Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-4-18

EXPERIMENTAL STUDIES ON SEISMIC BEHAVIOUR OF HIGH STRENGTH CONCRETE COLUMNS LATERALLY REINFORCED WITH HIGH STRENGTH STEEL BARS

Shunsuke SUGANO[1], Toshio NAGASHIMA[1], Hideki KIMURA[1] and Akio TAMURA[2]

[1]TAKENAKA TECHNICAL RESEARCH LABORATORY,
Koto-ku, Tokyo Japan.
[2]Building Design Department, Tokyo Main Office TAKENAKA CORPORATION,
Chuo-ku, Tokyo Japan.

SUMMARY

Two types of test, a uni-axial compression test and a lateral loading test, were conducted to investigate the seismic behavior of reinforced concrete columns of high strength concrete, and to obtain guidelines for the design of such members to be used for high-rise buildings. Concrete with three levels of compressive strength of 400,600 and 800kg/cm^2 was used. High strength steel bars having yield strengths of 3200, 8500 and 14000kg/cm^2 were used for the lateral reinforcements. Results indicated that high strength lateral reinforcement was quite effective at improving the ductility of high strength concrete columns.

INTRODUCTION

In Japan, the construction of tall reinforced concrete framed buildings of up to 30 stories has been increasing in recent years. These structures utilize the concrete of specified strength (Fc) ranging up to 420kg/cm^2. And the concrete strength for tall buildings tends to be increased as the number of stories increases. This paper presents the results of two types of test, a uni-axial compression test and a lateral loading test, of high strength concrete columns (Fc=600~800kg/cm^2) whose lateral reinforcement has the yield strengths ($_w\sigma_y$) of 3200, 8500 and 14000kg/cm^2. Emphasis was put on the use of high and ultra-high strength reinforcing bars so as to effectively confine the high strength concrete whose behavior becomes more brittle as the strength increases. The main objectives of these two tests were to determine the seismic behavior of high strength concrete columns and to obtain guidelines for the design of such members to be used for high-rise buildings.

UNI-AXIAL COMPRESSION TEST

Test specimens Seven column units with 25cm × 25cm cross section, as shown in Fig.1, were tested under monotonic uni-axial compression up to failure. The area ratio of longitudinal reinforcement was 2.44%. The variables were

1) the compressive strength of the concrete (Fc=400,600 and 800 kg/cm^2)
2) the full capacity of lateral reinforcement which is defined as the product $P_w * {}_w\sigma_y$, where Pw is the area ratio of lateral reinforcement and $_w\sigma_y$ is its yield strength.

The amount of lateral reinforcement in each unit is shown in Table 1. The mechanical characteristics of concrete and reinforcing bars are shown in Tables 2 and 3, respectively. Lateral reinforcement was arranged so as to restrain each longitudinal reinforcement against buckling, as shown in Fig.1. It should be

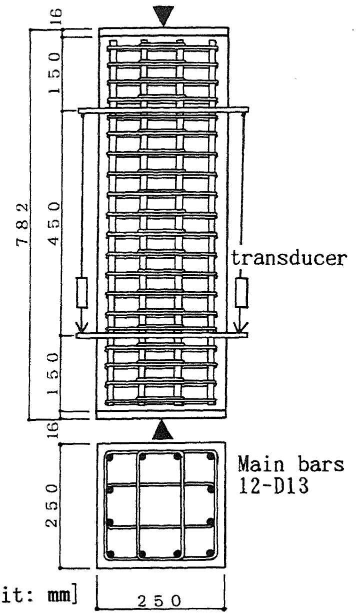

Fig.1 Unit for Uni-Axial Compression Test

Table 1 Units for Uni-Axial Compression Test

*1 : unit(kg/cm²)

Unit No.	Fc *1	$_w\sigma_y$ *1	Pw (%)	Pw $_w\sigma_y$ *1	$\frac{Pw\ _w\sigma_y}{Fc}$	Lateral reinf.
1	400	8490	0.57	48.4	0.121	4-5φ @55
2		8490	1.14	96.8	0.242	4-5φ @27.5
3	600	3210	1.01	32.4	0.054	4-D6 @50
4		8490	0.78	66.2	0.110	4-5φ @40
5		13880	0.70	97.2	0.162	4-U5.1φ @45
6	800	8490	0.90	76.4	0.096	4-5φ @35
7		13880	0.90	124.9	0.156	4-U5.1φ @35

Fc: Specified compressive strength of concrete
Pw: Area ratio of lateral reinf.
$_w\sigma_y$: Yield strength of lateral reinf.
* The ratio of total area of longitudinal reinforcement to area of concrete section in all unit is 2.44% .

Table 2 Mechanical charactaristics of concrete

*1 unit(kg/cm²)

	Fc *1	$_c\sigma_b$ *1	$E_{1/3}\,{}_c\sigma_b$ (10^5kg/cm²)	σ_t *1
Sealed Cylinders 20cm high* 10cm dia.	400	353	3.31	27
	600	680	3.90	34
	800	861	4.19	43

$_c\sigma_b$:Measured compressive strength of concrete
$E_{1/3}\,{}_c\sigma_b$: Secant Modulus of concrete at $_c\sigma_b/3$
σ_t :Measured splitting tensile strength

Table 3 Mechanical Charactaristics of Steel Bars

of steel bars *1 unit(kg/cm²)

Type of Steel Bars		σ_y *1	σ_u *1	ε_u (%)
Longit. Reinf.	Deformed Bar D13	4120	6116	17.5
Lateral Reinf.	Deformed Bar D 6	3211	4711	21.9
	High Strength Bar 5φ	8490	9290	13.1
	Ultra-High Strength Bar U5.1φ	13882	14315	7.5

σ_y : Yield strength of steel bars
σ_u : Tensile strength of steel bars
ε_u : Elongation

noted that all hoop steel of both deformed bars and high strength bars was butt-welded. For ultra-high strength bars, outer (perimeter) square spiral hoops and inner hoops with 135° bends extending for 8 bar diameters were provided.

Test results Table 4 gives the test results and Fig.2 shows the relationship between the axial compression load and the average axial strain of the columns. Increase of the compression load stopped when the cover concrete began to spall out. After that the yielding of lateral reinforcement started. The yielding of longitudinal reinforcement came out before the cover concrete spalled out, except for the units 1 and 2. The load-strain relationship of each test unit (see Fig.2) shows that the degree of descending in the load carry capacity was significantly affected by the full capacity of lateral reinforcement (Pw*$_w\sigma_y$). While the increase of maximum strength with the full capacity of lateral reinforcement was minimal.

Fig.3 shows the relationship between the full capacity of lateral reinforcement (Pw*$_w\sigma_y$) and compression ductility. This is represented as the ultimate compressive fiber strain (ε_{cu}') as proposed by Muguruma (Ref.1). The compression ductility increased in proportion to the full capacity of lateral reinforcement,

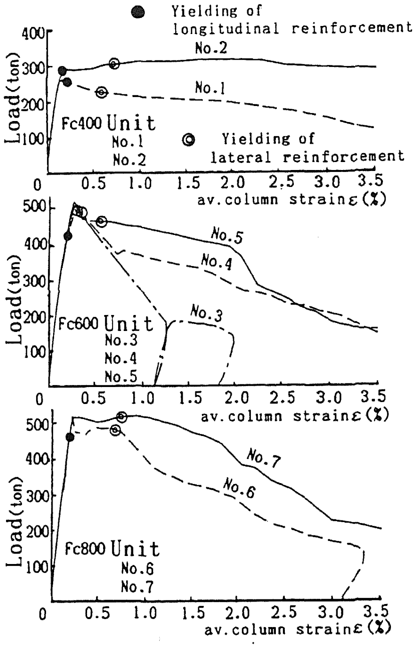

Fig.2 Relationship between Axial Compressive Load and Average Axial Strain of the Columns

Table 4 Test Results of Uni-Axial Compression Test

Unit No.	At Yielding of Longi. Reinf.		Maximum Strength		At Yielding of Lateral Reinf.	
	Load (ton)	ε_{av} (%)	Load (ton)	ε_{av} (%)	Load (ton)	ε_{av} (%)
1	257	0.24	266	0.18	228	0.60
2	292	0.22	317	1.63	304	0.70
3	420	0.20	498	0.30	498	0.30
4	440	0.20	508	0.28	491	0.34
5	431	0.19	519	0.27	463	0.55
6	470	0.19	519	0.22	481	0.69
7	460	0.19	519	0.90	516	0.75

ε_{av} : Average axial strain of the columns

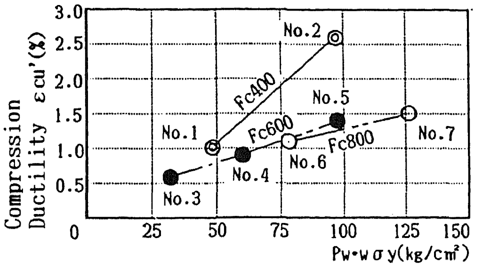

Fig.3 Relationship between the Full Capacity of Lateral Reinforcement and Compression Ductility

but this tendency became gradual as the concrete strength increased. Therefore, it was indicated that the full capacity of lateral reinforcement must be increased in proportion to the concrete strength to obtain equal compression ductility.

LATERAL LOADING TEST

Test specimen Eight column units with the same cross section and materials as those used in the uni-axial compression test were provided. Fig.4 shows the details of the test unit. The ratio of shear span length to column depth was 2.0 for all unit. The variables were also

1)the compressive strength of concrete (Fc=400,600 and 800kg/cm²),
2)the full capacity of lateral reinforcement (Pw*wσy) and
3)the ratio of axial stress to specified compressive strength of concrete (0.3 and 0.55).

Table 5 gives variables for each unit and the nominal shear stresses (τmu) calculated from the flexural strengths of the columns. The flexural strengths of the columns were determined by using Abe's empirical equations (Ref.2). The full capacities of lateral reinforcement of the units 1, 2, 3, 5, and 7 were determined so as to be approximately equal to the nominal shear stresses attained in each unit, respectively. The unit 4 had the full capacity of lateral reinforcement almost half times the nominal shear stress, while the units 6 and 8 had those 1.5 times the nominal shear stress. Reversed cyclic horizontal load was applied to each unit while the axial load was held constant.

Test results Table 6 gives the main test results. Fig.5 shows a comparison of measured horizontal load-displacement loops. The units 1 (Fc600) and 2 (Fc800),tested under the lower ratio of axial stress to specified compressive

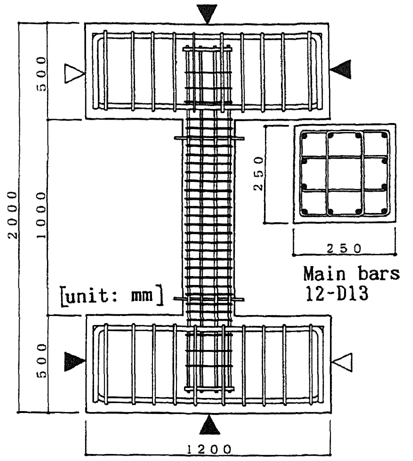

Fig.4 Unit for Lateral Loading Test

Table 5 Test Units for Lateral Loading Test

*1 : unit(kg/cm²)

Unit No.	Axial Load Ratio	Fc *1	τmu *1	wσy *1	Pw (%)	Pw·wσy *1	Lateral Reinforcement
1	0.30	600	62.0	8490	0.70	59.4	4-5φ @45
2		800	77.6	8490	0.90	76.4	4-5φ @35
3	0.55	400	46.8	8490	0.57	48.4	4-5φ @55
4		600	62.8	3210	1.01	32.4	4-D6 @50
5				8490	0.78	66.2	4-5φ @40
6				13880	0.70	97.2	4-U5.1φ @45
7		800	78.4	8490	0.90	76.4	4-5φ @35
8				13880	0.90	124.9	4-U5.1φ @35

Axial load ratio : Ratio of axial stress to specified concrete strength.
τmu: Shear stress calculated by Abe's empirical equation(Ref.2)
Remarks) Materials of units are the same as Tables 2 and 3 .

Table 6 Test Results of Lateral Loading Test

Unit No.	σo (N/BD) *1	cσB *2 *1	ηo $\frac{\sigma o}{c\sigma B}$	Yielding of Longit. Reinf.*3 *4 P *5	R *6	Failure Mode	Maximum Strength *3 Pmax *5	τmax *1	R *6
1	210	680	0.31	28.2	5.0	F	34.0	69.8	10.0
2	240	861	0.28	32.3	5.0	F	36.1	74.1	7.6
3	211	353	0.60	21.1	3.9	FC	22.1	45.4	7.5
4	386	680	0.57	19.2	2.1	FC	37.2	76.4	7.5
5	386	680	0.57	21.4	2.2	FC	36.5	74.9	7.7
6	386	680	0.57	25.1	3.0	FC	36.1	74.1	6.3
7	440	861	0.51	27.1	2.6	FC	35.8	73.5	5.0
8	440	861	0.51	31.0	3.4	FC	38.0	78.0	5.0

*1 : kg/cm² *2 : Values of Table 2 are used.
*3 : Values of Positive Loading *4 : Values at compression yielding.
*5 : ton *6 : /1000rad. F: Flexural failure FC: Flexural compression failure

strength of concrete (0.3), exhibited excellent ductility, the energy dissipating capability and the lateral load carrying capacity up to the displacement angle exceeding 5%. On the other hand, all other units, tested under high axial compressive stress of 55% of the specified concrete strength, behaved in less ductile manner when compared with units 1 and 2. The failure mode for units 1 and 2 was flexural failure , and for all other units it was flexural compression failure. The units 3 (Fc400), 5 (Fc600) and 7 (Fc800), had almost the same ratio of the full capacity of lateral reinforcement to the nominal shear stress of the column (Pw*wσy/τmax=1.0) and the same ratio of axial stress to the specified concrete strength (0.55), but different concrete strength. These units had almost the same ultimate displacement angle(Ru, approximately 2%) at which 80% of maximum lateral load was sustained. Comparing the units 4, 5 and 6 having the same concrete strength (Fc600) but different full capacity of lateral reinforcement, it was observed that the displacement ductility increased in proportion to the full capacity of lateral reinforcement. The same effect was also observed in comparison between the units 7 and 8 (Fc800).

The strain of lateral reinforcement of the units 1 and 5 of Fc600 is shown in Fig.6. The units 1 and 5 had almost the same ratio of the full capacity of lateral reinforcement to the nominal maximum shear stress (Pw*wσy/τmax), but were tested under lower and higher axial forces, respectively. The strain of lateral reinforcement of the unit 5 exceeded the yield strain at a displacement angle of 3%, while no yielding of the lateral reinforcing bar of the unit 1 was observed during the test. The displacement at which lateral reinforcing bars began to yield agreed with the displacement at which hysteresis loops became unstable not being able to carry the axial force. This shows the significant effect of the full capacity of lateral reinforcement on the ductility of columns, particularly under high axial force. It was also indicated that the strength of high strength lateral reinforcing bars was fully utilized.

The measured maximum strength in each unit was larger than the calculated flexural strength using the equation of AIJ code (Ref. 3) and Abe's empirical equations, particularly in the units tested under higher axial force. The relationship between the full capacity of lateral reinforcement normalized by measured concrete strength (Pw*wσy/cσb) and the ultimate displacement angle (Ru) is shown in Fig. 7. It was indicated that the ultimate displacement angle increased in proportion to the full capacity of lateral reinforcement in both units of Fc600 and Fc800. To obtain ductility up to the displacement level of 2% under the high axial compression stress of about 60% of the concrete strength, the full capacity of lateral reinforcement normalized by concrete strength (Pw*wσy/cσb) must be more than 0.1.

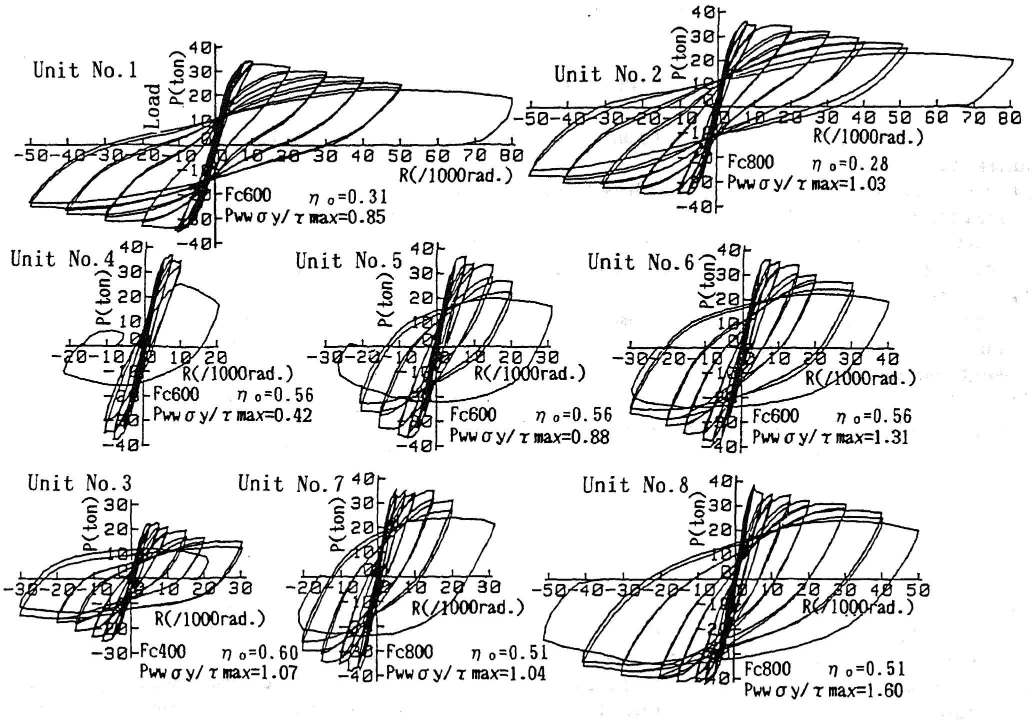

Fig.5 Comparison of Measured Holizontal Load-Displacement Loops

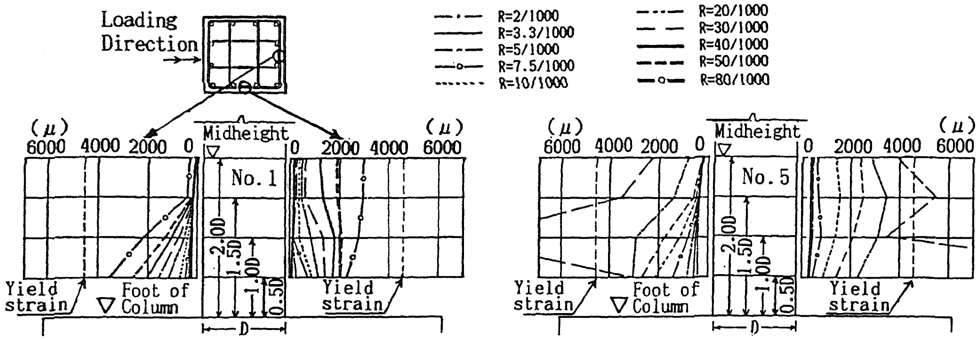

Fig. 6 Strain of Lateral Reinforcement

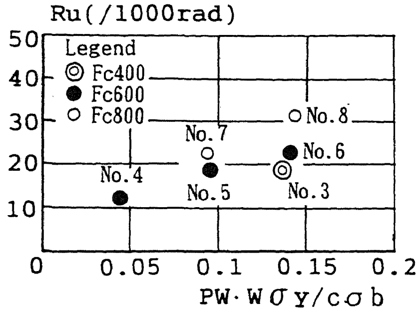

Fig. 7 Maximum Ultimate Disp. (Ru) versus the Full Capacity of Lateral Reinf. Normalized by Concrete Strength (Pw * wσy/ cσb)

CONCLUDING REMARKS

The results obtained from the tests on high strength concrete columns are summarized as follows.

1) The use of high or ultra-high strength steel bars is quite effective in confining high strength concrete up to 800kg/cm². Therefore, it is suggested that for high strength concrete columns subjected to high axial compression load, high or ultra-high strength lateral reinforcement should be utilized.
2) To ensure the ductile behavior of high strength concrete columns, the full capacity of lateral reinforcement (Pw*wσy) must be increased in proportion to the concrete strength, in other words, the full capacity of lateral reinforcement normalized by concrete strength (Pw*wσy/cσb) must be constant.
3) To obtain the ductility up to the displacement level of 2% under the high axial compression stress of 60% of concrete strength, the full capacity of lateral reinforcement normalized by concrete strength (Pw*wσy/cσb) must be more than 0.1 .

REFERENCES

1. H.Muguruma, 'On the Compressive Fiber Strain of Concrete at the Flexural Failure of Reinforced Concrete Beam Section' Journal of the Society of Materials Science, Japan, Vol.24, No.260, May 1975
2. K.Abe, 'A Proposition of Equations to Calculate Ultimate Bending Strength about the Principal and the Diagonal Axes of Reinforced Concrete Columns under All Range of Axial Force', CONCRETE JOURNAL, Vol.23, No.9, Sept.1985, Japan Concrete Institute (JCI No.240)
3. 'Standard for Structural Calculation of Reinforced Concrete Structure (in Japanese)', Architectural Institute of Japan, 1982.