EXPERIMENTAL STUDY ON RESIDUAL AXIAL LOAD CAPACITY OF R/C COLUMNS FAILING IN SHEAR

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ABSTRACT :

In order to avoid pancake type collapse of existing old R/C buildings during severe earthquakes, it is necessary to evaluate residual axial load capacity of existing R/C columns. This “residual axial load capacity” is defined as axial load carrying capacity of a column after the column suffers serious damage, which corresponds to the safety limit state. On the other hand Standard for evaluating method of seismic performances of existing R/C buildings, which is popularly used in Japan, shows evaluating methods of residual axial load capacities, which have dramatic effects on seismic performance indexes. Objectives of this study are to examine the residual axial load carrying capacity of R/C columns after shear failure. We pay special attention to confining effects of hoop reinforcement depending on their reinforcing details.

KEYWORDS: reinforced concrete structures, column, residual axial load capacity, reinforcing detail, shear failure

1. INTRODUCTION

The standard for seismic evaluation of existing R/C buildings by JPDPA revised in 2001 showed evaluating methods of residual axial load capacity and axial load capacity about column members used for determination of axial load bearing column or not. It had dramatic effects on seismic performance indexes. However, the evaluation method of residual axial load capacity has not been sufficiently proved in experiments.

KATI reported on the experiments about axial load capacity of R/C columns failing in shear, which had variable reinforcing details(KATO 2006). The primary objective of these tests was to study the relation of results between the uniaxial compressive loading test (axial force-axial deformation) and lateral loading test (drift angle where axial load capacity is lost). Test specimens for both the axial loading test and lateral loading test were conducted using specimens with the same properties. In this report we study the residual axial load capacity of R/C columns by reporting test results on specimens of residual axial load capacity, which had the same configuration as those reported by KATO(2006). In this study scope was the loading methods of residual axial load specimens, which were the main variables of the tests.

2. SUMMARY OF EXPERIMENT ON RESIDUAL AXIAL LOADING CAPACITY

2.1. Test specimens and loading equipment

We tested a total of 9 series of test specimens in two years. 4 series tested in 2005 are collectively called Series 2005, 5 series tested in 2006 are also collectively called Series 2006. Table 1 (a)(b) show each test specimens data for each series, Table 2 (a)(b) show loading method and test results of each test specimen. Fig.1 shows cross section and reinforcing details of each test specimen. Though the size of the test specimens was 180×180×1200 mm, the test section was a central section of 360mm because both ends of the test specimens were covered by foundation pieces as shown in the figure. The parameters of the test were concrete strength, hoop lateral tie diameter (web reinforcement ratio), and detail of hoop lateral tie (welded hoop tie, 135° hook, 90° hook). Test specimens were designed so that shear failure precedes flexural failure on both concrete strength and axial load. Axial deformation was measured at 4 points in total-two points on both sides of test p specimens in central

310mm area. The loading equipment is shown in Fig.2. The test specimens were covered on the top and bottom ends by foundation pieces. In the case of the axial load test, the jig at the top end was kept level by vertical jacks on both sides. On the other hand, in case of the lateral loading test, those vertical jacks were used to make the deformation at top and bottom of test specimens symmetrical.

2.2. Loading method (pre-loading and post-loading)

We conducted residual axial load tests on 8 test specimens; the loading method for each series varied. Loading methods for each specimen are shown in first half of Table 2. It also shows the test specimens reported by KATO(2006) in order to be used for comparison in this report (the loading method is described as uniaxial compression or lateral load). The loading methods of residual axial loading test were shown separately as pre /post loading. That means that for pre-loading, the lateral load was repeated under constant axial force, then for post-loading, axial load was conducted on a certain drift angle.

Table 2 depicts the constant axial force as pre-loading and maximum drift angle, and the drift angle as post-loading and its confining condition. Maximum drift angles of residual loading test specimens as pre-loading were determined as follows referring to the corresponding test specimens by KATO(2006). Lateral loading tests were conducted until axial load capacity is lost at 2 levels of axial force on each series by KATO(2006). In the residual axial load test effecting lower axial force, the same load was conducted by using higher axial force up to the maximum drift angle of the lateral load test specimen (namely, up to axial load carrying capacity).

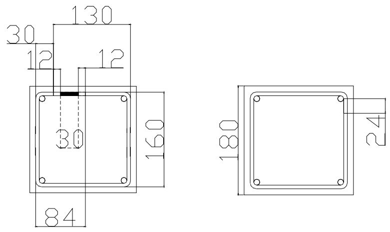
Lateral displacements given by the lateral load test in the case of pre-loading were 1/100,5/100, 2/100. 2.5/100 rad, . . . and basically repeated each of them 2 times. Though effects of loading history on residual axial capacity is large, this kind of cyclic load, which gradually increases maximum displacement, is generally considered to be one of the most severe methods to simulate behavior in the case of an earthquake. This study basically adopts this loading history. But, to consider the effects of damage level by pre-loading onto residual axial capacity, we assigned 1 specimen, WL-4, varying repeating number of lateral loading to same displacements, though WL-4's maximum drift angle in the case of pre-loading was the same as WL-3.

As for post-loading, we considered 3 confining conditions as following;
1) Centrically loaded: When it reaches given maxim drift angle as pre-loading, lateral displacement is returned to 0, keeping certain axial force on pre-loading (usual unload). And axial load is conducted while confining the lateral load 0 (described as centrically loaded hereafter). Confining in this case is conducted by giving lateral force so that lateral displacement can be kept 0.
2) Eccentrically loaded-confined: when it reaches given maxim drift angle as pre-loading, axial load is conducted confining the drift angle (described as eccentrically loaded hereafter). Confinement in this case is conducted by giving lateral force so that lateral displacement can be kept at its maximum level.
3) Eccentrically loaded-free: Though axial force is conducted at maximum drift angle as pre-loading, the lateral displacement procedure is not confined. In this case, axial loading is started with horizontal load at the time of pre-loading termination still acting. Accordingly, along with axial load, lateral displacement increases, on the other hand, lateral force decreases. (This is also eccentrically loaded. Its confining condition is described as free)

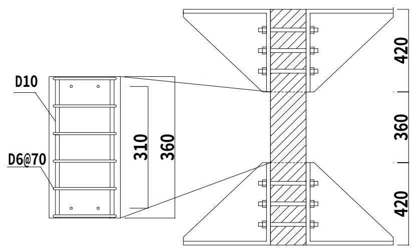
These 3 confining conditions were designed so as to consider the condition of buildings and columns for residual axial capacity evaluation after an earthquake. That is; in the case that the building is preserved and its residual deformation is almost 0, only the object column has the possibility of losing its axial capacity (centrically loaded). In the case where the building is significantly deformed and has residual deformation, however, it maintains its lateral capacity as a whole building (Eccentrically loaded-confined). Finally, a case in which most columns are damaged to the same degree (Eccentrically loaded-free). Since the same post-loading was conducted on the lateral loading test specimens after the original loading.

Table 1 Properties of test specimens

	specimen	Section(mm)	Height(mm)	main bar (yield stress (N/mm²))	Hoop (hook detail)	hoop yield stress(N/mm²)	hoop spacing(mm)	concrete strength (N/mm²)
series 2005	SH series	180 × 180	360	4－D10 (371)	2-D6 (90degree hook(4d))	316	70	32.2
	SL series							19.1
	WH series				2-D6 (welded hook)			32.2
	WL series							19.1
series 2006	H52LL series	180 × 180	360	4-D10 (345)	2-D6 (135degree hook(6d))	420	52	16.8
	H90LL series						90	
	H52L series						52	15.6
	S52L series				2-D6 (90degree hook(4d))			
	I52L series			8-D6 (333)	3-D6 (90degree hook(4d))			



(b) welded hoop (c) 90° hook(4d)



(a) specimen

Figure 1 Configuration and reinforcement of specimens (Series 2005)

Table 2 Loading method and test results

(a) Series 2005

series	specimen	loading method	pre loading: axial load(kN)	pre loading: maximum drift angle(rad)	post loading: drift angle at loading	post loading: confining condition	test result: maximum axial load(kN)	test result: residual axial load ratio *
SH	SH-0	uni axial					1018	1.00
	SH-1	lateral	300	0.02	0	confine	300	0.29
	SH-2	lateral	500	0.015	0	confine	500	0.49
	SH-3	residual	300	0.015	0	confine	884	0.87
	SH-4		300	0.015	-0.015	free	450	0.44
	SH-5		300	0.015	-0.015	confine	404	0.40
SL	SL-0	uni axial					618	1.00
	SL-1	lateral	150	0.025	0	confine	150	0.24
	SL-2	lateral	300	0.02	0	confine	300	0.49
	SL-3	residual	150	0.02	0	confine	569	0.92
WH	WH-0	uni axial					1001	1.00
	WH-1	lateral	300	0.02	0	confine	503	0.30
	WH-2	lateral	500	0.015	0.015	confine	560	0.50
	WH-3	residual	300	0.015	0	confine	967	0.97
WL	WL-0	uni axial					607	1.00
	WL-1	lateral	150	0.04	0	confine	210	0.25
	WL-2	lateral	300	0.02	0	confine	314	0.49
	WL-3	residual	150	0.02	0	confine	497	0.82
	WL-4		150	0.02**	0	confine	575	0.95
	WL-5		150	0.02	-0.02	free	315	0.52

* :maximum axial load(constant axial load in case of lateral loading

maximum axial load of accompanying uniaxial loading specimen

** :drift angle 0.02 of specimen WL-4 was given by one loading cycle

(b)Series 2006

Series	Specimen name	Loading method	pre loading: subjected axial load(kN)	pre loading: subjected maximum member deflection angle(rad)	post loading: member deflection angle at post loading(rad)	post loading: confining condition	Test result: Maximum axial strength (kN)	Test result: residual axial strength ratio*
H52LL	H52LL-0	centric axial loading					589	1.00
	H52LL-1	lateral	300	0.015	0	confined	309	0.51
	H52LL-2		150	0.03	0	confined	161	0.25
	H52LL-3	residual	300	0.01	0	confined	605	1.03
	H52LL-4		300	0.01	0.01	free	479	0.81
	H52LL-5		150	0.015	0.015	free	380	0.65
H90LL	H90LL-0	centric axial loading					572	1.00
	H90LL-1	lateral	300	0.015	0	confined	434	0.52
	H90LL-2		150	0.03	0	confined	150	0.26
	H90LL-3	residual	150	0.015	0.015	free	398	0.70
H52L	H52L-0	centric axial loading					615	1.00
	H52L-1	residual	50	0.015	0.015	free	413	0.67
	H52L-2		250	0.015	0.015	free	264	0.43
S52L	S52L-0	centric axial loading					646	1.00
	S52L-1	lateral	150	0.03	0	confined	150	0.23
	S52L-2	residual	150	0.02	0.02	confined	513	0.79
I52L	I52L-0	centric axial loading					569	1.00
	I52L-1	lateral	300	0.025	0	confined	337	0.53
	I52L-2		450	0.011	0	confined	450	0.79
	I52L-3	residual	300	0.011	0.011	free	517	0.91

* : maximum axial strength (subjected axial load at preloding in case of lateral loading specimen) devided by maximum axial strength of accompanying axial loading specimen

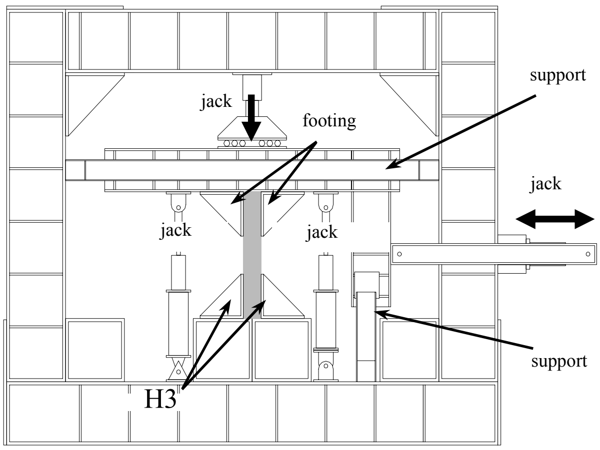


Figure 2 Loading setup

Table 3 Residual axial load capacity and axial load capacity proposed by Standard for seismic evaluation (2001)

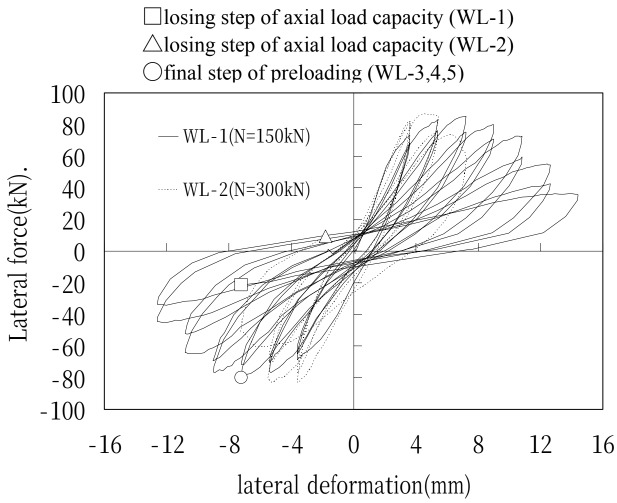
F value		1	1.27	2	3
story drift angle R(rad)		0.0040	0.0067	0.0123	0.0281
extremely fragle column	$0.4<pw$	0.4	0.3	0.1	0
	$0.2<pw<0.4$	0.3 [0.4]	0.1	0	0
	$pw<0.2$	0 [0.3]	0	0	0
shear column	$0.4<pw$	0.6	0.4	0.2	0
	$0.2<pw<0.4$	0.5	0.3 [0.4]	0.1	0
	$pw<0.2$	0.4	0 [0.4]	0	0
flexural column	$0.4<pw$	0.6	0.6	0.5	0.4
	$0.2<pw<0.4$	0.5	0.5	0.3 [0.4]	0.2 [0.3]
	$pw<0.2$	0.4	0.4	0 [0.3]	0 [0.2]

3. RESULTS OF TESTS AND EXAMINATION

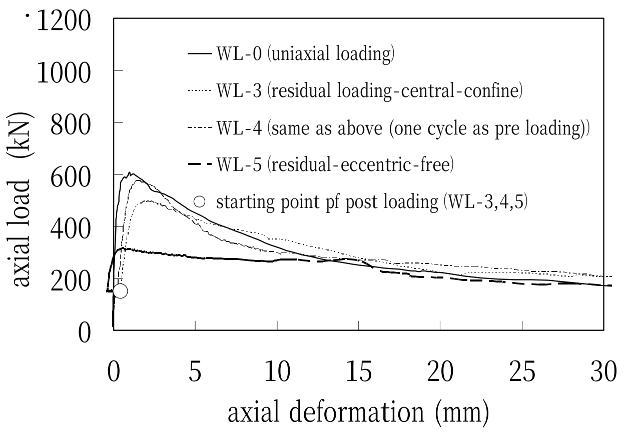
3.1. Results of tests and summary

The results of the lateral load test of WL series are shown in Fig.3(a). Full lines are for low axial load test specimens, dotted lines are for high axial load test specimens. As described before, pre-loading for residual loading test was conducted by low axial force until it reaches the same figure as maximum drift force in the case of high axial force. This behavior is not shown in the Fig., because it is almost same as for the test specimens that are shown by full lines, and the termination point of pre-loading are shown as ○.

After pre-loading termination, axial compression loading was conducted on some test specimens at their drift angle, also after returning their displacement to 0 on others, based on each confining condition. The maximum axial force by post-loading is shown in the test results in the latter half of Table 2. Also, in Fig.3(b), the relationship between axial force and axial deformation of WL series is shown compared with the results of uniaxial compression tests. ○ is axial load starting point of the post-loading. Summary of the results of the residual axial loading test are as follows.



(a)Results of lateral loading specimens and the terminated step of pre-loading of accompanying residual loading specimen (WL series)



(b)Comparison of axial load – axial deformation relationship between uni-axial loading specimens and residual loading specimens (WL series)

Figure 3 Example of test results

1)When the post-loading is conducted with returning lateral deformation to 0, and deformation (centrically loaded) confined, it showed the maximum axial capacity, which is 82-97% of the uniaxial compression test. (Test specimen SH-3, SL-3, WH-3, WL-3)

2)When the post-loading is conducted without returning lateral deformation to 0, and without confining the deformation of pre-loading termination (eccentrically loaded-free), the maximum axial capacity significantly declined. (Test specimen SH-4, WL-5)

3)When the post-loading is conducted without returning lateral deformation to 0, and confining the deformation of pre-loading termination (eccentrically loaded-confined), the maximum axial capacity was almost the same as when it was not confined (eccentrically loaded-free). (SH-4 and SH-5, see clause 3.1)

4)Damage level by pre-loading affected residual axial capacity. Test specimens that were loaded only once (WL-4 retained larger residual axial capacity than those that were loaded several times repeatedly (WL-3)).

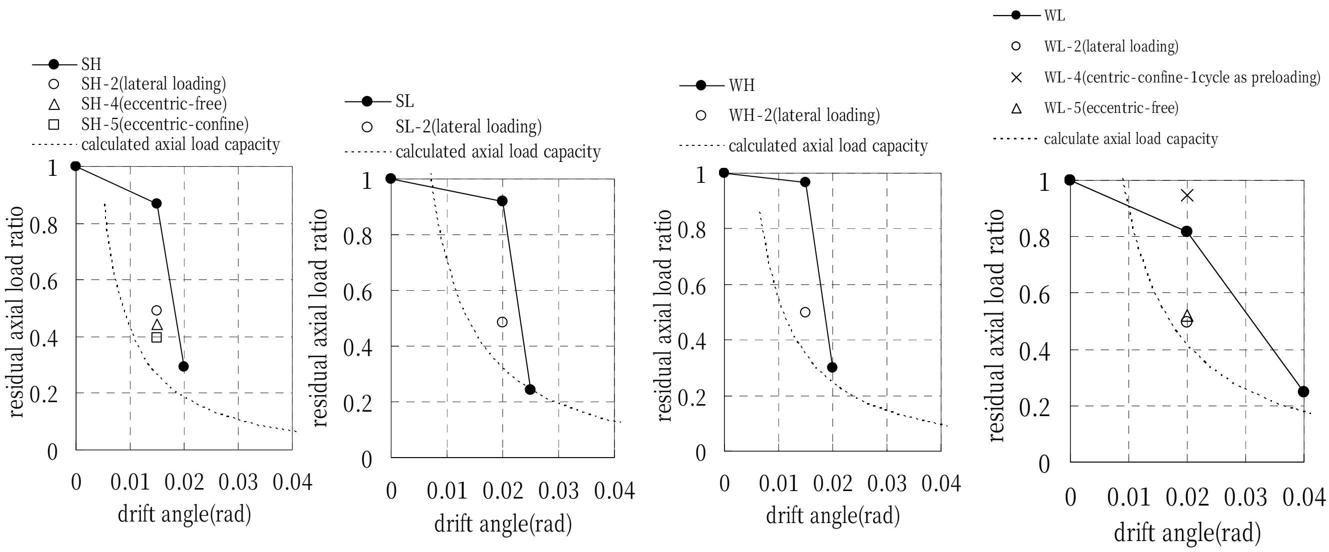
5)In the post-loading of lateral loading tests, as for the welded hoop tie, the axial capacity rose above that of pre-loading. (Test-specimen WH-1, 2 and WL-1, 2 in Table2). In the case of a 90-degree hook, it did not rise. (Test-specimen SH-1, 2 and SL-1, 2 in Table2).

6)Comparing result of each test specimen about reinforcing details, the axial capacity or residual axial load capacity of test specimens using welded hoop tie was not always higher than those of 90-degree hook (such as SL-0and WL-0 or SL-3 and WL-3). We consider this to indicate dispersion. That is to say, we assume the reinforcement effect on the axial force is small, and that pre-loading damages was also not severe. We would like to review this issue hereafter.

3.2. Consideration of results

In this clause, we would like to try to evaluate the results quantitatively. In the right end column of Table 2, we show the results for residual axial load ratio. This residual axial load ratio is obtained by dividing the maximum axial force of post-loading by the maximum corresponding axial capacity from uniaxial compression tests, and the maximum axial force on the of lateral loading test specimens is constant axial force, which was given in case of pre-loading. Fig.4 (a)-(d) shows the relationship between maximum lateral drift force and the residual axial load ratio of residual axial force test specimens (centrically loaded) in the case of pre-loading, for each series. Also, for comparison, the results of lateral loading test specimens, which are given the same constant axial force, and uniaxial compression test specimens are shown. For convenience sake, 3 points of same series were connected. The left points are axial compression test specimens (0 in horizontal axis, 1 in vertical axis), the right points are lateral loading test specimens. In each figure, test specimens for lateral loading are shown as ○, those for eccentrically loaded-free are shown as △, and those for eccentrically loaded-confined are shown as □. Here, the horizontal axis for test specimens eccentrically loaded are specified as drift angle at the starting time of post-loading. This is because, in this test lateral deformation proceeded after the maximum axial capacity revealed as explained in 3.1.

According to the results, those points (○△□) are located far below the centrically loaded test specimens. The most noteworthy thing about these figures is that the eccentrically loaded test specimens (△□) and laterally loaded test specimens (○), for which the maximum drift angle of these eccentrically loaded test specimens turns to a drift angle where axial load capacity is lost, are located in almost the same position (Fig.4 (a)(d)). In other words, after a column is loaded up to a certain drift angle, the residual axial capacity of the column is equal to the constant axial force applied to the lateral loading test column. This makes its drift angle turn to a drift angle where axial load capacity is lost. It is assumed that this is because although axial load capacity depends on the friction on the diagonal shear-crack surface, in both cases of eccentrically loaded and lateral loaded specimens, states of stress at the point of losing axial load capacity are approximately the same. (The difference is that axial force changes in case of eccentric loading, meanwhile, lateral force changes in case of lateral loading.)



(a)SH series (b)SL series (c)WH series (d)WL series

Figure 4 Relationship between subjected maximum drift angle during pre-loading and residual axial load capacity of residual loading specimens, comparing with results of uni-axial loading specimens and lateral loading specimens (Series 2005)

4. CONSIDERATION OF EVALUATION METHODS FOR RESIDUAL AXIAL CAPACITY OF SHEAR COLUMN

4.1. Evaluation method

According to the conclusion of 3.2, the residual axial capacity after shear failure can be possibly evaluated by the drift angle where axial load capacity is lost after shear failure (in case of eccentrically loaded). By KATO(2006) formula for evaluation of the drift angle where axial load capacity is lost after shear failure (which evaluates average of test values) was proposed. The equation is as follows;

$$R=\frac{0.027}{\eta} \qquad (\eta=\frac{{}_eN}{P_{fr,cal}}) \qquad (1)$$

$${}_eN=N+Q\frac{\sin^2\theta-\cos^2\theta-2\mu\cdot\sin\theta\cdot\cos\theta}{\sin\theta\cdot\cos\theta-\mu\cdot\cos^2\theta}$$

$$P_{fr,cal}=P_{fro}\cdot(1-0.5\cdot\frac{S}{D})\cdot R_d$$

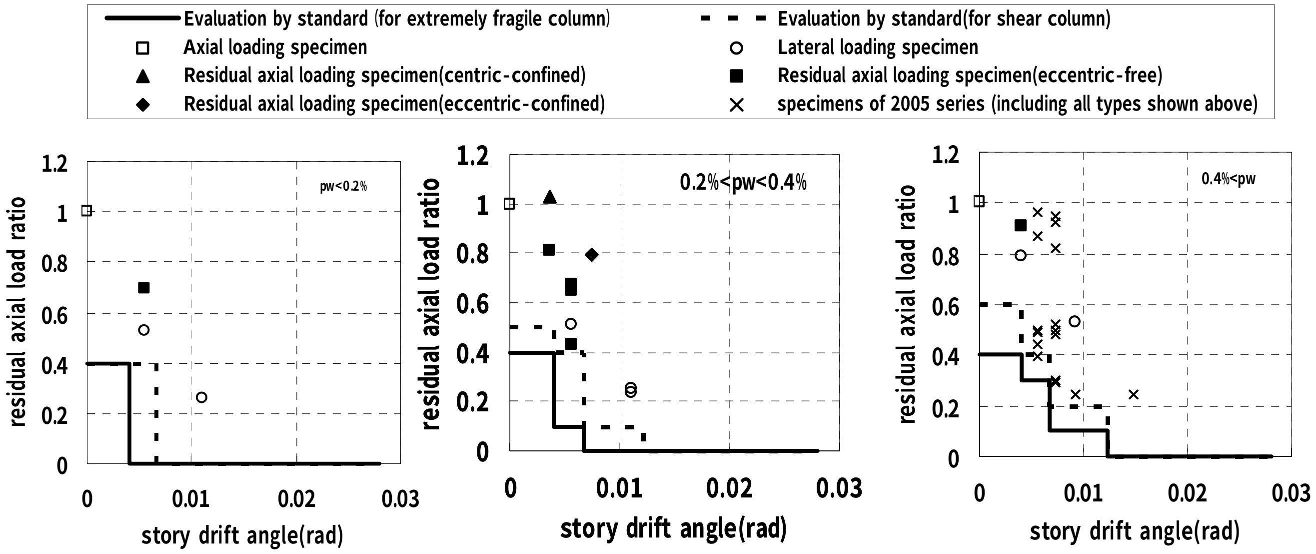
$$P_{fro}=b\cdot D\cdot p_w\cdot\sigma_{wy}\frac{\sin\theta\cdot\cos\theta+\mu\cdot\sin^2\theta}{\sin\theta\cdot\cos\theta-\mu\cos^2\theta}+A_s\cdot\sigma_y$$

In the formula, N is axial load, Q is shear force at the time of losing axial load capacity and they can be assumed to be shear strength. μ is the coefficient of friction on a slip surface, which is 0.77. θ is the slip angle, which is 60 degrees. b is width, D is the height of the cross section, p_w, σ_{wy}, and S mean web reinforcement ratio, yield strength, and space. A_s and σ_y are the cross section and yield strength of the main reinforcement. R_d is the effectiveness factor of reinforcing details, and the Rd for a welded tie hoop is 1, for 90 degrees hook is 0.8 (extra length 4d). Equation (1) is derived from the test data within the range that p_w is 0.4-0.68%, η is approximately $0.7<\eta<2.8$.

In the Fig. 4(a)-(d), calculated values by Equation (1) are shown in dotted lines. Horizontal axis represents the drift angle R by equation (1), varying axial load in each series. Vertical axis represents the axial load divided by ($bD\sigma_B$+$A_s\sigma_y$), where σ_B is concrete strength. Note that the axial force ratio of vertical axis is not η in Equation (1). As for shear strength Q is based on the method proposed by AIJ(1999). Since those calculated values are derived from the results of laterally loaded test specimens (○ and ●), those lines pass near the points of laterally loaded test specimens. Accordingly, residual axial capacity in case of eccentrically loaded specimens can be also evaluated by Equation (1).

4.2. Consideration of residual axial capacity in the standard for seismic evaluation and problems

In this clause, we will consider the feasibility of the evaluation method of residual axial capacity in the standard for seismic evaluation. In the standard for seismic evaluation, members are categorized as: extremely fragile column, shear failing column and flexural failing column. Furthermore, axial force ratio, which can be supported up to certain F value, is shown by each web reinforcement ratio. These are shown in Table 3. There, residual axial capacity is the axial force that the column can maintain when it goes over its F value. Also, axial load capacity is axial force that the column is able to maintain before it reaches the F value. In the standard for seismic evaluation, relationship between F value and story drift angle are accommodated. These values are also shown in the table.



(a)pw<0.2% (b)0,2%<pw<0.4% (c)0.4%<pw

Figure 5 Relationship between subjected maximum story drift angle during the pre-loading and residual axial load ratio of residual loading specimens, comparing with evaluating equations proposed by Standard for seismic evaluation(2001)

Fig.5 regards the relationship between subjected story drift angle during the pre-loading and residual axial load ratio for all the test specimens of series 2005 and 2006. The horizontal axis of drift angle is converted to the story drift angle of the intended building so as to compare with the standard for seismic evaluation. The conversion is based on Equation (2).

$$R_{story} = \frac{\delta}{H} = \frac{1}{\alpha} \cdot R_{mem} \cdot \frac{h_0}{H} = 0.37 \cdot R_{mem} \qquad (2)$$

In this formula, R_{story} is the story drift angle, R_{mem} is the column drift angle, δ is lateral displacement of the story. H is the height of the story, h_0 is the flexible length of the column. In this thesis, we took the safe side and set h_0/H=0.33. α as the deformation ratio of the column to whole story deformation, which is assumed to be 0.9 in this thesis.

Fig.5 shows relations by each web reinforcement ratio. Both relations of extremely fragile columns and shear columns shown in Table 3 were shown in this Fig. Although in the standard for seismic evaluation, axial force ratio is evaluated only by the concrete cross section, it is necessary to pay attention to the fact that the axial force ratio of this test includes longitudinal reinforcement.

According to the Fig., the test value of each web reinforcement ratio exceeded that of the standard of seismic evaluation in most test specimens. Considering that the standard for seismic evaluation neglects main reinforcement, this setting is on the safe side even in the case of eccentric loading, which is most unfavorable within this test range.

5. CLOSING AND ISSUES FOR THE FUTURE

1) In case that the returning lateral displacement is 0 and residual axial load is conducted while confining the deformation (centrically loaded), the values of its maximum axial capacity were high, which were as 82-97% of the uniaxial compression load test.

2) In the case that the residual axial load is conducted without returning the lateral displacement to 0(eccentrically loaded), the values of its maximum axial capacity declined significantly, which was regardless of the confined condition of lateral deformation.

3) Being loaded up to a certain drift angle (in case of eccentric loading), the residual axial capacity of a column was almost equal to constant axial force which was subjected to a laterally loaded accompanying column specimen, which lost the axial load capacity at the same drift angle.

4) Comparing the evaluation equation (eccentrically loaded) of residual axial capacity, which was derived from 3), with residual axial capacity based on the standard for seismic evaluation, it shows it was on the safe side within this test range.

5) Residual axial capacity of test specimens, of which pre- loading was uni-directional, was higher than that of test specimens, for which loading was repetitive. But not to the point of quantitative evaluation. This is an issue, which remains to be resolved in the future.

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