CYCLIC LOADING TESTS ON PRE-DAMAGED RC COLUMN STRENGTHENED WITH UFC PANELS

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SUMMARY

Earthquakes are accompanied by multiple subsequent earthquakes, even after the initial shock. Therefore, quick seismic strengthening after the mainshock is essential to reduce the damage caused by aftershocks by enhancing the deteriorated structural performance. In this study, ultra high strength fiber reinforced concrete (UFC) panels were applied to seismic strengthening for damaged RC columns as a quick and effective method. Four 1/3-scale specimens which replicated RC columns of the soft-first-story of a 10-story condominium building heavily damaged by the 2016 Kumamoto Earthquake were constructed and tested. The specimens were strengthened with the UFC panels after the pre-loading to the drift ratio at which the maximum strength was measured. The UFC panels were installed on the two faces parallel to the assumed loading direction, and the UFC or RC wing wall was also attached to either one of the column sides. Cyclic lateral load and varying axial load simulating an earthquake load were applied to the specimens. Through the proposed method, the maximum strength and the ultimate drift ratio were improved, and the initial stiffness of specimens with UFC panels and a wing wall was restored to that of a column specimen during the pre-loading.

***Keywords**: pre-damaged RC column; soft-first-story building; seismic strengthening; UFC panels; column with a wing wall; varying axial load*

INTRODUCTION

An earthquake is a natural phenomenon in which the ground shakes due to the momentary release of energy accumulated for a long time in the earth's crust due to internal activity and plate tectonic motion. The accumulated energy is released not once, but several times. Consequently, buildings damaged by an initial or main earthquake may sustain additional severe damage from subsequent earthquakes. In April 2016, a quake of moment magnitude scale (Mw) 6.5 struck Kumamoto, Japan. The Mw 7.3 earthquake struck two days later and was more potent than the first. Over 2,000 aftershocks occurred over four months, causing severe damage to people and property. Even buildings with minor damage to structural members from the initial or main earthquake may collapse severely in subsequent quakes of the same magnitude or more significant. To prevent this, rapid repairs and retrofitting are required.

This study suggests damaged columns strengthened with ultra-high-strength fiber-reinforced concrete (UFC) as a

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quick retrofit method. UFC is a composite material made by mixing steel fibers with concrete to produce concrete that doesn't require reinforcing bars. UFC has a high compressive strength of 180 N/mm^2 or more and has a higher tensile strength than plain concrete due to the steel fiber. It is formed from a panel and can be retrofitted quickly and easily by adhering it to a column with insufficient strength using an epoxy resin adhesive.

The authors conducted a cyclic loading test on a column in the soft first story of a RC building severely damaged in the 2016 Kumamoto Earthquake (Kumabe et al. 2021). The target column was made as 1/2 scale specimens, and flat UFC panels were attached to the two sides parallel to the loading direction with an epoxy resin adhesive. A high-strength non-shrinkable mortar was injected between the UFC panel and the stub. The experimental parameter was the level of damage to the column during preliminary loading, which was adjusted by preloading up to the specimen's drift ratio of 0.5 % and 3 %, respectively. At the drift ratio of 0.5 %, the specimen's maximum strength was measured, and its damage situation corresponds to damage class III in Table 1, which describes each damage class according to Japanese guidelines (JBDPA 2015). The specimen loaded with the drift ratio of up to 3 % before strengthening observed a decrease in strength, corresponding to damage class IV in Table 1. The maximum strength of the specimen preloaded up to the drift ratio of 3 % at the main loading was 74 % of the maximum strength before strengthening. On the other hand, the specimen strengthened with UFC panels after loading up to the drift ratio of 0.5 % exhibited 1.14 times the maximum strength during preliminary loading, confirming the retrofitting effect of the UFC panels.

The authors experimented using the various cross-sections of the UFC panel as a parameter to compensate for the premature termination of the experiment caused by the destruction of the joint mortar between the UFC panel and the stub before the UFC panel could not exert its maximum strength, which was a problem in the experiment using flat UFC panels (Lim et al. 2021). Five 1/3-scale specimens of the same target column were produced for a cyclic loading test, including the non-strengthened specimen. There are two UFC panel cross-sections attached to the column. First, the thickness of the panel's ends was double that of its middle to prevent stress concentration. Second, the UFC panels attached the column with an epoxy resin adhesive and the post-installation anchors without using the joint mortar. Two of the specimens had a wing wall on one side of the specimen strengthened with UFC sandwich panels. There were two types of wing walls: UFC and RC. Compared to the non-strengthened specimen, the maximum strength of the strengthened specimen increased by 1.33 to 1.88 times, the ultimate drift ratio by 2 to 3 times, and the initial stiffness by 1.23 to 3.24 times.

To determine whether the cross section confirmed to be efficient as a strengthening method for the column was also effective for the damaged column, four cross-sections using the UFC panel were applied equally to this experiment. The specimens were strengthened with UFC panels after being preloaded to a 0.5 % drift ratio and then subjected to the main loading until the ultimate state was reached. Comparison and analysis of the test results of each specimen, and the effect of damage to the column before strengthening for the same cross-section is discussed.

Table 1 Damage class definition of RC columns (JBDPA 2015)

Damage class	Description of damage
I	Visible narrow cracks on concrete surface (crack width is less than 0.2 mm)
II	Visible clear cracks on concrete surface (crack width is about 0.2 -1.0 mm)
III	Local crush of concrete cover Remarkable wide cracks (crack width is about 1.0 - 2.0 mm)
IV	Remarkable crush of concrete with exposed reinforcing bars Spalling off of concrete cover (crack width is more than 2.0 mm)
V	Buckling of reinforcing bars Cracks in core concrete Visible vertical and/or lateral deformation in columns and/or walls Visible settlement and/or leaning of the building

EXPERIMENTAL STUDY

Target column for strengthening

The target column is the column on the first story that has sustained the most damage by the 2016 Kumamoto Earthquake (Sarrafzadeh et al. 2017). The amount of shear reinforcement in the X and Y directions differed significantly, and the crossties were not reinforced to constrain the entire longitudinal rebar. Consequently, shear failure occurred, and concrete spalling occurred near the middle height, exposing the reinforcing bars. In addition, it was confirmed that the longitudinal rebar had buckled and the hoop had broken. In Table 1, the damage class of the target column was determined to be V, a level at which they nearly lost their strength.

Figure 1 depicts the outline of the target specimen used for the cyclic loading test, and four identical specimens were produced. A 1/3 scale model of the first floor to the bottom of the beam on the second floor of the target building was produced. The design compressive strength of the concrete was 35 N/mm^2 because the average of eight core samples taken from the first story of the target building was 35.4 N/mm^2. C-USJ-M was casted all at once, while the remaining specimens were poured into three sections: the lower stub, the column section, and the upper stub.

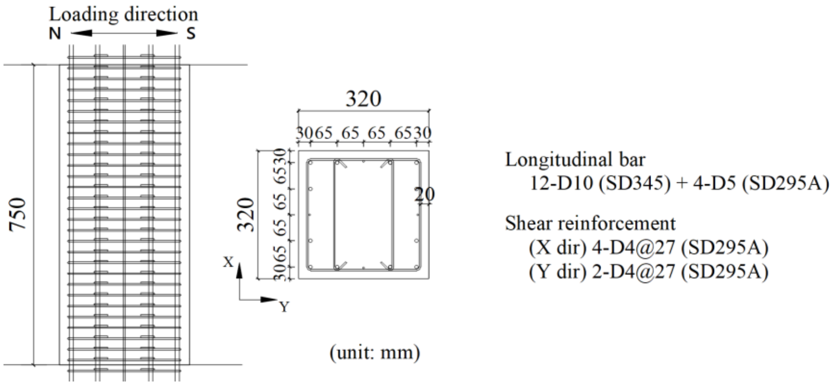


Figure 1 Overview of target specimen

Strengthened specimens

The specimens were subjected to repeated cyclic loading as a preload up to the drift ratio R = 0.5 %, representing the target specimen's maximum strength. After the specimens were damaged by preloading, UFC panels were attached to two opposite sides of the column, with or without a wing wall on one side, as shown in Fig.2. Table 2 lists strengthened specimens, where -M indicates preloading up to the drift ratio at which the target specimen's maximum strength was measured.

Table 2 List of specimens

C-US-M	Column - UFC Sandwich panels - Max. capacity
C-USJ-M	Column - UFC Sandwich panels with Joint mortar - Max. capacity
C-USJ-UW-M	Column - USJ - UFC Wing wall - Max. capacity
C-USJ-RCW-M	Column - USJ - RC Wing wall - Max. capacity

C-US-M was the only one with post-installed chemical anchors to assist in transferring force between the column and the panels. A non-shrink mortar was injected into the hole of the post-installed chemical anchor, and after it hardened, a 40 Nm torque was applied to tighten the anchor bolt. The joints of C-USJ-M were filled with high-strength and non-shrinkage joint mortar at both the top and bottom ends of the panels, and the ends of the panels were double the thickness of the middle part to prevent stress concentration.

The column part of specimens with a wing wall was identical to C-USJ-M. The UFC wing wall was attached to one side of the column in C-USJ-UW-M using an epoxy resin adhesive. In addition, the upper and lower ends of the UFC wing walls were injected with high-strength and non-shrinkage mortar, just like C-USJ-M. The C-USJ-RCW-M has RC wing walls on one side of the column strengthened with UFC panels. The RC wing wall's reinforcing bars were not anchored to the columns and stubs. The concrete was cast in place. For constructability, the upper 100mm of the RC wing wall is filled with high-flow and non-shrinking mortar. Table 3 displays the material strength results of the strengthened specimen.

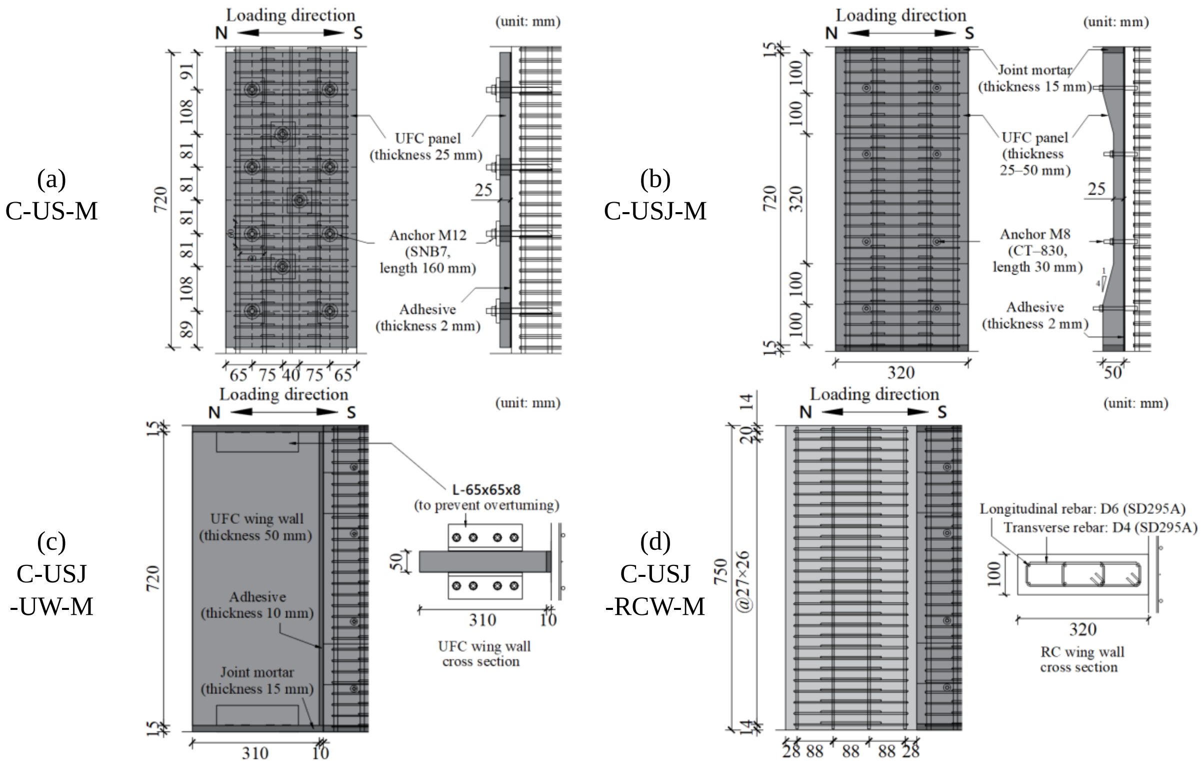


Figure 2 Overview of strengthened specimens

Table 3 Material test results

(1) Concrete

Specimen	Loading stage	Age (day)	Compressive strength (N/mm^2)	Strain at the compressive strength (%)	Elastic modulus (kN/mm^2)	Split tensile strength (N/mm^2)
C-US-M	Preliminary	153	48.7	0.260	28.7	3.1
	Main	238	48.1	0.224	28.6	2.9
C-USJ-M	Preliminary	124	40.7	0.232	27.0	3.1
	Main	174	40.7	0.229	27.0	2.7
C-USJ-UW-M	Preliminary	174	49.0	0.256	28.8	3.1
	Main	246	48.6	0.253	28.7	2.7
C-USJ-RCW-M	Preliminary	145	48.4	0.250	28.6	2.7
	Main	259 (42)*1	51.9 (47.4)*1	0.286 (0.311)*1	29.3 (28.5)*1	3.2 (3.3)*1

(2) Reinforcing bar

Type (steel type)	Location	Yield strength (N/mm^2)	Elastic modulus (kN/mm^2)	Tensile strength (N/mm^2)
D10 (SD345)	Column longitudinal	368.4	188.4	545.7
D5 (SD295A)		380.5*2	193.7	516.3
D4 (SD295A)	Column hoop	361.2*2	194.9	518.9
	RC wing wall transversal	347.0*2	193.5	513.2
D6 (SD295A)	RC wing wall longitudinal	475.8*2	192.6	564.4

(3) Mortar

Specimen	Location	Compressive strength (N/mm^2)	Specimen	Location	Compressive strength (N/mm^2)	Elastic modulus (kN/mm^2)

C-USJ-M	Joint	122.5 (40)[*3]	C-USJ-RCW	Joint	108.2 (57)[*3]	-
C-USJ-UW-M		129.1 (44)[*3]		RC wing wall	62.7 (40)[*3]	23.5

(4) Fiber in the UFC

Specimen	Density (g/mm^3)	Tensile strength (N/mm^2)	Diameter (mm)	Length (mm)
All specimen	7.8 × 10^{-3}	2.9×10^3	0.22	15.1

(5) UFC

	Compressive strength (N/mm^2)	Elastic modulus (kN/mm^2)	Flexural strength (N/mm^2)	Direct tensile strength (N/mm^2)
All specimen	216	52.9	60.6	22.8[*4]

[*1] ( ) is concrete of RC wing wall, [*2] 0.2 % offset strength, [*3] ( ) is age (day), [*4] is calculated by Eq. (1)

$$ {}_{UFC}f_b = 2.59\,{}_{UFC}f_t + 1.54 \qquad (\mathrm{N/mm^2}) \qquad (1) $$

where ${}_{UFC}f_b$ is the flexural strength of UFC obtained by a bending test, and ${}_{UFC}f_t$ is the direct tensile strength of UFC (JSCE 2004).

LOADING OVERVIEW

The elevation view of the load device is depicted in Fig. 3, where the axial force was applied by two 8000 kN vertical jacks and the lateral force was applied by a 3000 kN horizontal jack. The force is positive in the south direction.

As depicted in Fig. 4, all specimens were subjected to varying axial forces, emulating the force applied to the column on the soft first story of the RC structure during an earthquake. The solid red line in the figure represents the axial force path of C-US-M; for instance, the black dashed line indicates the shear force at the specimen's ultimate flexural strength Q_{mu}, and the solid black line represents its ultimate shear strength Q_{su}. The shear force at ultimate flexural strength and ultimate shear strength is equivalent to Eq. (2) and Eq. (3), respectively (JBDPA 2001). The long-term axial force N_0 at the point where the horizontal force is zero is $0.15bDf'_c$ considering the unit floor weight of approximately 12 kN/m^2 (Tani et al. 2019). The minimum axial force for tension was

(i) $N_{min} \le N < 0$ $\qquad M_{mu} = 0.5 a_g \sigma_y g_1 D + 0.5 N g_1 D$

(ii) $0 \le N < N_b$ $\qquad M_{mu} = 0.5 a_g \sigma_y g_1 D + 0.5 N D \left(1 - \dfrac{N}{bDf'_c}\right)$ $\qquad$ (N·mm) $\quad$ (2-1)

(iii) $N_b \le N < N_{max}$ $\qquad M_{mu} = \left\{0.5 a_g \sigma_y g_1 D + 0.024(1+g_1)(3.6-g_1) bD^2 f'_c\right\}\left(\dfrac{N_{max}-N}{N_{max}-N_b}\right)$

$$ Q_{mu} = 2M_{mu} / h_0 \qquad (\mathrm{N}) \qquad (2\text{-}2) $$

$$ Q_{su} = \left\{0.068 p_t^{0.23}(f'_c+18)/\left(M/(Qd)+0.12\right) + 0.85\sqrt{p_w \sigma_{wy}} + 0.1\sigma_0\right\} bj \qquad (\mathrm{N}) \qquad (3) $$

where N is the axial force, N_{min} (=$-a_g\sigma_y$) is the ultimate tensile strength, N_b (=$0.22(1+g_1)bDf'_c$) is the axial force at the balanced failure and N_{max} (=$bDf'_c+a_g\sigma_y$) is the ultimate compressive strength. For description of the other symbols, refer to JBDPA (2001).

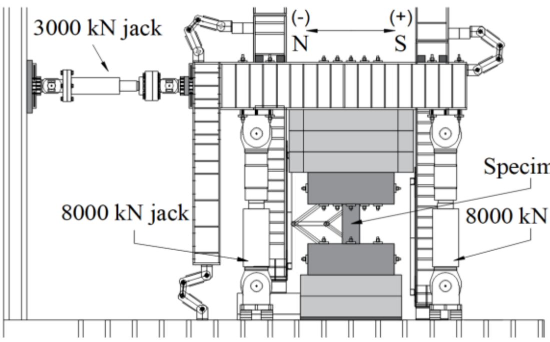


Figure 3 Loading setup (West side)

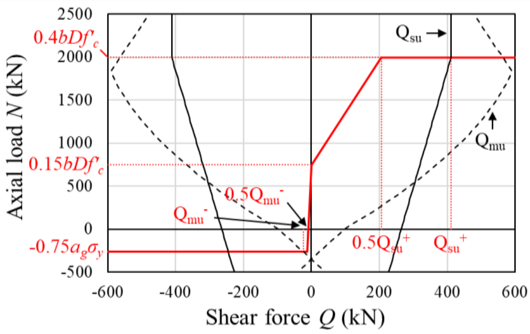


Figure 4 Axial load path (C-US-M)

-0.75$A_g\sigma_y$ (A_g: gross cross-sectional area of the longitudinal bars of the column, mm^2, σ_y: yield strength, N/mm^2). The maximum axial force for compression was 0.40bDf'_c, which corresponds to the axial force acting on the column under compression in the finite element (FE) analysis of the target structure (Tani et al. 2019). The lateral force maintained Q_{mu}/2 under axial tensile force and Q_{su}/2 under axial compressive force until the target drift ratio was reached. Each point linearly increased or decreased the axial force from the long-term axial force. In addition, even though the concrete compressive strength f'_c as determined by the material test was different at the time of preliminary loading and main loading when determining the loading path, the concrete compressive strength at the time of the preliminary loading was applied equally to the main loading.

The drift ratio R is calculated by dividing the relative horizontal displacement of the upper and lower stubs by the clear height of the column. After preliminary cyclic loading, the specimens were strengthened with the UFC panel, and then the main cyclic loading was performed to reach the specimen's ultimate state. The preliminary cyclic loading was conducted up to a drift ratio of 0.5 %, at which point the maximum strength of the target specimen was recorded (Lim et al. 2021). Under the preliminary cyclic loading, one cycle was applied to the drift ratio R = 0.03125 %, and two cycles were repeatedly applied to R = 0.0625 %, 0.125 %, 0.25 %, and 0.5 %, respectively. The main cyclic loading was carried out in the same manner as the preliminary cyclic loading, and R = 1 %, 2 %, 3 %, and 4 % were loaded repeatedly in two cycles, respectively. A pushover load was performed for the specimen that did not reach the ultimate state even after R = 4 %.

LATERAL LOAD-DRIFT RATIO RELATIONSHIP AND DAMAGE PROGRESS

Figure 5 shows the damage condition at the end of the preliminary loading of C-US-M and the end of the main loading of each specimen. The blue and red lines represent the cracks confirmed during positive and negative loading, respectively. The hatched area represents spalling of cover concrete, and the cross-hatched area indicates concrete falling. Figure 6 illustrates the lateral load–drift ratio relationship of C-US-M during preliminary loading and the lateral load–drift ratio relationship of all specimens during the main loading. The dashed line extending obliquely from the positive maximum strength point indicates strength reduction due to the P–Δ effect. The ultimate drift ratio was set as the point where the load after the maximum strength decreased to 80 % of the maximum strength. In the case of the longitudinal bar or shear reinforcement of the specimen yielded under the preliminary loading, it was not shown in the graph of the main loading.

Preliminary loading

All specimens exhibited flexural tensile cracks throughout the column when R = -0.03125 % cycle. During the R = 0.125 % or R = 0.25 % cycles, the longitudinal bars yielded in tension and compression. All specimens reached their positive and negative maximum yield strength when R = 0.5 % cycle, as depicted in Fig. 5 (a). In addition, the shear reinforcement yielded in tension, and shear cracks occurred. Table 4 indicates the maximum strength for the positive loading direction during the preliminary loading of each specimen. Although there was some variation according to the difference in material strength of each specimen, there was no considerable difference. Among the cracks that occurred in each specimen at the end of the preliminary loading, the largest crack was the shear crack that occurred on the west side, and the width was 0.04–0.1 mm. It was 0.12 to 0.30 mm when converted to real scale, corresponding to damage class II according to Table 1. However, based on the previous research (Lim et al. 2021), it is assumed that each specimen will reach its maximum strength at R = 0.5 %, so it can be determined that the damage class is III.

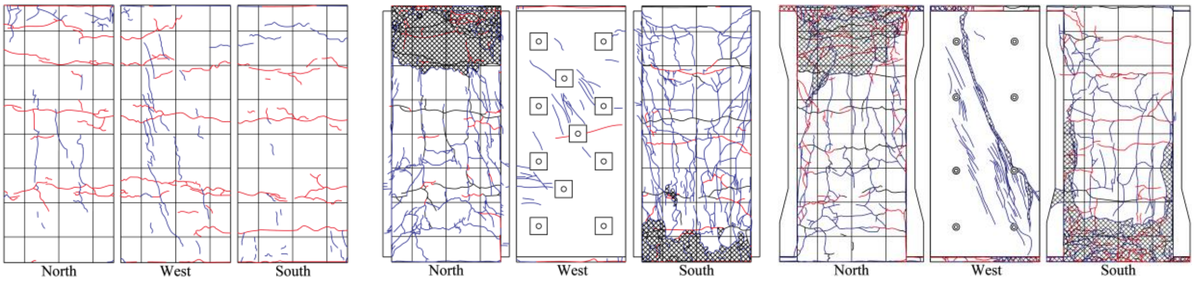
Main loading

Cracks that occurred during the preliminary loading on the north and south side of the column were reopened up to R = 0.125 % cycle for C-US-M, R = 0.25 % cycle for C-USJ-M and C-USJ-RCW-M, and R = 0.5 % cycle for C-USJ-UW-M. Then, as the drift ratio increased, new cracks occurred.

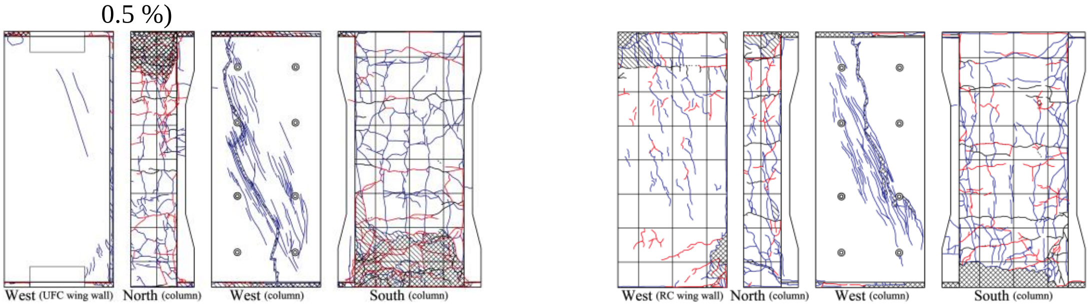
C-US-M: At the peak of the first cycle to R = +1 %, the maximum strength was recorded, and shear cracks were observed in the UFC panel. Horizontal cracks were found in the UFC panel during the first cycle, when R = -1 %. During the first cycle of R = +3 %, the lateral load was reduced considerably, and the concrete in the south side was peeled off due to buckling of the longitudinal bars near the bottom of the column. The loading was discontinued because the axial load could not be sustained.

C-USJ-M: The joint mortar between the UFC panel and the stub was partially crushed during the second cycle, when R = 0.5 %. At the first cycle to R = +1 %, shear cracks occurred in the UFC panel. The maximum strength was recorded during the first cycle to R = +2 %. During the first cycle, when R = +4 %, the axial collapse occurred owing to shear failure of the UFC panel, and the loading was terminated because the lateral load was reduced considerably.

C-USJ-UW-M: In the first cycle to R = +0.5 %, the joint mortar of the column part and UFC wing wall was crushed, and the shear crack occurred in the UFC panel. After measuring the maximum strength near the peak of the first cycle, when R = +2 %, the lateral load was decreased. The specimen's strength did not decrease after R = 4 % of cyclic loading, so pushover loading was carried out. Around R = +5.0 %, the shear crack of the UFC panel on the column was greatly widened, and the shear crack also occurred in the UFC wing wall, resulting in a considerable reduction in lateral load. In the near R= +6.0 %, the shear cracks of the UFC panel and the UFC

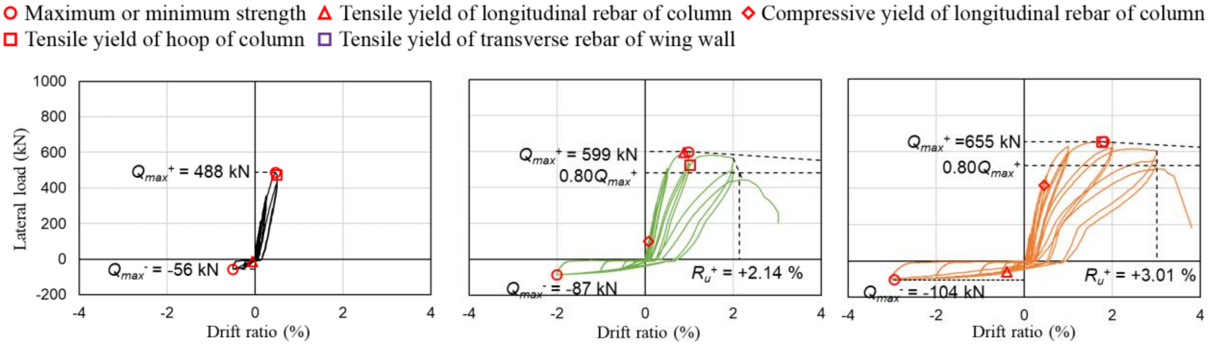


(a) C-US-M (Preliminary loading test, R = 0.5 %)   (b) C-US-M (R = 3 %)   (c) C-USJ-M (R = 4 %)

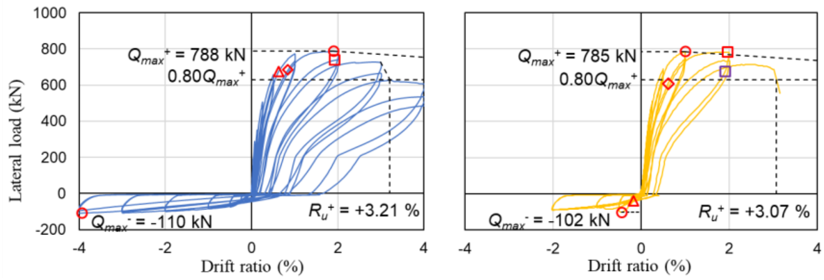


(d) C-USJ-UW-M (R = 5.8 %)   (e) C-USJ-RCW-M (R = 3 %)

Figure 5 Cracks and concrete crushing



(a) C-US-M (Preliminary loading test, R = 0.5 %)   (b) C-US-M   (c) C-USJ-M



(d) C-USJ-UW-M   (e) C-USJ-RCW-M

Figure 6 Lateral load – drift ratio relationship

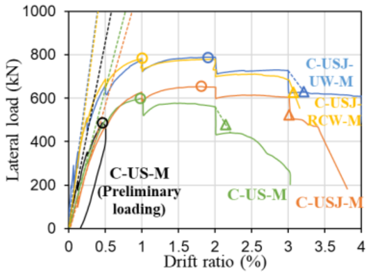


Figure 7 Envelope curve and initial stiffness

wing wall widened, and the joint mortar of the UFC panel and the UFC wing wall was completely crushed. The loading was stopped because it was determined that further loading would be dangerous.

C-USJ-RCW-M: During the first cycle to R = +0.5 %, the joint mortar between the UFC panel and the stub was partially crushed, and many vertical cracks occurred in the RC wing wall. In the first cycle to R = +1 %, the mortar on the top of the RC wing wall collapsed. Shear cracks occurred in the UFC panel, and the maximal strength was measured. In the subsequent cycle, the hoop of the RC wing wall yielded in tension at the first cycle to R = +2 %. Near the peak of the first cycle to R = +3 %, a considerable lateral load degradation accompanied by shear failure of the UFC panel occurred. The axial force could not be maintained, so the load was terminated.

COMPARISON OF EXPERIMENTAL RESULTS

Figure 7 depicts the envelope curves (solid lines) and the dotted lines indicating the initial stiffness of the lateral load–drift ratio relationships for the positive loading direction. Circular and triangular plots in Fig. 7 indicate the maximum strengths and the ultimate drift ratios, respectively. Table 4 displays the values of the positive maximum strength Q_{max}, ultimate drift ratio R_u, and the initial stiffness K_e at the time of preliminary and main loading for each specimen. The ratio to the preliminary loading value of each specimen is indicated in parentheses. The initial stiffness was defined as the secant stiffness connecting the start point of R = +0.03125 % cycle and the point where $Q = Q_{max}/3$ on the lateral load–drift ratio relationship envelope.

The maximum strength of C-US-M and C-USJ-M was improved by 1.23 to 1.43 times only by strengthening with the UFC panels. In contrast, the initial stiffness was 0.76 and 0.54 times that of the preliminary loading and did not recover to the value of the specimens under the preliminary loading. Meanwhile, the maximum strength of C-USJ-UW-M and C-USJ-RCW-M with the UFC or RC wing wall was improved to 1.58 to 1.66 times that of the preliminary load. This specimen had greater maximum strength than the one without the wing wall. The initial stiffness was 0.98 to 1.16 times that of the preliminary loading, which was almost similar to or slightly higher than the value of the undamaged specimens. It was possible to confirm a notable difference in the initial stiffness improvement depending on the wing wall's presence or absence. The ultimate drift ratio of all specimens was 2.14–3.21 %, and the deformation performance of the others was better than that of the specimen strengthened with UFC panels without joints. The deformation performance improvement by the wing wall was not significant.

To compare the effects according to the strengthening methods, Table 5 shows the ratio of the structural performance values of each specimen to C-USJ-M. As shown in Table 3, it should be noted that there was a difference in compressive strength and elastic modulus depending on the age of the concrete of the specimens, and the C-USJ-M has the lowest compressive strength of the concrete at 40.7 N/mm^2. Comparing C-US-M and C-USJ-M, which confirms the effect of the joint between the stub and the panel, the concrete compressive strength of C-USJ-M was approximately 7 N/mm^2 less than that of C-US-M, but its maximum strength was higher. The ultimate drift ratio of C-US-M was 0.71 times that of C-USJ-M, indicating a considerable difference in deformation performance. The initial stiffness was at an equivalent level considering the difference in the elastic modulus, so it can be confirmed that the stress was sufficiently transmitted through the epoxy resin

Table 4 Maximum strength, ultimate drift ratio and initial stiffness of tested columns

Seismic performance	C-US-M		C-USJ-M		C-USJ-UW-M		C-USJ-RCW-M	
Loading stage	Pre-liminary	Main	Pre-liminary	Main	Pre-liminary	Main	Pre-liminary	Main
Maximum strength Q_{max} (kN)	488	599 (1.23)	457	655 (1.43)	500	788 (1.58)	473	785 (1.66)
Ultimate drift ratio R_u (%)	–	2.14	–	3.01	–	3.21	–	3.07
Initial stiffness K_e (kN/mm)	227	172 (0.76)	291	157 (0.54)	288	334 (1.16)	346	339 (0.98)

Table 5 Structural performances of tested columns compared to C-USJ-M

Seismic performance	C-US-M	C-USJ-M	C-USJ-UW-M	C-USJ-RCW-M
Maximum strength Q_{max} (kN)	0.91	1.00	1.20	1.20
Ultimate drift ratio R_u (%)	0.71	1.00	1.07	1.02
Initial stiffness K_e (kN/mm)	1.09	1.00	2.12	2.15

adhesive and the post-installed anchor. The specimens with wing walls, C-USJ-UW-M and C-USJ-RCW-M, had 1.2 times and 2.12–2.15 times greater maximum strength and initial stiffness, respectively. However, the ultimate drift ratio was not considerably different. The influence of the wing wall type on structural performance is assumed to be minimal.

COMPARISON WITH NON-DAMAGED SPECIMENS BEFORE STRENGTHENING

The specimens without preliminary loading (after this, referred to as non-pre-damaged specimens) on the same target column were subjected to the strengthening method using the UFC panel suggested in this study (Lim et al. 2021). The maximum strength Q_{max}, the ultimate drift ratio R_u, and the initial stiffness K_e of the non-pre-damaged specimens are detailed in Table 8. The ratio of strengthened specimens after damage (after this, referred to as pre-damaged specimens) to non-pre-damaged specimens for the same strengthening method is also displayed. Even among specimens strengthened using the same method, there were specimens with substantial differences in concrete compressive strength and elastic modulus depending on the age of the concrete. The ratio of maximum strength Q_{max} between the pre-damaged and non-pre-damaged specimens ranged from 0.90 to 1.06. When considering the concrete compressive strength of the specimens, there was no substantial difference because the concrete compressive strength of C-USJ-M was 5.5 N/mm^2 lower than that of C-USJ and the concrete compressive strength of C-USJ-UW-M was 3.7 N/mm^2 higher than that of C-USJ-UW. Regardless of the strengthening method, the ultimate drift ratio R_u of the pre-damaged specimens was improved by 1.02 to 1.50 times. The ratio of the initial stiffness K_e of the pre-damaged specimen to the non-pre-damaged specimen was 0.36 to 0.58, and the influence of the presence or absence of damage to the column before strengthening was remarkably confirmed in all strengthening methods. Since the proposed strengthening method aims to restore within a short period, it did not repair cracks or crushing of columns caused by preliminary loading. As a result, the stiffness decreases of the column due to damage caused by the preliminary loading was reflected in the initial stiffness of the main loading.

Seismic performance	C-US	C-US-M/ C-US	C-USJ	C-USJ-M/ C-USJ	C-USJ-UW	C-USJ-UW-M/ C-USJ-UW	C-USJ-RCW	C-USJ-RCW-M/ C-USJ-RCW
Q_{max} (kN)	589	1.02	729	0.90	743	1.06	836	0.94
R_u (%)	2.01	1.07	2.01	1.50	3.01	1.07	3.00	1.02
K_e (kN/mm)	296	0.58	433	0.36	778	0.43	776	0.44

Table 6 Comparison of seismic performance with non-pre-damaged specimen

CONCLUSION

Four 1/3-scale specimens were subjected to reversed cyclic lateral load tests to determine whether the RC column strengthening method using the UFC panel was adequate for the damaged column. After a preliminary loading up to 0.5 % of the drift ratio measured by the maximum strength of the target column, the specimens were enhanced with UFC panels. The findings of this study are summarized in the paragraphs that follow.

(1) Comparing seismic performance before and after reinforcement, the maximum strength of the specimens increased by 1.23–1.66 times, and the ultimate drift ratio improved by 2.14–3.21 times. The degree of improvement in the ultimate drift ratio varied based on the presence or absence of joints, whereas the effect of the wing wall was negligible. The initial stiffness of the specimens without the wing wall was 0.54-0.76 times before strengthening, and there was no restoration effect of the initial stiffness. Specimens with the wing wall increased their initial stiffness by 0.98–1.16 times, equivalent to or greater than the specimen before strengthening.

(2) According to the strengthening method, the maximum strength and ultimate drift ratio of C-US-M were 0.91 and 0.71 times that of C-USJ-M, while the initial stiffness was 1.09 times that of C-USJ-M. It was determined that the stress was transferred adequately to the UFC panel through post-installation anchors and epoxy adhesive. The ultimate drift ratio of specimens with the wing wall differed slightly from C-USJ-M by 1.02 to 1.07 times. However, the maximum strength and initial stiffness were 1.20 and 2.12 to 2.15 times, respectively, confirming the effect of the wing wall on strengthening.

(3) The maximum strength of the pre-damaged specimens was 0.90-1.06 times that of the non-pre-damaged

specimens, which had the same target column and strengthening method. There was no significant effect on whether or not the column had damage before strengthening. The ultimate drift ratio was also 1.02–1.07 times that of the non-pre-damaged specimens, except in the case of C-USJ-M, which had 1.5 times that of C-USJ. On the other hand, damage before strengthening greatly affected the initial stiffness, measuring 0.36 to 0.58 times.

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