EXPERIMENTAL STUDY ON REINFORCED CONCRETE COLUMNNS HAVING WING WALLS RETROFITTED WITH CONTINUOUS FIBER SHEETS

Masato ISO[1], Yasuhiro MATSUZAKI[2], Yasuhisa SONOBE[3], Hiroyuki NAKAMURA[4] And Masayuki WATANABE[5]

SUMMARY

Since many reinforced concrete(R/C) buildings designed to old Japanese seismic codes before 1971 were severely damaged by the Hyogoken-Nanbu Earthquake of 1995, the necessity of seismic diagnosis and seismic retrofit for the existing buildings was strongly recognized.

As the seismic retrofit technique, steel or concrete jacketing has generally been used to increase the shear strength and ductility of R/C members. In recent years, a new method using fiber reinforced plastic(FRP) sheets, such as carbon, aramid and glass fibers, was proposed and has already been applied because of its simple construction process. However, available test data on seismic performance of R/C members retrofitted with FRP sheets are still limited. Moreover most researches have focused on the columns with square cross section in spite of the fact that the columns of most R/C building have the wing walls.

The objective of this research is to investigate the reinforcing effect and structural performance of R/C columns having wing walls retrofitted with FRP sheets. The specimens before retrofit were designed by the old Japanese seismic code before 1971. A total of 16 specimens were constructed and tested under simulated seismic loading.

The primary test variables were the configurations of the wing walls, sticking methods of FRP sheets, the kind of fibers and amount of FRP sheets as shear reinforcement.

As the results, the retrofit method using FRP sheets could enhance the seismic behavior of the R/C columns having wing walls. It was also demonstrated that the shear strengths increased linearly in proportion to the amount of the fiber as shear reinforcement. An equation to evaluate the shear strengths of R/C columns having wing walls retrofitted with FRP sheets was proposed.

INTRODUCTION

After the Hyogo-ken Nanbu Earthquake of 1995, the necessity of the seismic retrofitting of existing buildings and structures designed by the old Japanese seismic code was strongly recognized. A lot of seismic retrofitting technologies have been developed and many existing buildings designed by the former codes have been retrofitted. In recent years, the seismic retrofitting method using FRP sheets has attracted a lot of attention and has already been applied to many retrofitting construction works because of its excellent properties and of its simple construction process when compared with the steel plate or the concrete jacketing method. Previous studies on R/C members retrofitted with FRP sheets have already been reported that the seismic behavior of R/C members can be improved by using FRP sheets on the R/C members. However, almost research has been conducted on columns with rectangular cross sections in spite of the fact that many columns in buildings have wing walls.

In this research, R/C columns having wing walls retrofitted with FRP sheets were tested. The objective of this research is to investigate the effect of FRP sheets on the seismic behavior of R/C columns having wing walls.

1 *Tokyu Construction Co., Ltd., Kanagawa, Japan. FAX:81-42-763-9504*
2 *Dept of Architecture, Faculty of Engineering, Science University of Tokyo, Tokyo, Japan. Email: ymatsu@rs.kagu.sut.ac.jp*
3 *Department of Architecture, Faculty of Engineering, Ashikaga Institute of Technology, Tochigi, Japan. FAX:81-284-62- 423*
4 *Tokyu Construction Co., Ltd., Kanagawa, Japan. FAX:81-42-763-9504*
5 *Tokyu Construction Co., Ltd., Kanagawa, Japan. FAX:81-42-763-9504*

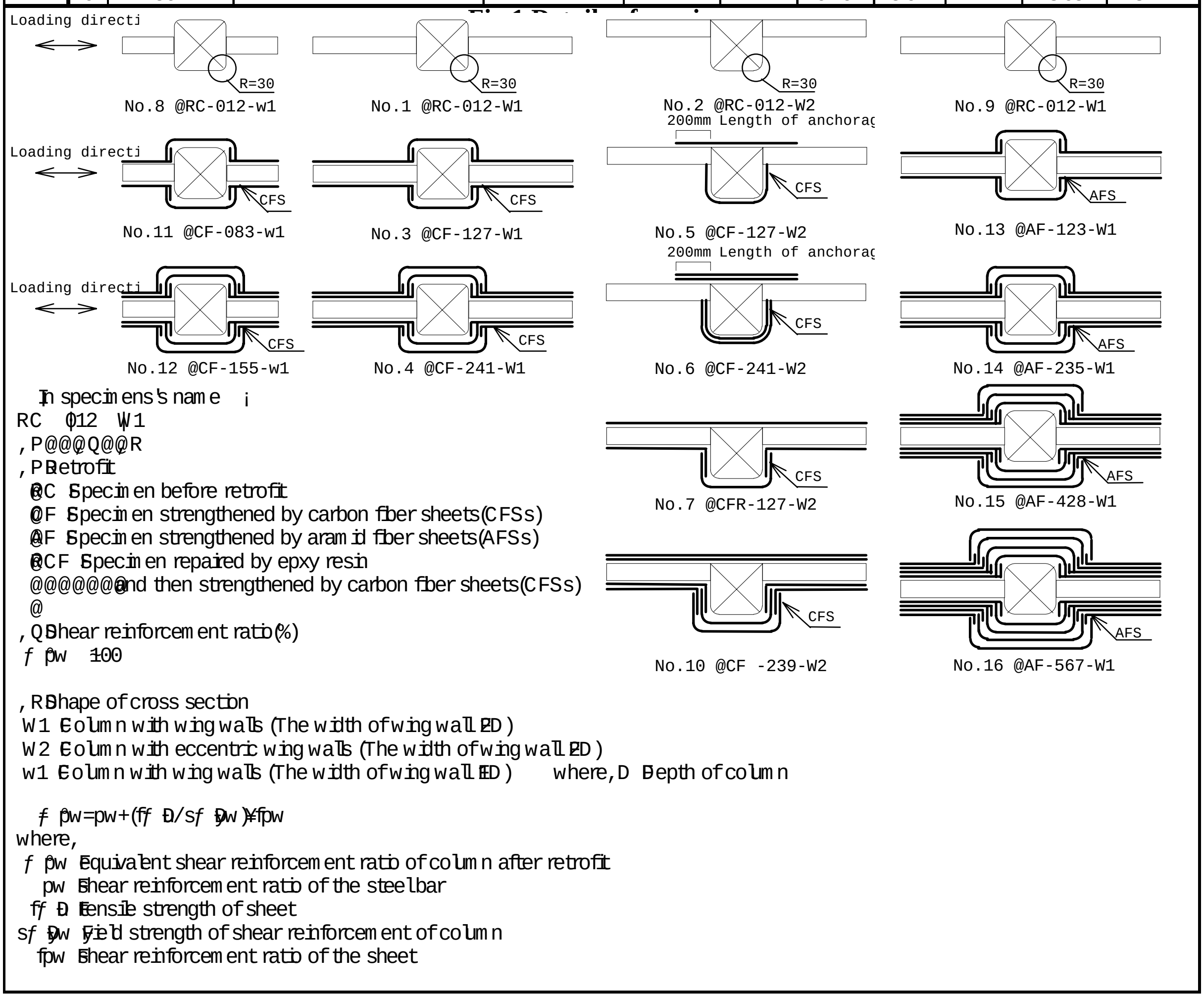
2. OUTLINE OF EXPERIMENT

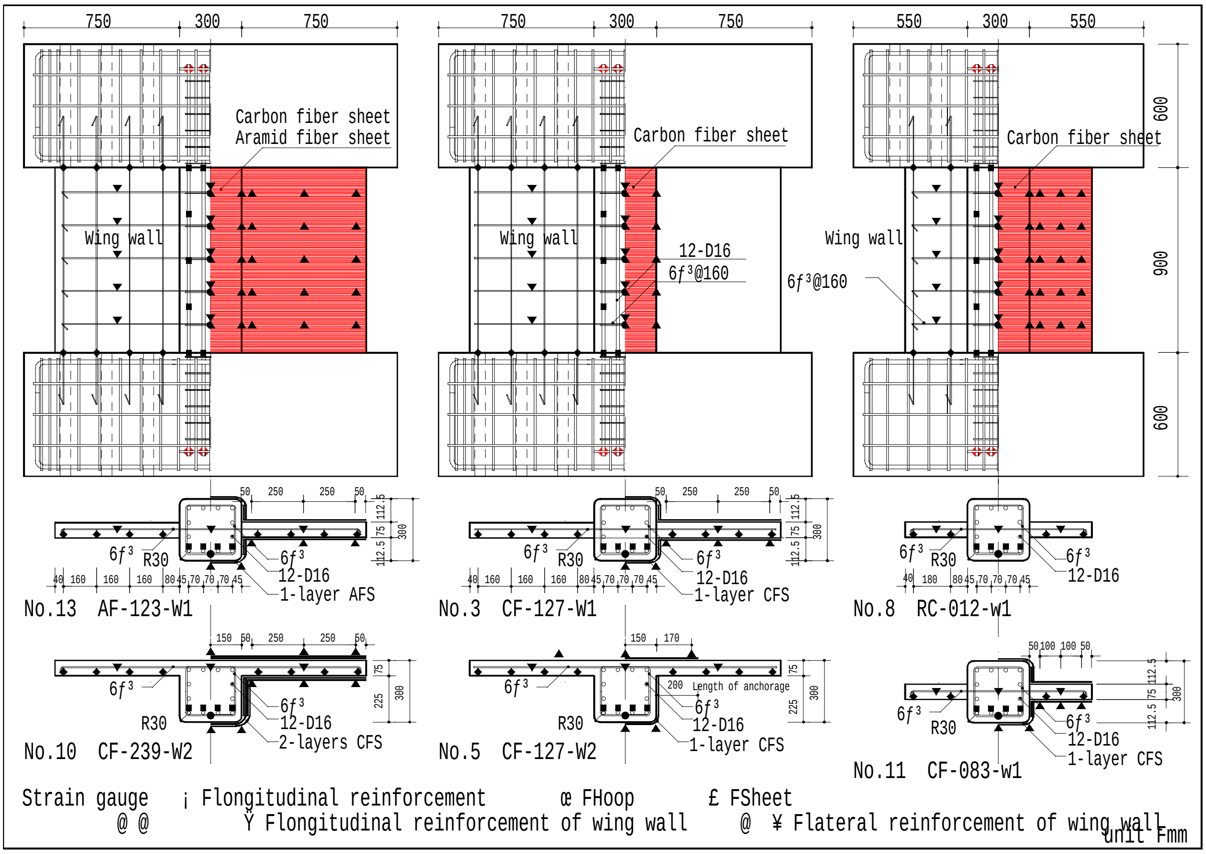
2.1 Specimens

The summary and the details of specimens are shown in Table 1 and Fig.1, respectively. All the specimens were of R/C columns having wing walls. The wing walls were placed on both sides of the column in the direction of loading as shown in Table 1. A total of sixteen specimens were constructed. The specimens before retrofit were designed by the old Japanese seismic code before 1971. The column section was 300(mm)wide × 300(mm)deep, and its shear span ratio a/D is 1.5, where a is shear span and D is the column depth. Deformed

Table 1 Summary of specimens

Series	No.	Specimen's name	Retrofit	Sheet		Column			Wing wall		
				Kind of sheet (weight g/m^2)	Layer of sheet	pw (%)	fpw (%)	ƒ pw * (%)	psh (%)	fpsh (%)	$_c$ƒB (MPa)
‡ T	1	RC -012-W1	RC			0.12			0.24		26.6
	2	RC -012-W2									26.6
	3	CF -127-W1	Strengthened	Carbon (300)	1		0.11	1.27		0.45	27.5
	4	CF -241-W1			2		0.22	2.41		0.89	28.2
	5	CF -127-W2			1(column)		0.11	1.27			26.8
	6	CF -241-W2			2(column)		0.22	2.41			26.6
	7	CFR-127-W2	Repaired and strengthened		1		0.11	1.27		0.45	28.2
‡ U	8	RC -012-w1	RC			0.12			0.24		26.6
	9	RC -012-W1									23.7
	10	CF -239-W2	Strengthened	Carbon (300)	2		0.22	2.39		0.89	27.8
	11	CF -083-w1		Carbon (200)	1		0.07	0.83		0.30	28.2
	12	CF -155-w1			2		0.15	1.55		0.59	29.5
	13	AF -123-W1		Aramid (415)	1		0.19	1.23		0.76	24.0
	14	AF -235-W1			2		0.38	2.35		1.53	32.6
	15	AF -428-W1			3		0.57	4.28		2.29	32.4
	16	AF -567-W1			4		0.76	5.67		3.05	32.4





steel bar D16 and plain round bar 6Φ were used for longitudinal and lateral reinforcement, respectively. The applied axial force N was 1/6 of ultimate axial strength of column (=${}_c\sigma_B$□b□D), where ${}_c\sigma_B$ is the compressive strength of the concrete and b is the column width. The corners of the columns were rounded by 30(mm) radius. The polymer used in the FRP sheets was epoxy resin. The primary test variables were the widths of the wing walls, the kind of the FRP sheets, its amount as shear reinforcement, and the arrangement of wing walls attached to the column. The specimen No.7 was obtained by repairing and strengthening specimen No.2 damaged by preceded test.

2.2 PROPERTIES OF MATERIALS AND LOADING METHOD

The mechanical properties of the material are shown in Tables 2, 3, and 4, respectively. The kinds of FRP sheets were carbon and aramid fibers. The Young's modulus of the FRP sheets were calculated using the secant modulus by connecting the points corresponding to 20 % and 40 % of the tensile strength.

The loading apparatus is shown in Fig.2. During the test, the axial load on column was held constant and reversed cyclic lateral load was applied at the mid-height of the column. The lateral loading program is shown in Fig.3. The loading program was controlled by story drift angle.

3. TEST RESULTS

Fig. 4 shows the final crack patterns. Although all the specimens showed shear failure except for the specimen No.7, there were some differences in failure modes according to the wing wall widths and the kind and amount of the FRP sheets. In all the specimens strengthened with the sheets, the rupture of the FRP sheets could not be observed

Failure mode of No.1, No.2, No.8 and No.9: These specimens were of R/C columns having wing walls before strengthening. As the lateral load increased, diagonal tension cracks formed and propagated. When the ultimate shear strengths were reached, the width of shear crack opened wide and the lateral reinforcing bars yielded. Immediately after, these specimens collapsed. In brief, these specimens showed “shear-tension failure”. After

Table 2 Mechanical properties of concrete

Series	Age (Days)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Young's Modulus (GPa)
I	46～132	26.6～28.2	2.25～2.81	23.7～27.3
II	7～107	23.7～32.6	1.93～3.23	20.4～28.4

Table 3 Mechanical properties of reinforcement

Series	Specimen No.	Type	Sectional Area (mm^2)	Yield Strength (MPa)	Young's Modulus (GPa)
I	No.1～7	D16	199	339	192
		6Φ	28	351	208
II	No.8～14	D16	199	400	190
	No.15,16			366	191
	No.8～14	6Φ	28	359	212
	No.15,16			288	207

Table 4 Mechanical properties of FRP sheet

Series	Kind of Fiber	Fiber Sheet Weight (g/m^2)	Thickness (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)
I	Carbon	300	0.167	3620	253
II	Carbon	200	0.111	3470	263
	Carbon	300	0.167	3670	252
	Aramid	415	0.286	2100	84

Manufacture (Product)
Carbon:Mitsubishi Chemical Co.,Ltd (Replark)
Aramid:Nihon Aramid Co.,Ltd (Towaron)

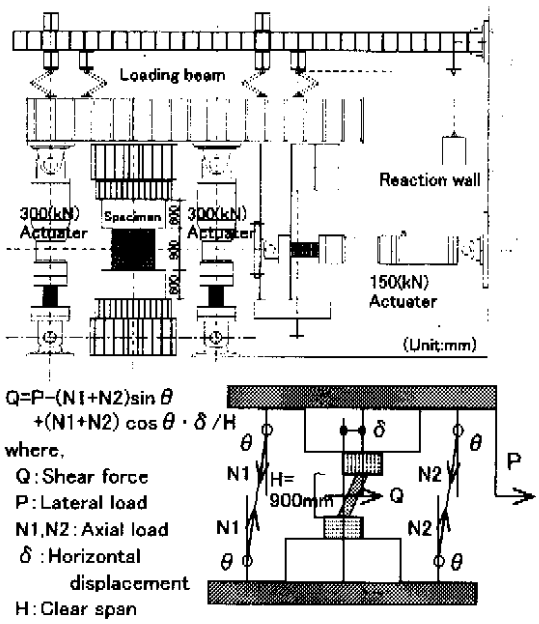


Fig.2 Loading apparatus

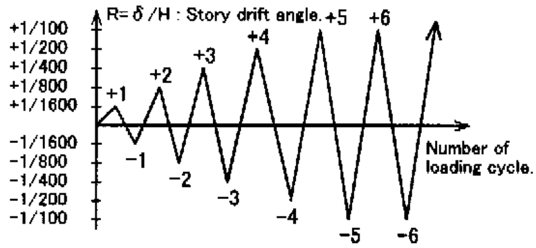


Fig.3 Lateral loading program

reaching the ultimate shear strength, No.1, No.2 and No.9 having wing walls with the width of 2D showed brittle behavior. On the other hand, No.8 having wing walls with the width of 1D showed stable behavior with concrete crushing in the compressive zone of the wing walls.

Failure mode of No.11 and No.12: These specimens, which have wing walls with the width of 1D, were strengthened with carbon fiber sheets (CFSs). As the lateral load increased, the FRP sheets peeled off gradually. When the failure stage was reached, the peeling area of the sheets expanded and the specimens failed by concrete crushing in the compressive zone of the wing walls. After reaching the ultimate shear strength, these specimens showed stable behavior in conjunction with the concrete crushing.

Failure mode of No.3 and No.4: These specimens, which have wing walls with the width of 2D, were strengthened with CFSs. When the ultimate shear strength was achieved, the FRP sheets peeled off suddenly, and these specimens collapsed. The failure mode was more brittle than those of No.11and No.12.

Failure mode of No.5, No.6, No.7 and No.10: These specimens, which have wing walls located eccentrically with the width of 2D, were strengthened with CFSs. No.5, No.6 and No.10 showed a similar failure mode as No.3 and No.4. On the other hand, the failure mode of the repaired No.7 was stable behavior because the repairing mortal at the compressive zone of wing wall showed compressive failure.

Failure mode of No.13, No.14, No.15 and No.16: These specimens, which have wing walls with the width of 2D, were strengthened with aramid fiber sheets (AFSs). No.13 and No.14 strengthened with 1 to 2 layers of

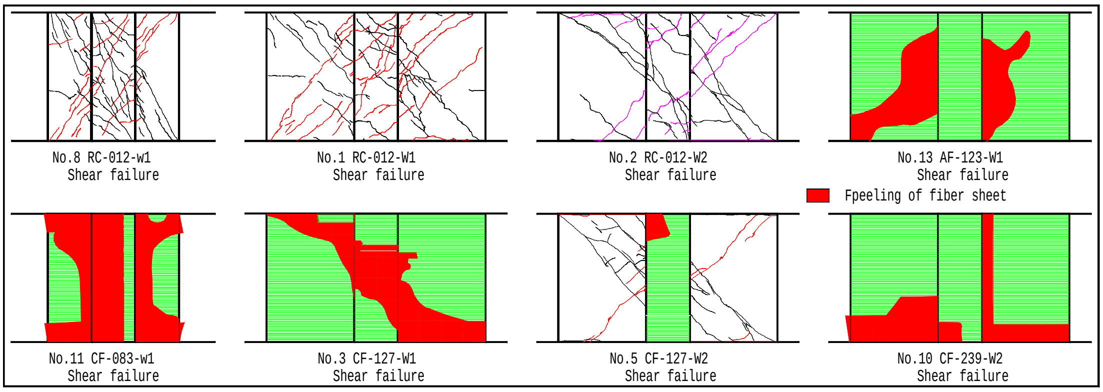


Fig.4 Examples of final crack patterns

AFSs, respectively, showed stable behavior because the FRP sheets peeled off gradually. However, the failure of No.15 and No.16 strengthened with 3 to 4 layers of AFSs, respectively, showed brittle behavior because the FRP sheets peeled off suddenly when the ultimate shear strength was achieved.

Table 5 Test results

Series	No.	Specimen's name	Maximum shear force				Failure mode
			+eQmax (kN)	+eƒ M̂ax (mm)	-eQmax (kN)	-eƒ M̂ax (mm)	
‡T	1	RC-012-W1	616	4.11	-765	-5.05	Shear
	2	RC-012-W2	672	3.68	-532	-2.32	
	3	CF-127-W1	882	7.05	-842	-4.60	
	4	CF-241-W1	1001	7.06	-870	-4.45	
	5	CF-127-W2	722	4.22	-610	-2.30	
	6	CF-241-W2	748	4.24	-593	-2.22	
	7	CFR-127-W2	907	8.31	-887	-8.45	Flexure
‡U	8	RC-012-w1	406	4.64	-403	-4.60	Shear
	9	RC-012-W1	609	4.34	-628	-3.68	
	10	CF-239-W2	796	4.39	-697	-2.20	
	11	CF-083-w1	488	4.53	-498	-4.48	
	12	CF-155-w1	534	6.38	-513	-4.57	
	13	AF-123-W1	668	4.44	-662	-4.05	
	14	AF-235-W1	777	4.55	-661	-4.48	
	15	AF-428-W1	927	4.57	-980	-4.54	
	16	AF-567-W1	930	6.02	-974	-4.51	

Note +eQmax :Maximun shear force under positive loading direction.
-eQmax :Maximun shear force under negative loading direction.
+eƒ M̂ax :Displacement at +eQmax.
-eƒ M̂ax :Displacement at -eQmax.

The list of test results is shown in Table 5.

3.2 Shear force and displacement relationship

Fig. 5 shows the Q-δ envelope curves of R/C specimens before strengthening. No.8 having wing walls with the width of 1D reached the ultimate shear strength at story drift angle of 1/200(rad.). After attaining the ultimate shear strength, the shear force decreased gradually. Although the ultimate shear strengths of No.1, No.2 and No.9 having wing walls with the width of 2 D were larger than that of No.8, the shear force decreased more rapidly after attaining the ultimate shear strength.

Fig. 6 shows the Q-δ envelope curves of the specimens No.1, No.3 and No.4 having wing walls with the width of 2 D. As the amount of CFSs increased, the ultimate shear strength increased. However, the shear force after attaining the ultimate shear strength decreased rapidly, showing brittle behavior.

Fig. 7 shows the Q-δ envelope curves of the specimens having wing walls located eccentrically. The shear strengths of No.2, No.5, No.6 and No.10 decreased suddenly after attaining the ultimate shear strength. Slight increase in the ultimate shear strength was observed with increasing the amount of CFSs. On the other hand, No.7 obtained by repairing and strengthening No.2 showed a hysteresis behavior with no rapid degradation of the shear force after attaining the ultimate shear strength.

□□Fig. 8 shows the Q-δ envelope curves of the specimens having wing walls with the width of 1D. As the amount of CFSs increased, the ultimate shear strength increased, and the decrease of the shear force after attaining the ultimate shear strength tended to be smaller.

Fig. 9 shows the Q-δ envelope curves of the specimens strengthened with AFSs. As the amount of AFSs increased, the ultimate shear strength increased. However, the ultimate shear strengths of No.15 (3 layers) and No.16 (4 layers) were almost the same, showing the limit of the strengthening effect of the FRP sheets. No.13 and No.14 strengthened with 1 to 2 layers of AFSs, respectively, showed a hysteresis behavior with no rapid degradation of the shear strength after attaining the ultimate shear strength. On the other hand, No.15 and No.16 strengthened with 3 to 4 layers of AFSs, respectively, showed a hysteresis behavior with a rapid degradation of shear force after attaining the ultimate shear strength. As the amount of AFSs was increased, the hysteresis behavior tended to be more brittle.

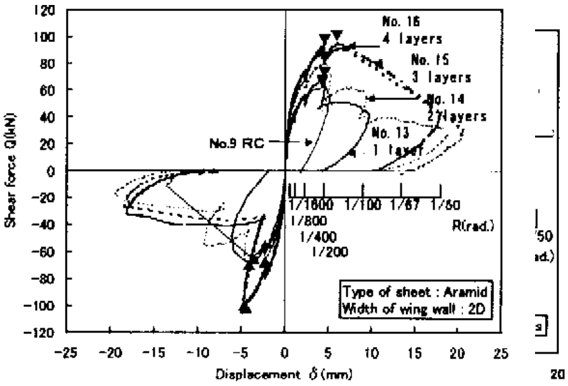


Fig.9 Q- δ envelope(Aramid)

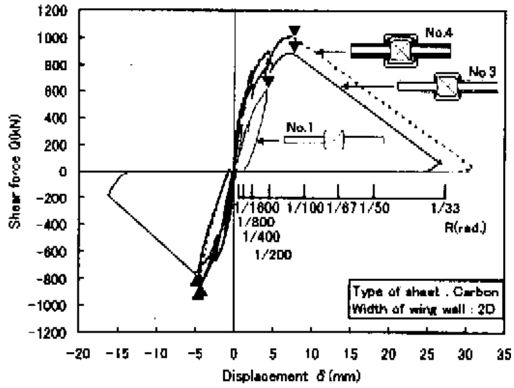


Fig.6 Q- δ envelope(Carbon)

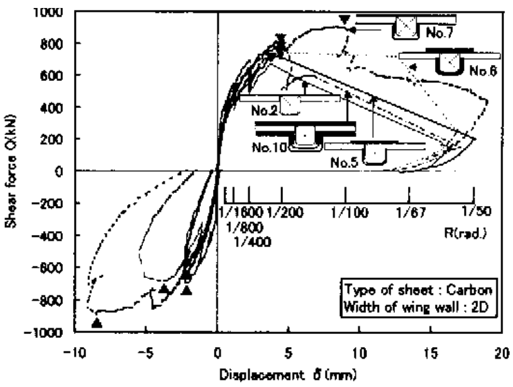


Fig.7 Q- δ envelope(Carbon)

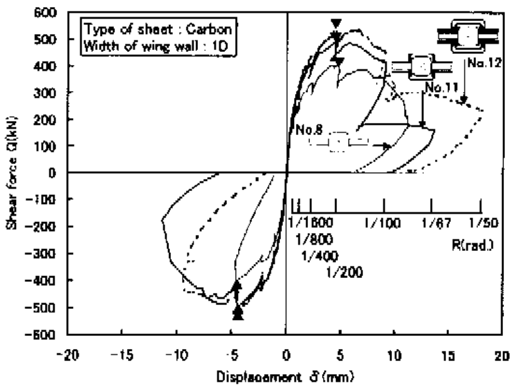


Fig.8 Q- δ envelope(Carbon)

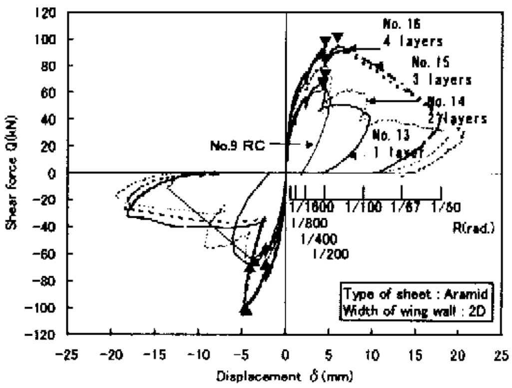


Fig.9 Q- δ envelope(Aramid)

4. RETROFITTING EFFECT OF CONTINUOUS FIBER SHEET

4.1 Maximum Strain of FRP Sheets at the Ultimate Shear Strength

Fig.10 shows the maximum strain of the FRP sheets at the ultimate shear strength. The maximum strains of CFSs and AFSs were 630(μ) to 2,570(μ) on the column, and 900(μ) to 4,630(μ) on the wing wall. The tensile strain of CFS and AFS was about 15,000(μ) and 24,000(μ), respectively. It was found that tensile strengths of CFS and AFS were not fully utilized for these specimens tested. It was also observed that the strains of CFS and AFS tended to decrease with an increase of the amount of the FRP sheets.

4.2 Maximum Shear Strength of the Columns having Wing Walls Retrofitted with CFS and AFS.

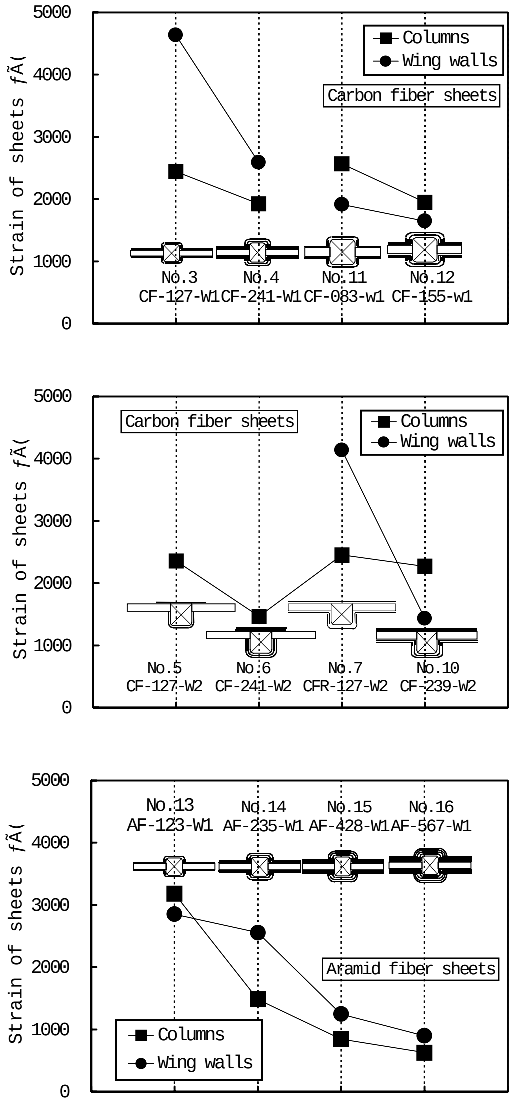


Fig. 11 shows the ultimate shear strength and the amount of the FRP sheets relationship. Fig.11 is shown in CGS unit in order to adopt the Arakawa's formula [AIJ,1987] for the evaluation of the ultimate shear strength of R/C columns having wing walls. As shown in Fig.11, a linear relationship was found between the ultimate shear strength and the amount of the FRP sheets. However, for the specimens No.15 and No.16 strengthened with 3 and 4 layers of AFSs, the ultimate shear strengths of those specimens were almost the same, indicating a limitation of retrofitting effects with the FRP sheets.

A linear regression analysis was carried out in order to evaluate the retrofitting effect of the FRP sheets. The gradient of the regression equations ranged from 0.034 to 0.090 as shown in Fig.11. The gradient of the regression equation for the column having wing walls located eccentrically was slightly smaller than that of the other types. The average gradient in the regression equations was 0.065. Using these results, an empirical equation to evaluate the retrofitting effect of the FRP sheets (τ_{fu}), was obtained as follows:

$$\tau_{fu} = 0.065\left\{ {}_f p_w \cdot {}_f\sigma_u \left(\frac{b}{b_e}\right) + {}_f p_{sh} \cdot {}_f\sigma_u \left(\frac{t}{b_e}\right) \right\} \qquad (1)$$

where, b : web width of column t : thickness of wing wall ${}_f p_w$: shear reinforcement ratio of FRP sheet on column ${}_f p_{sh}$: shear reinforcement ratio of FRP sheet on wing wall ${}_f\sigma_u$: tensile strength of FRP sheet b_e : $=A_w/L_w$

A_w : total cross section area of column having wing walls L_w : total depth of column including wing walls

In order to evaluate the ultimate shear strength of R/C columns having wing walls retrofitted with the FRP sheets, eq. (1) was applied to Arakawa's formula [AIJ,1987], and was proposed as follows:

$$cQsu = \left\{ \frac{0.053 p_{te}^{0.23}(Fc+180)}{a/d_e + 0.12} + 2.7\sqrt{p_w \cdot \sigma_{wy}\left(\frac{b}{b_e}\right) + p_{sh} \cdot \sigma_{sh}\left(\frac{t}{b_e}\right)} + 0.065\left[{}_f p_w \cdot {}_f\sigma_u \left(\frac{b}{b_e}\right) + {}_f p_{sh} \cdot {}_f\sigma_u \left(\frac{t}{b_e}\right)\right] + 0.1\sigma_{0e} \right\} b_e \cdot j_e \qquad (2)$$

where, ${}_s p_w$: shear reinforcement ratio of steel bar of column ${}_s p_{sh}$: shear reinforcement ratio of steel bar of wing wall ${}_s\sigma_{yw}$: yield strength of shear reinforcement of column ${}_s\sigma_{yh}$: yield strength of shear reinforcement of wing wall P_{te} : equivalent tensile reinforcement ratio F_c : compressive strength of concrete a : shear span d_e : equivalent effective depth of column having wing walls j_e : $=(7/8)d_e$ σ_{0e} : $=N/(b_e \cdot j_e)$ N : axial load

Fig. 12 shows relationship between the measured ultimate shear strengths and the calculated ones by eq. (2), where the measured compressive strengths of concrete in Table 2 were used. It can be seen that the proposed eq. (2) evaluated the measured values with safe margin.

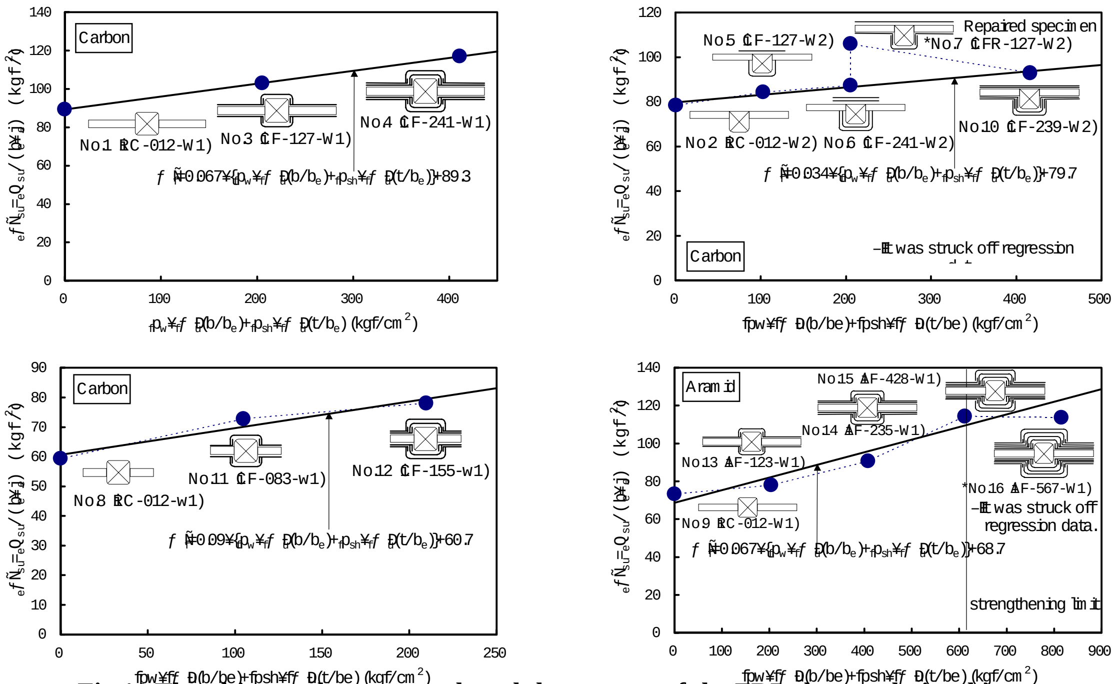


Fig.11 The ultimate shear strength and the amount of the FRP sheets relationship

CONCLUSION

The retrofitting method using carbon fiber sheets and aramid fiber sheets can enhance the seismic behavior of columns having wing walls, in terms of shear strengths. The shear strengths increased linearly in proportion to the amount of the fiber as shear reinforcement. However, a limitation of retrofitting effects of FRP sheets on the ultimate shear strength was found.

The retrofitting effect of carbon fiber sheets was confirmed for the columns having the wing wall with widths of 1D and 2D.

An equation to evaluate the ultimate shear strength of R/C columns having wing walls retrofitted with FRP sheets was proposed. It could be seen that the proposed equation evaluated the measured values with safe margin.

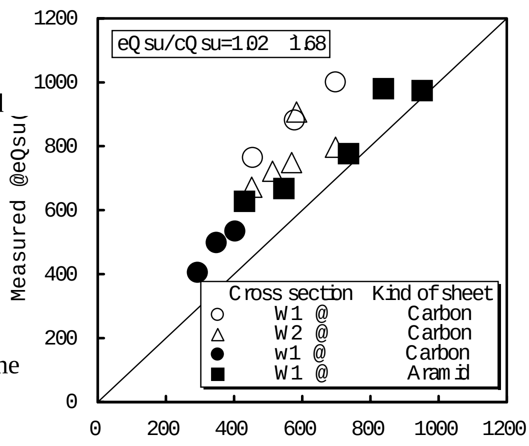


Fig.12 Relationship between measured and calculated shear strengths

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