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BEHAVIOR OF HIGH STRENGTH FIBER REINFORCED CONCRETE SQUARE COLUMNS WITH HYBRID BARS

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The paper presents test results on 20 high-strength fiber reinforced concrete square columns subjected to concentric and eccentric loading. The study aim was to examine the effect of the weight of steel fibers on the strength and behavior of HSC columns under concentric and eccentric loading. All columns were longitudinally reinforced with 4 GFRP bars 6 mm diameter, and two steel bars 10 mm diameter, making the reinforcement ratio ($\rho g = 0.0181$), and steel ties at 64 mm spacing. The studied test variables included the steel fiber weight ratio and the eccentricity. To prevent premature spalling in the concrete cover, it was discovered that it helps to add steel fibers to HSC mixtures in concrete columns. In addition, this also increases the strength of eccentrically loaded reinforced columns compared to that for concentrically loaded columns. The strength and behavior were predicted also by the proposed method. The predicted and the experimental results found to be in a good agreement.

Keywords: Axial, Compression, Eccentric, GFRP, Reinforcement, Steel.

1 INTRODUCTION

High-strength concrete (HSC) has been increasingly used over the last decades due to the fast strides in developing concrete technology, use of mineral, and chemical admixtures. HSC is primarily used in high-rise buildings ACI 363R-10 (2010) where it reduces the dimensions and therefore concrete volume of the lower-story's columns for the structure.

The inclusion of short discrete steel fibers SF into plain concrete mixture enhance the compressive strength and ductility of concrete, Hsu and Hsu (1994), Mansur *et al.* (1999), and ACI 544-02 (2002).

The design life of RC structures is limited by some factors like corrosion of steel bars in RC members. Significant research has shown that fiber reinforced polymer (FRP) materials can be effectively used as reinforcement in concrete structures ACI 440.1R-06 (2006).

Hales *et al.* (2016) tested short and slender concrete columns reinforced longitudinally with a combination of steel and GFRP bars, and GFRP or steel spirals. It was found that slender columns loaded with small eccentricity was governed by material failure, while that of slender columns loaded with large eccentricity was governed by a buckling failure. They also concluded that GFRP spirals and GFRP longitudinal bars are a suitable alternative for reinforcing slender concrete columns subjected to eccentric compression loads.

The influence of the type of reinforcing bars (steel and GFRP), spacing of transverse reinforcement, addition of SF and loading condition were studied by Hasan *et al.* (2017). They concluded that GFRP and steel bars have the same efficiency as reinforcement of HSC columns in sustaining concentric axial load. They found that GFRP-HSC specimens has eccentric axial load 10-12% lower than the load sustained by the steel-HSC specimens. The SF increased the axial strength of columns reinforced with GFRP bars by 3-13%, and the ductility by 14-27%.

Hadi *et al.* (2017) studied the effect of the type of longitudinal reinforcement (steel and GFRP), spacing of the helices, and loading condition on the performance and behavior of (HSC) columns. They concluded that columns reinforced with GFRP bars carried similar axial load as columns reinforced with steel bars, but the efficiency of columns reinforced with GFRP bars in sustaining axial loads decreased with the load eccentricity. Replacement of longitudinal steel bars by the same area of GFRP bars in HSC specimens decreased the ductility by about 30% compared to that under axial load.

The objective of this study is to investigate the effect of SF content on the behavior and strength of HSC column specimens reinforced with HYBRID bars under axial and eccentric loads. The effects of SF in tension were taken into account in the proposed method to determine the axial compression and bending moment capacity of HSC columns.

2 EXPERIMENTAL PROGRAM

Twenty square specimens with 125 mm side length and 710 mm height were cast, Figure 1. The clear concrete cover was (15 mm). Specimens were designated by one letter that refer to the specimen, the second to the eccentricity, and the third to the SF weight percentage. The specimens were tested at the age of 56 days using 3000 kN compression machine. Ordinary Portland cement ASTM C150-11 (2011), river sand ASTM C33-03 (2003), crushed gravel of (10 mm) maximum size ASTM C33-03 (2003), and silica fume that meets the requirements of ASTM C1240-03 (2003) were used to produce HSC, Table 1. A high-range water-reducing admixture was added ASTM C494-04 (2004). Copper coated SF 13×0.2 mm was used with a tensile strength of 2850 MPa complying with ASTM A820-11 (2011). Specimens were reinforced with one steel bar 10 mm diameter with yield strength of 573 MPa, and two GFRP bars 6 mm diameter on each face with tensile strength of 1100 MPa, making the reinforcement ratio ρ_g = 0.0181. Steel bars 6 mm diameter with yield strength of 598 MPa spaced at 64 mm were used as ties. The workability of the HSC mixes was determined using the slump test. Specimen formworks were made from steel. The specimens were removed from the molds 24 hours after casting, and immersed in a water-curing tank for 52 days. All specimens were tested under a constant loading rate of 0.3 kN/sec in a compression machine with a capacity of 3000 kN. Lateral deflections at the mid height were measured using LVDT, concrete surface strains, and bars strains were recorded using a data logger, AlDoski (2018).

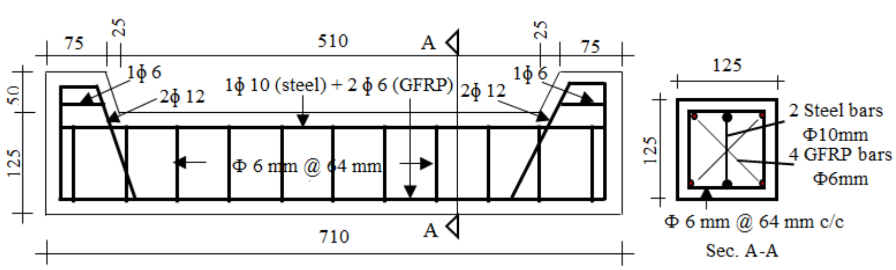

Figure 1. Longitudinal and cross-section of the tested columns.

Table 1. Proportion of the concrete mixes by weight.

Cement	Sand	Gravel	Silica fume	W/C	Hyperplast PC 200	Steel fibers*
1	1.15	1.5	0.15	0.3	0.015	0, 1.2, 2.4, 3.6

* Weight fraction, percentage of the total weight of the fibers to the concrete weight.

3 RESULTS AND DISCUSSION

Table 2 shows the slump and mechanical properties of the four concrete mixes that can be used practically, the slump is decreased and the various strengths increased with the SF weights as demonstrated by previous researchers ACI 544-02 (2002), and Thomas and Ramaswamy (2007).

Table 2. Properties of fresh and hardened concrete mixes.

Fiber weight %	Slump (mm)	Strength (MPa)		
		Compression	Splitting	Flexure
0	120	99.3	6.8	7.2
1.2	60	100.3	7.6	13.6
2.4	40	103.5	8.3	13.9
3.6	20	107.5	10.3	14.7

Table 3 shows the details of the tested columns. The increase in strength ranged from 0.88 to 27.93%. For axially loaded columns, the increase in the strength of the columns due to SF is in agreement with the increase of the load carried by concrete, if the compression load carried by the reinforcement is excluded as shown in Table 4 below. The load carried by the steel and GFRP bars for the axially loaded columns is calculated from the measured strains, Figure 2. The Figure shows a marginal decrease of the load percentage carried by the bars with the SF percentage and this can be attributed to the minor increase in the compression strength of concrete and the load carried by concrete. For the eccentrically loaded columns (with e = 16 mm), the increase in the column strength due to SF addition ranged from 0.9 to 1.2%. For other values of eccentricities, the stress resultant increased marginally in compression and in tension there will be an increase due to the tension stiffening of the steel fibers, and the net increase in the column carrying capacity is the algebraic sum of the negative compression and the positive tension. The column strength shows an increase with SF content but does not show any trend with the eccentricity.

Table 3. Columns experimental failure loads.

Column ID	Failure load (kN)	Increase in Strength due to fibers additions %	Column ID	Failure load (kN)	Increase in Strength due to fibers additions %
H00	1547.6	0	H322.4	771.0	11.0
H01.2	1587.7	2.6	H323.6	777.1	11.9
H02.4	1628.9	5.3	H480	417.4	0
H03.6	1662.3	7.4	H481.2	494.7	18.5
H160	1125.6	0	H482.4	511.7	22.6
H161.2	1135.5	0.9	H483.6	523.1	25.3
H162.4	1137.7	1.1	H640	266	0
H163.6	1138.8	1.2	H641.2	300.6	13.0
H320	694.6	0	H642.4	312.8	17.6
H321.2	753.5	8.5	H643.6	340.3	27.9

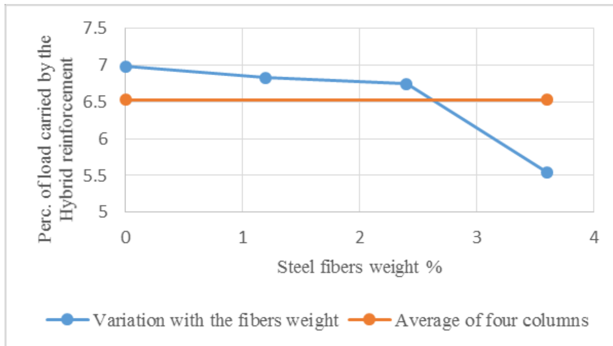

Figure 2. Percentage of load carried by the bars for the axially loaded columns with the fiber's addition.

Table 4. Compression strength of concrete and failure loads of axially loaded columns.

Specimen ID	**H00**	**H01.2**	**H02.4**	**H03.6**
$f_c^{'}$ (MPa)	99.3	100.3	103.5	107.5
% increase in $f_c^{'}$	-----	1.0	4.2	8.3
Exp. failure load (kN)	1547.6	1587.7	1628.9	1662.3
% increase in Exp. failure load	-----	2.6	5.3	7.4
% increase in load carried by concrete	-----	2.8	5.8	8.1

The procedure used for the analysis of the tested columns is that used for conventionally reinforced concrete columns using the strength design method with the contribution of the SF in the tension zone. The post cracking tensile strength of SF concrete (σ_{tu}) is estimated as in Eq. (1):

$$\sigma_{tu} = \eta_o \times \tau_u \times V_f \times L_f / D_f \tag{1}$$

η_o is an orientation factor = 0.5 as proposed by Hannant (1978), τ_u interfacial bond strength between the SF and concrete and the relationship proposed by Ng *et al.* (2012) is used in Eq. (2):

$$\tau_u = k_s \sqrt{f_c^{'}} \tag{2}$$

k_s is a shape factor = 0.4 for smooth fibers and 0.8 for shaped fibers, V_f, L_f, and D_f are the volume, length and diameter of the fibers respectively. The predicted values of the strength using the ACI 318-19 (2019) are higher than those predicted using the CSA A23.3-04 (2004) by 8.8 to 22.5%, Figures 3-6.

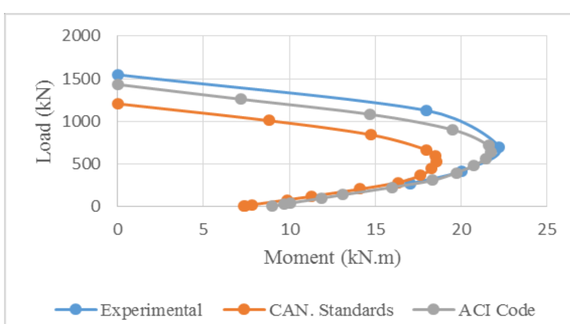

Figure 3. Experimental and predicted interaction diagrams ($W_f = 0$).

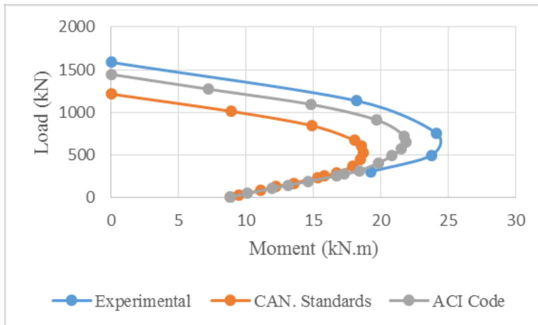

Figure 4. Experimental and predicted interaction diagrams ($W_f = 1.2\%$).

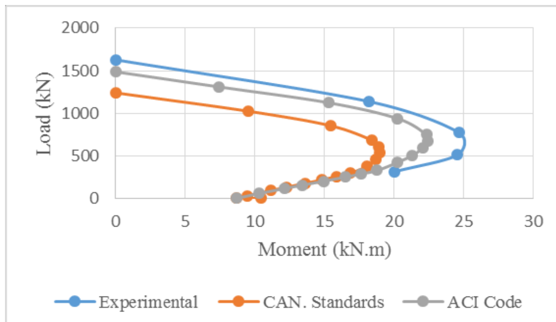

Figure 5. Experimental and predicted interaction diagrams ($W_f = 2.4\%$).

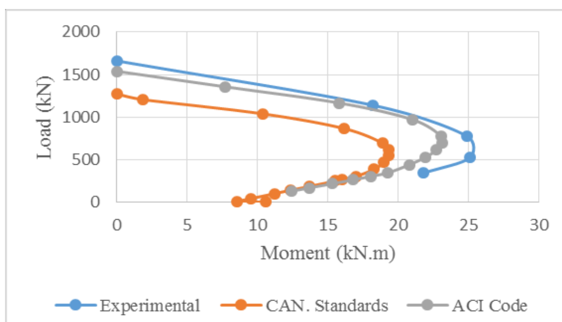

Figure 6. Experimental and predicted interaction diagrams ($W_f = 3.6\%$).

This may be attributed to the product of the stress block parameters, which is about 15% higher than that using the CSA A23.3-04 (2004). However, this is more pronounced in axially loaded columns or columns with small eccentricity. However, both recommendations gave safe and conservative prediction of the ultimate load. The difference between the predicted values of the failure loads is decreasing with the increased eccentricity where the area under compression is minimized and the influence of the stress block parameters is decreased also as mentioned above.

4 CONCLUSIONS

Twenty square HSC column specimens reinforced with HYBRID bars were cast and tested to investigate the influence of weight content of SF on the strength and behavior. The specimens were tested under concentric and different eccentric loads. The SF increased the maximum load of the specimens, premature concrete cover spalling of HSC columns can be delayed or prevented by using SF, the strength of both concentrically and eccentrically loaded columns were predicted satisfactorily by the proposed method using the ACI 318-19 (2019) which gave higher strength than the CSA A23.3-04 (2004), and the difference diminishes with the load eccentricity. More experimental results concerned with fatigue and durability are required to serve as a design guide.

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