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Experimental studies on seismic behavior of reinforced concrete columns strengthened with NCS unit

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ABSTRACT : For improved deformation capacity of reinforced concrete columns subject to high axial compression stress, the authors developed columns strengthened with NCS unit. An NCS unit is a closed steel spring with a concrete core. An experimental study was carried out to investigate the seismic behavior of reinforced concrete columns strengthened with NCS unit. Result indicated that NCS unit was very effective at improving the deformation capacity of reinforced concrete columns subject to high axial compression stress.

1 INTRODUCTION

In recent years, there has been successful construction of 30 story high-rise reinforced concrete buildings in Japan. In these buildings, the exterior columns at the first story are subject to high axial compressive stresses, and at the bottom portion of these columns plastic hinges would be formed in severe earthquakes. It is necessary for these columns to have ductility in addition to strength. For improved deformation capacity, the authors developed columns strengthened with NCS(Non Clearance Spring) unit. An NCS unit is a closed steel spring with a concrete core, as shown in Fig.1. The structural characteristics of NCS unit are as follows.

1) Compressive strength and ductility are very high because of the confining action of the heavy spiral spring.

2) Tensile strength is almost equal to tensile strength of the core concrete.

By strengthening the reinforced concrete column with the NCS units, as shown in Fig.1, the compressive capacity and ductility of column can be increased but the flexural capacity remains unchanged since an NCS unit is resisting the compression force only. This paper presents the results of three types of test, a uni-axial compression test for NCS units, a uni-axial compression test and a lateral loading test for reinforced concrete columns strengthened with NCS units. The main objectives of these tests are to investigate the seismic behavior of reinforced concrete columns with NCS units.

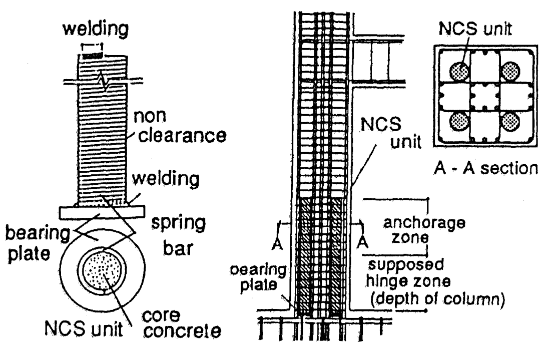

Fig.1 NCS Unit
and Column Strengthened with NCS Units

2 UNI-AXIAL COMPRESSION TEST FOR NCS UNITS

2.1 Test specimens

Table 1 gives variation for each unit and measured strength of concrete and spring bars.

Table 1 Units for Uni-Axial Compression Test

specimen's name	D' (mm)	p_s (%)	scale	σ_B (N/mm²)	d (mm)	σ_y (N/mm²)
A−1	53.9	27.7	1/3.25	45.4	φ5	436.6 (468.8)
A−2				54.8		
A−3				68.5		
B−1	53.9	27.7		22.8	φ5	465.4 (479.3)
B−2	44.8	32.7		41.8		
B−3	53.9	27.7				
B−4						
B−5	62.4	24.1				
B−6	53.9	27.7		61.9		
C−1	148	31.7	1/1	43.0	φ16	418.8 (397.5)
C−2	176	27.0				
C−3						258.5 (397.5)
C−4		—		—		418.8 (453.0)
C−5	202	23.7		43.8		

INDEX D' : diameter of NCS unit d : diameter of spring bar
p_S: area raito of spring bar σ_y: yield strength of spring bar
σ_B : compressive strength of core concrete

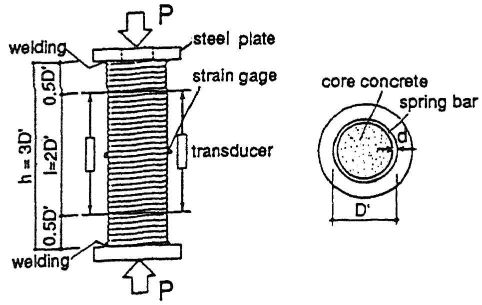

Fig.2 Column Strengthened with NCS Units

Fig.2 shows the details of the test unit.
The main variables are
1) the area ratio of spring bar (ps=24.1～32.7%) and
2) compressive strength of core concrete(σ_B=22.8～68.5N/mm^2).
The diameter of spring bar(d) was constant for each series. The area ratio of spring bar(ps) was changed by changing the diameters of NCS unit(D'). All units except for B-4 were tested under monotonic uni-axial compression up to failure. B-4 unit was tested under cyclic uni-axial compression.

2.2 Test results

As the typical pattern, the relationship between the axial compression stress and the average axial strain of B series units was shown in Fig.3. The measured maximum compressive stress of all

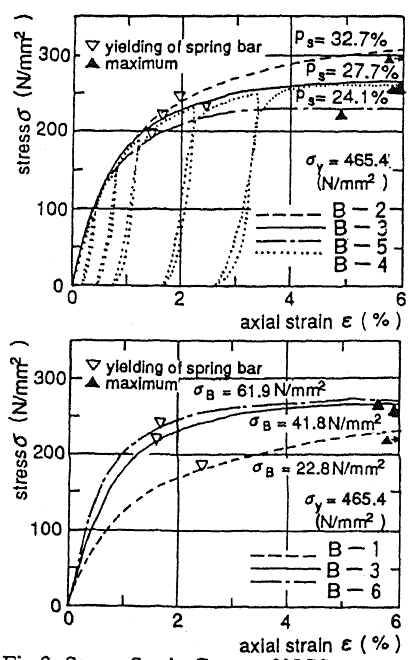

Fig.3 Stress-Strain Curve of NCS unit

units were very large, exceeding 200N/mm^2. NCS units with larger ps and σ_B demonstrated larger maximum compressive capacity as shown in Fig.3. All units exhibited excellent ductility and the compressive load carrying capacity up to the axial strain exceeding 6%. NCS unit and core concrete had almost the same stress-strain curve up to the stress 2/3 σ_B. On the other hand, there was no marked difference on skeleton curve between the monotonic loading(B-3) and cyclic loading(B-4).

3 UNI-AXIAL COMPRESSION TEST FOR COLUMNS

3.1 Test specimens

The column specimens are listed in Table 2. The mechanical characteristic of reinforcing bars and concrete are shown in Table 3 and 4, respectively. Three column specimens with 292mm×292mm cross section were tested under monotonic uni-axial compression up to failure. Two specimens were strengthened with NCS unit of different diameter and a third was without. The area ratio of NCS unit to column cross section of specimen C2 and C3 are 9.8% and 12.8%, respectively. All hoop steel of column was butt-welded

Table 2 Specimens for Uni-Axial Compression Test

specimen's name	C 1	C 2	C 3
section of specimens			
area ratio of NCS units	0	9.8 %	12.8 %
diameter of NCS units	0	ϕ 45	ϕ 53

common factor
B x D : 292mm x 292mm
main reinforcement : 24-D13 (pg=3.57%)
lateral reinforcement : 4-D6@39 (pw=1.12%)
spring bar of NCS units : ϕ 5

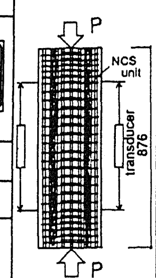

Table 3 Mechanical Charactaristics of Steel Bars

bar size	yield strength (N/mm^2)	tensile strength (N/mm^2)	young's modulus (×10^5 N/mm^2)	note
D13	397.7	596.7	1.92	main reinf.
D 6	364.9	521.0	1.96	lateral reinf.
ϕ 5	465.5	479.3	2.14	NCS units

Table 4 Mechanical Charactaristics of concrete

part of placing	compressive strength (N/mm^2)	young's modulus (×10^4 N/mm^2)
column specimens	48.7 ～ 49.0	2.88 ～ 3.20
NCS units	39.9	3.02

3.2 Test results

The relationship between the axial compression stress and the average axial strain of the column is shown in Fig.4. Increase of the compression load stopped when the cover concrete began to spall out. After that , the yielding of lateral reinforcement and spring bar of NCS unit started. The stress-strain relationship of each specimen shows that, by strengthening reinforced concrete columns with NCS units, the compression ductility was improved remarkably and the maximum compressive capacity increased. This trend became more marked as the diameter of NCS unit increased.

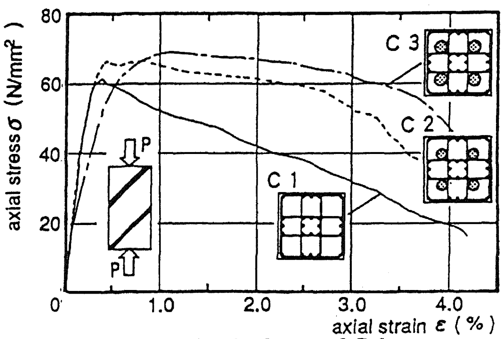

Fig.4 Stress-Strain Curve of Columns

4 LATERAL LOADING TEST FOR COLUMNS

4.1 Test specimens

Table 5 gives variables for each specimens. Eleven column specimens with the same cross section and materials as those used in the uni-axial compression test for columns were provided. The main variables were

1) strengthening with NCS units or non NCS units,
2) the ratio of axial load to maximum compressive capacity of column as determined by ACI code (η =0.35, 0.50, 0.65, 0.80),

Table 5 Specimens for Lateral Loading Test

specimen's name	N (kN)	η	h_0/D	direct. of load	D' (mm)	common factor
C50	2128	0.50	5.0	main	—	scale : 1 / 3.25
C65	3079	0.65				b x D = 292 x 292 mm
C65a	2922	0.65	2.2			main reinf. 24 - D13 pg = 3.57%
C80	3472	0.80	5.0			
SC35	1628	0.35	5.0	main	ϕ53	hoops 4 - D6 @39 pw = 1.12%
SC50	2128	0.50				
SC65	3079	0.65				
SC65a	2922	0.65	2.2		ϕ53	length of NCS unit
SC65b	3079	0.65	5.0	dia.	ϕ53	h_0/D =5.0 l=584mm
SC65c				main	ϕ45	h_0/D =2.2 l=642mm
SC80	3472	0.80			ϕ53	

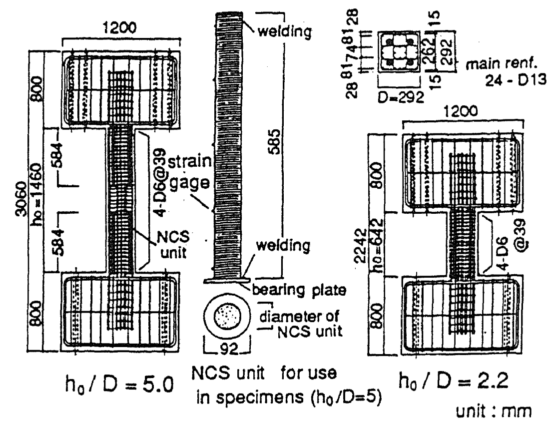

Fig.5 Column Specimens

Table 6 Mechanical charactaristics of concrete

specimen's name	compressive strength (N/mm²)	young's modulus (×10⁴ N/mm²)
C65, SC65c SC65, SC65b	50.5	3.04
C65a, SC65a	46.6	3.07
C50, SC50	43.6	3.12
C80, SC80	44.7	3.14
SC35	49.0	2.88
NCS units	41.8	3.71

3) column height-depth ratio(h_0/D=2.2,5.0) and
4) the area ratio of NCS units to column cross section (Pncs= 9.8%, 12.8%).

Fig.5 shows the detail of the specimen. The mechanical characteristic of concrete at the test days are shown in Table 6. The specimen, with h_0/D=5, was strengthened at both ends to a distance of the twice column depth (2D) with four NCS units. Reversed cyclic lateral loads were applied to each specimen while the axial load was held constant.

4.2 Test results

Fig.6 shows comparison of skelton curve of column specimen with and without NCS units. The failure mode for all specimens with column height-depth ratio h_0/D=5.0 was flexural compression failure. Both column specimns with NCS unit and without NCS unit behaved in less ductile manner as the axial load ratio increased. The column specimens with NCS units exhibited excellent ductility, energy dissipating capability and lateral load carrying capacity, up to the high axial load ratio η =0.80. The column specimen without NCS unit behaved in much less ductile manner as compared with the specimen with NCS units under the same axial load. The NCS unit was very effective at improving the ductility of the reinforced concrete column which failed with flexural compression failure mode under the high axial load. Improvement on deformation capacity by strengthening with NCS unit became remarkable as the axial load ratio increased. On the other hand, the failure mode for specimen C65a and SC65a with ho/D=2.2 was shear failure. There was no remarkable difference for the skeleton curve between the specimen C65a and SC65a. It is indicated that the NCS unit was less effective for the column which failed with shear failure mode.

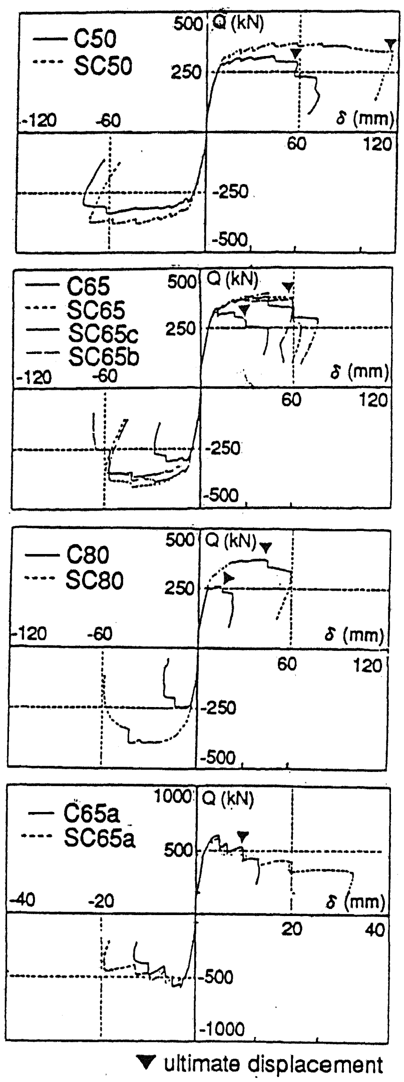

Fig.6 Skeleton Curve of Columns

Fig.7 shows the relationship between the axial load ratio and ultimate displacement angle at which 80% of maximum lateral load was sustained. The deformation capacity of column specimens, both with NCS units and without NCS units, decreased as the axial load ratio increased. The ultimate displacement of the column specimens with NCS units was almost

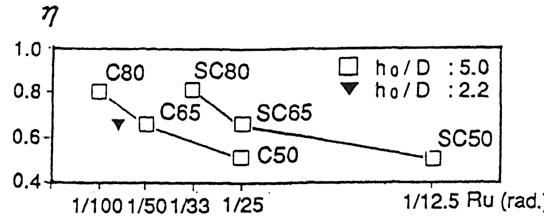

Fig.7 Relationship between Axial Load Ratio and Ultimate Displacement Angle

twice that of the column specimens without NCS units.

Fig. 8 shows the relationship between the axial shortening and lateral displacement of column specimen C65 and SC65. Axial shortening of the column specimen with NCS units under repeated lateral load was smaller than that of column specimen without NCS units. It is suggested that the ability to sustain axial force was improved by strengthening the reinforced concrete column with NCS units.

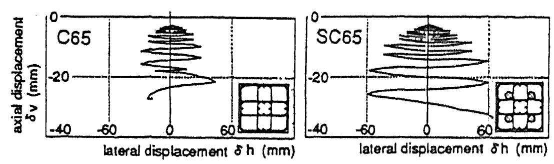

Fig.8 Relationship between Axial Shortening and Lateral Displacement

5 CONCLUDING REMARKS

The results obtained from the test on NCS units and reinforced concrete column strengthened with NCS units are summarized as follows.

1) The maximum compressive capacity of NCS units are very large, exceeding 200N/mm^2, and behavior is extremely ductile.

2) By strengthening reinforced concrete column with NCS units, the compression ductility of columns can be improved remarkably and the maximum compressive capacity increases.

3) NCS unit is very effective at improving the earthquake resistant capacity of reinforced concrete columns subject to high-axial compression stress.

4) Hence forth, we intend to study the application of NCS unit to the high-rise multistory shear wall and prestressed concrete members subject to high-axial compressive stress.

REFERENCES

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