Experimental Study on the Strengthening and Repair of R/C Wall-Frame Structures with an Opening by CF-Sheets or CF-Grids

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ABSTRACT: In this study, the first story in a multi-storied reinforced concrete structural wall with openings was strengthened using carbon fiber sheets (CF sheets) and carbon fiber grids (CF grids). The effect of shear reinforcement and repair on earthquake resisting behavior were examined with a horizontal forcing experiment for several specimens having different opening positions and opening shapes. The maximum strength and deformability were improved by the CF grid reinforcement of the wall irrespective of opening positions, etc. The deformability was greatly improved by establishing vertical slits in the wall at the four corners of the opening, and reinforcing the columns and sleeve walls using CF sheets. It was possible to evaluate approximately the ultimate flexural and shear capacities of the test specimens in which the reinforcement method differs, by correlating with the fracture modes.

1 INTRODUCTION

Reinforced concrete structural walls overwhelmingly increase the share of the horizontal force in seismic force action in comparison with other members for high rigidity, and are not a negligible influence in the design of structural walls for the earthquake resistance of the whole structure. Therefore, it is desirable that the structural walls that are the original strength resistive members, show not only strength in earthquake action but can also be expected to show toughness and consequently high input energy absorption performance. We reported the possibility that reinforcing the opening with CF sheets could be expected to have a stiffening effect on those structural walls, having a window or door opening between the columns and a low shear capacity as designed according to previous Building Standards of Japan that had been applied until 1971. In this report, we examine new reinforcement methods using CF grids on walls and using CF sheets wrapped on flange walls separated by vertical slits set at the corners of window openings. The final purpose is to propose that the strengthening method produces both excellent strength and toughness in the wall-column structures by reinforcing the wall and adjacent columns.

Table 1 Variables of specimens

Specimen	Opening conditions	Strengthening method	σ_B (MPa)
WA-04S-01	Door opening located at bottom and left side height = 720 mm width = 520 mm	Non	17.5
WA-04S-R*		Repair + Column:S	25.5
WA-04S-CW3*		Column:S + Sleeve:S	23.5
WA-04S-RG		Repair + Column:S + Sleeve:G	21.8
WA-04C-00*	Window opening located at center height = 520mm width = 720mm	Non	21.3
WA-04C-C3*		Column:S	24.6
WA-04C-CW3*		Column:S + Sleeve:S	21.8
WA-04C-CO3*		Column:S + Walls:S	22.6
WA-04C-CWG		Column:S + Sleeve:G	21.5
WA-04C-CW3s		Slits + Column:S + Sleeve:S	22.1

[Notes] *: reported in a previous paper, S: CF-sheets, G: CF-grids , Sleeve: sleeve-wall
Walls: two sleeve-walls + hanging-wall + high-waist-wall, σ_B: concrete strength
Repair: repaired cracks after pre-loading

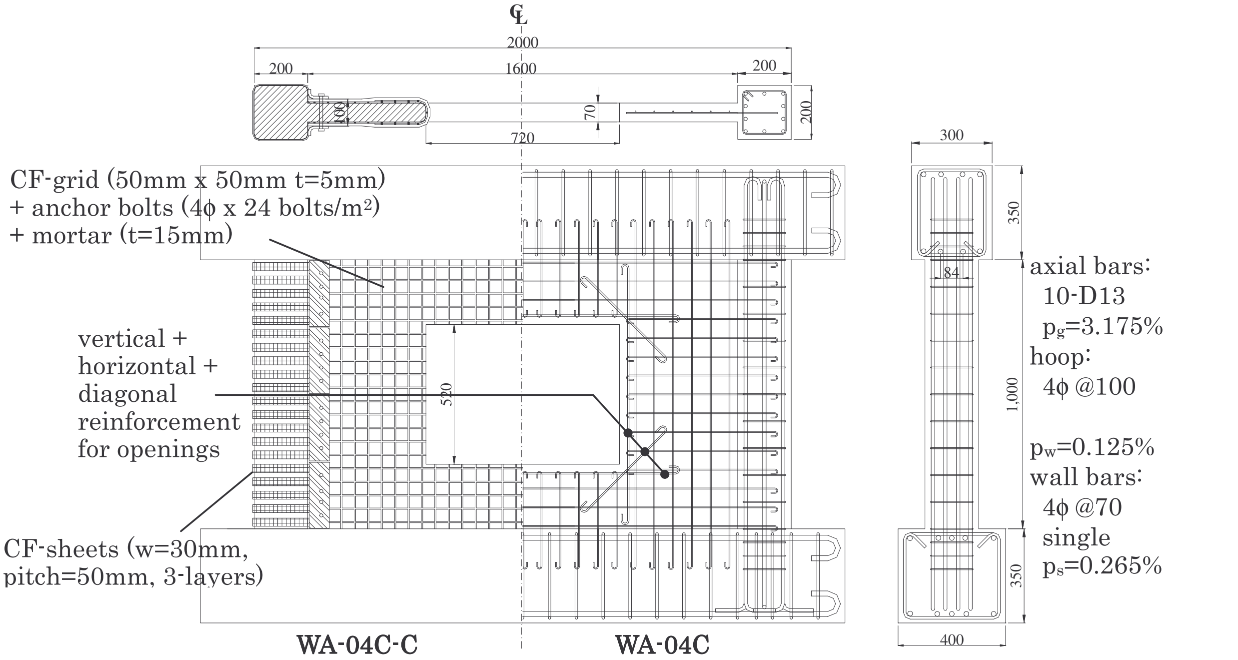


Figure 1-a. Proportions and reinforcements of specimens

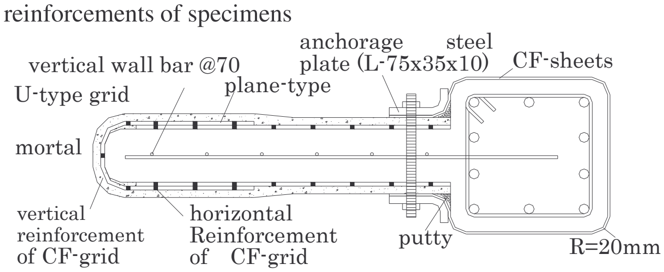


Figure 1-b. Details of CF sheets and grids jacketing

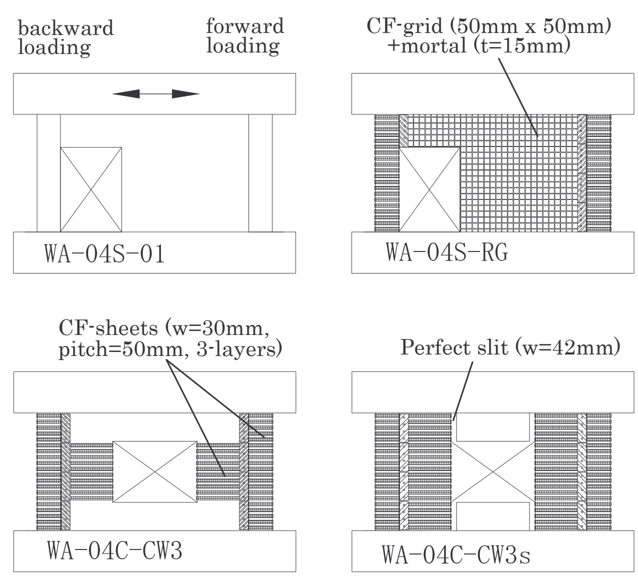


Figure 1-c. Variables in four specimens

2 TEST PROGRAMS

2.1 *Description of test specimens*

The configuration and bar arrangement are drawn in Figure 1. The list of test specimens and the mechanical properties of the materials are shown in Tables 1 and 2, respectively. The test specimens were assumed as the first story of a one-span structural wall in a three-story building, and were produced in a total of nine bodies reduced in models to about 1/3 size (the ten body minute in the test species). In these specimens, a total of six bodies, consisting of four bodies which had the window opening in the center of the wall and two bodies in which the (vertical) door opening was located in the column side as reported in a previous paper (Matsuura, 2002). The test specimens in this paper were the following: a) a non-strengthened Specimen WA-04S-01 with a localization door opening (S-01), b) Specimen WA-04S-RG that was repaired, after it gave a horizontal force to Specimen S-01 up to a drift angle R = about 10×10^{-3} rad, and the wall strengthened with a CF grid and the column with CF sheets (S-RG), c) Specimen WA-04C-CWG (C-CWG) which had a center window opening and was strengthened in the same way as S-RG, d) Specimen WA-04C-CW3s (C-CW3s) that had four vertical slits at the corners of the window opening and the columns and sleeve walls strengthened with CF sheets. The wall panels were 70 mm thick, had an inner width of 1600mm, and an inner height of 1000 mm. An equivalent opening periphery ratio of 0.4 was established. The opening circumference was reinforced with reinforcing steel according to the AIJ-RC Standard (AIJ,1999). The cross sections of the columns on both sides were 200 × 200 mm2, and the inner heights were 1000 mm.

The column axial reinforcement was 10-D13 (SD345), hoops were 4f-@200 (expressed as a round bar of 4 mm in diameter and 200 mm spacing) (equivalent to SR295) and wall bars were arranged vertically and horizontally with 4f-@70 (SR295 equivalent, SR345 equivalent for Specimen C-CWG). The opening reinforcing bars were arranged with 2-6 f vertically, horizontally and diagonally. For Specimen S-RG, the severely flaking portions were replaced with a cross-section repairing material in the cement series, and the crack repair was carried out with epoxy series resin. As for the CF grid strengthening method of the wall of Specimens S-RG and C-CWG, firstly the wall surface was blasted for adhesion force security between the existing wall and the additional mortar. The CF grid was then fixed by steel anchors 4 mm in diameter and 200 mm apart on the wall surface. The mortar was sprayed on each side to a thickness of 15mm. The total wall-thickness after the CF grid reinforcement was 100mm. As for the CF sheet reinforcement method, after the surfaces of the concrete members had been blasted and chamfered, some epoxy-system backing-material was applied to the corner division (radius of 20 mm), and CF sheets of 30mm width were stuck on after hardening using epoxy system resin at 50mm intervals in three layers. The CF sheet was fixed using L form steel (35×75×10, outer size radius 20 mm) and M12 high strength bolts (@50 mm) in the wall edge. In Specimen C-CW3s, the vertical slits, starting at the four corners of the window opening in the wall, were established in order to separate perfectly the sleeve walls, the high waist-wall and the hanging wall. The columns and sleeve walls were reinforced using CF sheets.

2.2 *Loading Method*

Repeated static horizontal loads with displacement increments were applied at loading heights equivalent to a shear-span ratio of 1.13 in order to reproduce the first-story stress-diagram in a three-story structural wall which receives uniform horizontal forces at each floor. A constant axial force which corresponded to an axial force ratio of 1/6 (= σ_0 / σ_B) was applied to both column heads. The loading program was one time forward and backward loading at R = 0.5 $\times 10^{-3}$ rad (hereafter, '$\times 10^{-3}$ rad' is omitted), and twice repeated forward and backward loadings at R = 1, 2, 5, 10, 15, 20, 25, where R was the story drift-angle measured between the top of the lower reaction-beam and the bottom of the upper loading-beam. Additional loading was then carried out at R = 30, 35, 40 for specimens which had relatively small damage.

3 EXPERIMENTAL RESULTS AND CONSIDERATIONS

3.1 *Destruction*

The loading system and common names for each part are shown in Figure 2. The final distraction of each specimen is shown in Figure 3. The whole deformations of the strengthened specimens at the ultimate stage (R = 30.0) are shown in Figure 4.

S-01 (forward loading): Shear cracks of the sleeve wall and of the lower part in the compressive column widened at R = 5.1, and lateral reinforcements of the wall and column around these cracks yielded. Finally, just after the specimen reached maximum strength, the lateral resistance rapidly lowered by shear failure around such yield positions.

S-01 (backward loading): In the whole sleeve wall, shear cracks were generated in great numbers, the specimen reached maximum strength at R = 8.3, and the lateral resistance lowered by widening of these cracks. Another shear crack widened in the lower part of the independent column, which was in the compression side and without a sleeve wall, and the hoop near the shear crack yielded at maximum strength.

S-RG (forward loading): A horizontal bending

Table 2 Properties of materials

Steel bar	Grade	Yield stress (MPa)	Yield strain (μ)	Young's modu. (GPa)	Elongation (%)
Column bar : D13	SD345	399	2020	194	20.3
Hoop & wall bar: 4ϕ	SR295	393	1990	195	24.2
Wall bar(C-CWG): 4ϕ	SR345	529	4780	189	9.7
Opeing reinforcement: 6ϕ	SR295	357	1760	201	20.8
CFRP	**Tens. Strength (MPa)**	**Young's modu. (GPa)**	**Elongation (%)**	**Thickness for design (mm)**	**Sectional area (mm^2/string)**
Carbon fiber sheet*	3480	230	1.5	0.111	---
Carbon fiber grid*	1400	100	1.5	---	26.5
Polymer mortal (example)	**Comp. Strength σ_B (MPa)**	**Tens. Strength (MPa)**	**Bond strength (MPa)**	**Young's modu. at σ_B/3 (GPa)**	**Young's modu. at σ_B2/3(GPa)**
WA-04S-RG	36.6	9.18	1.88	11.4	10.2
WA-04C-CWG	46.5	9.06	1.94	11	9.9

[Note] * : all values exhibited on catalog crack starting from the opening side was generated at the bottom of the sleeve wall, and the main bars of the tensile column and vertical reinforcement in the bottom of the sleeve wall yielded. After that, the wall-column structure was rotated around the bottom of a compressive column. The displacement increased while the lateral resistance was maintained at an almost constant value, reaching its maximum strength at R = 19.3. In the region beyond the maximum strength, the compressive column collapsed, and the bottom of the sleeve wall and compressive column started sliding in the loading direction. The lateral resistance lowered.

S-RG (backward loading): The main bars of the tensile column yielded at R = 5.1, and the specimen reached maximum strength. The vertical boundary line between the tensile column and the sleeve wall began to open in the forward loading under the effect of the bending crack that occurred at the bottom of the sleeve wall along the stub. The whole sleeve wall then started sliding in the loading direction, and the lateral resistance lowered. The CF sheet around the lower part of the tensile column broke due to this effect, and degradation of the lateral resistance increased, since the tensile column also started sliding with the sleeve wall in the loading direction.

C-CWG (forward and backward loadings): The main bars of the lower part in the tensile column yielded at R = 5.0, and the stiffness reduced. Bending cracks along the top and bottom stubs widened, the strain of the vertical wall bars increased, and the specimen reached maximum strength at R = 14.1. Afterwards, the concrete in the vicinity of the opening corner crashed by compressive stress. Consequently the right and left columns with the sleeve wall were deformed in bending separately to each other. The lateral resistance lowered with the progress of this collapse. The compressive column and sleeve structure wall

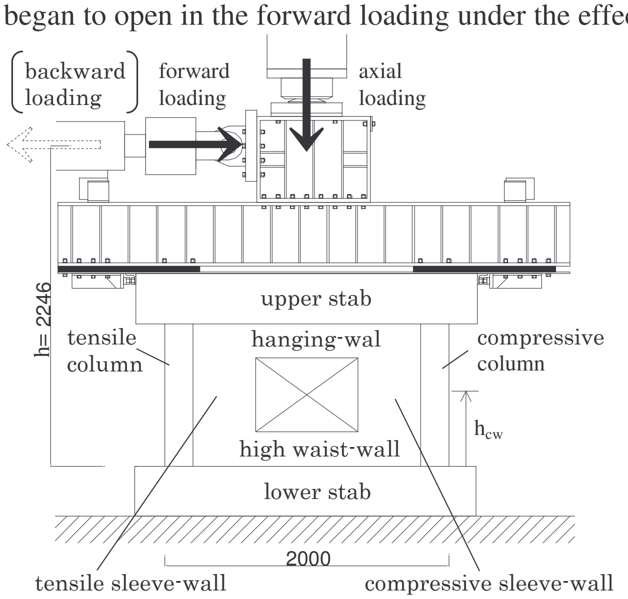


Figure 2. Schema of loading system

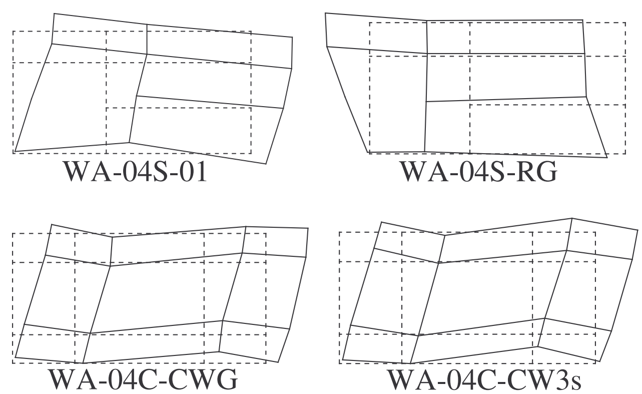


Figure 4. In-plane deformations of specimens at drift angle of 0.03 radian

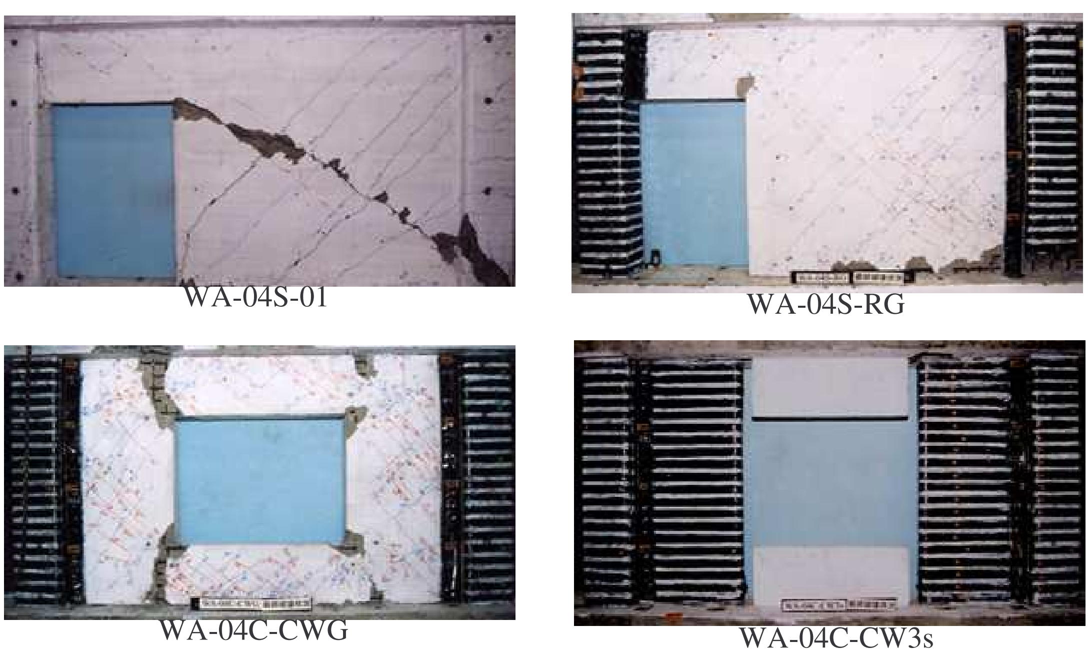


Figure 3. Final failure of each specimen

then began to slip as with a one-body structure (without separation at the boundary between the column and the sleeve wall) in the loading direction at R = 20.0 along the bending cracks which occurred laterally at the top and bottom stubs.

C-CW3s (forward and backward loadings): bending cracks produced laterally along the bottom stub in the sleeve wall of the compression side and the top stub in the sleeve wall of the tension side, opened remarkably. The column and sleeve wall-structure in each side was deformed in bending as a one-body structure, and reached its maximum strength at R = 15.2. Afterwards, the sleeve walls near the top and bottom stubs collapsed, and the lateral resistance was gradually lowered.

3.2 *Deformation vs. load relationship*

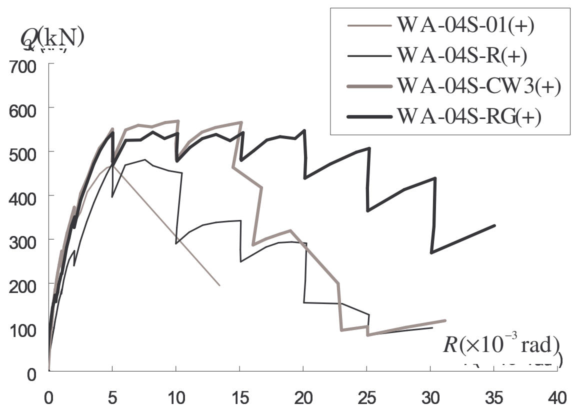
Comparison of the envelope curves for all specimens is shown in Figure 5.

3.2.1 *Strengthening effect of structural walls with an asymmetric door opening*

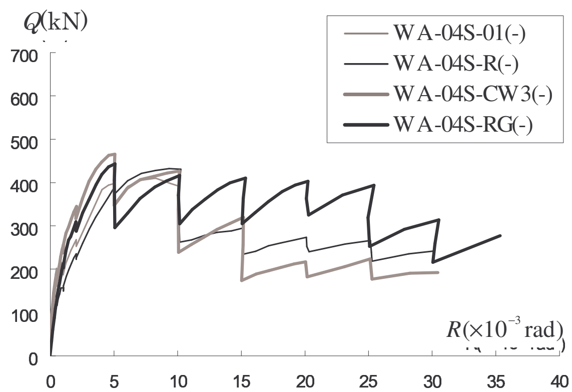
The initial stiffness of repaired specimens S-RG and S-R lowered a little in comparison with that of the undamaged specimens, but remarkable differences in the initial stiffness could not be observed in all specimens. The maximum strengths of strengthened specimens in both the forward and backward loading directions were higher than those of the non-strengthened specimen S-01 without relation to repair and non-repair. Therefore, it can be said that when CF sheet strengthening of the columns is minutely carried out, the shear fracture in the early stages of the column can be prevented and lateral resistance increased.

In forward loading, S-RG maintained its lateral resistance higher than that of S-R by large deformation, while the maximum strength of S-R decreased by shear fracture of the sleeve wall at R = 10.0. These behaviors were caused by the effect in which the whole wall-column frame deformed in flexure and rotated around the bottom of the compressive column, since the CF grid strengthening of the walls prevented shear cracks widening of the sleeve walls of S-RG, and consequently raised the rigidity. In comparison with S-RG and S-CW3, the reduction of lateral resistance of S-RG caused by the bending crush around the lower part of the compressive column, was small even at R = 25.0, while the lower part of the compressive column in S-CW3 could not keep yielding and collapsed in bending crush at R = 15.0 which rapidly caused lateral resistance lowering. This performance of S-RG was the effect of the additional plastered mortar in the CF grid strengthening work, and was because the share of the bending compressive force by the sleeve wall, increased.

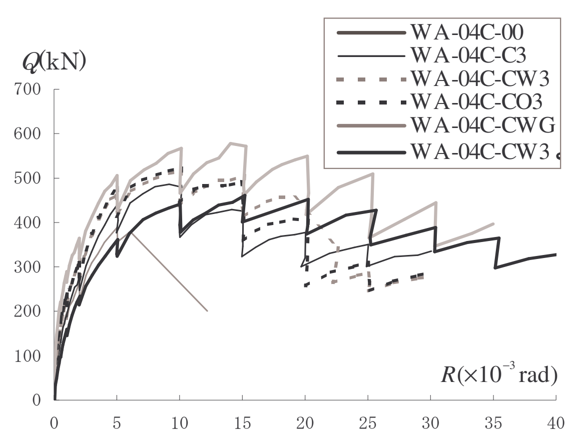
Lateral resistance rise of the strengthened specimens against the non-strengthened specimens in backward loading, was less than that in forward loading. This was due to the sleeve wall sliding in the opening side along the diagonal shear crack-line in the sleeve wall for S-R, and along the lateral-bending crack at the bottom of the sleeve wall for S-CW3 and S-RG after dividing at the boundary between the column and wall. Especially, since breaking the column CF sheets caused not only wall sliding but also column sliding for S-CW3 and S-RG, improvement in the strengthening method for sliding is a future problem.



(a) Asymmetric door opening type under forward loading



(b) Asymmetric door opening type under backward loading



(c) Window opening type in wall center

Figure 5. Lateral load and drift angle relationships

3.2.2 *Strengthening effect of walls with a center window opening*

In C-CW3s, the initial stiffness lowered most in all specimens, because the wall was divided into four parts by the slits and a diagonal compression strut in the wall was not formed. Specimens C-CW3 and C-CO3 were able to prevent shear-crack widening in the strengthening portions. However, there was not a large improvement in lateral resistance and deformability, since the shear fracture in the non-strengthening portions progressed. The whole wall of Specimen C-CWG was strengthened by the CF grids and the wall shifted to the flexure fracture mode, since shear crack widening in the wall was prevented. Consequently, there was a rise of 18.9% at maximum strength, high lateral resistance was maintained in the large deformation, and there was an improvement in the deformability. When C-CW3s was compared with other strengthened specimens, although the maximum strength lowered, the mechanical properties of the sleeve wall and column structures became that of a one-body structure in each side by the slits set up at the four corners of the window opening. Therefore, the lateral resistance at R = 25.0 was the highest after C-CWG among all the specimens, and the deformability in large deformation was the best.

3.3 *Comparison between measured and calculated maximum strengths*

Table 3 shows the measured horizontal force and story drift-angle at maximum resistance with the calculated values.

3.3.1 *Ultimate flexural strength of RC structural wall* ${}_{B}Q$

${}_{B}Q$ is defined by Equation 1 as the minimum value between the ultimate flexural capacity of structural walls calculated as a one-body structure ${}_{B}Q_{w}$ (JBDPA, 2001) and the flexural capacity summing capacities of the columns and of the sleeve wall ${}_{B}Q_{cw}$.

$$ {}_{B}Q = \min\left[{}_{B}Q_{w} \;,\; {}_{B}Q_{cw} \right] \qquad (1) $$

Ultimate bending capacity of RC column-wall structure evaluated as one-body system ${}_{B}Q_{w}$ is defined by the following:

$$ {}_{B}Q_{w} = \frac{M_{u}}{h}, $$

$$ M_{u} = a_{t} \cdot \sigma_{y} \cdot l_{w} + \beta \cdot a_{w} \cdot \sigma_{wy} \cdot l_{w} + 0.5N \cdot l_{w}, \qquad (2) $$

where,

β : factor according to opening location

h : reflection height of one-body system (mm) (=height of lateral loading, see Figure 2)

a_{t} : total cross-sectional area of column bars (mm^2)

σ_{y} : yield stress of column bars (N/mm^2)

σ_{wy} : yield stress of wall bars (N/mm^2)

a_{w} : total cross-sectional area of vertical wall bars (mm^2)

l_{w} : distance between both columns (mm)

N : column axial force (N)

Ultimate bending capacity of RC column-wall structure summing capacities of column-sleeve wall system ${}_{B}Q_{cw}$ is defined by the following:

$$ {}_{B}Q_{cw} = \sum {}_{B}Q_{cw}' $$

:for door opening located eccentrically,

$$ {}_{B}Q_{cw} = {}_{B}Q_{cw}' + {}_{B}Q_{c} $$

:for window opening located in center,

where, $ {}_{B}Q_{cw}' = \frac{M_{u}}{h_{cw}} $

Table 3. List of experimental maximum strengths and calculated ultimate strength

Specimen	σ_B (MPa)	r	Q_{exp} (kN)	R ($\times10^{-3}$rad)	${}_{B}Q_{w}$ (kN)	${}_{B}Q_{cw}$ (kN)	${}_{B}Q$ (kN)	${}_{S}Q_{h}$ (kN)	${}_{S}Q$ (kN)	Q_{cal1} (kN)	Q_{exp}/Q_{cal1}	Q_{cal2} (kN)	Q_{exp}/Q_{cal2}	Failuer mode
WA-04S-01(+)	17.5	0.86	467	5.1	500	580	500	383	402	383	1.22	402	1.16	Shear failure in C&S
WA-04S-01(-)		0.76	410	8.3	522	506	506	339	341	339	1.21	341	1.20	Shear failure in S
WA-04S-R(+)	25.5	0.86	481	7.6	553	636	553	451	553	451	1.07	553	0.87	Shear failure in S
WA-04S-R(-)		0.76	432	9.3	555	566	555	399	488	399	1.08	488	0.88	Shear failure in S
WA-04S-CW3(+)	23.5	0.86	568	10.2	533	692	533	710	644	533*	1.07	533*	1.07	Bending failure of whole wall
WA-04S-CW3(-)		0.76	466	5.1	544	507	507	627	547	507*	0.92	507*	0.92	Sliding failure at wall bottom
WA-04S-RG(+)	21.8	0.86	547	19.3	523	651	523	835	721	523*	1.05	523*	1.05	Bending failure of whole wall
WA-04S-RG(-)		0.76	443	5.1	545	515	515	738	596	515*	0.86	515*	0.86	Sliding failure at wall bottom
WA-04C-00 (±)	21.3	0.59	389	5.0	534	562	534	285	353	285	1.36	353	1.10	Shear failure in C&S
WA-04C-C3 (±)	24.6	0.59	486	9.2	551	581	551	304	476	304	1.60	476	1.02	Shear failure in S
WA-04C-CW3 (±)	21.8	0.59	516	10.1	537	565	537	477	512	477	1.08	512	1.01	Shear failure in hanging wall
WA-04C-CO3 (±)	22.6	0.59	523	10.2	541	569	541	482	519	482	1.09	519	1.01	Shear failure in S
WA-04C-CWG (±)	21.5	0.59	578	14.1	543	571	543	587	552	543*	1.06	543*	1.06	Bending failure of whole wall
WA-04C-CW3s (±)	22.1	0.59	461	15.2	538	479	479	479	515	479*	0.96	479*	0.96	Bending failure of C&S
Q_{cal1}=min.[${}_{S}Q_{h}$, ${}_{B}Q$] , Q_{cal2}=min.[${}_{S}Q$, ${}_{B}Q$]							**Average**				1.12		1.01	
							Standard deviation				0.19		0.11	

*** : Values show ${}_{B}Q$**

$$M_u = a_t' \cdot \sigma_y \cdot l_w + 0.5 \cdot a_w \cdot \sigma_{wy} \cdot l_w + 0.5 N_e \cdot l_w \quad (3)$$

h_{cw} : reflection height of column with sleeve wall (mm) (it appears at mid-height of the column normally, see Figure 2),

a_t' : vertical cross-sectional area in virtual column (mm^2),

N_e : column axial force considering with variable axial load (N).

A virtual column of which the width and depth were equal to the wall-thickness and column depth respectively, was established in the opening side of the sleeve wall, as shown in Figure 6, and ${}_BQ_{cw}$ was calculated using Equation 3. The height of the reflection point of the column with the sleeve wall, was evaluated as the height of the reflection point calculated in the portal frame consisting of the columns with and without the sleeve wall and the beam with a hanging wall, by using the D-value Method. However, the height of the reflection point was reduced considering the rigid zone in the height direction and appeared by the high-waist-wall for the center window-opening specimen without the slits.

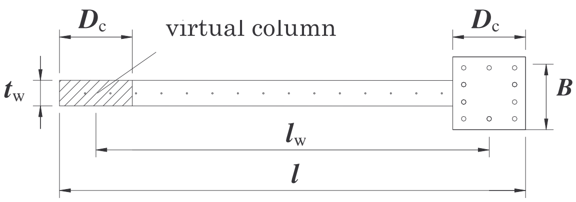


Figure 6. Notation of column with sleeve wall

3.3.2 *Shear capacity based on Hirosawa's Modified Equation ${}_sQ_h$ (AIJ, 1990)*

${}_sQ_h$ was obtained by multiplying a reduction factor gamma γ to the shear capacity without any opening. The factor was defined as $(1 - A_e)/A$, where A_e was the area which the opening occupied in the compressive diagonal strut zone, and A was the area of the compressive diagonal strut zone, as shown in Figure 7. The CF grid strengthened specimens S-RG and C-CWG seemed to change from the shear fracture mode to the flexure fracture mode, since the shear capacity increased highly by the arch mechanism caused by the mortar used in the CF grid reinforcement, in addition to the increase of the shear capacity in the truss mechanism by the CF grid itself. The compressive strength of the concrete was then estimated as the weighted-average compressive strength of the existing wall-concrete and additional mortar in consideration of the weight given at both cross sectional areas, and shear-capacity increment by the arch mechanism of the concrete included in Equation 4.

$${}_sQ_h = r \cdot \left\{ \frac{0.068 \cdot p_{te}^{0.23}(\sigma_B + 17.7)}{\sqrt{M/(Q \cdot D) + 0.12}} + 0.85\sqrt{p_{wh} \cdot \sigma_{sy} + \alpha \cdot p_{wf} \cdot \sigma_f} + 0.1\sigma_0 \right\} b_e \cdot j \quad (4)$$

where,

p_{te} : reinforcement ratio of column axial bars $(= a_t / b_e \times l_w)$,

p_{wf} : reinforcement ratio of CF sheets or CF grids $(= a_f / b_e \times x_f)$,

x_f : spacing of CF sheet or CF grid (mm),

a_f : cross-sectional area of CF sheets or CF grids (mm^2),

b_e : equivalent thickness of wall-column structure (mm),

j : moment arm = l_w

σ_f : tensile strength of CF sheets or CF grids (MPa),

σ_B : equivalent compressive strength of concrete with polymer mortal (MPa),

σ_0 : axial stress ratio of equivalent cross-section (MPa),

α : reduction factor for opening defined by Figure 7.

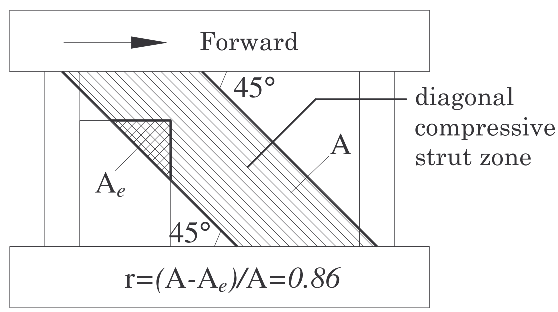


Figure 7. Evaluation of decreasing ratio by opening

3.3.3 *Shear capacity based on summation of shear strengths of all resistant members ${}_sQ$*

${}_sQ$ was defined in the following so that the calculation formula would correspond to the strengthened position. The strengthening method and fracture pattern of each test specimen, and the relationship between each Q and its member is shown in Figure 8.

In the case of walls with a central opening:

$${}_sQ = [\, {}_sQ_c + {}_sQ_w \,]\text{tension} + \min[({}_pQ_c + {}_sQ_w), ({}_sQ_c + {}_sQ_w)]\text{comp.} \quad (5)$$

In the case of walls with an asymmetric opening:

$${}_sQ = \min[({}_sQ_c + {}_sQ_w), ({}_pQ_c + {}_sQ_w)]\text{column with sleeve wall} + \min[{}_bQ_c, {}_sQ_c]\text{independent column} \quad (5)'$$

where, ${}_sQ_c$: the shear capacity of the strengthened columns calculated from Hirosawa's Modified Equation (AIJ, 1990),

${}_sQ_w$: shear capacity of walls without columns calculated from the following equation (JBPDA, 2001),

$$ {}_sQ_w = [\ \sigma_B / 20 + 0.5\ (p_s \times \sigma_{sy} + \alpha \times p_f \times \sigma_f)] \times t_w \times l_w \qquad (6)$$

α : 1/10, which was assumed from the wall-sheet strain measured at the maximum resistance,

${}_pQ_c$: punching shear-strength of the side columns,

$$ {}_pQ_c = \tau_{min} \times \sigma_0 \times b_e \times D \qquad (7)$$

${}_bQ_c$: flexural capacity of independent column (AIJ, 1900),

The calculated shear-capacities Q_{cal1} and Q_{cal2} of each specimen were defined by the following:

$$ Q_{cal1} = \min\ [{}_bQ,\ {}_sQ_h], \qquad Q_{cal2} = \min\ [{}_bQ,\ {}_sQ] \qquad (8)$$

It was possible that the calculated values Q_{cal1} and Q_{cal2} agreed with experimental values as well as the calculated fracture modes determined using Equation 8 since they corresponded to the experimental fracture modes. It was possible that the maximum strength of the specimens that failed in flexure, could be estimated approximately by Equation 1. The shear capacity of C-CW3s with the slits could be estimated by Equation 3 because it had a flexure fracture pattern. Equation 4 had no good correspondence to specimens of the shear-fracture type, since the representation in the equation does not include the effect of CF sheets on column strengthening. Therefore the calculated shear-capacity of C-C3 did not show good results. In the meantime, when the shear capacity was calculated using Equation 5, the increase in maximum strength caused by differences in the reinforcement position was evaluated, and good correspondence was shown.

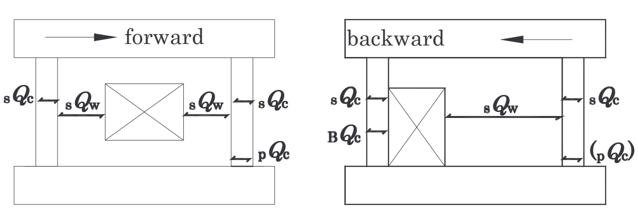


Figure 8. Relationship of shear capacities Q and their positions

4 CONCLUSIONS

We investigated by experimental tests, the development of a new method using carbon fiber sheets or grids to strengthen existing RC structural walls which were framed by strong beams and columns with weak shear capacity and which had a window opening in the wall center or a door opening beside one column asymmetrically. The test results conclude as follows.

(1) The strengthening method covered by CF-grids and polymer mortar on whole surfaces of walls in a frame, shifted the shear-fracture mode to the flexure-fracture mode, regardless of the asymmetry of the opening, since shear-crack widening in the walls was prevented. Thus, lateral shear-capacity and deformability of the wall structure could be improved.

(2) When the wall with a central window opening was set up with vertical slits at the four corners of the window opening and both the sleeve wall and column structures separated by the slits were strengthened by CF sheets, maximum strength and stiffness of the new structures became lower. However bending deformation that appeared individually in each of the sleeve wall and column structures predominated and the deformability was largely improved.

(3) The ultimate flexural-capacity of structural walls with an opening could be evaluated from the minimum value between the flexural capacity as a one-body structure and a calculated value summing the flexural capacities of the columns with the sleeve wall.

(4) The ultimate shear-capacity could be evaluated by summing the minimum shear capacities of the columns and the sleeve walls, because of estimating the strengthening effect of each member using CF sheets or grids.

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