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Inelastic Behavior of Confined Steel Fiber Reinforced Concrete Under Compessive Load

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鋼繊維と横補強筋を併用したコンクリートの圧縮塑性変形挙動

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The high rotation capacities are required for reinforced concrete members to secure the seismic safety of reinforced concrete structures against such a large earthquake motion as in Japan. It is well known that their plastic rotation capacities are closely related to the stress-strain behavior of concrete under compression.

This paper describes the complete stress-strain behavior of steel fiber reinforced concrete confined with lateral reinforcement (confined SFRC). Prismatic column specimens are uniaxially loaded in a new type of high rigidity compression testing machine. The stress-strain curves of confind SFRC up to a large plastic strain are measured,and the effects of the volume fraction of steel fiber, the spacing and the yield strength of lateral reinforcement, the casting direction of concrete and the watercement ratio on stress-strain relationship are examined in detail.

INTRODUCTION

The plastic rotation capacities of reinforced concrete members are closely related to the stress-strain curve of concrete under compression 〔Ref. 1〕. The authors have been studying the inelastic behavior of steel fiber reinforced concrete (SFRC) and confined concrete subjected to compressive load for improving the ductility of concrete 〔Refs. 1-5〕. In the present paper, the complete stress-strain curves of steel fiber reinforced concrete confined with lateral reinforcement (confined SFRC) under uniaxial compression are reported.

It is well known that SFRC has been applied to structural members subjected to tensile or flexural load in general, because of the excellent properties under such loads. However, SFRC has another one that the ductility under compressive load is very high 〔Refs. 6 and 7〕. The earlier test results obtained by the authors indicated that the stress-strain curves of SFRC are extremely varied with the casting direction of concrete and that SFRC is applied more effectively to reinforced concrete columns than to reinforced concrete beams 〔Ref. 1〕.

On the other hand, it is also well known that the behavior of concrete confined with lateral reinforcement such as hoop, stirrup, or tie is very ductile under compression 〔Refs. 8-11〕.

In this study, the effects of the volume fraction of steel fiber, the spacing and the yield strength of hoop, the casting direction of concrete, and the water-cement ratio on the inelastic behavior of confined SFRC are examined based on the experimental data obtained by prismatic column specimens.

1. EXPERIMENTAL PROCEDURES

1.1 TEST SPECIMENS

The experiment as shown in Table 1 was carried out in order to examine the stress-strain curves of confined SFRC up to a large compressive strain. As shown in Fig. 1, 15×15×45cm prismatic specimens which are laterally reinforced with mild steel bars (yield strength=2,500kg/cm^2) or PC wires (proof stress=11,300kg/cm^2) were prepared for the experiment. The nominal diameter of mild steel bar or PC wire was kept to 6mm. The depth of concrete cover was 0 cm, and the spacings of hoops were 30, 10, 5, and 2.5cm, respectively. The end zone of 7.5cm of the specimens was reinforced with mild steel bars at the spacing of 3.75cm to prevent the local failure.

The cylindrical specimens of Φ10×20cm were also prepared.

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1.2 FABRICATION AND CURING OF SPECIMENS

Ordinary Portland cement, river sand (maximum size=5mm), river gravel (size range=5−15mm), and steel fiber (cross section=0.35×0.6mm, length=30mm) were used for the fabrication of the specimens.

The water-cement ratio of concrete (W/C=0.5, 0.6, and 0.7), the volume fraction of steel fiber (V_f=0, 0.75, and 1.5%) and the casting direction of concrete were varied in the experiment. The specimens were cast in parallel to the loading axis in general, except for some specimens (H-series) cast perpendicularly.

The forms of prismatic specimens and cylindrical specimens were removed at the age of 1 day and 2 days, respectively, and then cured in air until the test except for some cylindrical specimens for water curing. Tests were carried out at the age of 4 weeks.

1.3 METHODS OF LOADING AND MEASUREMENT

All the specimens were loaded uniaxially in a new type of high rigidity compression testing machine [Ref. 1] under the constant strain rate of about 1.7×10^{-3}/min. The longitudinal strain was measured by two differential transformers. The measurement lengths were 30cm for prismatic specimens and 18.8cm for cylindrical specimens.

Complete stress-strain curves of prismatic specimens and cylindrical specimens were recorded up to the strain of $15\times10^{-3}$and 10×10^{-3}, respctively.

2. TEST RESULTS AND DISCUSSION

In this experiment, the effects of the volume fraction of steel fiber, the spacing and the yield strength of hoops, the casting direction of concrete, and the water-cement ratio on the stress (σ) -strain (ε) curves of confined SFRC were examined in detail.

2.1 EFFECT OF VOLUME FRACTION OF STEEL FIBER

The effect of the volume fraction of steel fiber on the stress-strain curves of prismatic specimens with different spacing of hoops (S) is shown in Figs.2 (a) thrugh 2 (d). In all the specimens, the stress-strain curves in the stress descending portion become less steep with increasing volume fraction of steel fiber, and this effect is more remarkable as the spacing of hoop is increased.

Fig.3 and Fig.4 show the effects of the volume fraction of steel fiber (V_f) on the compressive strength (F_c) and the strain at the maximum stress (ε_m) of prismatic specimens, respectively. As shown in Fig.3, the compressive strength increases with increasing volume fraction of steel fiber except for some specimens. The increase of strength in the specimen reinforced with PC wire is almost costant, regardless of the spacing of hoops. On the other hand, the increase of strength in the specimens reinforced with mild steel bars whose spacing is large is similar to that of the specimens reinforced with PC wire, but the specimens whose spacing of steel bars is small do not necessarily show the increase of strength.

The strain at the maximum stress becomes larger in proportion to the volume fraction of steel fiber, independently of the kind of hoop, and the increasing rate is higher as the spacing of hoop decreases, as shown in Fig.4.

The relationship between relative absorbed energy (A_b) and volume fraction of steel fiber (V_f) is indicated in Fig.5, where the relative absorbed energy is defined as the ratio of the area enclosed by the stress-strain curve of each specimen up to the longitudinal strain of 15×10^{-3} to that of the specimen of S=30cm and V_f=0%. As shown in this figure, the relative absorbed energy of concrete becomes larger with increasing volume fraction of steel fiber, and the increasing rate is higher as the spacing of hoops increases, that is, the effect of steel fiber on the improvement of ductility of concrete becomes more

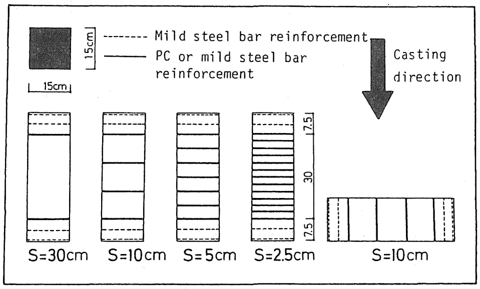
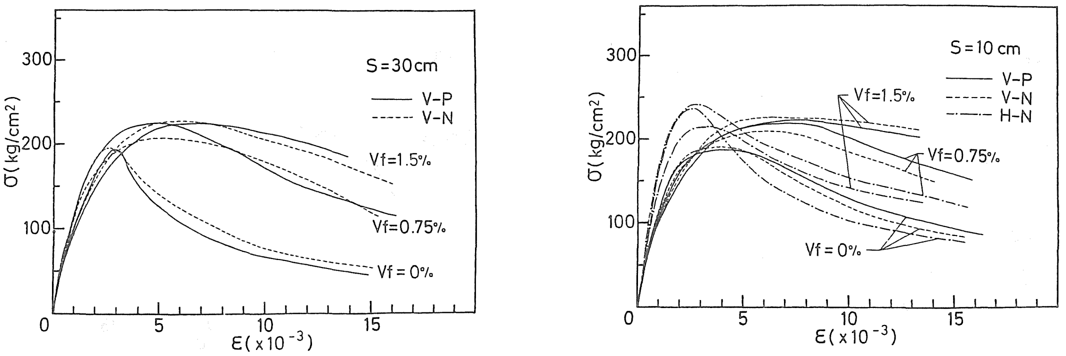


Fig. 1　Test specimens.

Table 1　Outline of experiment.

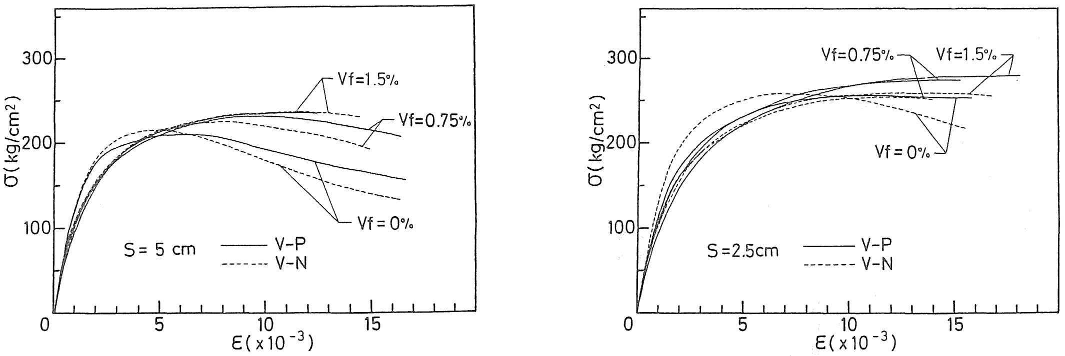
Series No.	W/C (%)	V_f (%)	Casting direction of concrete	Spacing of hoop (cm)	Kind of hoop
0−60	60	0	V (H in a part)	30 10 5 2.5	PC wire (P) Mild steel bar (N)
0.75−60	60	0.75			
1.5−60	60	1.5			
1.5−70	70	1.5			
1.5−50	50	1.5			
H−1.5−60	60	1.5	H		

[Notes] W/C : Water cement ratio, V_i : Volume fraction of steel liber, V : Specimens cast in parallel to the loading axis, H : Specimens cast perpendicularly to the loading axis.



(a) Spacing of hoop (S) = 30cm

(b) Spacing of hoop (S) = 10cm



(c) Spacing of hoop (S) = 5cm

(d) Spacing of hoop (S) = 2.5cm

Fig. 2 Effect of volume fraction of steel fiber (V_f) on stress (σ)-strain (ε) curves.

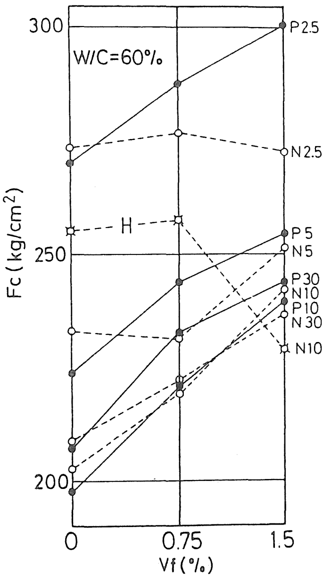


Fig. 3 Relationship between F_c and V_f.

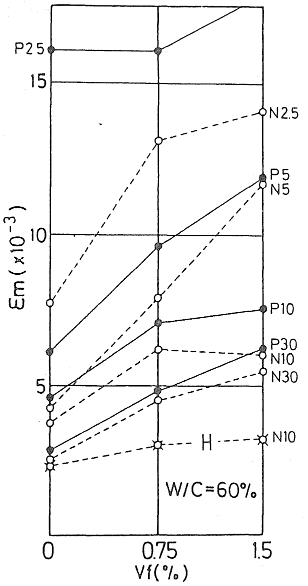


Fig. 4 Relationship between ε_m and V_f.

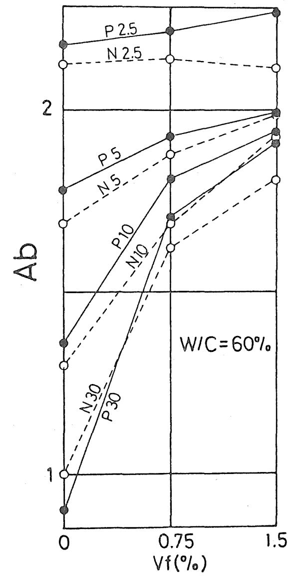
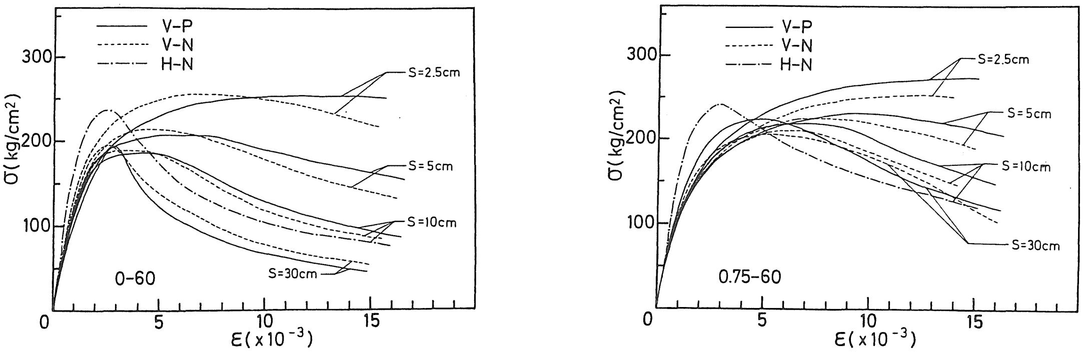
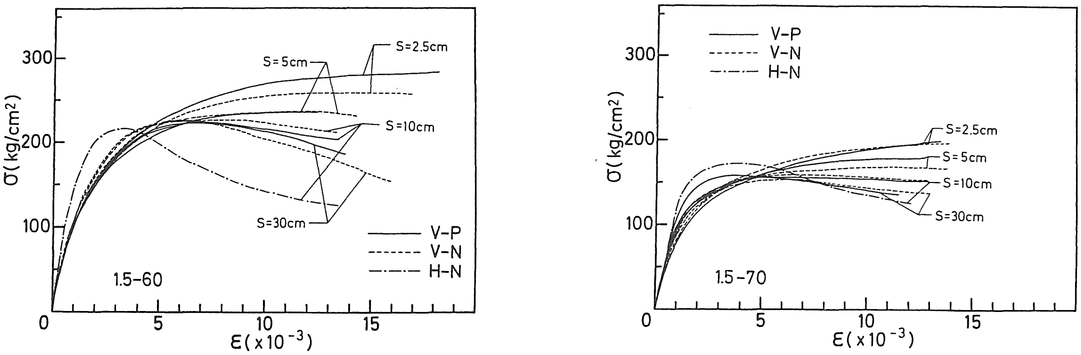


Fig. 5 Relationship between A_b and V_f.



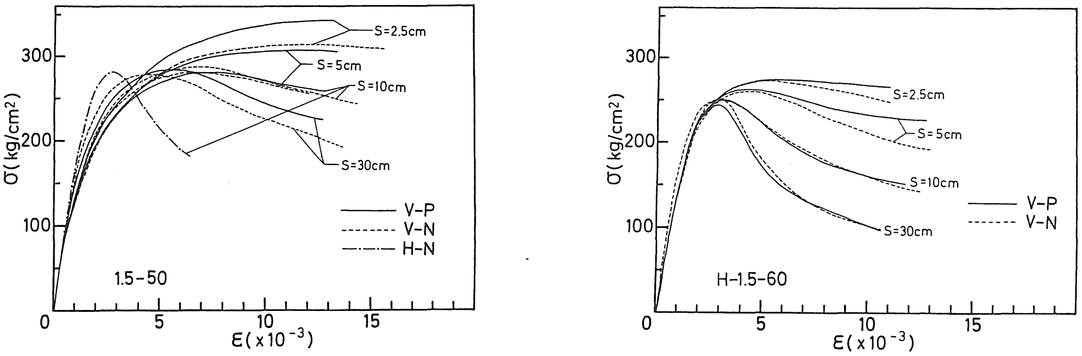
(a) 0 - 60 series.

(b) 0.75 - 60 series.



(c) 1.5 - 60 series.

(d) 1.5 - 70 series.



(e) 1.5 - 50 series.

(f) H - 1.5 - 60 series.

Fig. 6 Effect of spacing of hoops (S) on stress (σ)-strain (ε) curves.

remarkable for the specimens with larger spacing of hoops.

2.2 EFFECT OF SPACING OF HOOP

The effect of the spacing of hoops on the stress-strain curves of confined SFRC is shown in Figs.6(a) through 6(f). The descending portions of all the stress-strain curves of concrete become less steep with decreasing spacing of hoops, and the improvement of ductility is more remarkable as the volume fraction of steel fiber and the water-cement ratio decrease.

The compressive strength (F_c), the strain at the maximum stress (ε_m), and the relative absorbed energy (A_b) are plotted in Figs.7, 8, and 9 against the volumetric ratio of hoops (P_w), respectively. Generally, the values of F_c, ε_m, and A_b increase in proportion to the volumetric ratio of hoops (P_w).

Fig.10 shows the comparative effects of volume fraction of steel fiber (V_f) and volumetric ratio of hoops (P_w) on the relative absorbed energy (A_b) of confined SFRC, where the contour lines of relative absorbed energy are schematically drawn. The following statements can be made from the figure.

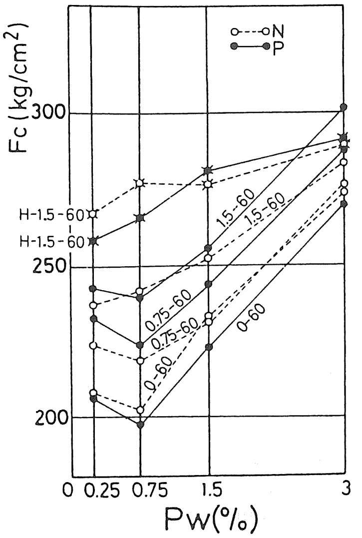


Fig. 7 Relationship between F_c and P_w.

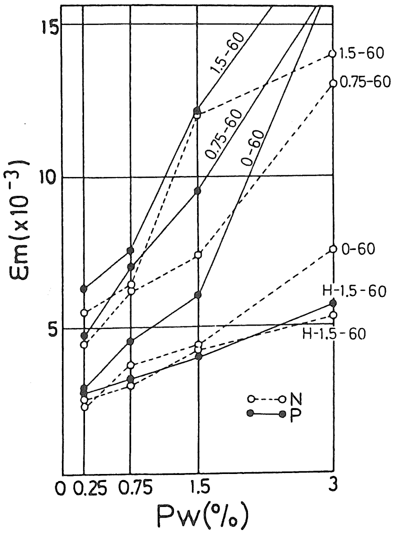


Fig. 8 Relationship between ε_m and P_w.

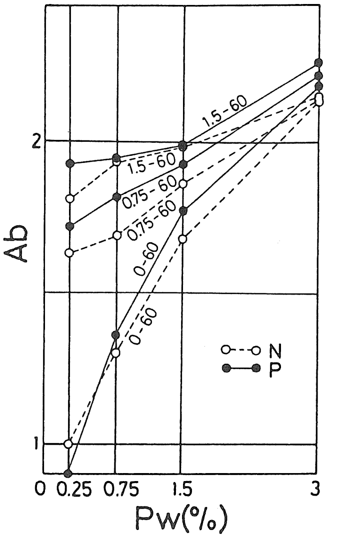


Fig. 9 Relationship between A_b and P_w.

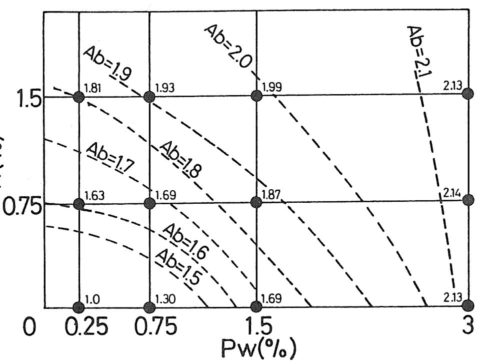


Fig. 10 Comparative effects of steel fiber and lateral reinforcement.

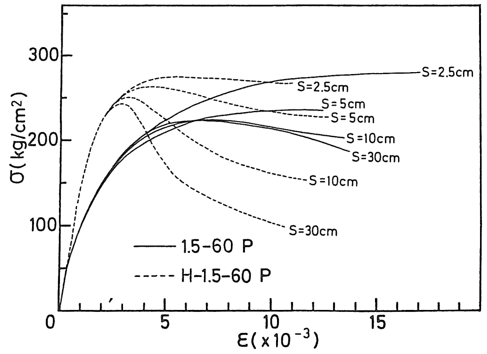


Fig. 11 Effect of casting direction of concrete on stress (σ) - strain (ε) curves.

1) Steel fiber is more effective for improving the ductility of concrete than lateral reinforcement when the volume fraction of steel fiber (V_f) and the volumetric ratio of hoops (P_w) are less than 1.5%. The value of relative absorbed energy at $V_f=1.0\%$ and $P_w=0\%$ is almost equal to that at $V_f=0\%$ and $P_w=1.5\%$.

2) The improvement of ductility by steel fiber gradually decreases as the volumetric ratio of hoops increases.

3) The contour lines are a little convex against the origin. However, the linearly additional effect of steel fiber and lateral reinforcement on the relative absorbed energy can be roughly expected when their volume fractions are less than 1.5%. For example, the value of A_b at $V_f=0.75\%$ and $P_w=0.75\%$ is almost equal to that at $V_f=0\%$ and $P_w=1.5\%$.

2.3 EFFECT OF YIELD STRENGTH OF HOOP

According to Figs.2, 4, 5, 6, 8, and 9, the specimens reinforced with PC wires show more ductile behavior than that with mild steel bars, and this tendency is more remarkable as the volume fraction of steel fiber increases and as the spacing of hoops and the water-cement ratio decrease.

2.4 EFFECT OF CASTING DIRECTION OF CONCRETE

The compressive strength and the strain at the maximum stress of the specimens cast perpendicularly to the loading axis (H-series) are hardly affected by the volume fraction of steel fiber, as shown in Figs.2 and 3. The strains at the maximum stresses (ε_m) of such specimens are very small, compared with those of the specimens cast in parallel to the loading axis. It is indicated in Figs.7 and 8 that the increases of the strength and the strain at the maximum stress by lateral reinforcement are more remarkable in the specimens cast in parallel to the loading axis (V-1.5-60 series) than in the specimens cast perpendicularly to it (H-1.5-60 series).

The effect of the casting direction of concrete on the stress-strain curves is shown in Fig.11. The stress-strain curves of V-series specimens are more ductile than those of H-series as mentioned above, and the Young's modulus of H-series specimens is much higher than that of V-series specimens. This may be resulted from the orientation of steel fiber and bleeding caused by different casting direction.

CONCLUSIONS

In the present paper, the effects of the volume fraction of steel fiber, the spacing and yield strength of hoops, the casting direction of concrete and the water-cement ratio on the complete stress-strain behavior of steel fiber reinforced concrete confined with hoops (confined SFRC) were examined. The test results are summarized as follows :

1) The stress-strain curve of concrete shows more ductility with increasing volume fraction of steel fiber, and this tendency is more remarkable as the spacing of hoops increases.

2) The efficiency of lateral reinforcement on the improvement of ductility of concrete becomes higher with decreasing volume fraction of steel fiber and water-cement ratio.

3) The effect of steel fiber on the improvement of ductility of concrete is more remarkable than that of lateral reinforcement when the volume fraction of steel fiber (V_f) and the volumetric ratio of hoops (P_w) are less than about 1.5%. For example, the value of relative absorbed energy at $V_f=1.0\%$ and $P_w=0\%$ is almost equal to that at $V_f=0\%$ and $P_w=1.5\%$.

4) The specimens confined laterally with PC wire are more ductile than those with mild steel bars, and this tendency becomes more remarkable with increasing volume fraction of steel fiber and decreasing volumetric ratio of hoops and water-cement ratio.

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