First European Conference on Earthquake Engineering and Seismology
(a joint event of the 13th ECEE & 30th General Assembly of the ESC)
Geneva, Switzerland, 3-8 September 2006
Paper Number:347

AXIAL LOAD CAPACITY OF R/C COLUMNS WITH VARIOUS REINFORCING DETAILS AND CONCRETE STRENGTH

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SUMMARY

In order to avoid pancake type collapse of existing old R/C buildings during severe earthquakes, it is necessary to evaluate axial load carrying capacity of existing R/C columns with poor reinforcing details and low concrete strength. Such columns are vulnerable to fail in shear. Objectives of this study are to examine the axial load carrying capacity of R/C columns after shear failure. We paid special attention to confining effects of hoop reinforcement depending on their reinforcing details and concrete strength. For this purpose static loading tests of R/C columns were conducted. Thirty nine 180 mm square section R/C columns with the height of 360mm were tested. Main variables were the details of hoop reinforcement and concrete strength. Confinement of hoop reinforcement to core concrete was one of the most important effects to be discussed so four types of columns with different hoop reinforcement details were tested, i.e. i)welded hoop for good confinement type, ii)hoop with 135 deg hook for normal confinement type, iii)hoop with 90 deg (long anchorage length) hook for medium poor confinement type and iv)hoop with 90 deg hook (short anchorage length) for poor confinement type. Two types of loading methods were applied, i.e. i)centrical axial loading test to examine the basic confining effects of hoop reinforcement and ii)lateral loading test under constant axial load to examine the axial load carrying capacity.

1. INTRODUCTION

In order to avoid pancake type collapse of existing old R/C buildings during severe earthquakes, it is necessary to evaluate axial load carrying capacity of existing R/C columns with poor reinforcing details and low concrete strength. Such columns are vulnerable to fail in shear. Axial load carrying capacities of columns have been studied for columns failing in flexure [Kato,2001] and for columns failing in shear [Pujol ,2000],[Moehle,1999], [Nakamura,2002],[Kitada,1998], [Kato,2003,2004]. Objectives of this study are to examine the axial load carrying capacity of R/C columns after shear failure. We paid special attention to confining effects of hoop reinforcement depending on their reinforcing details and concrete strength. For this purpose static loading tests of R/C columns were conducted. Thirty nine 180 mm square section R/C columns with the height of 360mm were tested. Main variables were the details of hoop reinforcement and concrete strength. Confinement of hoop reinforcement to core concrete was one of the most important effects to be discussed so four types of columns with different hoop reinforcement details were tested, i.e. i)welded hoop for good confinement type, ii)hoop with 135 deg hook for normal confinement type, iii)hoop with 90 deg (long anchorage length) hook for medium poor confinement type and iv)hoop with 90 deg hook (short anchorage length) for poor confinement type. Two types

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of loading methods were applied, i.e. i)centrical axial loading test to examine the basic confining effects of hoop reinforcement and ii)lateral loading test under constant axial load to examine the axial load carrying capacity.

2. OUTLINE OF TEST

2.1 Specimens

In order to understand axial load capacity centric axial loading test is the most basic testing method. But the actual axial load capacity should be discussed using columns subjected to axial load and lateral load reversals. These two cases which are called “axial loading test” and “lateral loading test” were studied in this study.

Table 1 shows properties of axial loading specimens and Table 2 shows properties of lateral loading specimens. 13 types of specimens were made. Every type has one axial loading specimen and 1 – 3 lateral loading specimens. Consequently 13 axial loading specimens and 26 lateral loading specimens were tested. Figure 1 shows examples of specimens and reinforcement. All specimens were rectangular reinforced concrete columns with steel footings at both ends for repeatable use. 180mm square section and D6 hoop reinforcement were commonly used for all specimens. Variables were concrete strength (19.1 – 35.2 N/mm^2), longitudinal reinforcement (ϕ4, D10 or D13), hoop spacing (52 – 90 mm) and details of hoop reinforcement. It is noted that specimens with round main bar(ϕ4) was assumed to be specimens with no longitudinal reinforcement. Main bars ϕ4 were necessary for construction only. Four types of hoop details were used that is welded hoop, 135 degrees hook, 90 degree hook with anchorage length of 8d(=8 × 6=48mm) and 90 degree hook with anchorage length of 4d(=4 × 6=24mm).

2.2 Loading method

Figure 3 shows loading setup. Triangle steel footings were repeatable footings. Note that the confinement from the footing base could be different from that of normal type specimen with H shape type. But as far as failure occurs around the middle part of the specimen the difference can be neglected. Two types of loading methods were applied, i.e. i)monotonic and centric axial loading test to examine basic confining effects of hoop reinforcement and ii)reversed lateral loading test under constant axial load, which were conducted until specimens lost their axial load carrying capacities.

3. TEST RESULTS

3.1 Test result of axial loading test series

Figures 4(a)(b) show axial load-axial deformation relationship of axial loading specimens. Maximum strength of these specimens were listed in Table 3. But effects of hoop details on axial strength were not so dominant. For examples the maximum strength of specimen D13S-0 was almost same as that of specimen D13W-0 with same properties except for hoop details. However effects of hoop details to descending part were quite significant. For examples the descending part of specimen D13S-0 was different from that of specimen D13W-0. These results indicated that another strength expressing differences of confinement caused by difference of hoop details should be introduced.

From this view point strength by friction (Pfr) was introduced in this study. Figure 4(a) shows the analogous lines of the descending part of this axial load - axial deformation relationship and how to determine strength by friction(Pfr). The most basic strength resisted by friction (Pfr0) can be evaluated by Eq. (1).

$$Pfr0 = b \cdot D \cdot pw \cdot \sigma wy \frac{\sin\theta \cdot \cos\theta + \mu \cdot \sin^2\theta}{\sin\theta \cdot \cos\theta - \mu \cos^2\theta} + As \cdot \sigma y \tag{1}$$

where, b and D are width and depth of column, pw is hoop reinforcing ratio $(=\frac{aw}{bS})$, S is spacing of hoop, σwy is yield strength of hoop reinforcement, As is total area of main bars and σy is yield strength of main bar. Symbol θ is angle of diagonal crack to horizontal line and symbol μ is coefficient of friction of crack surface of concrete. Equation (1) was derived assuming that axial load was resisted by friction of the surface of diagonal crack in the descending part of axial load - axial deformation relationship. Note that contribution of main bars are added to Eq. (1). Angle θ was assumed to be equal to 60deg for all specimens taking the observed angle during the test [Kato, 2003] into account in this study. Coefficient μ was assumed to be 0.77 tentatively according to experimental data by Richart[1928].

Point C of Fig.4(a) represents this basic strength resisted by friction(Pfr0) and descending part was analogized by two linear lines based on Pfr0. Point A represents maximum axial load (Pmax) of this specimen and the first line for analogy is obtained by linear line connecting point A and B, which is the experimental data at the average load of Pmax and Pfr0. On the other hand the second line for analogy is obtained by line connecting point C and D, which is the experimental data at half of Pfr0. Strength Pfr0 is the most basic strength in the descending part but is independent from hoop details. Figures 4(a)(b) show that effects of hoop reinforcement details on the inclination of the second line are significant. From this view point strength by friction (Pfr), which is defined as the strength of the point of intersection of two lines (Point E of Fig.4(a)), can be the most effective strength to express differences of confinement caused by difference of hoop details. Obtained friction strength (Pfr) and stiffness of analogous lines are listed in Table 3.

3.2 Test result of lateral loading test series

Figure 5 shows lateral load-lateral deformation relationship of all lateral loading specimens. And circle marks represent losing points of axial load carrying capacities. In other words the specimens could not sustain their scheduled axial load after these points. The observe maximum strength are listed in Table 4. Also observed lateral deformation and axial deformation at losing point of axial load carrying capacity are listed in Table 4.

Effects of hoop reinforcing details are observed in these figures. For examples observed losing point of specimen D13S-1 was smaller than that of specimen D13W-1 with the same properties except for hoop reinforcing details. However it must be noted that observed losing point of specimen D13S-2 was almost as same as that of specimen D13W-2 with the same properties except for hoop reinforcing details. The differences of these two set of specimens were only the magnitude of subjected axial load. The axial load ratio of specimen D13S-1 and D13W-1 was about 1/3 whereas that of specimen D13S-2 and D13W-2 was about 2/3. It can be concluded that effects of hoop reinforcing details were significant for specimens with low axial load ratio. Same tendency can be seen in specimens WH-SH series and specimens WL-SL series.

4. RELATION BETWEEN AXIAL LOAD RATIO AND LOSING POINT OF AXIAL LOAD CAPACITY

Figures 6(a)(b) show relations between subjected axial load ratio and lateral drift at losing point of axial load carrying capacity. Y-axis of this figure represents subjected axial load ratio evaluated using maximum strength of accompanying axial loading specimen. And X-axis represents observed maximum lateral drift before losing point of axial load carrying capacity of lateral loading specimen. Figure 6(a) shows relations of only specimens with welded hoop, which was assumed to be good detail, and indicates that correlation between lateral drift and axial load was not good even for specimen with same hoop reinforcing detail. Furthermore this figure shows that correlation of specimens with axial load ratio higher than 0.4 was not bad but that of specimens with axial load ratio lower than 0.4 was quite bad.

Figure 6(b) shows axial load ratio – lateral drift relations of all specimens with various hoop reinforcing details and indicates that correlation was not good. Furthermore this figure shows that correlation of specimens with axial load ratio higher than 0.4 was almost as same as that of Fig. 6(a) with only specimens with welded hoop but correlation of specimens of specimens with axial load ratio lower than 0.4 was much worse than that of Fig. 6(a). It can be concluded that axial load ratio using maximum strength of accompanying axial loading specimen is not a suitable indicator to estimate lateral drift at losing point of axial load carrying capacity especially for specimens with low axial load ratio.

On the other hand Figs. 7(a)(b) show same relation as Figs.6(a)(b) but axial load ratio of Y-axis was replaced by different axial load ratio, which was evaluated using friction strength of accompanying axial loading specimen. Figure 7(a) shows relations of only specimens with welded hoop and indicates that correlation between lateral drift and axial load was good except for specimen with no main bar (actually ϕ4 bar was used for construction) plotted by square marks. Furthermore this correlation can be expressed by two linear lines shown in Fig.7(a).

Figure 7(b) shows relations of all specimens with various hoop reinforcing details and indicates that correlation was still good. And this correlation can be also expressed by same two linear lines shown as Fig.7(a). It can be concluded that axial load ratio using friction strength of accompanying axial loading specimen can be a suitable indicator to estimate lateral drift at losing point of axial load carrying capacity.

5. CONCLUSIONS

(1)Axial loading specimens:
Effects of hoop details on axial strength were not so dominant. However effects of hoop details to descending part were quite significant.

(2)Lateral loading specimens:
Effects of hoop reinforcing details were significant for specimens with low axial load ratio.

(3)Relation between axial load ratio using maximum strength and losing point of axial load capacity:
Axial load ratio using maximum strength of accompanying axial loading specimen is not a suitable indicator to estimate lateral drift at losing point of axial load carrying capacity especially for specimens with low axial load ratio.

(4)Relation between axial load ratio using friction strength and losing point of axial load capacity:
Correlation between axial load ratio using friction strength and losing point of axial load capacity was good for all specimens with various hoop reinforcing details and concrete strength except for specimens with no main bars. And this correlation can be expressed by two linear lines. It can be concluded that axial load ratio using friction strength of accompanying axial loading specimen can be a suitable indicator to estimate lateral drift at losing point of axial load carrying capacity.

6. REFERENCES

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Table 1 :Properties of axial loading specimens

specimen name	main bar	yield strength of main bar(N/㎜2)	hoop	hoop spacing(㎜)	yield strength of hoop(N/㎜2)	concrete strength(N/㎜2)
H-0	4-D10	383	D6(135deg hook(6d))	70	303	35.2
P-0			D6 (90deg hook(8d))			
W-0		377	D6 (welded)			23.4
S-0			D6 (90deg hook(4d))			
W52-0		382	D6 (welded)	52	341	28.2
W90-0				90		
D13S-0	4-D13	335	D6 (90deg hook(4d))	70	335	26.7
D13W-0			D6 (welded)			
ϕ4W-0	4-ϕ4	502				
D10WH-0	4-D10	371			316	32.2
D10SH-0			D6 (90deg hook(4d))			
D10WL-0			D6 (welded)			19.1
D10SL-0			D6 (90deg hook(4d))			

Table 2 :Properties of lateral loading specimens

specimen name	main bar	yield strength of main bar(N/㎜2)	hoop	hoop spacing(㎜)	yield strength of hoop(N/㎜2)	concrete strength(N/㎜2)	subjected axial load (kN)	accompanying axial loading specimen
H-3	4-D10	383	D6(135deg hook(6d))	70	303	35.2	400	H-0
H-4							200	
P-3			D6 (90deg hook(8d))				400	P-0
P-4							300	
W-3		377	D6 (welded)		303	23.4	300	W-0
W-4							500	
S-3			D6 (90deg hook(4d))				300	S-0
W52-1		382	D6 (welded)	52	341	28.2	500	W52-0
W52-2							350	
W90-1				90			350	W90-0
W90-2							200	
D13S-1	4-D13	335	D6 (90deg hook(4d))	70	335	26.7	300	D13S-0
D13S-2							500	
D13W-1			D6 (welded)				300	D13W-0
D13W-2							500	
D13W-3							500	
ϕ4W-1	4-ϕ4	502					300	ϕ4W-0
ϕ4W-2							500	
D10WH-1	4-D10	371	D6 (welded)		316	32.2	300	D10WH-0
D10WH-2							500	
D10SH-1			D6 (90deg hook(4d))				300	D10SH-0
D10SH-2							500	
D10WL-1			D6 (welded)			19.1	150	D10WL-0
D10WL-2							300	
D10SL-1			D6 (90deg hook(4d))				150	D10SL-0
D10SL-2							300	

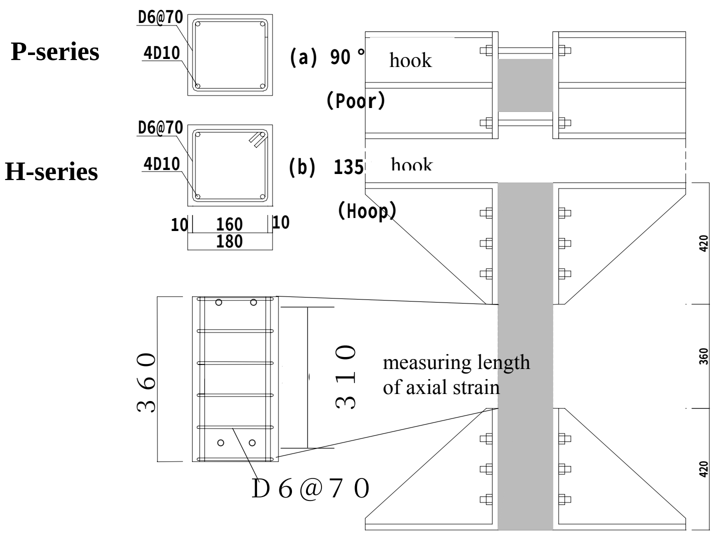
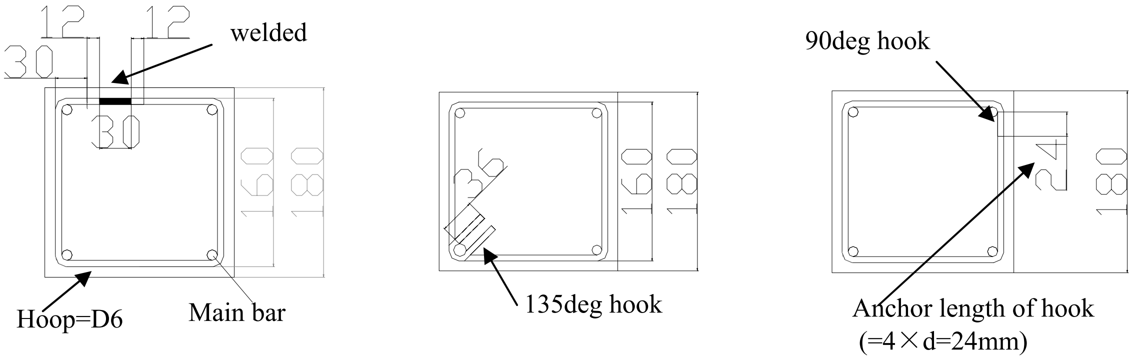


Figure 1 : Specimen and reinforcement (H-series,P-series)



(a) welded hoop (W-series,W52-series,W90-series,D13W-series,ϕ4W-series,D10WH-series,D10WL-series)

(b)hoop with 135deg hook (H-series)

(c)hoop with 90deg hook with anchor length of 4d (S-series,D13S-series,D10SH-series,D10SL-series)

Figure 2 : Examples of sections of specimens

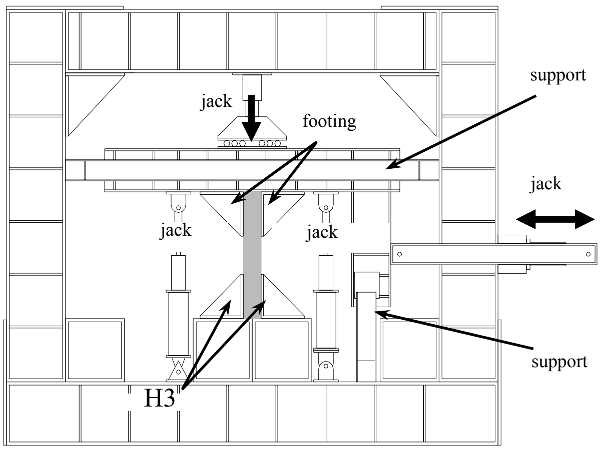
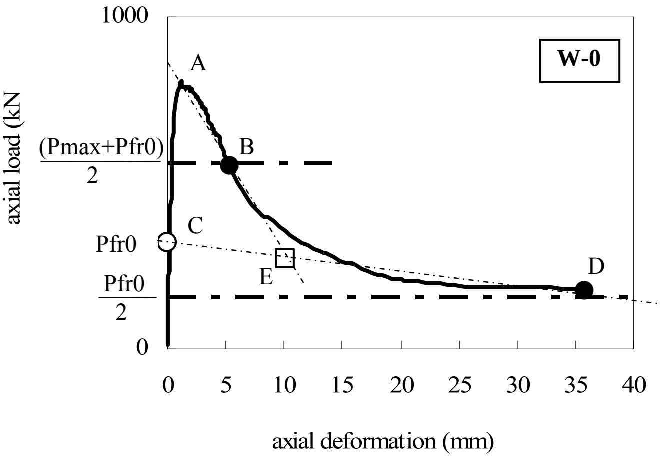
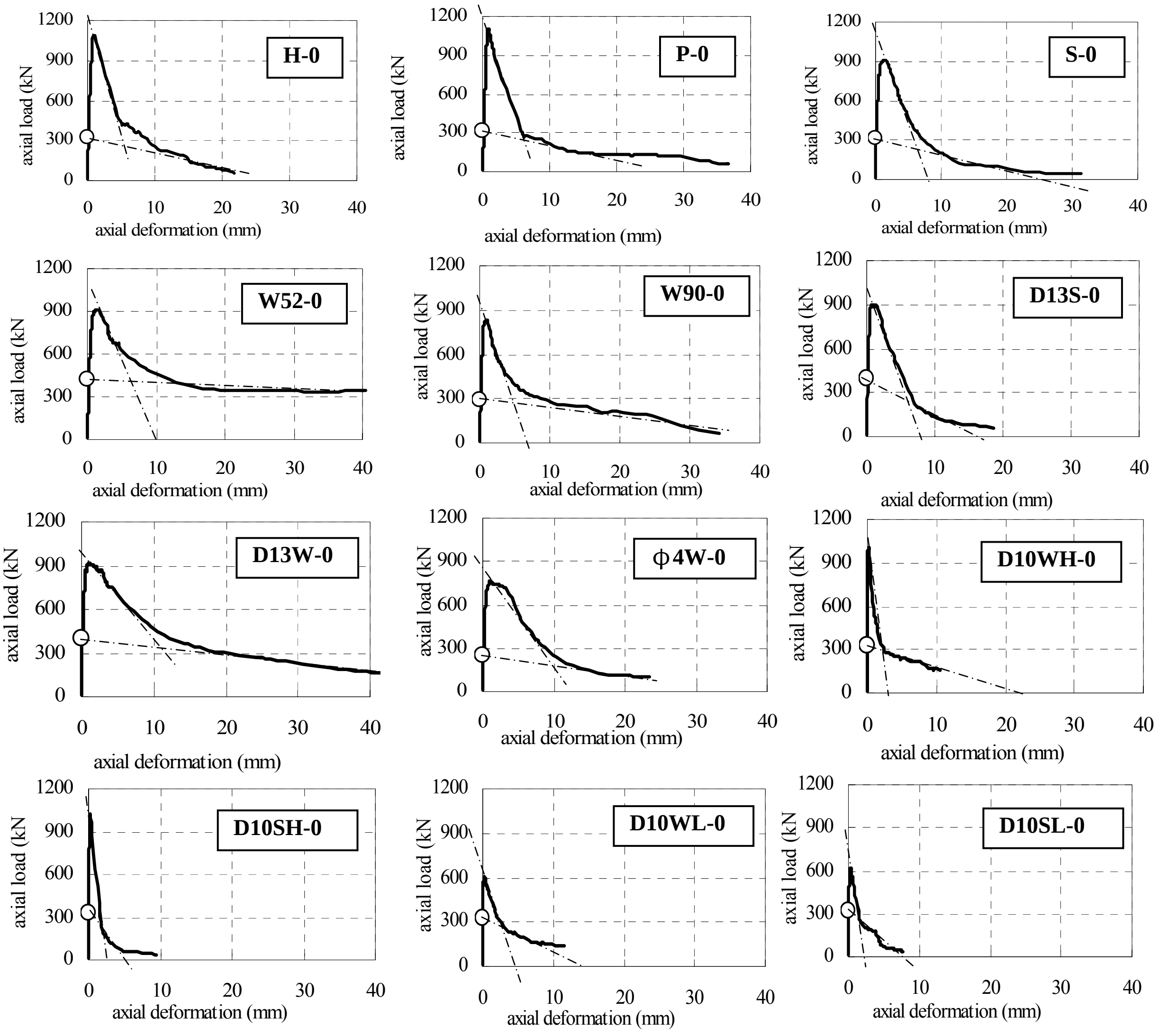


Figure 3 : Loading setup



(a) specimen W-0 (showing how to determine Pfr, which means strength of point E)



(b)results of other specimens

Figure 4 : Axial load-axial deformation relationship **of axial loading test series**

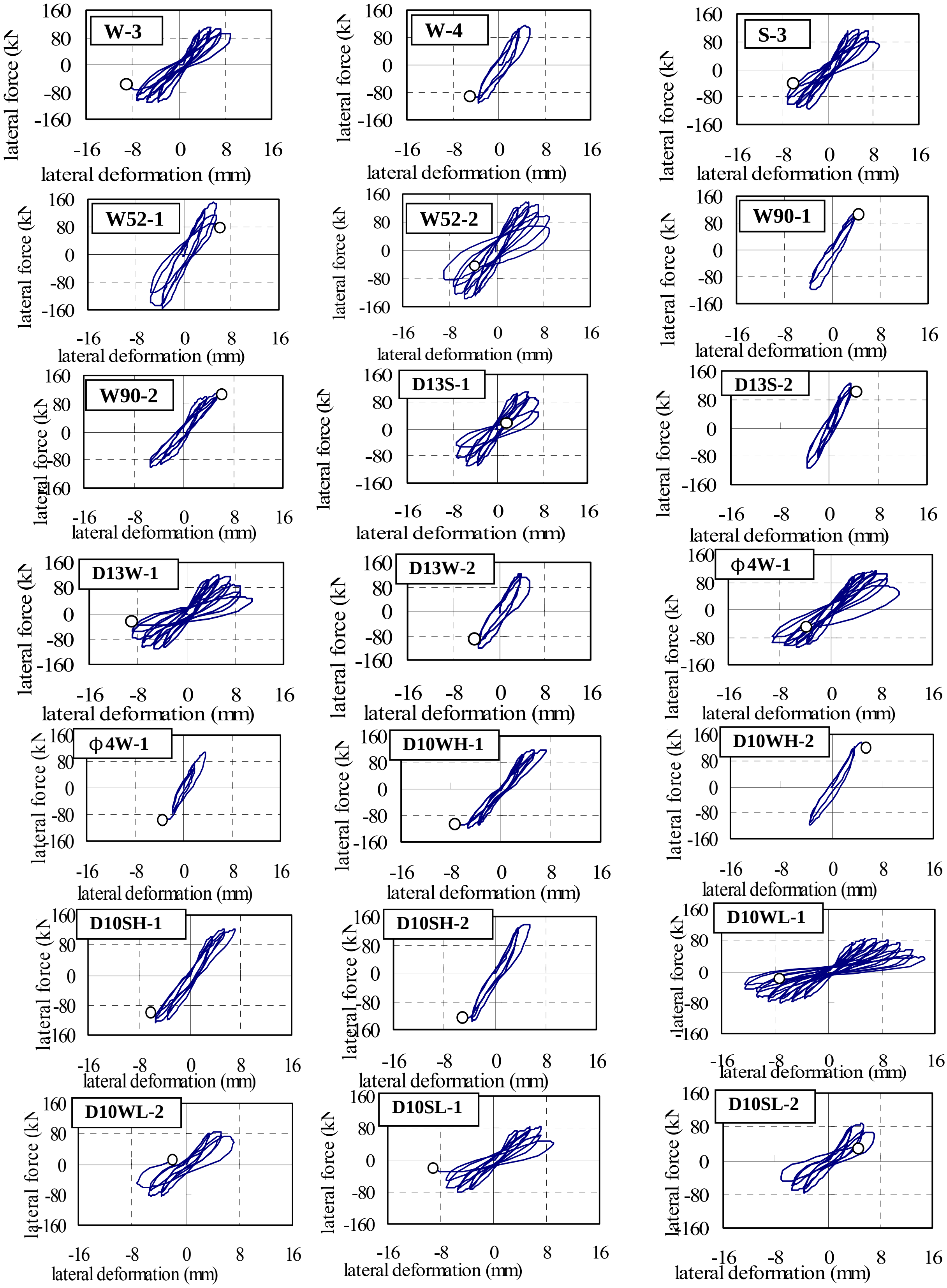


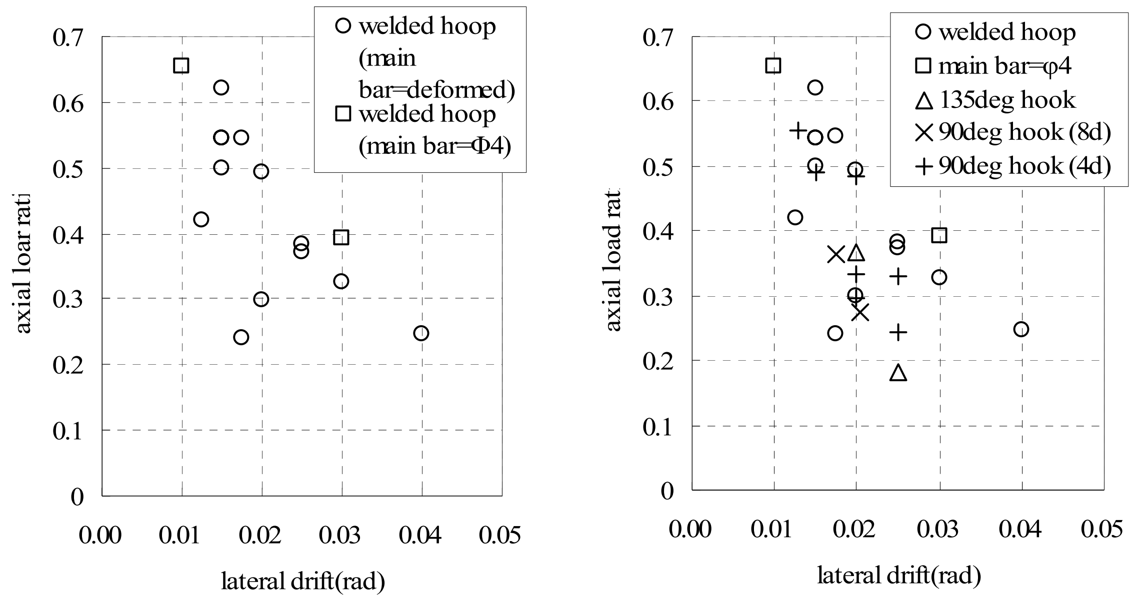
Figure 5 : **L**xial load-lateral deformation relationship **of lateral loading test series**
(o **: losing point of axial load carrying capacity)**

Table 3 :Test results of axial loading specimens

specimen name	maximum strength		friction strength		Stiffness (kN/mm)	
	strength(kN)	deformation (mm)	strength(kN)	deformation (mm)	just after peak	resisted by friction
H-0	1092	1.11	263	5.64	176	9.86
P-0	1098	0.91	250	5.75	179	11.9
W-0	805	1.2	272	10.19	60	4.25
S-0	911	1.56	229	6.54	134	13.3
W52-0	916	1.37	404	7.71	82	2.1
W90-0	834	0.94	269	4.06	185	5.67
D13S-0	893	0.66	225	6.67	111	25.9
D13W-0	920	1.14	335	11.46	55	5.87
φ4W-0	764	1.08	168	10.82	60	7.97
D10WH-0	1002	0.15	299	1.27	623	16.9
D10SH-0	1018	0.22	217	1.71	529	62.5
D10WL-0	607	0.19	276	2.19	170	21.3
D10SL-0	618	0.24	248	1.69	246	43.4

Table 4 :Test results of lateral loading specimens

specimen name	maximum lateral strength (kN)	losing point of axial load carrying capacity	
		lateral deformation(㎜) (drift angle (rad))	axial deformation (mm)
H-3	137	7.2 (0.020)	0.93
H-4	110	9 (0.025)	11.90
P-3	149	6.3 (0.018)	1.65
P-4	134	7.3 (0.020)	5.50
W-3	111	9 (0.025)	1.08
W-4	114	5.4 (0.015)	1.08
S-3	117	9 (0.025)	1.86
W52-1	155	6.3 (0.018)	2.20
W52-2	137	9 (0.025)	6.50
W90-1	120	4.5 (0.013)	0.44
W90-2	109	6.3 (0.018)	0.46
D13S-1	110	7.2 (0.020)	2.62
D13S-2	126	4.6 (0.013)	0.75
D13W-1	122	10.8 (0.030)	7.20
D13W-2	130	5.4 (0.015)	1.20
D13W-3	116	5.4 (0.015)	3.41
φ4W-1	111	10.8 (0.030)	3.42
φ4W-2	108	3.6 (0.010)	0.84
D10WH-1	120	7.2 (0.020)	0.07
D10WH-2	134	5.4 (0.015)	0.09
D10SH-1	127	7.2 (0.020)	0.12
D10SH-2	139	5.4 (0.015)	0.10
D10WL-1	85	14.4 (0.040)	1.67
D10WL-2	87	7.2 (0.020)	0.70
D10SL-1	83	9 (0.025)	0.59
D10SL-2	87	7.2 (0.020)	0.77

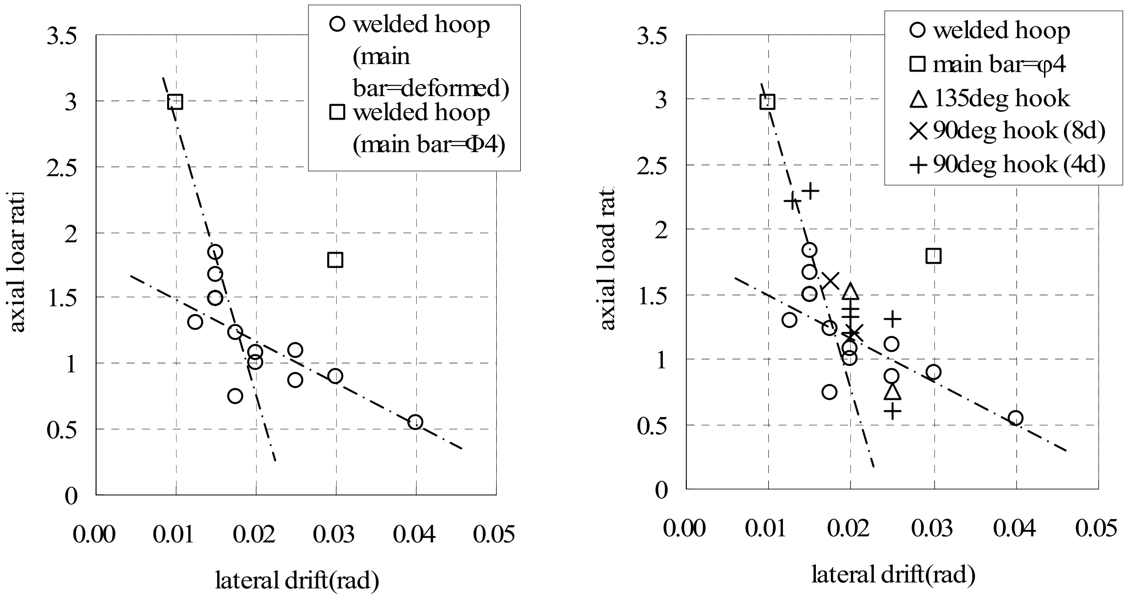


(a) only specimens with welded hoop **(b) all specimens**

Figure 6 : Relation between axial load ratio using maximum strength and lateral drift at losing point of axial load capacity

Y-axis :subjected axial load ratio (evaluated using maximum strength of accompanying axial loading specimen)

X-axis : observed maximum lateral drift before losing point of axial load capacity of lateral loading specimen



(a) only specimens with welded hoop **(b) all specimens**

Figure 7 : Relation between axial load ratio using friction strength and lateral drift at losing point of axial load capacity

Y-axis :subjected axial load ratio (evaluated using friction strength (carried by friction of shear surface)of accompanying axial loading specimen)

X-axis : observed maximum lateral drift before losing point of axial load capacity of lateral loading specimen