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CONFINEMENT EFFECTS OF TRANSVERSE HOOPS IN HIGH-STRENGTH CONCRETE

Y.P. SUN, T. OBA, F.S. TIAN, and T. IKEDA

Department of Architecture, Faculty of Engineering, Kyushu University,
Fukuoka 812, JAPAN

ABSTRACT

An experimental study was made of the confinement effect of transverse hoops on the stress-strain behavior of high-strength concrete. Thirty-one specimens made of high-strength concrete with compressive strength f_c'=60 MPa and rectilinearly confined by transverse hoops with yield strengths f_{yh}=342-1026MPa were tested. Concrete confined by perimeter hoops with intermediate hoops or crossties exhibited higher strength and more ductile behavior than concrete confined by perimeter hoops only. Test results also indicated that the confinement provided by normal strength perimeter hoops only was insufficient to flatten the descending portion of the stress-strain curve of high-strength concrete, even a large amount of hoops were used.

KEYWORDS

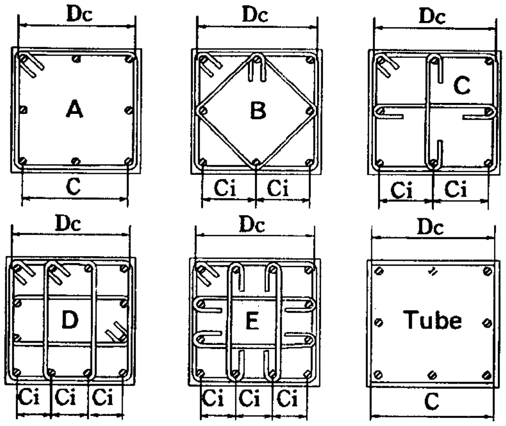
High-Strength Concrete; Rectilinear Transverse Hoops; Confinement Effect; Compressive Strength; Strain at Maximum Stress; Stress-Strain Curve; Ductility; Confined Concrete.

SIGNIFICANCE

The use of high-strength concrete in the columns of tall building has an advantage of making the column's section smaller, thus providing more floor space and design freedom. In order to promote the use of high-strength concrete in structures, it is of great importance to improve the brittle failure mode of high-strength concrete.

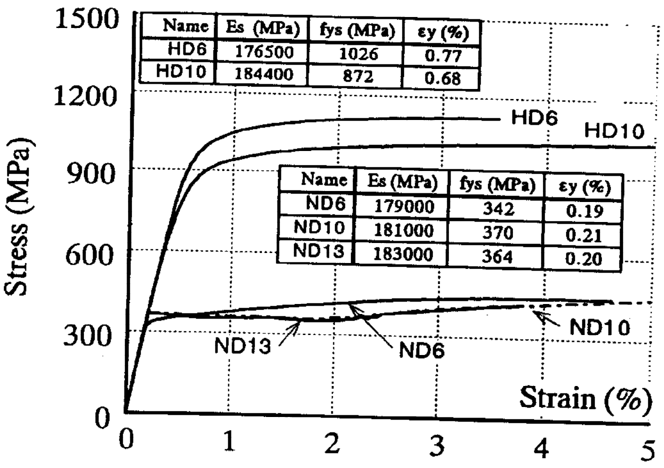
It is generally accepted that the use of rectilinear transverse hoops results in increased strength and ductility of the confined concrete, though the confinement efficiency of rectilinear hoops is less than that of circular hoops or spirals. Unlike confinement by circular hoops, confinement due to the rectilinear hoops is affected by not only the amount of hoops but also by the bending stiffness, hence the configuration and diameter, of hoops, since the rectilinear hoops tend to bend the sides outward as concrete bears out. Sheikh *et al* (1980) have experimentally proved that the rectilinear hoops with better configuration can provide stronger confinement effect to the confined normal-strength concrete. However, published experimental results on the confinement effects of the rectilinear hoops on the stress-strain behavior of high-strength concrete are scarce.

The purposes of this paper are 1) to present experimental information on the stress-strain behavior of high-strength concrete confined by rectilinear hoops, and 2) to study the applicability of some current confinement models.



C=max(Ci) for each configuration

Fig. 1 Configurations of rectilinear steels



Name	Es (MPa)	fys (MPa)	εy (%)
HD6	176500	1026	0.77
HD10	184400	872	0.68

Name	Es (MPa)	fys (MPa)	εy (%)
ND6	179000	342	0.19
ND10	181000	370	0.21
ND13	183000	364	0.20

Fig. 2 Tensile stress-strain curves of steels

EXPERIMENTAL PROGRAM

The experimental program was designed to study the stress-strain relationship of rectilinearly confined high-strength concrete with respect to four parameters, namely: (1) the volumetric ratio; (2) the configuration type; (3) the diameter; and (4) the yield strength, of rectilinear hoops. Thirty-one 200x200x500mm square short columns were fabricated and tested under monotonic axial compression until the axial strain of concrete reached value of 0.05. The same testing set-up and measurement as described in Sun *et al* (1993) were used in the experiment.

Six different configurations of rectilinear hoops were used to confine the core concrete, as shown in Fig. 1. Square steel tube shown in Fig. 1 represents a limit state of ordinary hoops with zero hoop spacing. Of thirty-one specimens, twenty-nine were confined by conventional rectilinear hoops, and the other two were confined by square steel tube with yield strength of 304MPa. Details of specimens are given in Table 1 along with the primary experimental results. The alphanumeric characters in the titles of specimens (e.g. HB6-30) have the following meanings. The first letter represents the grade of hoops (High- or Normal-strength). The second letter represents the configuration of hoops (See Fig. 1). The number after the second letter indicates the diameter of hoops in mm. The letter 'M' after the second letter means that the confinement was provided by combining perimeter hoops of ND10 bars and intermediate hoops or crossties of ND6 bars. The last number represents the hoop spacing in mm.

Ready mixed concrete, with maximum aggregate size of 13mm, was used in making specimens. The target compressive strength of concrete was 60 MPa. Compressive strengths of the concrete cylinder at the stage of testing are given in Table 1. Longitudinal reinforcement in each specimen comprised of eight or twelve D13 deformed bars with yield strength 362MPa according to the configuration of hoops. Conventional rectilinear hoops were provided by four kinds of deformed bars , whose mechanical properties and tensile stress-strain curves are shown in Fig. 2. Each curve in Fig. 2 represents the average of three tests.

EXPERIMENTAL RESULTS

Table 1 lists the primary experimental results of all specimens. Experimental relationships between axial stress and strain of the confined concrete are plotted in Fig. 3. Confined concrete means the core concrete measured from center to center of perimeter hoop. The stresses of confined concrete in Table 1 and Fig. 3 were calculated by assuming that the shell and core concrete share the load carried by concrete N_c until strains of 0.0016-0.002, where

Table. 1 Details and primary experimental results of test specimens

Specimen	fc'	Details of hoops						Nmax[1]	No[2]	Results of confined concrete					
										measured		analytical			
	(MPa)	shape	dia (mm)	C (mm)	s (mm)	ρh (%)	fyh (MPa)	(kN)	(kN)	fcc'	ε_{co}	fcc'	ratio[3]	ε_{co}	ratio
HA6-20	51.5	A	6.4	162	20	3.48	1025	2297	2073	62.7	0.55	61.6	1.02	0.49	1.13
HA6-30					30	2.32		2195	2073	58.4	0.43	58.0	1.01	0.40	1.06
HA6-40					40	1.74		2091	2073	55.1	0.40	56.2	0.98	0.36	1.10
HB6-35	51.5	B	6.4	81	35	3.39	1025	2631	2073	72.4	1.01	70.2	1.03	0.69	1.46
HB6-50					50	2.38		2500	2073	67.9	1.28	63.2	1.07	0.55	2.34
HB6-70					70	1.70		2208	2073	58.7	0.65	59.9	0.98	0.45	1.45
HA10-35	53.6	A	9.6	158	35	4.40	872	2548	2144	69.8	0.43	72.8	0.96	0.68	0.63
HA10-47					47	3.28		2445	2144	66.4	0.50	67.4	0.99	0.56	0.89
HA10-60					60	2.57		2426	2144	65.8	0.43	64.0	1.03	0.48	0.89
HB10-60	52.0	B	9.6	79	60	4.40	872	3018	2091	84.5	1.69	87.1	0.97	1.75	0.96
HB10-80					80	3.30		2650	2091	73.1	0.86	76.5	0.96	0.82	1.05
HB10-100					100	2.64		2479	2091	67.3	0.63	70.4	0.96	0.67	0.94
NA6-20	52.9	A	6.4	165	20	3.48	342	2590	2063	58.4	0.38	57.9	1.01	0.36	1.06
NA6-30			6.4	165	30	2.32	342	2372	2063	58.9	0.38	56.2	1.05	0.32	1.18
NA10-47			9.6	161	47	3.28	344	2426	2063	62.5	0.43	59.7	1.05	0.41	1.06
NB6-35	53.4	B	6.4	82.5	35	3.39	342	2519	2111	66.3	0.53	62.8	1.06	0.45	1.18
NB6-50			6.4	82.5	50	2.38	342	2430	2111	63.3	0.44	59.7	1.06	0.39	1.14
NB10-75			9.6	81	75	3.51	344	2514	2111	66.1	0.49	66.5	0.99	0.55	0.90
NC6-30	52.5	C	6.4	82.5	30	3.48	342	2489	2083	65.3	0.47	62.3	1.05	0.47	0.99
NC6-43			6.4	82.5	43	2.43	342	2421	2083	63.4	0.42	59.1	1.07	0.40	1.05
NC10-70			9.6	81	70	3.31	344	2421	2083	63.1	0.49	65.1	0.97	0.54	0.91
ND6-47	52.9	D	6.4	55	47	3.45	342	2671	2211	66.6	0.49	66.7	1.00	0.56	0.87
ND6-70			6.4	55	70	2.32	342	2543	2211	62.7	0.41	61.5	1.02	0.45	0.92
NE6-40	52.9	E	6.4	55	40	3.48	342	2680	2211	67.0	0.56	67.1	1.00	0.57	0.98
NE6-60			6.4	55	60	2.32	342	2666	2211	66.6	0.41	61.8	1.08	0.45	0.91
NBM-60	52.9	B	9.6	82.5	60	3.39	344	2571	2063	67.9	0.58	66.0	1.03	0.55	1.05
NBM-75			9.6	82.5	75	2.71	344	2377	2063	61.7	0.47	62.9	0.98	0.48	0.98
NCM-60	52.5	C	9.6	82.5	60	3.15	344	2435	2083	63.5	0.43	64.7	0.98	0.53	0.81
NCM-75			9.6	82.5	75	2.52	344	2391	2083	61.9	0.39	61.8	1.00	0.47	0.84
T6-1	52.0	T	5.63	189	0	11.96	304	2354	2167	66.1	0.60	65.9	1.00	0.57	1.06
T6-2			5.63	189	0	11.96	304	2184	2167	62.0	0.57	65.9	0.94	0.57	1.00
												Mean	1.01	Mean	1.06
												St. Dev.	0.03	St. Dev	0.16

1) Nmax : Experimental maximum load 2) No : Nominal load capacity =0.85fc'(Ag-As)+f_{sy}As

3) ratio=the measured/the analytical

the cracks in shell concrete were firstly observed, and that only the core concrete sustains the load N_c at strain beyond 0.004. Cubic curves are assumed to obtain the stresses between these two strains. N_c was obtained by subtracting the steel contribution N_s from the total applied load, while N_s was calculated by assuming that the strain in the longitudinal steel is equal to the strain in the concrete and the steel be elastic perfectly plastic material.

About the stress-strain behavior of rectilinearly confined high-strength concrete, the following observations can be made from Fig. 3: (1) the strength of confined concrete increased as the volumetric ratio of hoops increased; (2) for specimens with almost equal amount and same diameter of hoops, concrete confined by perimeter hoops with intermediate hoops or crossties showed larger enhancement in strength and ductility than concrete confined by perimeter hoops only; (3) confinement by normal-strength perimeter hoop only was insufficient to flatten the descending portion of stress-strain curves of high-strength concrete even a large amount of hoops were used (See specimen NA6-20 in Fig. 3); (4) the higher the yield strength of hoops, the larger the enhancement in strength and ductility of the confined concrete; (5) increase of confinement effect by the use of thicker hoops or better configuration could balance the decrease from larger hoop spacing.

To estimate the confinement degree of high-strength hoops, the lateral strain readings of the strain gages on perimeter hoops are plotted in Fig. 4 against hoop spacing. Measured lateral strains represent the strains of perimeter hoops at the stage when the stress-strain curves of the confined concrete reached peak points. Solid and white points in Fig. 4 show the experimental results of high-strength hoops with and without intermediate hoops or crossties, respectively.

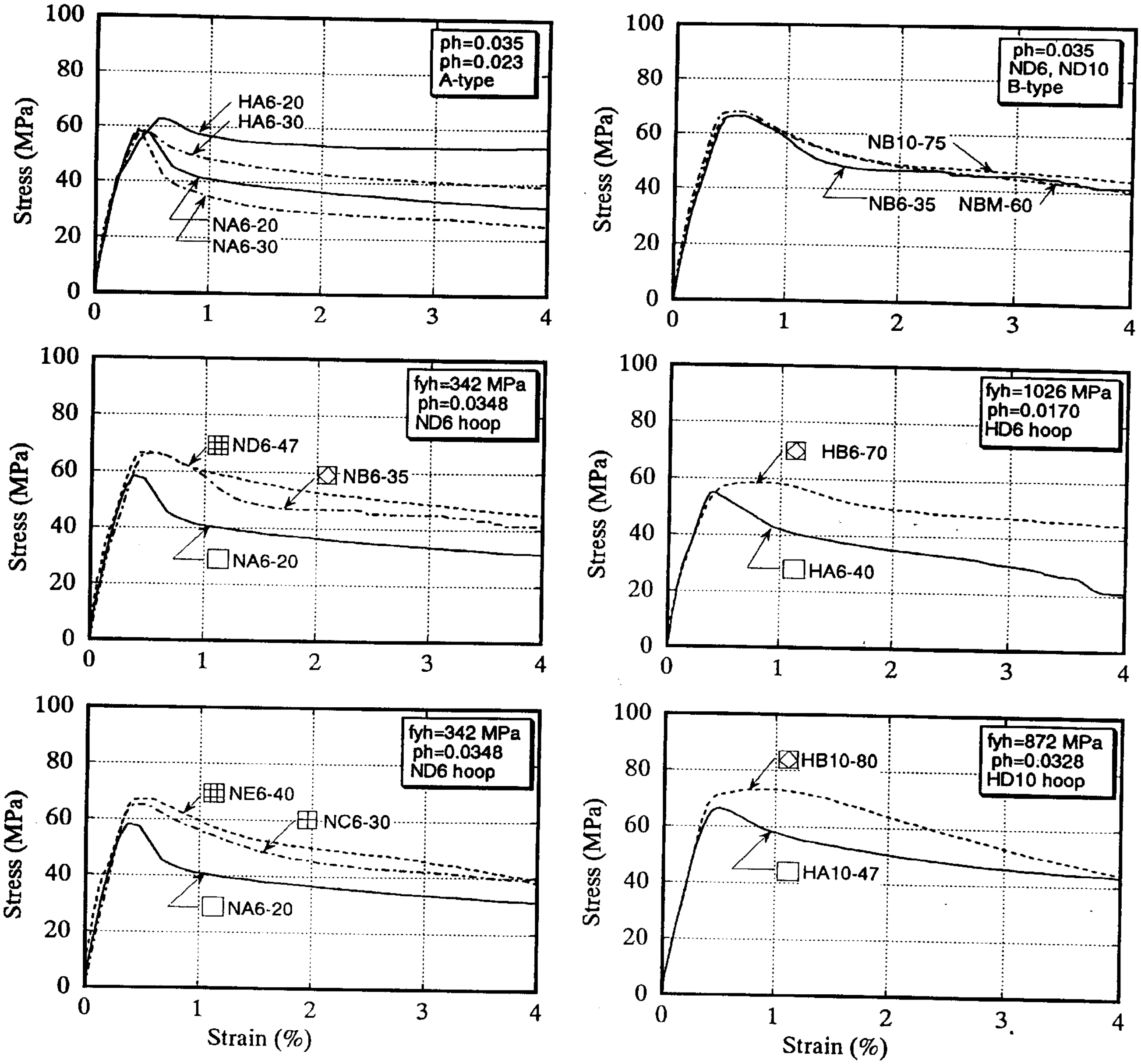


Fig. 3 Experimental stress-strain curves of the confined concrete

Figure 4 indicates that the experimental strain readings of hoops with intermediate hoops or crossties showed larger values than those of hoops without intermediate hoops or cross ties. This would mean that rectilinear hoops with more rational configuration are more effective in confining the core concrete. The hoop strains decreased as hoop spacing increased. However, to quantitatively evaluate the relation between hoop strain and hoop spacing, further experimental work remains to be done, because the test results at present are inadequate. It can also be observed from Fig. 4 that the high-strength hoop did not yield at the peak points of the stress-strain curves of confined concrete. This fact should be kept in mind when evaluating the confinement efficiency of high-strength hoops.

CONFINEMENT MODEL AND APPLICABILITY

Several analytical stress-strain relations for rectilinearly confined concrete have been proposed. Among these, the relations presented by Sheikh and Uzumeri (1982), Park *et al.* (1982), and Sakino and Sun (1994) will be studied to determine the applicability to the specimens. Details of Sheikh's and Park's confinement models can be found in the literature and will not be given here. The confinement model proposed by Sakino and Sun (1994) is illustrated in Fig. 5 and is based on an equation proposed by Sargin (1971). Besides the amount of hoops and concrete

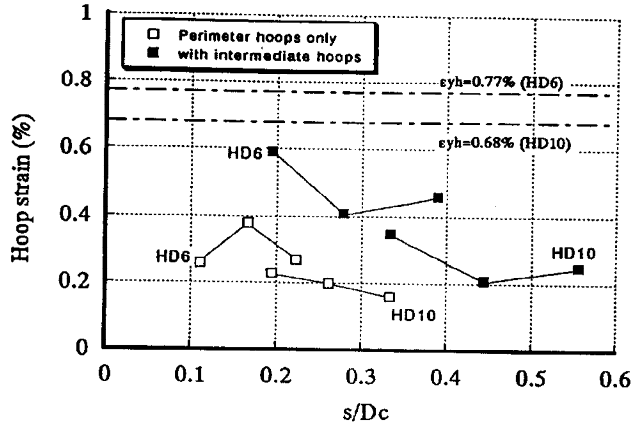


Fig. 4 Hoop strains at the peak of stress-strain curve

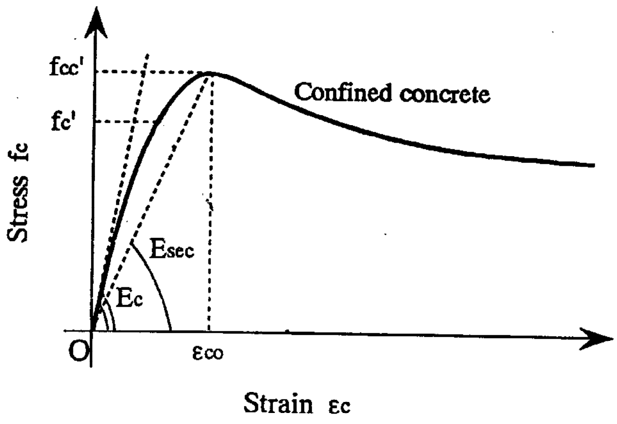


Fig. 5 Stress-strain curve for confined concrete proposed by Sakino and Sun (1994)

strength, this model also take factors such as the configuration and diameter of rectilinear hoops into consideration, hence has characteristic to be applicable to both conventional hoops and square steel tube. Mathematical expression for the stress-strain relation is defined as follow:

$$\frac{f_c}{f_{cc}'} = \frac{AX + (D-1)X^2}{1 + (A-2)X + DX^2} \tag{1}$$

in which, $X=\varepsilon_c/\varepsilon_{co}$; f_c and ε_c are the stress and strain; f_{cc}' and ε_{co} are the stress and strain at the peak; $A=E_c/E_{sec}$; $E_c=(0.69+0.332(f_c')^{1/2})x10^4$ is the Young's modulus of elasticity of concrete in MPa (Martinez *et al* , 1984); $E_{sec}=f_{cc}' / \varepsilon_{co}$ is the secant modulus at the peak point; and D is the parameter mainly governing the slope of descending portion of the stress-strain curve. The peak stress, hence the strength of confined concrete, f_{cc}' and the peak strain ε_{co} and the parameter D are evaluated in terms of effective lateral pressure factor f_{re}, and given in the forms of

$$f_{cc}' = f_c' + 11.5 f_{re} = f_c' + 11.5 \rho_h f_{hs} \frac{d''}{C}\left(1 - \frac{s}{2D_c}\right) \tag{2}$$

$$\frac{\varepsilon_{co}}{\varepsilon_o} = \begin{cases} 1 + 4.7(K-1), & K \le 1.5 \\ 3.35 + 20(K-1.5), & K > 1.5 \end{cases} \tag{3}$$

$$D = 1.5 - 1.7 \times 10^{-2} f_c' + \gamma \sqrt{(K-1) f_c' / 23} \tag{4}$$

where f_c' is strength of concrete cylinder in MPa; ρ_h is volumetric ratio of hoops to the confined core measured center-to-center of perimeter hoop; f_{hs} is stress of hoops at peak in MPa; d'' is nominal diameter of perimeter hoop; C is center-to-center distance between longitudinal bars supported by perimeter hoops or intermediate hoops (inner width) as shown in Fig. 1; s is hoop spacing (zero); D_c is distance between the centroids of perimeter hoop (inner width); $\varepsilon_o=0.94(f_c')^{1/4}x10^{-3}$ is strain at peak for unconfined concrete (Popovics, 1973); and $K=f_{cc}'/f_c'$ is strength enhancement of confined concrete; γ=1.6 (2.4). Note that the values in parentheses are for the square steel tube.

When using Eq. (2) to calculate the strength of confined concrete f_{cc}', hoop stress f_{hs} can be taken equal to it's yield strength f_{yh} for simplicity. For high-strength hoops, however, it is necessary to set an upper limit on the value of f_{hs}, since the high-strength hoops generally did not yield at the peaks of stress-strain curves as seen in Fig. 4. Based on their test results, Sakino and Sun (1994) have also proposed an upper limit, 687 MPa (7000kgf/cm^2), for f_{hs}. This value is used in this paper to calculate the strength enhancement of the concrete confined by high-strength

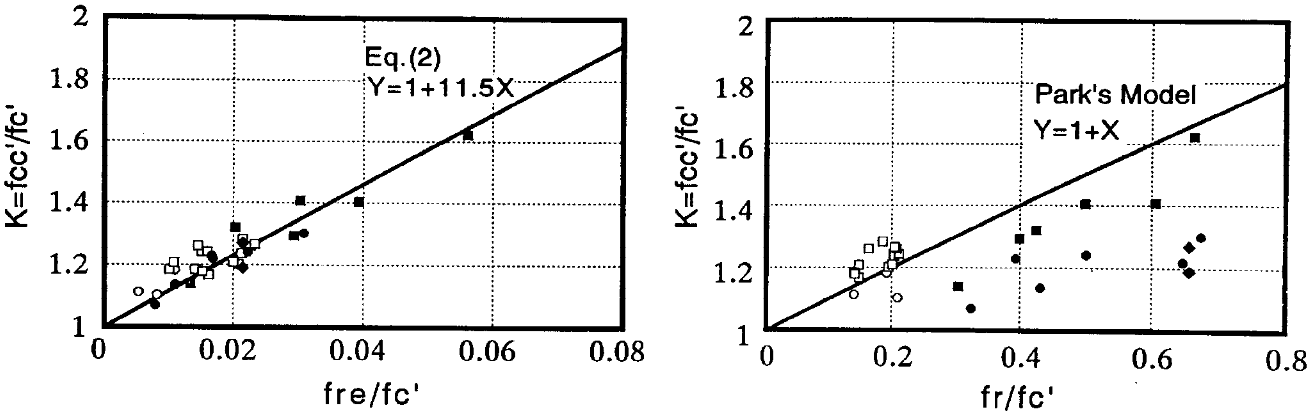


Fig. 6 Evaluation of strength of the confined concrete

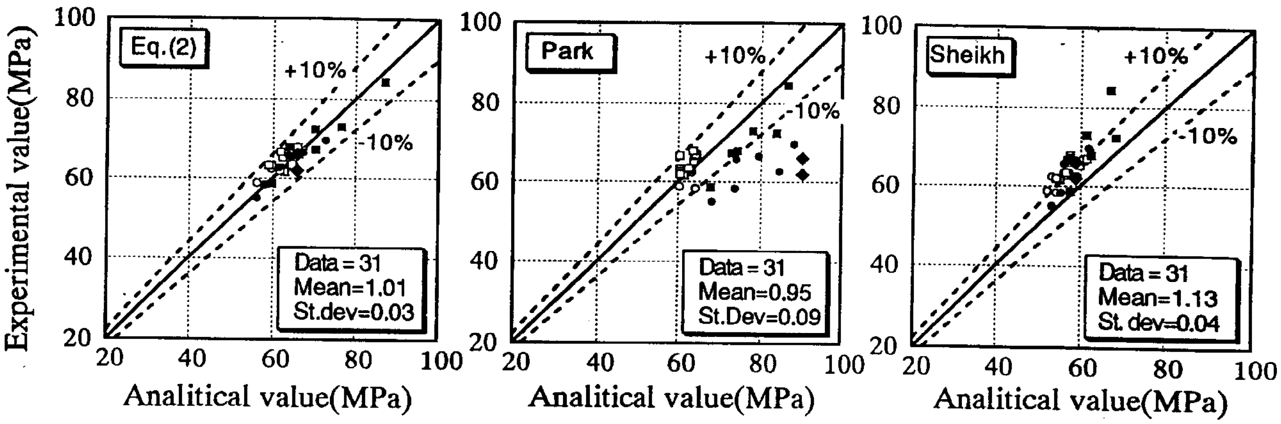


Fig. 7 Comparison between the experimental and theoretical strengths of the confined concrete

HD6 and HD10 hoops.

Fig. 6 displays the experimental compressive strengths of confined concrete. In Fig. 6, f_{re} is the effective lateral pressure factor and is defined by the right-hand term in Eq. (2), and $f_r=\rho_h f_{hs}$ is the lateral confining pressure, a term usually utilized to evaluate the confinement effect of circular hoops. Solid circles and squares plotted in Fig. 6 show the results of specimens confined by high-strength HD6 and HD10 hoops, respectively. White circles and squares represent the results of specimens confined by normal-strength ND6 and ND10 hoops, respectively, and solid diamonds express results of specimens confined by square steel tube. Strong correlation between the confined concrete strength f_{cc}' and the effective lateral pressure factor f_{re} is apparent. On the other hand, the term f_r can not appropriately evaluate the confinement effect of rectilinear steels with different configurations.

Theoretical strengths of the confined concrete obtained by Sakino and Sun's model (Eq. (2)), Sheikh's model and Park's model, are compared with the experimental results in Fig. 7. Predicted by Eq. 2 and measured values for the peak strength f_{cc}' and the peak strain ε_{co} are also listed in Table 1. Very good agreement between the experimental and theoretical f_{cc}' obtained by Sakino and Sun's model can be observed. For the peak strain ε_{co}, with the exception of only three columns of HB6-series, agreement between the measured and theoretical results is also quite good.

Comparison between the theoretical stress-strain curves predicted by above-mentioned models and the experimental results are shown in Fig. 8. From Fig. 8, it will be noted that the stress-strain model proposed by Sakino and Sun (Eqs. (1)-(5)), as compared with Park's model and Sheikh's model, predict much better the stress-strain curves for concrete confined by rectilinear hoops with any typical configuration up to large strain.

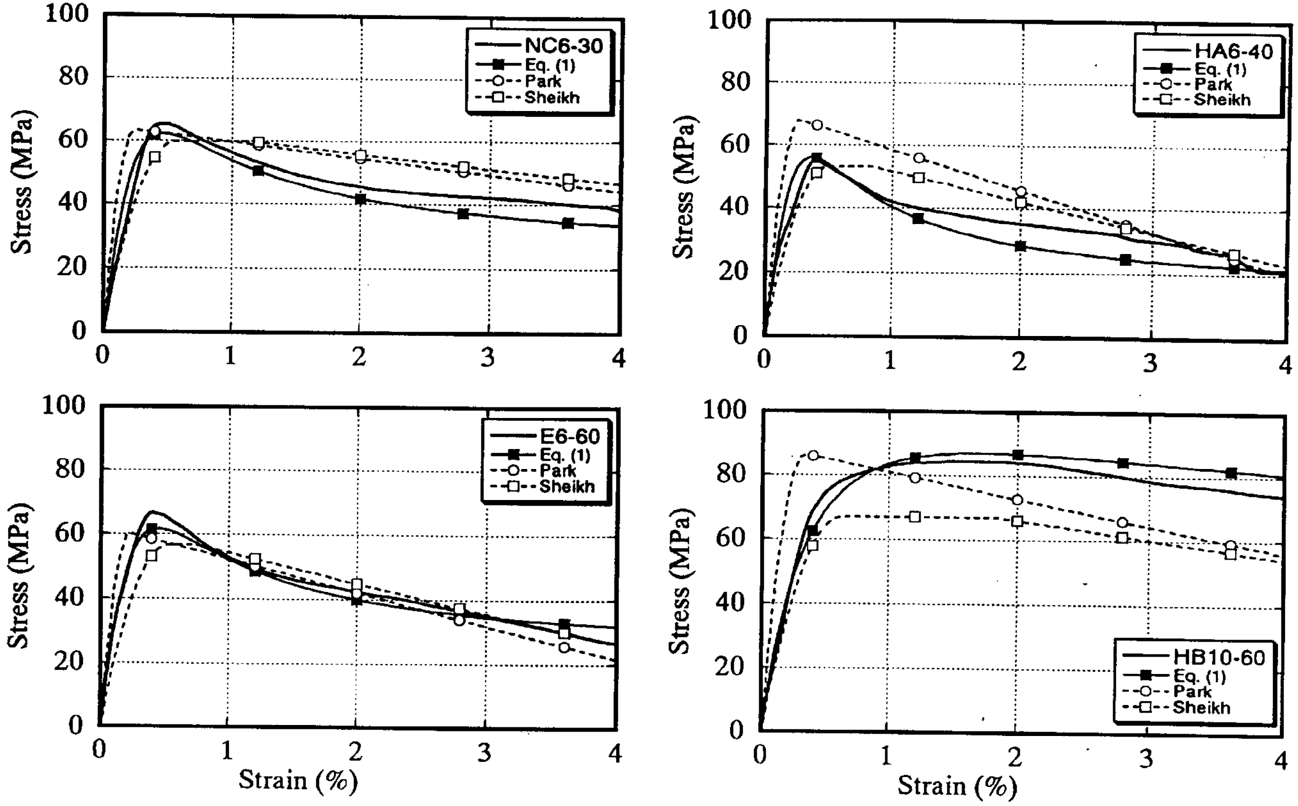


Fig. 8 Comparison between the experimental and theoretical stress-strain curves of the confined concrete

CONCLUSIONS

Tests were conducted on high-strength concrete short columns confined by rectilinear transverse hoops. The loading was applied concentrically. Confinement effects of rectilinear hoops on the stress-strain behavior of high-strength concrete were investigated. The following conclusion remarks have been drawn.

1) As the volumetric ratio of hoops increased, the confined strength increased and the slope of stress-strain curve flattened. However, Confinement provided by normal-strength perimeter hoops only could not satisfactorily flatten the slope of stress-strain curve for high-strength concrete, even a large amount of hoops were used.

2) When the same amount of rectilinear hoops were used, the gains in the strength and ductility of high-strength concrete confined by rectilinear hoops with intermediate hoops or crossties were much higher than those of concrete confined by perimeter hoops only. Also the increase of confinement effect by using thicker hoops can balance to some extent the decrease due to larger hoop spacing.

3) The influence of the configuration and diameter of rectilinear transverse reinforcement can be appropriately predicted in terms of effective lateral pressure factor f_{re} (See Eq. (2)). When one compute by using f_{re} the strength enhancement of concrete confined by high-strength rectilinear hoops, an upper limit on the hoop stress f_{hs} should be placed, considering the fact that high-strength hoops generally did not yield at the peaks of the stress-strain curves. The upper limit value for f_{hs}, 686 MPa (7000kgf/cm^2), proposed by Sakino and Sun (1994), has been used in this paper to predict the peak stress f_{cc}' of confined concrete, and very good agreement between the experimental and theoretical results of f_{cc}' was observed.

4) Peak stress f_{cc}' and peak strain ε_{co} and stress-strain curve for the high-strength concrete confined by rectilinear hoops with various configurations can be well predicted by Sakino and Sun's confinement model (1994).

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