A state of the art review of fiberless and steel fiber reinforced high strength concrete columns behavior under various loadings

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Abstract. Efficient supplementary materials flourish the structural performance and sustainability of reinforced concrete structures. Steel fiber is one of these materials that have significant influence on enhancing tensile and flexural strengths and ductility of high strength reinforced concrete columns. This paper presents a review study on the structural performance of steel fiber reinforced concrete columns. The studied case was related to the columns that subjected to concentric or eccentric compression loads or combined compression loads and cyclic lateral loads. The current survey is divided into two branches; the first is related to fibreless HSC columns, while the other is specialized by SFRHSC ones. In addition to the prime actuator (steel fiber content), the investigated parameters were included concrete strength, transverse reinforcement properties, and axial load ratio. The results of this investigation showed that the positive influence of adding steel fiber on improving the flexural strength, fatigue life and resistance, delaying spalling failure of the exterior concrete shell and outward buckling of the longitudinal steel reinforcing bars. The optimum volume fraction of steel fiber used is 0.5% to 2% (by weight) and when 2% of steel fibers are introduced into the concrete mix, the columns’ cover didn’t spall away.

Keywords: Steel-fiber reinforced concrete, fibreless concrete columns, high strength concrete columns, columns’ transvers reinforcement, moment resisting columns, cyclic loading on columns, concrete columns ductility, concrete compressive strength.

1. Introduction

Till nowadays normal strength concrete is frequently used in columns of low-rise buildings. Nevertheless, high strength concrete has proved to be indispensable for high rise buildings. Besides, the high strength concrete has become the optimum choice for columns in bridges and the piled deep foundation [1].

In general, high strength concrete surpasses its conventional predecessor; the normal strength concrete, in terms of the principal strength respect after hardening (i.e., compression, tension, shear, splitting and rupture), in addition to the elasticity modules. The main purpose behind using high
strength concrete columns is to reduce the dimensions of the cross-sections and, thereby, the entire volume of concrete for the reinforced concrete structure as a whole [1].

However successive research studies in the specialized field of hardened concrete mechanical properties have shown that the high strength concrete performs in a brittle manner under compression when compared to normal strength concrete. Furthermore, the confinement furnished to the compressed high strength concrete is not as effective as that given to normal strength concrete subjected to compression. In specific, the superiority of reinforced columns cast with high strength concrete revealed through its distinct cover spalling relative to that for reinforced normal strength concrete columns [1].

Steel fibers are short and closely spaced in comparison with reinforcing bars so the steel fibers have the ability to bridge the concrete cracks and hold them against further development. Moreover, the superior mechanical properties of steel fiber can eliminate the shrinkage cracks, elevate the load-carrying capacity and increase concrete durability. Many experiments have been conducted on steel fiber reinforced concrete which has shown great results in the concrete resistance such as fatigue resistance, abrasion resistance, resistance to cavitation or erosion damage, impact resistance in addition to improving flexural properties. So, the addition of steel fiber to the reinforced high strength concrete has benefited the structural performance and confined the concrete. Thus, this review paper highlighted the difference in the structural behavior of high strength concrete columns with and without steel fiber content [2].

This article throws light on the evolution in the research field of investigating performances of high strength concrete columns in which steel fibers of different sizes or shapes may be optionally used. It aims to introduce the state of the art in that issue.

2. Fibreless High Strength Concrete Columns

High Strength Concrete (HSC) offers improvement in performance as well as the economy of construction. The use of HSC has become imperative in multi-story and high-rise building constructions, especially in columns. HSC columns have more brittle and much less post-peak deformability than Normal Strength Concrete (NSC) ones [2].

HSC has been widely used in structural elements, such as girders, columns, piles, etc. to improve the economy due to the reduction in the size of the members or elements and it offers efficiency opportunities in multi-story or high-rise buildings. It is widely believed that HSC became less ductile because of the material's brittleness (Rangan [3], Cusson and Paultre [4], Hsu et al. [5], Hisham and MacGregor [6], ACI-ASCE Committee 441 [7], Saatcioglu and Razvi [8]).

Itakura et al. [9] showed that the longitudinal reinforced columns reduced in strength as lower axial strain levels compared to those without longitudinal reinforcement, since longitudinal reinforcement caused spiral reinforcement fracture due to buckling effect. Later, the authors indicated the good performance of the columns which was attained with occurrence of the major strain increments of the spiral reinforcement.

Cusson et al. [10], studied the behavior of large-scale high-strength concrete columns confined by rectangular ties under concentric loading. The study showed that tie spacing and its configuration had a great effect on confined the concrete core, as presented in Figure 1. Published data on the efficiency of the large-scale HSC tied columns (smallest dimension more than 200 mm) are scarce (Nagashima et al. [11]; Bjerkeli [12]; Itakura et al. [9]).
In addition, the early spalling of concrete cover was observed before the lateral confinement becomes effective that led the columns to loss their axial capacity. However, great achievements in ductility, strength, and toughness were determined for the well-confined columns [10]. Therefore, this study suggested that the axial compressive strength for the high strength concrete columns should depends only on the area of the concrete core, except if special care is taken to curb the separation of the concrete cover [10]. The confinement efficiency of low strength concrete was higher in comparison with high strength concrete, when the longitudinal and transverse reinforcement satisfactory detailing was available, ductile behavior and large strength gain was obtained. The improvements in the strength were relatively 50% to 100% and in ductility were relatively 10 to 20 times more than that of unconfined concrete columns having 99.9 MPa and 52.6 MPa compressive strengths, respectively [10].

Watson et al. [13], found that the amount of transverse reinforcement needed for confinement to satisfy any specific need for ductility rises with increasing axial load level, concrete strength, concrete cover thickness. As well, additional transverse reinforcement is required for confinement of rectangular and square columns more than circular columns.

Wang et al. [14], conducted analytical work to determine the effect of the stirrups volume ratio, axial load ratio, concrete strength on HSC columns ductility. The study based on using and testing of 48 high strength and normal strength reinforced concrete columns under monotonic and cyclic loadings. The test results showed that the most important factor on the ductility of HSC columns is the axial load ratio. The column ductility was influenced by the pattern of damage as shown in Figure 2.

Through testing of the columns under monotonic loading, three damage patterns were observed. The first is tension damage, this kind of failure is initiated by yielding of the tension steel and fails in compression region but it has good ductility even with the low stirrup ratio as shown in Figure 2. (a). The second pattern is compression damage, after the lateral load was applied and reached (0.2-0.5) $P_{\text{max}}$, the longitudinal bars yielded in the compression region but did not yield in the tension region, the columns with this damage pattern have less ductility as shown in Figure 2.(b). The last pattern is the shear-compression damage as shown in Figure 2. (c). This pattern of damage was developed with axially high load ratio, especially with a small span to depth ratio and low stirrup ratio of the member, and it causes brittle damage without warnings. The ductility of the HSC columns is less for the same axial load ratio and stirrups ratio than for the NSC columns.
Figure 2. Different damage patterns of members (Wang et al. [14])

Ho et al. [15], tested four High Strength Reinforced Concrete (HSRC) columns containing transverse reinforcement and subjected to low compressive axial load level \( \left( \frac{P}{A_{f}f_{cu}} \leq 0.1 \right) \) under large reversed cyclic inelastic displacement excursions. The flexural ductility of columns was not altered at given range of transverse reinforcement volumetric ratio for spacing provided less than 0.75d, which is the column cross-section effective depth.

Canbay et al. [16], studied the actions of 11 HSC columns that are confined by ties or cross ties under monotonic loading with two different eccentricities. The columns in Series I were tested under a small eccentricity \( (e = 20 \text{ mm}, e/h = 0.08) \), and the columns in Series II were tested by applying uniaxial load first followed by axial load at an eccentricity of \( e = 400 \text{ mm} \). Figure 5 shows the geometry and reinforcement details of Series I and II. The results showed that the specimen of 135° hooks at both ends behaved identically to the specimen with 135° hooks at one end and bents at the other end with 90°. The specimens that were confined with an external tie and an internal diagonal tie, and significantly higher transverse reinforcement ratio also behaved identically.

Figure 5. Geometry and reinforcement details of specimens (Canbay et al. [16])
Ahn et al. [17], experimentally investigated the behavior of (HSRC) columns subjected to reversed cyclic load and axial compression. The objective of the study was to discover the relation between lateral reinforcements amount and axial load ratios. The test results showed that the axial load ratio and the lateral reinforcement formation could dramatically affect and change the action of HSRC columns under inelastic cyclic loadings. Column stiffness and strength were characterized by concrete strength, the amount of lateral reinforcement and axial load ratios. A major improvement in the column's ductility and energy dissipation capacities resulted from the increase in the amount of lateral reinforcement. The increase in the energy dissipation capacity and ductility, tended to be proportional to the amount of lateral reinforcement increment. Even so, the necessary amount of lateral reinforcement is correlated with the axial load. Thus, in certain situations, the axial load should be reduced when extremely ductile performance is needed.

Dundar et al. [18], Investigated the strength of short and slender biaxially loaded HSRC columns. In this study, HSRC columns in square and L-shaped sections were constructed and tested to achieve the load-deformation action and column strength. The experimental work determined that the buckling of longitudinal reinforcement and the brittle behavior of failure were the main critical issues for HSRC columns. As well, the loss of ductility occurred with increasing of concrete compressive strength and load eccentricity. Decreasing the lateral reinforcement spacing could improve the ductility of the eccentrically loaded reinforced concrete columns. The slenderness and the load eccentricity parameters have considerable effects on the strength capacity of RC columns with high strength concrete.

Jin et al. [19], performed many laboratory experiments on the mechanical efficiency of twelve geometrically identical moderate HSRC columns with two different stirrup ratios (0% and 0.66%). The tested columns with various dimensional geometries and without stirrups failed in compression-shear mode, under the small-eccentric compression. Meanwhile, the failure occurred in the middle part where a wedge-shaped pattern formed for the RC columns with middle stirrups. Also, the longitudinal reinforcement observed buckling failure between the stirrups, as shown in Figure 5, and raising the stirrups ratio increased the columns’ strength and the observed failure was less brittle due to the confinement action.

**Figure 5.** Typical failure patterns for the high strength RC columns (Jin et al. [19]). (a) HA series without middle stirrups and (b) HB series with middle stirrups.
Liao et al. [20], presented an experimental research on the cyclic behavior of three HSRC columns with multiple detailed configurations for transverse reinforcement. The three HSRC columns composed of various detailing arrangements for transverse reinforcement, which were traditional closed-hoops, butt-welded hoops and single closed-hoops with cross-ties, as shown in Figure 6. The columns were constructed of HSC with compressive strength of 70 MPa and high strength steel with yield stresses of 685 MPa and 785 MPa, respectively. To check the adequacy of transverse detailing, static cyclic displacement tests subjected to high axial compressive loading of 0.3$A_gf'_c$ were carried out. The experimental results showed that test performance with butt-welded hoops appeared to be identical to that of traditional closed-hoop specimens. Hence the usage of high strength butt-welded hoops in their RC columns was suitable for confining reinforcement. The shear equivalent to the maximum possible moment appeared to occur in columns under high axial compression loading.

According to the results that shown in Table 1, the yielding of longitudinal reinforcement has closely corresponded to the peak lateral load. When the longitudinal reinforcement stress reached its maximum stress (1.25 times yield stress), an increase might happen in the post-yield lateral force. Consequently, applying factor 1.25 at high axial load level would not increase the column flexural strength and would overestimate the actual ultimate lateral force contributing to the flexural strength.

| Specimen ID | Idealized yield drift % | Peak lateral strength (kN) | Ultimate lateral strength (kN) | Ultimate drift % | Ductility |
|-------------|--------------------------|---------------------------|------------------------------|------------------|----------|
| a           | 0.57                     | 2888                      | 2311                         | 3.17             | 5.56     |
| b           | 0.57                     | 2715                      | 2172                         | 3.05             | 5.35     |
| c           | 0.56                     | 2654                      | 2132                         | 2.31             | 4.12     |

Figure 6. Square column with different detailing configurations of transverse reinforcement (Liao et al. in [20]). (a) conventional closed hoops; (b) butt welded-hoops; (c) closed hoop with cross-ties

3. Steel-Fiber Reinforced High Strength Concrete Columns

Steel fiber is a metal reinforcement that produced from recycling waste tires. It is available in different size and length. It improves the flexural concrete strength depending on the proportion of fibers added on the mix design. Steel fiber also transforms the concrete failure from brittle to more ductile mode. Besides, steel fiber exhibits higher post-crack flexural strength, better crack resistance, improved fatigue strength, higher resistance to spalling. As a result, many experimental studies have been conducted to characterize the structural behavior of RC columns having steel fiber [21].

Foster et al. [22], tested 21 columns with fiber-reinforced concrete in either concentric or eccentric compression. The test finding determined that introducing steel fiber by 2% of the column weight
prevented the concrete cover from spalling away. The columns with steel fiber content observed a superior performance in comparison to the non-fiber columns, particularly for post-failure ductility.

Yousef et al. [23], investigated the effect of steel fibers on the behavior of high strength reinforced concrete circular columns confined by spiral steel and subjected to monotonically concentric axial load. The two main variables were fiber content and concrete compressive strength. The fiber content remarkably influenced the behavior of high strength fiber reinforced concrete circular columns and 0.5% by volume steel fibers was the optimum content.

Serkan Tokgoz [24], described the impact of varying amounts of steel fiber on the action of eccentrically loaded HSC columns. Fourteen slender and short square-section steel fiber with plain HSRC column specimens were built. The eccentric load test was conducted to examine the impact of the inclusion of the steel fiber on the load-deflection action, ductility, confinement and ultimate strength capacity. The finding results proved that using steel fiber in the HSC columns changed the actions of the post-peak columns, as shown in Figure 7. As well, this study determined that 40 to 60 kg/m$^3$ of the steel fiber dosages typically increased the confinement, deformability of HSC columns and ductility. However, it was stated that steel fibers had no major influence on the modulus of elasticity and compressive strength of concrete. It also declared that steel fibers could decrease the propagation and width of crack for the HSC columns, and more specifically, avoid the early cover spalling of the HSC columns.

![Figure 7. Experimental stress-strain relations for steel fiber and plain high strength concrete (Serkan Tokgoz [24])](image)

Caballero-Morrison, et al. [25], experimentally applied combined cyclic lateral and constant compression loads on slender columns. In this study tests were performed on fifteen elements to investigate the behavior of these columns under the load combination. Many variables were studied such as slenderness, axial load level, volumetric steel-fiber ratio, concrete strength and transverse reinforcement. The claim of improving the deformation capacity of the concrete when the steel fiber included in the concrete mixture was confirmed. Also, under cyclic load and to increase the performance of steel fibers without a substantial decrease in the carrying capacity, the transverse reinforcement should be minimum. The use of steel fibers in the HSC will have comparable ductility values to those of NSC. The results of the study showed that the use of steel fibers for NSC and HSC had a significant impact on the delaying of the buckling of the longitudinal reinforcement bars and concrete cover spalling in compression. Besides, marginal damages were found in the region of the plastic hinge and the curvature and displacement ductility were increased. Despite all these changes, the ultimate load capacity for NSC or HSC was not greatly improved by steel fiber. The decrement of the residual tensile strength f$_{y3}$ was the favorable effect with the cyclic load’s application. The ultimate displacement ductility and the ultimate curvature ductility were improved by the increasing in the confinement level, the amount of steel fiber, the column slenderness, and the reduction in the axial load level.
Baek-II Bae, et al. [26], examined the influence of the inclusion of steel fiber on the structural efficiency of SFRHSC columns when seven HSC specimens were tested with and without steel fiber. Two series of transverse reinforcement were used in this study which is V series with 0.12% transverse reinforcement ratio and 300 mm spacing of transverse reinforcement and T series with 0.49% transverse reinforcement ratio and 130 mm spacing of transverse reinforcement as shown in Figure 8.

![Figure 8. Details of test specimens (Baek-II Bae, et al. [26])](image)

All specimens examined were exposed to cyclic lateral loads and axial load. Number of experiments have been performed on RC columns with finite element modeling in order to describe the action of columns under repeated cyclic load. (Priestley et al. [27]) proposed a decrease in shear strength according to the member's ductility using the results of (Ghee et al. [28]) and (Wong et al. [29]). The model proposed by (Priestley et al. [27]) demonstrated high precision at low displacement ductility ratios but poor precision at higher displacement ductility ratios. In the study of (Baek-II Bae, et al. [26]), The steel fiber inclusion surprisingly improved the structural efficiency of the columns in terms of energy dissipation capacity and strength more than increasing the transverse reinforcement ratio. The ductility of the matrix was influenced by the compressive strength. High strength matrix column specimens demonstrated better results than normal strength matrix column samples. The addition of steel fiber greatly increased the energy dissipation capacity, shear strength and ductility of columns, as shown in Figure 9, under the same transverse reinforcement ratio. Even so, the rate of increase in these results decreased with an increase in the steel fiber volume of the fraction. Steel fiber proved to be greatly effective in avoiding spalling and rotting (cracks) under shear stress. Preventing spalling of cracks,
SFRHSC column specimens demonstrated a significant improvement in ductility, particularly with high transverse reinforcement ratio [26].

Figure 9. Cumulative dissipated energy (Baek-II Bae, et al. [26])

4. Summary and Conclusions
1. Although, the load-carrying capacity of reinforced HSC columns is higher than that for reinforced NSC columns, the latter reveal further ductility when steel fiber is absent.
2. For concentrically compressed reinforced HSC columns, the concrete cover first spalls outward, after which the compressive force drops by 10-15%.
3. Owing to the early cover spalling of the reinforced HSC columns with low confinement provided by transverse reinforcement, the steel ties placement is the prime actuator creating cover spalling to be less influenced by the concrete strength.
4. Using steel fiber in HSC columns prevents the early cover spalling, elevates the load-carrying capacity and improves ductility.
5. When HSC columns provided by end-hooked ties are exposed to large reversed cyclic lateral excitation with low axial compression, the 90°-end hooks are more susceptible to be opened (when pushed by the buckled longitudinal steel bars) than the 45°-end hooks.
6. For HSRC columns without steel fiber and subjected to biaxial eccentric compressive forces, the ultimate load capacity depends primarily on the ultimate strain of the concrete compressed fibers.
7. Compressive resistance and ductility of HSRC columns without steel fiber of moderate slenderness is directly susceptible to stirrups ratio which is the prime creator of the confinement action.
8. Configuration of the transverse reinforcement detailing in HSRC columns subjected to cyclic loading has a vital role and distributing axial forces over the longitudinal reinforcement (which may be compressive or tensile) depend on those bars’ locations relative to the cyclic load protocol. Once the column attains its flexural capacity, the tensile longitudinal steel bars yield while the compression bars remain unyielded.

9. The amount of steel fiber has the primary role in improving ductility, confinement and deformability of eccentrically loaded HSRC columns.

10. Inclusion of steel fibers in concrete of slender columns exposed to monotonic axial compression accompanied by cyclic lateral loading has a major influence on delaying both cover spalling and buckling of the longitudinal steel reinforcing bars.

11. In regard to the effect of steel fiber on performance of HSRC columns under axial loads and reversed periodic lateral loads, the steel fiber remarkably increases the shear strength and energy dissipation capacity.

12. Using steel fiber in concrete columns subject to shear stresses (due to reversing cyclic loading) is recommended since it is effective in arresting cover spalling and crack concentration in the zones of high shear stresses.

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