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SEISMIC PERFORMANCE OF COMPOSITE COLUMNS USING CORE STEEL UNDER VARYING AXIAL LOAD

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SUMMARY

As recent damages by earthquakes, there observed many piloti type buildings which have soft 1st story where the top and bottom of 1st story columns ruptured in flexural mode and their main bars buckled.
To prevent such rupture, it is necessary to improve the deformation performance of 1st story columns of new piloti type buildings so that their top and bottom can hold against axial load even after their yields in bending during earthquake.
In this research, therefore, we have studied experimentally on the upgrading effect of deformation performance and axial load carrying capacity for RC columns by adding a core steel.

INTRODUCTION

In the recent damages of the piloti type buildings which have soft 1st story by earthquakes, there observed many cases where the top and bottom of 1st story columns ruptured in flexural mode and their main bars buckled even though they have been constructed in accordance with latest building codes (later than 1981).
To prevent such rupture, there is a demand to develop a design method that can improve the deformation performance of 1st story columns of new piloti type buildings so that their top and bottom can hold against axial loads even after their yields in bending during earthquake as well as enable their continuous use after earthquakes. To hold against axial loads of 1st story columns even with yield in bending at their top and bottom, it is necessary to upgrade the horizontal deformation performance of the columns. Since the overturning moment of a whole building by horizontal load concentrates at 1st story columns, it seems that their axial loads increase.
In this research, therefore, we carried out a series of tests to study on the upgrading effect of deformation performance and axial load carrying capacity for RC columns by adding a core steel.

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TRIAL DESIGN

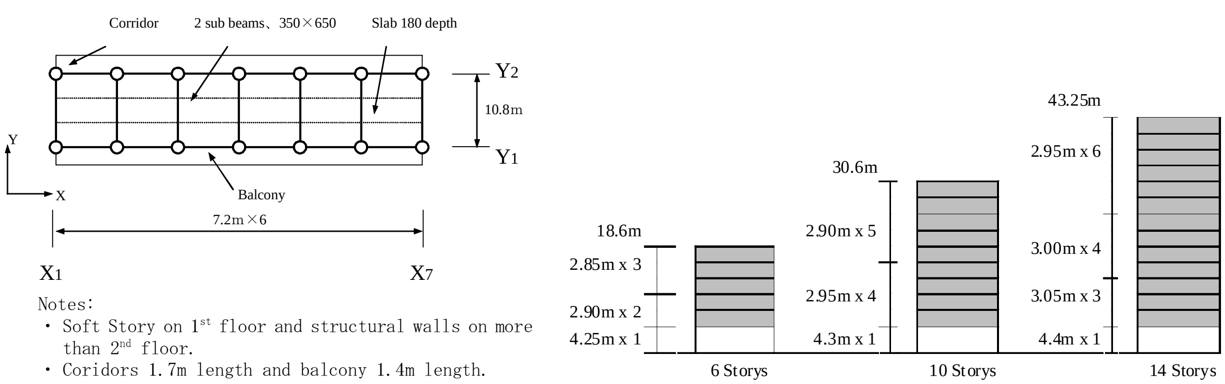
For trial design of the piloti type buildings, we decided as our design criteria to comply with two Standards: old one and the amended one after Kobe Earthquake. According to the amended Standard, it is required to provide a rupture pattern that prevents 1st story columns of the piloti type building from yield in bending. As shown in Table 1, a design Standard on axial strength, flexural failure mode and shear failure mode is introduced.

When we made trial designs for a model building shown in Figure 1 according to our design criteria, the items were determined as shown in Table 2 for 1st story columns of a 14-story piloti type building. In the case of trial design based on the amended standard, it is required to make its section bigger and its reinforcement bars more as well as to use stronger materials in comparison with those designed according to the old standard. The resulting axial load ratio (load-to-strength) are 0.53 at compression side and -0.89 at tension side for the old one as well as 0.40 at compression side and -0.40 at tension side for the amended one.

Table 1 Design criteria of piloti column

	Before Kobe earthquake	After Kobe earthquake
Axial strength	・$-N_{UT} \leqq N_m \leqq 0.55 N_{UC}$	・$-0.75 N_{UT} \leqq N_m \leqq 0.55 N_{UC}$
Flexural failure mode	—	・For tensile column, $M_u > 1.0 M_m$ ・For compressive column, $M_u \geqq 1.2 M_m$
Shear failure mode	・$Q_{su} \geqq 1.1 Q_m$	・$Q_{su} \geqq 1.4 Q_m$ ・$Q_{su} \geqq$ (Q when column top and bottom moments are max.)

Notes)
N_{UT}: Ultimate axial strength in tensile.
N_{UC}: Ultimate axial strength in compressive.
Mu: Ultimate flexural moment
Mm: Moment by load
Qsu: Ultimate shear strength
Qm: Shear force by load



(1)Plan **(2)Elevation**

Fig. 1 Model Building

Table 2 Column on soft 1st story of 14 stories model building

(1)Design by the code before 1995

Story	Section	Main bars	Stirrup
1	1,200×1,200	X10-D29/Y9-D29	10/12-D13@100
		pt=0.42% in Y direction	pw=1.27%

Notes) Concrete strength Fc=33 N/mm², Steel bar type of D25 is SD390, Steel bar type of D13 is non-nominal and has yield strength of 685 N/mm²

(2)Design by the code after 1995

Story	Section	Main bars	Stirrup
1	1,300×1,300	X12-D32/Y13-D32	10/12-D13@100
		pt=0.61% in Y direction	pw=1.27%
		＋Composite steel bars 8-D32	

Notes) Concrete strength Fc=36 N/mm², Steel bar type of D32 is SD390, Steel bar type of D13 is non-nominal and has yield strength of 1,300 N/mm²

Table 3 Specimen Overview

(Columns on soft 1st story of 14 stories, Scale:1/3)

Specimen	Section	Main bars	Stirrup
RC (Model building desined by old code)	400×400 Fc=33	X5-D16 ／Y4-D16 SD390	4-UHD6@50 4-UHD6@50 SHD685
		pt=0.52% in Y direction	pw=0.64%
SRC1 (Specimen RC + BH-125- 125)	Same as the above and Build-up H Shaped Steel(BH)-125×125×20×20 (SS400) Steel area ratio=4.19%		
SRC2 (Decreased Stirrup ratio of SRC1)	〃	〃	2-UHD6@40 2-UHD6@40 SHD685 pw=0.40%
	BH is same as the above		

Notes)
1.UHD6 is the diameter 6 mm steel bar of Type SHD685.
2.SHD685 has material property of 685N/mm² yield strength

SPECIMEN

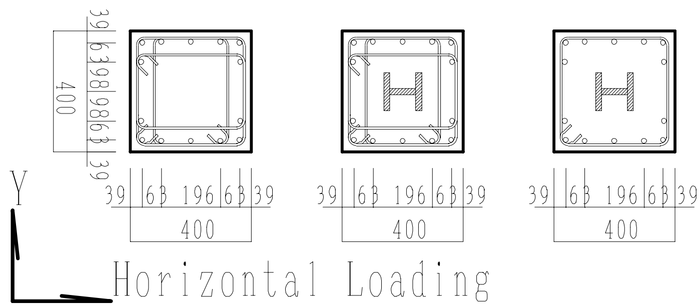
As specimens for this test, we referred to 1st story column of 14-story piloti type building determined in the preceding section "Trial Design" according to the old standard before amendment. We have prepared three specimens (Table 3): RC specimen, SRC1 specimen (RC plus core steel) and SRC2 specimen (SRC1 minus stirrup ratio).

We set the specimen size to 1/3 to reduce a maximum axial load of 24,703kN at 1st story column at specific horizontal yield strength to be accommodated by the loading devise of 4,000kN. The section size: 400X400, concrete material: Fc=33, main bar: D16(SD390) are common in all three specimens. X-Y direction of the specimens indicated in Table 3, Figure 2 and Figure 3 are different from that of Figure 1 for trial design. The loading direction of specimens (X-direction in Figure 3) corresponds to the span direction in the trial design (Y-direction in Figure 1).

We calculated the ultimate flexural strength and the ultimate shear strength (Table 4, Table 5) for one RC specimen in accordance with the part of Reinforced Concrete Buildings in Guidelines of Building Structural Codes[1] as well as for two SRC specimens as added strength of two parts of RC and core steel in accordance with AIJ Standard for Structural Calculation of Steel Reinforced Concrete Structures [2]. For rupture mechanisms of specimens, we assumed all as flexural rupture. To enable the RC specimen easily rupture in shearing along with increase in horizontal drift, we decreased the stirrup ratio to pw=0.64% from pw=1.27% in its trial design.

The core steel section size is about a size of about 1/3 of the column section and a build-up steel:BH-125×125×20×20. Since the axial load carrying capacity deteriorates when the axial strength ratio of core steel (axial load / core steel axial stength) is too big, we preferred a bigger section area and selected SS400 for its material. As a result, the core steel area ratio (percentage area of core steel against column section) is set as pa=4.19% as well as the axial strength ratio of core steel alone (axial load / core steel axial strength) are set to 1.74 during compression and -0.59 during tension. Compared with the existing test [3] of RC column using core steel, the core steel area ratio is large enough. Since the axial strength ratio of core steel alone is also large, however, there seems a possibility that this core steel cannot hold against axial load during large drift.

As to the stirrup, we adopted the same arrangement of 4-UHD6@50 (SHD685) for both the RC and SRC1 specimens for comparison purpose. We also set the stirrup arrangement of 2-UHD6@40 (SHD685) for the SRC2 specimen to check the validity for the upper limit of the stirrup ratio pw=0.6% specified in the SRC Standard [2].
Table 6 and Table 7 show material properties.



(1)RC (2)SRC1 (3)SRC2

Fig. 2 Sections of Specimens

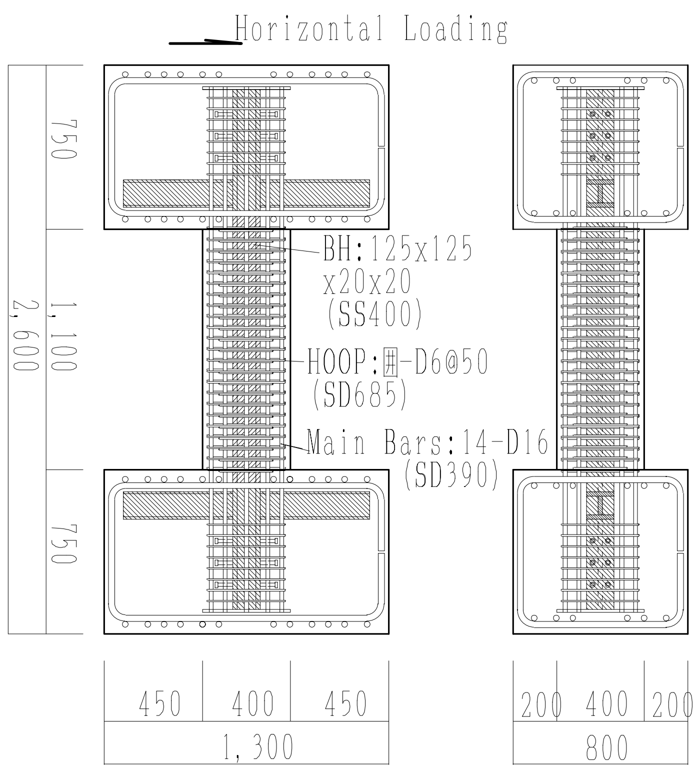


Fig. 3 Elevation of Specimen SRC1

Table 4 Ultimate Strengths of Specimens

(1)Under Compressive Axial Load

Specimen	Qmu (kN)	Qsu,min (kN)	Qsu,min ／Qmu	τ (N/㎜ ^{2}) at Qmu	τ (N/㎜ ^{2}) at Max. lateral load of model design
RC	513	600	1.17	3.21	
SRC1	648	743	1.15	4.05	3.99
SRC2	648	658	1.01	4.05	

Notes)

Equations of ultimate strengths for Specimen RC

Qmu(Flexural ultimate strength)

$$M_u=\{0.5a_g\cdot\sigma_y\cdot g_1\cdot D+0.024(1+g_1)(3.6-g_1)b\cdot D^2\cdot F_c\}\left(\frac{N_{max}-N}{N_{max}-N_b}\right)$$

Qsu,min(Shear ultimate strength)

$$Q_{su}=\left\{\frac{0.053{p_t}^{0.23}(F_c+18)}{M/(Q\cdot d)+0.12}+0.85\sqrt{p_w\cdot\sigma_{wy}}\right\}b\cdot j$$

(2)Under Tensile Axial Load

Specimen	Qmu (kN)	Qsu,min (kN)	Qsu,min ／Qmu	τ (N/㎜ ^{2}) at Qmu	τ (N/㎜ ^{2}) at Max. lateral load of model design
RC	35	317	9.08	0.22	
SRC1	77	743	9.65	0.48	0.25
SRC2	77	658	8.55	0.48	

Equations of ultimate strengths for Specimen SRC1 and SRC2

Qmu(Flexural ultimate strength)

$$ {}_sZ_p\cdot{}_s\sigma_Y \text{、} \quad {}_m a_t\cdot{}_m\sigma_Y\cdot{}_m d+\frac{{}_rN_U\cdot D}{2}\left(1-\frac{{}_rN_U}{{}_cr_U\cdot F_c\cdot bD}\right)$$

Qsu,min(Shear ultimate strength)

$${}_rQ_{sU1}=b\cdot{}_rj(0.5F_s\cdot{}_r\alpha+0.5{}_wp\cdot{}_w\sigma_Y)$$

$${}_rQ_{sU2}=b\cdot{}_rj\left(F_s\frac{b'}{b}+{}_wp\cdot{}_w\sigma_Y\right)$$

Table 5 (1)Compressive Axial Strengths

Specimen	Axial strength (kN)	Axial load (kN)	Load／Strength	Load／Strength of BH	Load/Strength of model design
RC	5178		0.53	—	
SRC1	6755	2745	0.41	1.74	0.53
SRC2	6755		0.41	1.74	

Table 5 (2)Tensile Axial Strengths

Specimen	Axial strength (kN)	Axial load (kN)	Load／Strength	Load／Strength of BH	Load/Strength of model design
RC	-1093		-0.85	—	
SRC1	-2670	-933	-0.35	-0.59	-0.89
SRC2	-2670		-0.35	-0.59	

Table-6 Material Property of

Type	σc	Ｅc	εc
Fc33	43.6	3.06	2,167

Notes) σc: Compressive Strength (N/㎜ ^{2})

Ｅc : Young's modulus $\times 10^4$(N/㎜ ^{2})

εc : Strain at σc $\times 10^{-6}$(㎜/㎜)

Table 7 Material Property of Steel Bar and Steel Plate

Type	σt	Ｅs	εs	σo
Bar:	683	1.87	3,663	872
Bar: D16(SD395)	466	1.55	3,011	636
Steel: (SS400) Thickness=200, Width=400	277	2.061	1,341	423

σt: Yield Strength (N/㎜ ^{2})

Ｅs: Young's modulus $\times 10^5$(N/㎜ ^{2})

εs: Strain at σt $\times 10^{-6}$(㎜/㎜)

σo: Tension Strength (N/㎜ ^{2})

LOADING AND MEASURING METHODS

As a loading method, we applied the horizontal cyclic load without rotations at top level in horizontal direction and the varying axial load in vertical direction using an loading setup shown in Figure 4.

We have applied the horizontal load in which its horizontal drift angle peaks at R1=1/1600, 1/800, 1/400, 1/200, 1/133, 1/100, 1/67, 1/50, 1/33 and 1/20(rad.) respectively and repeated peak-to-peak twice at each horizontal drift after 1/800.

By referring to the analysis carried out during its trial design, we have applied the varying axial load in proportion with its horizontal drift. The start axial load is 911kN at R1=0 for dead load and live load. The max. axial load is 24,703kN/9= 2,745kN as the same as the axial load of 1st story column at ultimate horizontal strength at R1=1/50 and the min. is -8,397kN/9=-933kN at R1=-1/50 (Figure 5).

When we applied the horizontal load with the above axial load to the RC specimen, the shear failure did not took place even if it was expected. That is why we increased the axial load up to the values corresponding to its axial strength ratio (load/strength) at design stage for the SRC1 and SRC2 specimens. As the axial load for the SRC1 and SRC2 specimens, accordingly, we have applied the start axial load (axial strength ration) of 1,176kN (0.14) at R1= 0, maximum axial load (axial strength ration) of 3,577kN (0.41) and min. -931kN (-0.30) at R1=-1/50 in proportion with its horizontal drift. To make them rupture at R1=1/20, we fixed the axial load to its maximum axial load during applying the second peak-to-peak horizontal load.
We changed the axial load at the horizontal load of 0kN and maintained it until the horizontal load returns to 0kN again after releasing load at its peak horizontal drift.
For loading purpose, we installed 2 units of hydraulic jacks for horizontal direction and 4 units of actuators for vertical direction. We placed 2 units of hydraulic jacks for horizontal direction at a mid-height of the specimen and controlled them to synchronize their movements with motor pump. We placed 4 units of actuators for vertical direction around the specimen and controlled them to maintain the levelness of the top of columns and the constant axial load.
For measurement purpose, we used the displacement transducers to measure the deformation of concrete surface and the strain gauges to measure the strains of reinforcing bars and core steel.

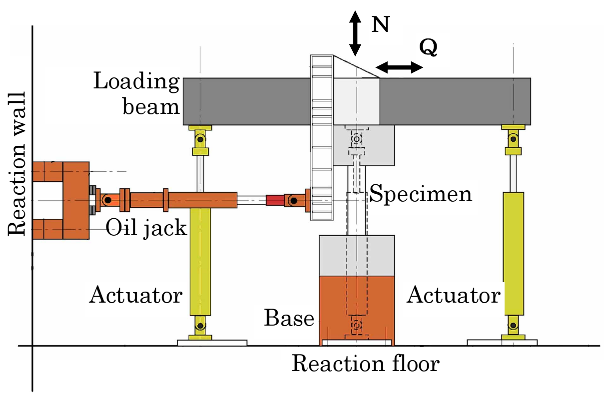
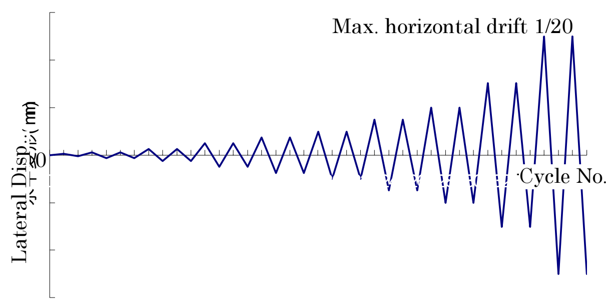
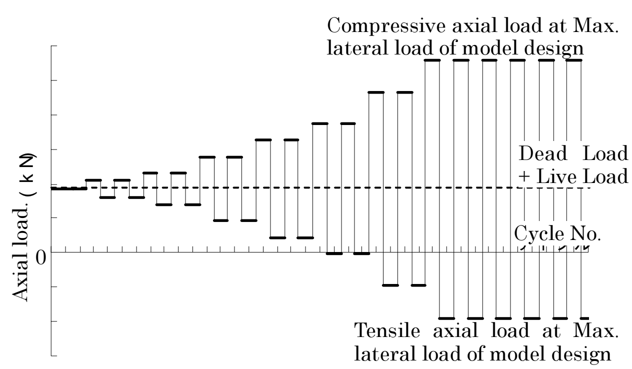


Fig.4 Loading setup



(1)Lateral loading history



(2)Axial loading history

Fig.5 Loading history

Table 8(1)Axial loads in compressive

Specimen	Axial load strength (kN)	Max. axial load (kN)	Load／Strength
RC	6967	2744	0.39
SRC1	8820	3577	0.41
SRC2	8820	3577	0.41

Table 8(2)Axial loads in tensile

Specimen	Axial load strength (kN)	Min. axial load (kN)	Load／Strength
RC	-1298	-931	-0.72
SRC1	-3152	-931	-0.30
SRC2	-3152	-931	-0.30

TEST RESULT

Figure 6 shows the relationship between horizontal load and horizontal displacement of each specimen. All three specimens held against axial load up to R1=1/50. RC specimen held against axial load up to R1=1/20 because of smaller load/strength ratio with no core steel. SRC1 specimen held against the increased axial load up to R1=1/20 because of built-in core steel. However, SRC2 specimen could not hold against the increased axial load up to R1=1/20 because of decreased stirrup ratio. Photo 1 is the cracks after loading.

We report more detailed behaviors of each specimen next.

(1) RC Specimen

The outside main bars yielded at top and bottom of column as of R1=1/133, then the middle-placed main bars yielded as of R1=1/100~1/67. The specimen held against axial load up to R1=1/20.

As of R1=1/20, the concrete crushed at top and bottom of column with no oblique crack. No stirrup yielded at 5 points for strain measurement.

(2) SRC1 Specimen

Both of outside main bars and the core steel yielded at top and bottom of column as of R1=1/133, then the middle-placed main bars yielded as of R1=1/67. As of R1=1/33, the stirrups yielded at mid three points among 5 points for strain measurement.

The specimen held against the increased axial load up to R1=1/20 during peak-to-peak first loading. We applied the axial load of 3,577kN similar value to maximum instead of usual minimum (- 931kN) for the second horizontal loading. As a result, the specimen still held against the further increased axial load but almost all cover concrete dropped off, then we stopped loading. The measured strain of the core steel on critical section at the top and bottom of column was quite small: Max. 0.01mm/mm or less.

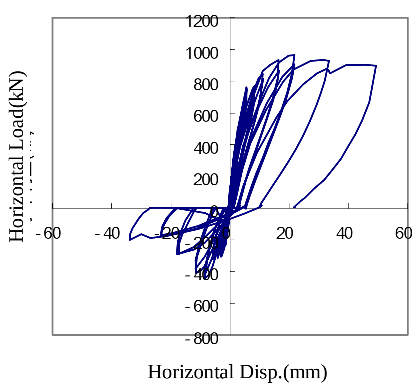
(3) SRC2 Specimen

Both of outside main bars and the core steel yielded at the bottom of column as of R1=1/133.

As of R1=1/133~1/100, the stirrups yielded at mid three points among 5 points for strain measurement.

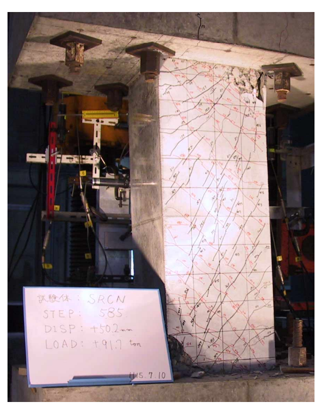
As of first loading for R1=1/20 under maximum axial load, the stirrup end 135 degrees hooks were disengaged from main bars due to expansion by core concrete. Since the specimen was enabled to hold against the axial load, we stopped loading. For the stirrup end 135 degrees hooks, a required length of 6d (d= diameter of bar) was satisfied as normal.

The measured strain of the core steel at the top and bottom of column was quite small: Max. 0.01mm/mm or less.



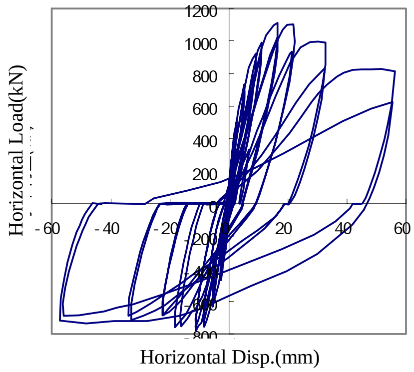
(1)Specimen RC

Fig.6 Relationship between horizontal load and horizontal displacement



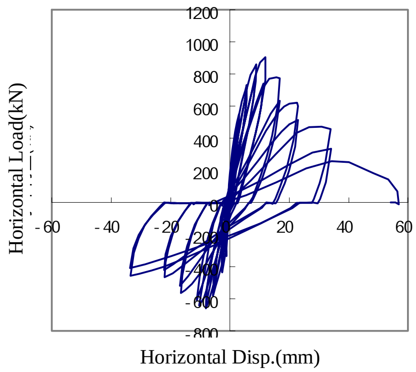
(1)Specimen RC

Photo 1 Cracks after loading



(2)Specimen SRC1

(2)Specimen SRC1



(3)Specimen SRC2

(3) Specimen SRC2

Fig.6 Relationship between horizontal load and horizontal displacement

Photo 1 Cracks after loading

DISCUSSION

On the maximum strength and critical deformation of the specimens, we have compared with the calculated values used at design stage.
Table 9 shows the calculated values versus the test values of maximum strength and its horizontal drift. Regarding with the maximum strength under the compressive axial load, the test values appear bigger than the calculated values of ultimate shear strength by an extent of 1.2 ~ 1.5 thus corresponding well to each other. However, the maximum strength under the tensile axial load are far beyond the calculated values of ultimate flexural strength.
Table 10 shows the calculated values versus the test values of ultimate drift. We calculated the ultimate drift value (Ru) using the formula introduced in the reference [4] about RC columns subjected to flexural failure with the core concrete compression strength (f'c) increased based on the reference [5].

$$Ru=\begin{cases}(1-\eta eq)/57 & (\text{if } Ru\leqq 0.01)\\(1-2\eta eq)/14 & (\text{if } 0.01\leqq Ru\leqq 0.06)\end{cases}$$

where
ηeq: Axial load/strength ratio of concrete under varying axial loading [4]

From Table 10, the test values and the calculated values seem corresponding well to each other in both RC and SRC1 specimens. In the SRC2 specimen, however, the test value is lower than the calculated value probably due to the effect of stirrup expansion by core concrete.

Table 9 Comparison of Ultimate Strengths

(1) Under Compressive Axial Load

Specimen	Calculation			Test result		Comparison
	Qmu (kN)	Qsu,min (kN)	Qsu,min ／Qmu	Max. Strength Qexpc(kN)	Drift at Qexpc (rad.)	Qexpc/Qsu,min
RC	818	637	0.78	964	1/51	1.51
SRC1	834	813	0.97	1110	1/67	1.37
SRC2	834	729	0.87	905	1/93	1.24

(2) Under Tensile Axial Load

Specimen	Calculation			Test result		Comparison
	Qmu (kN)	Qsu,min (kN)	Qsu,min ／Qmu	Max. Strength Qexpt(kN)	Drift at Qexpt (rad.)	Qexpt/Qmu
RC	-80	-354	4.45	-446	1/128	5.60
SRC1	-106	-813	7.67	-779	1/99	7.35
SRC2	-106	-729	6.88	-659	1/136	6.22

Table-10 Comparison of Ultimate Drifts

(Under Compressive Axial Load)

Specimen	Calculation	Test Result
	Ultimate Drift Ru (rad.)	Ultimate Drift Rexp(1) (rad.)
RC	1/30	1/20
SRC1	1/40	1/33
SRC2	1/47	1/67

(1) Rexp: Drift available at 80% of maximum strength due to deterioration

CONCLUSION

Through the above trial design and test, we obtained the following knowledge.

(1) Addition of the core steel to the RC column improves its horizontal deformation performance.

(2) Despite of the above improvement, decreasing of the stirrup ratio causes deterioration in both horizontal deformation performance and axial load carrying capacity.

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