrete and ultra-high performance fiber reinforced concrete are class of concrete that has different mechanical characteristic require different design formulas other than those used for normal concrete. Many research works have been devoted for this purpose [5]. This research is intended to assess the suitability of this class of concrete for building in moderate and high seismic risks. Design values for the tensile reinforcement ratio, volumetric fiber content that favorably affect the seismic resistance and seismic forces induced from earthquakes are reached.

From the pre-mentioned presentations and discussions the main effects of adding fibers on the seismic design and behavior of *HSFRC* and *UHPFRC* structures are listed below:

1. Adding fibers increases the tensile resistance and reduces the number and width of cracks in tension, which increases the integrity of the tension zone of reinforced concrete members subject to cyclic flexure during earthquake. Also adding fibers increases the shear resistance, flexural resistance, and over-strength factor, which lead to stable hysteretic loops of loading into the post-yield range.
2. Adding fibers increases ductility and the energy absorption (toughness) of reinforced concrete members in flexure. These are two important characteristics for structural members in seismic areas as they increase the dissipation of seismic energy during ground excitations. As a consequence they lead to higher force reduction factor (*R* -factor) and hence to lower seismic force design demand.
3. Adding fibers to concrete has little effect on the secant stiffness; therefore it will not reduce the structure's natural period of vibration, keeping the seismic force design demand unchanged.

Finally the detailed conclusions of the study for both the behavior of *UHPFRC* and *HSFRC* beams are enumerated as follows:

1. The lower the tensile steel reinforcement ratio, the higher the displacement ductility, the curvature ductility and the over-strength of *UHPFRC* beams. However, it is indifferent for those of the *HSFRC* beams.
2. The amount of fibers has affects the displacement ductility, the curvature ductility and the over-strength of *UHPFRC* beams, while its effect is insignificant on these properties for *HSFRC* beams.
3. The higher the tensile steel reinforcement ratio, the higher the secant stiffness for both *UHPFRC* and *HSFRC* beams. While the fiber content has almost no effect on the secant stiffness both *UHPFRC* and *HSFRC* beams.
4. The maximum design reinforcement ratio(ρ_{max}) required to give appropriate ductility (assumed to be inherent in ordinary concrete structures) shall be reduced for ultra- high strength concrete *UHSC* and ultra-high performance concrete *UHPC* from the value of $\rho_{max} = 0.5\ \rho_b$ given by concrete design codes [16, 17] for normal strength concrete to about $0.17\ \rho_b$. This value can be increased by adding fibers, where for fiber content of $V_f \geq 3\%$ it can be increased to $0.35\ \rho_b$.
5. The high fiber content, the higher energy absorption and toughness for both *HSCFC* and *UHPFRC*, energy absorption is very important
6. The addition of fibers to concrete result in less cracking and high integrity of the tension zone which contribute to the reinforced concrete ability to safely sustain many cycles of loading into the inelastic range which is expected during earthquakes.

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