WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945
DOI: 10.24425/ace.2020.131800
ARCHIVES OF CIVIL ENGINEERING
Vol. LXVI ISSUE 2 2020

STRESS-STRAIN MODEL FOR CONFINED FIBER-REINFORCED CONCRETE UNDER AXIAL COMPRESSION

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Confinement in concrete can improve the descending branch of the stress-strain relationship of concrete. The addition of steel fiber in concrete can also improve the descending branch of the stress-strain relationship of concrete. The combination of the use of both can double the impact significantly on the post-peak response. It can be seen from the trend of the post-peak response that the values of both $0.85f_{ccf}$ and $0.5f_{ccf}$ can be well predicted. The study involved an experimental investigation on the effect of confinement on square column specimens reinforced with steel fiber. From the experimental program, it is proven that the use of combination of confining steel and steel fiber works very well which is indicated by the better improvement on the post-peak response. The proposed equations can predict the actual stress-strain curves quite accurately which include the effects of confinement parameters (Z_m) and steel fiber volumetric parameter (V_f).

Keywords: Confinement, post-peak response, steel fiber, square concrete columns, stress-strain curves.

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1. INTRODUCTION

Confinement in columns has been studied for very long time by several researchers [1-6]. All studies confirm that the presence of confinement in column increases the peak stress, extends the strain, and improves the post-peak response [7-14]. Similarly, studies have been carried out by many researchers on the use of steel fiber in concrete [8,10,12,14]. The results also show that the use of steel fiber not only increases the peak stress of concrete, but also enhance its post-peak response.

All the studies carried out by the researchers aim to investigate the effect of confining steel and the contribution of steel fiber separately in increasing the peak strength, extending the ultimate strain, and improving the post-peak response of concrete. The post-peak response represents the axial compressive strain ductility (performance) of concrete. This ductility of concrete can be significantly improved by the introduction of transverse steel as confinement of concrete core. Scott et al. [15] has modified the stress-strain model of Kent and Park with a confinement parameter, Z_m. The smaller the value of Z_m, the better the ductility of concrete. With the presence of adequate confinement, the post-peak responses at 85 percent and 50 percent [16-18] of the peak strength of confined concrete can be well improved. The study by Ezeldin and Balaguru [11] among others has shown an increase in terms of peak strength of concrete. However, the post-peak response of confined concrete can be further improved if better confinement is introduced.

The modified Kent and Park stress-strain model for confined concrete without steel fiber [15] is given as follows:

Region AB: $\varepsilon_c \le 0.002K$,

$$f_c = Kf'_c\left[\frac{2\varepsilon_c}{0.002K} - \left(\frac{\varepsilon_c}{0.002K}\right)^2\right] \tag{1.1}$$

where f_c is the compressive stress of concrete (MPa), K is the ratio of the strength of confined concrete to the strength of unconfined concrete in which the confined core is defined as the area bounded by the center line of the perimeter tie [18], f'_c is the specified compressive strength of concrete (MPa), and ε_c is the compressive strain of concrete.

Region AB: $\varepsilon_c > 0.002K$,

(1.2)
$$f_c = Kf_c'[1 - Z_m(\varepsilon_c - 0.002K)]$$

where Z_m is the confinement index, ρ_s is the volumetric ratio of stirrups to concrete core measured from outer-to-outer of stirrups.

However, the value obtained from Eq. (1.2) should no lesser than $0.2Kf_c'$,

(1.3)
$$K = 1.25\left(1 + \frac{\rho_s f_{yh}}{f_c'}\right)$$

where f_{yh} is the yield strength of stirrup (MPa).

(1.4)
$$Z_m = \frac{0.625}{\left[\dfrac{3 + 0.29 f_c'}{145 f_c' - 1000}\right] + \dfrac{3}{4}\rho_s\sqrt{\dfrac{b''}{s_h}} - 0.002K}$$

where b'' is the dimension of confined concrete core measured from outer-to-outer of stirrup (mm), s_h is the center-to-center spacing of stirrups (mm).

The stress-strain models of unconfined steel-fiber reinforced concrete have been widely developed. However, most of the models are the further development of the Ezeldin and Balaguru model [11], which are given as follows:

(1.5)
$$\frac{f_c}{f_{cf}'} = \left[\frac{\beta\left(\dfrac{\varepsilon_c}{\varepsilon_{of}}\right)}{\beta - 1 + \left(\dfrac{\varepsilon_c}{\varepsilon_{of}}\right)^{\beta}}\right]$$

where f_{cf}' is the compressive strength of steel-fiber reinforced concrete (MPa), β is the material parameter, ε_{of} is the strain corresponding to compressive strength.

In generating the stress-strain curve for a given value of f_{cf}' using Eq. (1.5), only two values are required, namely ε_{of} and β.

Based on the findings discussed above on the influences of both confining steel and steel fiber separately, it is deemed necessary to study further the combined impact of both confining steel and steel fiber together on the peak strength and post-peak response of concrete. It is interesting to investigate the contribution of each material when they are used together particularly in improving the post-peak response of concrete. The study includes the use of two different confining steels with the $Z_{m\text{-}dsg}$ values of 17.34 and 29.33 (obtained from Eq. (1.4)), while the volumetric ratios of the steel fiber used in concrete (V_f) were varied as 1.0, 1.5, and 2.0 percent. The experimental behavior of concrete were then observed and discussed. A proposed new equation to account for the influence of confining steel (Z_m) and steel fiber (V_f) was given and validated with the test results.

2. RESEACH SIGNIFICANCE

The stress-strain relationships of confined and unconfined concretes are very different, particularly in their post-peak descending branches, in which the confined concrete behaves more ductile than the unconfined concrete. Likewise, the stress-strain curves of plain and fiber concretes are also different in their post-peak responses. The post-peak stress of confined concrete is falling slower than that of fiber concrete. To the authors' knowledge, none of the previous studies accounted for both effects of confinement and steel fiber simultaneously on the stress-strain models of concrete under compressive loading. Furthermore, the combined effect of confined fiber concrete has not been well explored to present, and hence, no model, if it cannot be said rare, is applicable to account for its combined effect on the stress-strain relationship. Thus, it is deemed necessary to propose a stress-strain model which considers the combined effect of the present of both confining steel and fiber in concrete on the actual stress-strain relationship.

3. EXPERIMENTAL PROGRAM

3.1. MATERIALS PROPERTIES

Ordinary Portland Cement (OPC) with and local aggregates with a maximum size of 20 mm were used. The mixing water and local aggregate used for preparing the specimens all conformed to ASTM C33/C33M-18 [19].

For confinement, steel bars with 6-mm diameter were used as closed hoops/stirrups (transverse steel). The steel bars conformed to SNI 2052:2017 [20]. To investigate the actual yield strength of the steel bars, a set of tensile tests were carried out. The tests were conducted conforming to ASTM E8/E8M-16a [21]. The steel bars were carefully evaluated and selected only those had the uniform yield strengths and satisfied with SNI 2052:2017 [20]. The specified yield strength of the steel bars used was 400 MPa. The steel fiber used in the test specimens was 3D Dramix with the properties as shown in Figure 1.

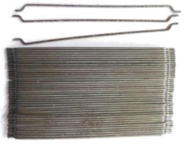


Fig. 1. Hooked-end steel fiber–3D Dramix (tensile strength =1225 MPa, Young's modulus = ± 210,000 MPa, length (*l*) = 60 mm, diameter (*d*) = 0.75 mm, aspect ratio (*l*/*d*) = 80) [22]

The concrete cylinder strength (f_c') was designed to be 22.5 MPa. The concrete mix design was proportioned in accordance with ACI 211.1 [23]. The results of the concrete mix design for all the specimens are given in Table 1.

Table 1. Mix design

Material	Volume (0.035 m^3)
Cement (OPC)	10.68 kg
Coarse aggregate (5-10) mm	8.66 kg
Coarse aggregate (10-20) mm	18.52 kg
Fine aggregate	41.24 kg
Water	5.63 kg
Retarder	37 ml
Superplasticizer	64 ml
Steel fiber	1.0, 1.5, and 2.0%

The average compressive strength ($f_{c,avg}$) of three 150 × 300 mm cylinders at the time of the column tests was 23.25 MPa. The results indicate that there is no significant difference in terms of concrete sample compressive strength (CS_1, CS_2, and CS_3). The different is less than 3.5 MPa [24]. It can be seen that all the values are very close to f_c' (22.5 MPa). The test results are given in Table 2.

Table 2. Compressive test results of concrete cylinder samples

Specimen ID	$f_{c,\text{avg}}$ (MPa)	Δf_c (MPa)
CS_1	24.51	2.01
CS_2	21.96	0.54
CS_3	23.28	0.78
Average	23.25	1.11

Note: Δfc = data margin

3.2. TEST SPECIMENS

The test specimens were 150 × 150 mm square in sections and 300 mm in height. A concrete slump of around 180 mm was used. After 21 days of wet curing they were then dried up in the room temperature for at least until 7 days before the tests. There were six specimens confined with closed hoops/stirrups of two different spacings (s_h = 36 and 52 mm) and reinforced with steel fiber of three different volumetric ratios (1.0, 1.5, and 2.0 percent). No longitudinal bars were used in order to eliminate their effect and ensure that only the contribution of stirrups and steel fiber present. Instead, straightened steel wires were used to minimize the effects and to maintain the formation of the stirrups during casting and compaction. From the tensile tests, the average yield strength ($f_{yh,avg}$) and the maximum elongation (ε_{su}) of the stirrups were obtained approximately 466 MPa and 14.1 percent, respectively. The details of test specimens are listed in Table 3 and shown in Figure 2. The details of test specimen stirrups are also given in Figure 3.

Table 3. Details of test specimens

Specimen ID	Stirrup (mm)	V_f (%)	Concrete (MPa)		Stirrup (MPa)		ρs	Z_m	
			f'_c (specified)	$f_{c,avg}$ (average)	$f_{yh,spc}$ (specified)	$f_{yh,avg}$ (average)		$Z_{m,dsg}$ (design)	$Z_{m,act}$ (actual)
SC_1	∅6–36	1.0	22.5	23.25	400	466	0.0262	17.34	17.30
SC_2	∅6–36	1.5	22.5	23.25	400	466	0.0262	17.34	17.30
SC_3	∅6–36	2.0	22.5	23.25	400	466	0.0262	17.34	17.30
SC_4	∅6–52	1.0	22.5	23.25	400	466	0.0181	29.33	29.29
SC_5	∅6–52	1.5	22.5	23.25	400	466	0.0181	29.33	29.29
SC_6	∅6–52	2.0	22.5	23.25	400	466	0.0181	29.33	29.29

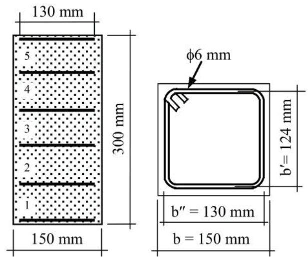


Fig. 2. Details of test specimen

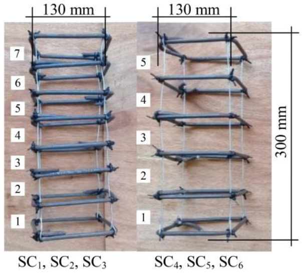


Fig. 3. Details of test specimen stirrups: SC_1–SC_3, $s_h = 36$ mm; SC_4–SC_6, $s_h = 52$ mm

3.3. TEST SETUP AND PROCEDURE

The specimens were tested using a closed-loop UTM of 2000-kN load capacity. The monotonic concentric compression was applied at a slow strain rate control of 0.6425 mm/s which was set to capture the post-peak part of the measured load-deformation curve. The load was measured using a 1000 kN load cell, while the shortening of the specimen (Δ_h) was also measured using two LVDTs and averaged.

An initial load of approximately 20 percent of the total ultimate load was applied, and the displacement were monitored on the monitor to ensure concentric loading. Shims were used when necessary to minimize accidental eccentricity. During testing, the load and displacement were fed to a universal recorder (UR) and stored on a laptop computer. The overall view of the test setup can be seen in Figure 4 (a) and (b).

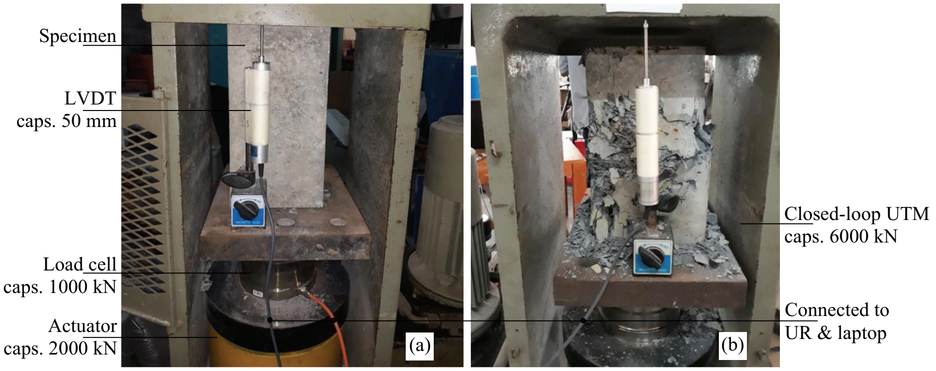


Fig. 4. Test setup: (a) front view; (b) back view.

4. RESULTS AND DISCUSSION

The effects of the introduction of a combination of stirrups as confining steel and steel fiber as reinforcement in “non-slender” concrete column test specimens are discussed here. The derivation of the new proposed stress-strain model equations to accommodate both effects are also presented.

4.1. PROPOSED STRESS-STRAIN MODEL

Most of the available stress-strain models of concrete subjected to axial compressive force are intended to account for either the effect of confining steel or steel fiber only. The proposed equations for modeling the stress-strain curves of concrete under axial compressive load include several important parameters, namely the concrete cylinder strength (f_c'), the yield strength of steel bars for stirrups (f_{yh}), the spacing of stirrups (s_h), the volumetric ratio of stirrups (ρ_s), and particularly the confinement index (Z_m) as well as the volumetric ratio of steel fiber (V_f). In the study, a stress-strain model which includes the effects of both confinement and steel fiber is proposed as shown in Figure 5. The corresponding proposed equations are given from Eqs. (4.1) to (4.6).

Ascending branch, $0 < \varepsilon_c \leq \varepsilon_{ccf}$:

(4.1)
$$f_{ccf} = Kf'_c C_1 \left[\frac{2\varepsilon_c}{\varepsilon_{ccf}} - \left(\frac{\varepsilon_c}{\varepsilon_{ccf}} \right)^2 \right]$$

(4.2)
$$\varepsilon_{ccf} = (0.083V_f)\ln f'_c$$

(4.3)
$$C_1 = 1600V_f^2 - 34V_f + 0.84$$

Descending branch, $\varepsilon_c > \varepsilon_{ccf}$:

(4.4)
$$f_{cf} = f_{ccf}[1 - \alpha(\varepsilon_c - \varepsilon_{ccf})]$$

(4.5)
$$\alpha = (Z_m)^{V_f} + C_2$$

(4.6)
$$C_2 = -400V_f + 14$$

where f_{ccf} is the peak stress of steel-fiber reinforced concrete (MPa), C_1 is the coefficient to account for the effect of volumetric ratio of steel fiber (V_f) at the ascending branch, C_2 is the coefficient to take into account the presence volumetric ratio of steel fiber (V_f) at the descending branch, α is the multiplication factor, ε_{ccf} is the strain at peak stress of steel-fiber reinforced concrete.

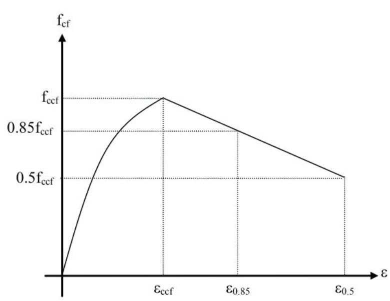
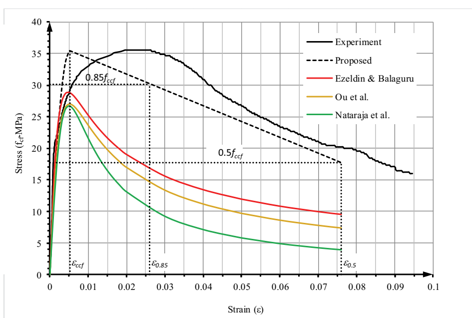


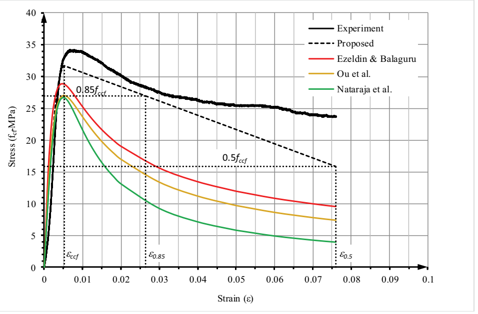
Fig. 5. Proposed stress-strain relationship of steel-fiber reinforced and confined concrete

4.2. COMPARISONS WITH TEST RESULTS

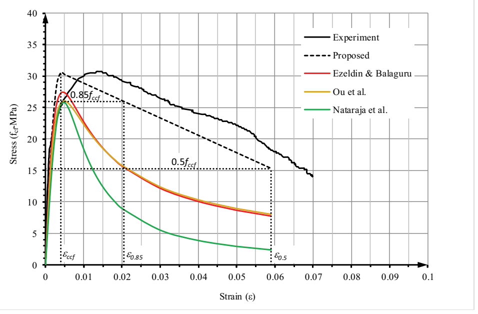
The stress-strain curves generated from the proposed model discussed previously are then compared with the available models by others for steel fiber reinforced concrete, e.g. Ezeldin and Balaguru [11], Nataraja et al [12] and Ou et al [13]. Many of the available stress-strain models for steel fiber reinforced concrete were originally developed by Ezeldin and Balaguru [11]. From their studies, it was proven that there was a significant improvement in terms of stress-strain curves of steel-fiber reinforced concrete. However, the findings from the study has indicated that there is additional considerable improvement in terms of stress-strain relationship when the steel fiber concrete is confined internally with the closed stirrups, higher than those proposed by Ezeldin and Balaguru, Ou et al, and Nataraja et al, particularly in terms of the post-peak response. The post-peak responses show that the combination between the steel fiber and stirrups works very well. The comparisons between the proposed and other models including the experimental results of unconfined and confined steel-fiber reinforced concrete are given in Figure 6(a) to (g).



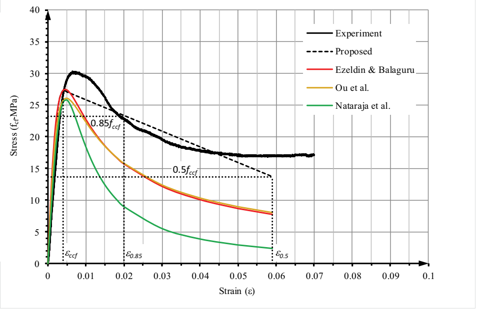
(a) Specimen SC_3 with s_h = 36 mm, V_f = 2 percent



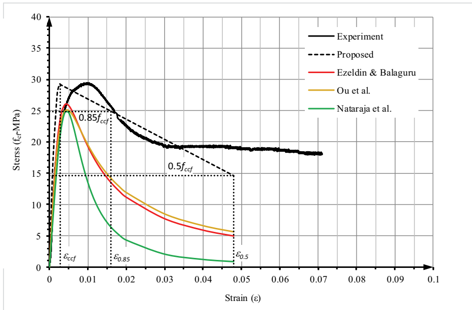
(b) Specimen SC_6 with s_h = 52 mm, V_f = 2 percent



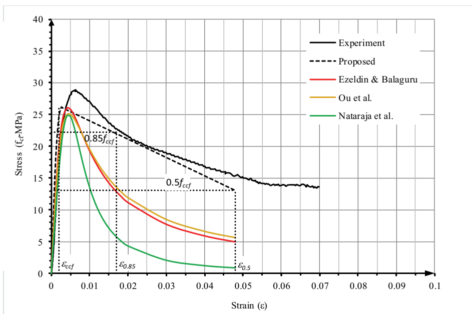
(c) Specimen SC_2 with s_h = 36 mm, V_f = 1.5 percent



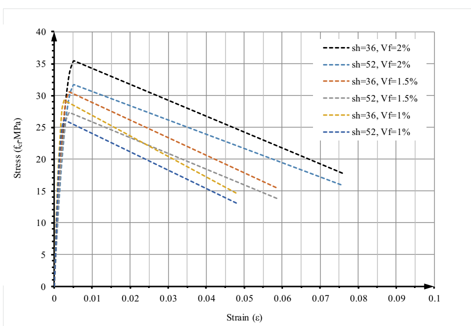
(d) Specimen SC_5 with s_h = 52 mm, V_f = 1.5 percent



(e) Specimen SC₁ with s_h = 36 mm, V_f = 1 percent



(f) Specimen SC₄ with s_h = 52 mm, V_f = 1 percent



(g) Analytical curves for all specimens (SC_1, SC_2, SC_3, SC_4, SC_5, SC_6)

Fig. 6. Comparisons between stress-strain models and experimental data of unconfined and confined steel-fiber reinforced concrete

4.3. FAILURE MODES

The failure modes of the concrete were found to depend on the spacing of the stirrups and the volumetric ratio of steel fiber (V_f). The failure of the specimens with the spacing of stirrups (s_h) of 52 mm were found earlier than those with s_h of 36 mm. The specimens with s_h of 52 mm typically failed at the strain only up to 0.05 as shown in Figure 7, whereas the specimens with s_h of 36 mm can reached up to 0.08 as can be seen in Figure 8. This also applies to specimens with less steel fiber compared to those with higher content of steel fiber.

Fig. 7. Typical failure mode of specimen with s_h = 52 mm failed at ε = 0.05

Fig. 8. Typical failure mode of specimen with s_h = 36 mm failed at ε = 0.08

5. CONCLUSIONS

From the results of the study, it can be concluded that the combination of confining steel and steel fiber simultaneously causes an improvement in terms of stress-strain curves of concrete, particularly in the post-peak branch which can be represented by greater strain values at $0.85f_{cf}$ and $0.5f_{cf}$. The prediction of the proposed model slightly underestimates the experimental data, whereas other models fail to predict the experimental data accurately since they only account for the effect of confinement in concrete without steel fiber. The proposed model has accommodated the effect of confinement (Z_m) and steel fiber (V_f) in the formulation.

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LIST OF FIGURES AND TABLES:

Received 12.08.2019, Revived 18.02.2020