

Large-Scale Experimental Study on the Retrofitting Effect of Concrete Filling in Hollow Reinforced Concrete Columns

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Abstract: When hollow reinforced concrete (RC) columns are retrofitted with concrete filling, the hollow interior cannot always be accessed to treat the internal surface. Without this treatment, an optimal bond between the newly introduced concrete and the existing column cannot be established; as a result, the two parts do not behave as a single unit. This study conducted cyclic loading tests on three types of large RC column specimens: a hollow RC column, hollow RC column with a solid section at the column base, and hollow RC column retrofitted with concrete filling (lacking inner surface treatment). The aim of this study was to investigate the effectiveness of a concrete-filling retrofitting method for hollow RC columns when the filled and existing portions behave separately, assuming a situation in which the bond between the filled and existing portions cannot be strengthened. The results indicated that concrete-filling retrofitting can suppress the inward buckling of the internal longitudinal bars, thereby enhancing the flexural deformation capacity of hollow RC columns to some

extent. However, this did not prevent the significant axial settlement and reduction in the lateral load capacity that occurred when the inner longitudinal bars buckled. This is because the filled portion cannot resist axial forces when the filled and existing portions behave separately. Additionally, it was suggested that retrofitting with concrete filling does not substantially improve the shear resistance of a hollow RC column when the filled section behaves separately from the existing section.

Introduction

Hollow reinforced concrete (RC) columns can be advantageous for high piers, especially in mountainous areas, as they not only reduce the load on the ground foundation by lowering the self-weight of the piers, but also reduce costs. Recently, there has been an increase in research on precast hollow RC members for the Accelerated Bridge Construction (ABC) method, leading to increased interest in hollow RC columns (Wang et al. 2014; Cha et al. 2017; Jin et al. 2022; Zhou et al. 2022).

Hollow RC columns have a distinct rebar arrangement and cross-sectional configuration compared to standard solid RC columns, prompting many investigations into their specific failure characteristics during earthquakes. Mo and Nien (2002) conducted cyclic loading tests to investigate the seismic performance of hollow RC bridge columns using high-strength concrete. Their findings indicated that the hollow bridge columns, which met the ACI standard, demonstrated acceptable seismic performance. Pinto et al. (2003) conducted cyclic loading tests to evaluate the seismic performance of existing hollow RC piers with low reinforcement ratios that do not satisfy current seismic codes. Qiang et al. (2013) conducted cyclic loading tests to evaluate the seismic performance of hollow RC columns under bidirectional loading. Their results revealed that damage in one direction considerably affected the lateral load capacity in the opposite direction, leading to a marked degradation in stiffness and strength compared to unidirectional loading. Lee et al. (2015) observed that the lateral load capacity significantly decreased in hollow RC columns when the internal longitudinal bars buckled, following the buckling of the external longitudinal bars. Sun et al. (2019)

52 conducted quasi-static cyclic loading tests on thin-walled hollow RC columns. Based on their findings,
53 they recommended against the construction of new rectangular hollow piers with a wall thickness-to-
54 width ratio of less than 0.15 or a wall slenderness ratio exceeding 10.0.

55 In addition, several studies have focused on the shear capacity and shear failure patterns of
56 hollow RC columns. Takahashi et al. (2000) emphasized that shear effects on hollow RC columns
57 cannot be disregarded, even for columns designed for flexural failures, owing to the thinness of the
58 column walls. Delgado et al. (2009) conducted cyclic loading tests on hollow-section RC columns with
59 varying transverse reinforcement ratios to evaluate the differences in the restoring force properties of
60 these columns. Kim et al. (2012) conducted an experimental study to evaluate the contribution of
61 concrete to the shear strength of RC hollow columns and subsequently proposed an empirical equation
62 for this contribution. Additionally, the numerical analysis accurately simulated the nonlinear behavior
63 of hollow RC columns subjected to significant shear deformation. Cassese et al. (2017, 2020)
64 conducted cyclic loading tests on hollow rectangular or circular RC columns with low transverse
65 reinforcement ratios to assess the lateral load capacity and damage states in which shear failure
66 followed flexural yield. Other studies have evaluated the seismic performance of hollow RC columns,
67 including investigations using large specimens with a cross-section of 1.5 m $\times$ 1.5 m and a height of 6
68 m, and another study examined how the amount of inner hoop reinforcement influences the seismic
69 behavior of circular hollow RC columns (Yeh et al. 2002a, b; Li et al. 2020).

70 Several methods for the seismic retrofitting of hollow RC columns have also been investigated.
71 Mo et al. (2004) and Pavese et al. (2004) demonstrated through cyclic loading tests that the ductility
72 of hollow RC columns can be augmented by jacketing them with fiber-reinforced polymer (FRP)
73 sheets. Similarly, Cheng et al. (2003, 2005) confirmed that repairing hollow RC columns with FRP
74 jacketing improves their ductility compared to that of the original intact columns, although it does not
75 restore their lateral load capacity. Lignola et al. (2007) and Han et al. (2014) reported that the flexural
76 performance of hollow RC columns was enhanced when jacketed with carbon fiber-reinforced polymer

77 sheets. Furthermore, studies have focused on the axial compression performance of hollow RC
78 members wrapped in FRP sheets (Kusumawardaningsih and Hadi 2010; Hadi and Le 2014; Jameel et
79 al. 2017). Some studies developed numerical models to evaluate the effects of retrofitting with FRP
80 sheet jacketing (Lignola et al. 2009, 2012).

81 Hollow concrete-filled RC columns have also been investigated. Cha et al. (2018) and Zhou
82 et al. (2022) explored precast hollow columns with internal concrete filling and confirmed their
83 excellent seismic performance. Jin et al. (2022) also proposed precast hollow RC columns with
84 concrete-filled bases and conducted cyclic loading tests using the depth of the concrete filling as a
85 parameter. The findings indicated that concrete filling depth had no significant influence on the
86 maximum strength of the columns; however, there was an observable enhancement in energy
87 dissipation as the depth of the concrete filling increased. While these studies were not explicitly aimed
88 at seismic retrofitting, the "concrete-filling retrofitting method"—in which the hollow interior of a
89 column is filled with concrete—has become the predominant method for seismic retrofitting of hollow
90 RC columns in Japan. This is attributed to findings indicating that damage extending to the inner
91 section of the base of hollow RC columns can impair their seismic performance. After the 2016
92 Kumamoto earthquake, this concrete-filling retrofitting approach was utilized to repair damaged
93 hollow RC bridge piers and restore their seismic performance (Miyahara et al. 2020). However, no
94 research has evaluated the difference in seismic performance between a solid RC column cast as a
95 single piece and hollow RC columns filled with concrete without appropriate internal surface treatment.
96 Given the prevalence of hollow RC columns and the recent trend of using precast hollow RC columns
97 in the ABC method, evaluating the retrofitting effects of concrete-filled hollow RC columns is crucial,
98 particularly in situations where the filled and existing portions might not act as a unified entity.

99 This study examined the effectiveness of a concrete-filling retrofitting method for hollow RC
100 columns when the filled and existing portions behave separately, assuming a situation in which the
101 bond between the filled and existing portions cannot be strengthened. Specifically, cyclic loading tests

were conducted on pier specimens that were sufficiently large to replicate the rebar arrangement and cross-section of existing hollow RC piers. These specimens represented three distinct cross-sectional configurations of the column base: hollow, solid, and filled (lacking inner surface treatment). In previous studies, several experiments compared the seismic performance of solid- and hollow-section RC columns (Lee et al. 2015; Jin et al. 2022), as well as hollow- and filled-section RC columns (Zhou et al. 2022). Unlike these studies, the present study investigated the seismic performance of hollow RC columns with either solid or filled cross-sections at their bases, in addition to examining fully hollow RC columns. The same rebar arrangement and loading conditions were adopted across all specimens to examine the impact of the cross-sectional configuration of the bases of hollow RC columns on their seismic performance.

Experimental Protocol

Experimental Specimens

Fig. 1 shows an overview of the experimental specimens. **Tables 1** and **2** present the rebar and concrete material properties, respectively. The arrangement of the rebars was consistent across all specimens, with only the cross-sectional configuration of the base differing. For the specimens used in this study, the cross-sectional and pier heights were set to 800 and 3950 mm, respectively. **Fig. 2** shows the structural information of hollow RC piers in Japan managed by the West Nippon Expressway Company. It should be noted that the information presented in **Fig. 2** was extracted from a subset of the hollow RC piers managed by this company. In real-life hollow RC piers, D51 deformed bars are commonly employed for longitudinal reinforcement, whereas D22–D29 deformed bars are used as stirrups. Considering the relationship between the cross-sectional and pier heights illustrated in **Fig. 2(a)** and the marketability of the rebars, D10-SD345 deformed bars were chosen as the longitudinal bars, while D6-SD345 deformed bars were selected as the stirrups. The specimens in this study were approximate one-fifth scale models of a hollow RC pier, with dimensions of 20 meters in height and 4

127 meters in cross-sectional height. The wall thickness ratio, void ratio, and rebar ratio of the specimens
128 were set to the standard values of actual hollow RC piers, as illustrated in **Figs. 2(b) and (c)**.
129 Specifically, the wall thickness ratio and void ratio of the hollow section were 0.188 and 0.39,
130 respectively. The longitudinal bar and stirrup ratios were 2.78% and 0.70% for the hollow sections and
131 0.169% and 0.26% for the solid section, respectively. In addition, the maximum size of the coarse
132 aggregate was reduced to 15 mm, which is smaller than the typical size of 20–25 mm. This adjustment
133 was necessary for the scaled-down specimens, which had narrow rebar spacing and concrete cover
134 widths.

135 The hollow RC column specimen (H-RC) had a hollow cross-section extending from the base
136 to a height of 3200 mm. The hollow RC column specimen with a solid base (H-RC-SB) featured a
137 solid cross-section from the base to a height of 1600 mm, transitioning to a hollow cross-section above
138 this height. According to the Japanese seismic design codes (JRA specification for highway bridges
139 (2012)), hollow RC piers must have a solid section from the column base extending to a height equal
140 to four times the plastic hinge length. Accordingly, H-RC is not compliant with current Japanese
141 seismic codes, whereas H-RC-SB conforms to current Japanese seismic codes.

142 The hollow RC column specimen with a filled base (H-RC-FB) involved post-filling the
143 hollow section from the base to a height of 1600 mm with concrete, leaving the portion from 1600 mm
144 to 3200 mm hollow. During the construction of H-RC-FB, to imitate the real scenario of concrete
145 filling in an actual hollow bridge pier, concrete was initially poured into the space demarcated by the
146 inner and outer formworks to form the hollow section, after which it was poured into the hollow. The
147 concrete-filled portion of H-RC-FB is referred to as the "filled portion," and the section outside the
148 filled portion is called the "existing portion." To investigate the efficacy of the concrete-filling
149 retrofitting method, particularly when the filled and existing portions behave separately, tape was
150 applied to the inner side of the column to minimize friction.

151 For these specimens, the nominal compressive strength of the concrete was set to 24 MPa.

Table 2, however, indicates that the actual compressive strength varied across each lift. Despite these variations, no localized failures were observed at the cast-in-place surface joints or in the filled concrete portions during the experiments. Thus, the differences in the concrete's compressive strength between lifts did not significantly affect the overall integrity.

Loading Protocol and Experimental Setup

The experimental setup is shown in **Fig. 3**, and **Fig. 4** illustrates the lateral loading protocol. In these experiments, the reference amplitude was defined as the lateral displacement δy_0 at which the outer longitudinal bars initially yielded; this was determined to be 16 mm. A sequence of cyclic loadings, with each amplitude subjected to three such cycles, was performed at integer multiples of this reference value, referring to the Japanese seismic design codes (JRA specification for highway bridges (2012)). When the actuator pulled on the specimen, the lateral displacement was defined as being positive. The ultimate displacement was identified as the point at which the longitudinal bars buckled on both the positive and negative sides. Buckling of the longitudinal bars was visually observed via concrete spalling at the base of the column. Furthermore, multiple cyclic loadings with the same amplitude were applied to the specimens at the ultimate displacement level. The aim of this approach was to investigate the decrease in the lateral load capacities of the specimens when subjected to multiple cyclic deformations, and to reveal the damage states of the columns. **Fig. 2 (d)** illustrates the correlation between the longitudinal bar ratio and axial stress in real-life hollow RC bridge piers managed by Nippon Expressway Company Limited. Referring to **Fig. 2 (d)**, the axial load force was set as 1150 kN for the experiments, corresponding to 2.95 MPa for the hollow sections and 1.80 MPa for the solid sections.

Sectional analysis for experimental specimens

Cross-sectional analyses were conducted on the column bases of the specimens to numerically evaluate

the effects of the cross-sectional configuration on the bending performance of the specimens. In the cross-sectional analysis of H-RC-FD, the cross-section was treated as a hollow section to ensure a conservative evaluation. The constitutive law for the longitudinal bars was modeled using a perfect elastoplastic bilinear model, with the material parameters listed in **Table 1**. The constitutive law for concrete was defined by the following equations described in the Japanese seismic design codes (JRA specification for highway bridges (2012)):

$$\sigma_c = \begin{cases} 0 & (\varepsilon_c < 0) \\ E_c \varepsilon_c \left\{ 1 - \frac{1}{n} \left(\frac{\varepsilon_c}{\varepsilon_{cc}} \right)^{n-1} \right\} & (0 \leq \varepsilon_c \leq \varepsilon_{cc}) \\ \sigma_{cc} - E_{des}(\varepsilon_c - \varepsilon_{cc}) \geq 0 & (\varepsilon_{cc} < \varepsilon_c) \end{cases} \quad (1)$$

$$n = \frac{E_c \varepsilon_{cc}}{E_c \varepsilon_{cc} - \sigma_{cc}} \quad (2)$$

$$\sigma_{cc} = \sigma_{ck} + 0.76 \rho_s \sigma_{sy} \quad (3)$$

$$\varepsilon_{cc} = 0.002 + 0.0132 \frac{\rho_s \sigma_{sy}}{\sigma_{ck}} \quad (4)$$

$$E_{des} = 11.2 \frac{\sigma_{ck}^2}{\rho_s \sigma_{sy}} \quad (5)$$

$$\rho_s = \frac{4A_h}{sd} \leq 0.018 \quad (6)$$

where σ_c is the stress of concrete, σ_{ck} is the compressive strength of concrete, ε_c is the strain of concrete, E_c is the Young's modulus of concrete, A_h is the sectional area of a stirrup, s is the interval between stirrups, d is the largest split length of confined concrete section divided by stirrups, and σ_{ck} is the yield strength of a stirrup. The material parameters for concrete were based on the values for Lift 1, as listed in **Table 2**.

Fig. 5 shows the relationship between the bending moment and curvature derived from the cross-sectional analyses. This figure indicates that the curves were similar across different cross-sectional configurations, suggesting that the hollow and solid sections of the experimental specimens exhibited comparable bending performance. However, it is important to note that the cross-sectional

analysis did not consider the effects of longitudinal bar buckling and shear deformation on the columns.

Measurement Data

Lateral and axial forces were evaluated using load cells installed on horizontal and vertical jacks. Draw-wire displacement sensors measured the lateral displacements at six specific section heights, including the lateral loading point, as shown in **Fig. 6**. At the vertical loading point, contact displacement sensors were used to evaluate vertical displacement.

As illustrated in **Fig. 7**, the contact displacement sensors measured the vertical displacements at each column height across 24 section heights on the column sides. These displacement data were used to calculate the section curvature of the column at each height. Note that some vertical displacement data had to be supplemented due to inadequate measurements at specific points during the experiments. The supplementation method is detailed in the Appendix.

Strain gauges were employed to measure the strain of the longitudinal bars and stirrups. The placement of these gauges on the longitudinal bars and stirrups is illustrated in **Fig. 8**. During the third maximum displacement of each loading step, cracks on the specimens' surfaces were observed and documented through photographs to record the crack damage state. Additionally, a network camera was positioned at the bottom of the inner surface of the hollow to continuously monitor and record the internal conditions. After the cyclic loading tests, the specimens were vertically cut at the center of the cross-section to examine the internal damage on the column side (**Fig. 9**).

Experimental Results

Lateral displacement was defined as being positive when the actuator pulled on the specimen; the second cycle of $+7 \delta y_0$ is referred to as " $+7\delta y_0-2$ ". Furthermore, the location of the column surface was characterized in terms of the azimuth. **Fig. 8** illustrates the relationship between the azimuth of the column sides (N, S, E, and W sides) and the loading direction.

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Crack pattern

The crack patterns on the column side (N side) are depicted in **Fig. 10**. The crack pattern within the filled portion was observed by cutting the specimens vertically through the center of the cross-section after the loading test.

In H-RC, cracks initially formed horizontally at the flange before diagonally propagating upon reaching the web (**Figs. 10 (a)**). This type of cracking pattern has been observed in previous experiments on rectangular hollow RC columns (Mo and Nien 2002; Cassese et al. 2017; Sun et al. 2019) and is characteristic of such structures. H-RC-SB exhibited roughly horizontal cracks at column heights of 1,600 mm or less at a displacement amplitude of $2\delta y_0$ (**Fig. 10 (b)**). This observation indicates that the difference in the cross-sectional configuration of the column base between H-RC and H-RC-SB affected the cracking patterns of the columns. In contrast, in H-RC-FB, cracks initially formed horizontally at the flange and then propagated diagonally upon reaching the web, demonstrating a crack pattern similar to that observed in H-RC (**Fig. 10(c)**). Additionally, horizontal cracks were evident in the filled portion, indicating that the filled and existing portions behaved separately, as intended. Previous studies have not conducted cyclic loading tests on hollow RC columns of various base types (hollow, solid, or filled) under identical conditions. The current experiments demonstrated that hollow RC columns retrofitted with concrete filling exhibit crack patterns similar to those observed in unfilled hollow RC columns when the filled and existing portions behave separately.

Lateral Load-Displacement Relationship and Damage State of the Column

Up to a Displacement Amplitude of $\pm 7\delta y_0-3$

Fig. 11 illustrates the lateral load-displacement relationship. All specimens exhibited spindle-shaped hysteresis loops up to $\pm 7\delta y_0-3$, which indicates the typical lateral load capacity of RC columns of the

flexural failure type. In particular, the hysteresis loops up to a displacement amplitude of $6\delta y_0$ displayed similar patterns in all specimens. This result can be attributed to the similar bending performance of the solid and hollow cross-sections of these specimens, as demonstrated by the cross-sectional analysis results in **Fig. 6**. **Fig. 12** illustrates the accumulated energy dissipation at the end of the third cycle for each lateral displacement amplitude. The accumulated energy dissipation exhibited generally consistent patterns across all specimens, although these values were marginally lower for H-RC-SD.

However, a marked decrease in lateral load was observed at $+7\delta y_0/3$ in H-RC (**Fig. 11(a)**). Simultaneous inward buckling of the inner longitudinal bars on the compression side (W side) was observed from an image captured by a webcam inside H-RC. The relationship between vertical and lateral displacement further indicated the occurrence of axial settlement at $+7\delta y_0/3$ in H-RC (**Fig. 14(a)**). Therefore, it can be considered that the inward buckling of these inner bars inflicted substantial damage to the flange of the hollow section. This damage likely diminished the axial load-bearing capacity of the column, resulting in the observed decrease in its lateral load. Experiments conducted by Cassese et al. (2017) demonstrated that the buckling of longitudinal bars significantly reduces the lateral load capacity of rectangular hollow RC columns, with similar observations in circular hollow RC columns (Li et al. (2020); Lee et al. (2015)). Similarly, experiments by Cheng et al. (2003) and Sun et al. (2019) revealed that damage at the base caused by longitudinal bar buckling led to a significant lateral load decrease in hollow RC columns. Moreover, some experiments have demonstrated that the rupture of longitudinal bars triggered a decrease in the lateral load in hollow RC columns. The specimens used in these experiments had different structural parameters from those of H-RC, such as fewer longitudinal bars (24 in Cassese et al. (2020) and 10 in Cha et al. (2017)), or a larger wall thickness ratio in the cross-section (0.48 in Mo et al. (2004) and Mo and Nien (2002)). Thus, it is considered that the number of longitudinal bars and the wall thickness ratio of the cross-section can influence the failure behavior of hollow RC columns. Given that the number of longitudinal bars and wall thickness ratio for H-RC were set to values typical for hollow RC piers in Japan, H-RC

is considered to generally reproduce the failure behavior observed in real-life Japanese hollow RC piers.

In contrast, H-RC-FB maintained superior lateral load capacity without substantial axial settlement, similar to H-RC-SB at a displacement amplitude of $7\delta y_0$ (**Figs. 11 and 14**). Hence, the lateral load capacity properties of both H-RC-SB and H-RC-FB were similar up to their ultimate state, indicating the beneficial impact of concrete-filling retrofitting even when the filled and existing portions behaved separately.

Beyond a Displacement Amplitude of $\pm 7\delta y_0/3$

In H-RC, axial settlement and a decrease in the lateral load, initiated at $+7\delta y_0/3$, continued to progress significantly, as illustrated in **Figs. 11 (a) and 14 (a)**. **Fig. 13 (a)** indicates that considerable damage was caused to the flange concrete on both the inner and outer portions of the column base by the inward buckling of the internal longitudinal bars on the W side. **Figs. 15-17** illustrates the relationship between the damage state at the column base, the strain distribution across its cross-section, and the extent of axial settlement. The strain distribution across the cross-section was determined using the vertical displacement data measured by the contact displacement sensors at the second height from the bottom (**Fig. 7**). As depicted in **Fig. 15**, for H-RC, the neutral axis of the cross-section shifted to the midpoint owing to the buckling of the inner longitudinal bars at $+7\delta y_0/3$, causing all regions of the flange to compress. This behavior increased the damage to the flanges and intensified the axial settlement. These results suggest that the longitudinal bar buckling was a major factor contributing to the substantial reduction in the lateral load capacity of H-RC. Additionally, this decline in lateral load capacity was not the result of amplified loading displacement, but was due to repeated loading at the same amplitude. Therefore, in hollow RC columns, once the inner longitudinal bars buckle, subsequent cyclic responses can cause a significant reduction in the lateral carrying capacity, even when the response displacement does not increase.

In H-RC-SB, no significant decrease in lateral load or axial settlement was observed after ten

repeated loadings at a displacement amplitude of $7 \delta y_0$, followed by a single repetition at a displacement amplitude of $8 \delta y_0$ (**Figs. 11 (b), 14 (b), 16**). Owing to limitations in the experimental planning, further loading was not conducted on H-RC-SB. The authors previously conducted cyclic loading tests on a medium-sized RC column with a solid section (**Fig. 18**). During this experiment, the specimen underwent ten cyclic loadings at a displacement amplitude of $7 \delta y_0$, which led to the buckling of the longitudinal bars. It was then subjected to an additional ten cycles at a displacement amplitude of $8 \delta y_0$. Consequently, no significant reduction in the lateral load or substantial axial settlement was observed. As this specimen did not replicate H-RC-SB, making direct comparisons is difficult. Given that the concrete in H-RC-SB remained at its base as much as, or even more than, in the previous experiment (**Fig. 13 (b)**), it can be inferred that H-RC-SB could maintain its lateral force capacity even after multiple loadings at a displacement amplitude of $8 \delta y_0$.

In H-RC-FB, no significant reduction in lateral load or axial settlement was observed at a displacement amplitude of $7 \delta y_0$ (**Figs. 10(c) and 14(c)**). **Fig. 17** shows that the shift in the position of the neutral axis within H-RC-FB was minimal, even when the external damage due to cyclical loading at $7 \delta y_0$ was equal to or greater than that in H-RC. This suggests an enhancement in the axial load-bearing capacity of the columns, which is attributed to the suppression of internal damage by concrete-filling retrofitting. However, at a displacement amplitude of $8 \delta y_0$, there was a pronounced decrease in lateral load and axial settlement, similar to the case of H-RC at a displacement amplitude of $7 \delta y_0$. As shown in **Fig. 13 (c)**, the inner longitudinal bars buckled outward, causing significant damage to the existing portion that primarily supported the axial force. Observations of H-RC-FB indicate that severe damage to the existing portion at the column base, due to the buckling of the longitudinal bars, significantly diminishes the column's capacity to bear axial loads. This is because the filled portion cannot contribute to resisting axial forces when the filled and existing portions behave separately. Jin et al. (2022) also conducted cyclic loading tests on hollow RC columns with concrete-filled bases. However, this experiment was concluded before detecting a significant reduction in the lateral load,

and failure behavior similar to that of H-RC-FB was not observed. The findings of the present experiment suggest that concrete-filling retrofitting does not prevent a pronounced reduction in the lateral load capacity and the axial settlement of the column once the inner longitudinal bars buckle when the filled and existing portions behave separately.

Height Distribution of Curvature and Plastic Hinge Length

Fig. 19 shows the height distribution of the curvature for each specimen. The curvature at the column's base includes the rotational deformation resulting from the longitudinal bars pulling out from the footing. **Fig. 19** illustrates that there is no significant variation in the curvature distribution on the cast-in-place joint surface and at points of abrupt changes in cross-sectional configuration. Moreover, the height distributions above the section with notable damage were similar across all specimens. However, in the column base experienced significant damage, H-RC-SD exhibited a smaller curvature at the lower end of the column and a larger curvature at the second level compared to those of the other specimens. H-RC and H-RC-FD exhibited similar results. Therefore, with concrete-filling retrofitting, when the filled and existing sections behave separately, the curvature distribution does not change from that of the original hollow RC columns.

Additionally, the column heights at which significant damage was observed in the experiments were compared with the plastic hinge lengths calculated using the equations proposed in previous studies. The plastic hinge length L_p was determined using the following equation proposed by Priestley et al. (1996):

$$L_p = 0.08L + 0.022f_{ye}d_{bl} \geq 0.044f_{ye}d_{bl} \quad (7)$$

where L is the distance from the critical section of the plastic hinge to the contraflexure point, f_{ye} is the yield strength of the longitudinal bar, and d_{bl} is the diameter of the longitudinal bar. In the current Japanese seismic design codes (JRA specification for highway bridges (2012)), the plastic hinge length is calculated using the following equation:

$$L_p = 9.5 \cdot f_{ye}^{\frac{1}{6}} \cdot \left(\frac{384E_0I_h}{n_s l_w^3 s} + 0.01c_o \right)^{-\frac{1}{3}} \cdot d_{bl} \leq 0.15L \quad (8)$$

where E_0 is the Young's modulus of the stirrups, I_h is the sectional secondary moment, n_s is the number of compression-side longitudinal bars in the largest confining concrete section, l_w is the largest horizontal length of the concrete section confined by the stirrup parallel to the lateral load direction, s is the interval between stirrups, and c_o is the thickness of the cover concrete. This equation considers the confining effects of the stirrups on the concrete and the thickness of the cover concrete. Eqs. (7) and (8) yield the same plastic hinge lengths for both hollow and solid RC columns, provided that the column heights, material parameters, and rebar arrangements are identical. Sun et al. (2019) evaluated the plastic hinge length of hollow RC columns with a low wall thickness ratio by employing the equation for the plastic hinge length of structural walls proposed by Paulay and Priestley (1993), as shown below:

$$L_p = 0.02l_w + 0.044L \quad (9)$$

This equation, which is intended for application to structural walls, can be used to calculate the plastic hinge lengths of H-RC and H-RC-FD.

The plastic hinge lengths derived from Eqs. (7-9) are listed in **Table 3**. The equations from the JRA specification (2012) and those proposed by Priestley et al. (1996) provided similar plastic hinge length values. These results generally aligned with the column heights at which significant damage was observed in the experiments. This alignment suggests that Eqs. (7) and (8) are reliable for estimating the plastic hinge lengths of hollow RC columns retrofitted with concrete filling, as well as solid or fully hollow RC columns. However, the equation given by Paulay and Priestley (1993) exhibited lower reproducibility than the others. Therefore, for wall thickness ratios exceeding 0.188, the Paulay and Priestley (1993) equation may not be suitable for evaluating the plastic hinge lengths of hollow RC columns.

Height Distribution of Stirrup Strain

Fig. 20 shows the height distribution of the stirrup strain. The strain data at each height represent the average values derived from the measurement data. In H-RC, the stirrup strain notably increased at all heights with an increase in displacement amplitude. Importantly, at a displacement amplitude of $7 \delta y_0$, the stirrup strain values reached the yield strain at multiple measurement points—specifically, 13 out of the 44 measurement points recorded values exceeding the yield strain. In H-RC-SB, although the stirrup strain gradually increased with an increase in displacement amplitude, the strain values up to a displacement amplitude of $7 \delta y_0$ were lower than those observed in H-RC. Only two of the 44 measurement points reached the yield strain. Similar to H-RC, H-RC-FB exhibited an increase in the stirrup strain as the displacement amplitude increased. At a displacement amplitude of $7 \delta y_0$, the stirrup strain values reached the yield strain at multiple measurement points. Ultimately, 11 of the 44 measurement points recorded strain values exceeding the yield strain.

Fig. 21 illustrates the strain histories of the outer stirrups at column heights of 878 and 1118 mm on the N side, highlighting a notable difference between H-RC-SB and H-RC-FB. In **Fig. 21**, the horizontal axis signifies loading cycles represented as $+1\delta y_0-1$, $-1\delta y_0-1$, $+1\delta y_0-2$, and so on. Furthermore, **Fig. 21** illustrates the crack patterns on the N-side column height ranging from 600 to 1400 mm during the third cycle of each loading amplitude. In H-RC-SB, the stirrup strain value increased steadily with the growth and emergence of oblique cracks, primarily from a displacement amplitude of $3 \delta y_0$ onwards. These findings suggest that when the displacement amplitude was small, the concrete mainly resisted the shear force, with the stirrups subsequently contributing more to the shear force resistance. In contrast, numerous oblique cracks were observed in both the Hollow-section and H-RC-FB at smaller displacement amplitudes, resulting in a marked stirrup strain increase by a displacement amplitude of $2 \delta y_0$. These results indicate that the filled portion in H-RC-FB did not significantly contribute to the shear resistance of the column, as it behaved separately from the existing portion.

Deformation Component of Column

The horizontal displacement of a column, δ , can be decomposed into three types as shown in Eq. (1): displacement due to bending deformation, δ_b ; displacement due to shear deformation, δ_s ; and displacement due to rotation, δ_r .

$$\delta = \delta_b + \delta_s + \delta_r \quad (10)$$

δ_b can be calculated by integrating the curvature of each cross-sectional interval over the height of the column. δ_r is a result of the longitudinal bars pulling out from the footing. The extent of longitudinal bar pull-out from the footing was calculated using the vertical displacement data of the columns. The shear deformation was computed by subtracting the horizontal displacements caused by bending and rotation from the total horizontal displacement of the column.

Fig. 22 illustrates the proportion of horizontal displacement attributable to bending, shear, and rotation in relation to the total horizontal displacement of the column. In the case of H-RC, the shear deformation constituted approximately 28% of the horizontal displacement at a displacement amplitude of $3 \delta_{y0}$ and decreased to about 13% with increasing displacement. For H-RC-SB, this percentage decreased from approximately 22% to 7%, whereas for H-RC-FB, it decreased from about 34% to 15%. These results indicate that the shear deformation component was more significant in both H-RC and H-RC-FB than in H-RC-SB. **Fig. 23** presents the absolute horizontal displacements due to bending, shear, and rotation for each specimen. As depicted in **Fig. 23**, H-RC-FB displayed reduced bending deformation compared to H-RC-SB. Concurrently, both the shear and rotational deformations appeared to increase, mirroring the trends observed in H-RC. From these observations, it can be inferred that concrete-filling retrofitting measure does not substantially enhance the shear resistance of a hollow RC column when the filled portion behaves separately from the existing portion. Consequently, concrete-filling retrofitting might not be the optimal strategy for increasing the shear capacity of hollow RC columns with low shear strength, particularly when strengthening the bond between the filled and existing portions is not feasible. Incidentally, H-RC and H-RC-FB exhibited

larger rotational deformations than H-RC-SB. This disparity arose from differences in the extent of longitudinal bar pull-out from the footing, as shown by the data in **Fig. 18**. However, the exact mechanism underlying this difference remains unclear, indicating the need for further exploration.

Conclusions

To investigate the effects of concrete-filling retrofitting on hollow RC columns, cyclic loading tests were conducted on large RC column specimens: a hollow RC column specimen (H-RC), a hollow RC column specimen with a solid section at the column base (H-RC-SB), and a concrete-filled retrofitted hollow RC column specimen (H-RC-FB). In particular, the effectiveness of the concrete-filling retrofitting method was evaluated when the filled and existing portions behaved separately. The findings of this study are as follows.

- In H-RC and H-RC-FB, cracks initially formed horizontally at the flange before diagonally propagating upon reaching the web. This type of crack pattern is characteristic of hollow RC columns and is distinct from the patterns observed in H-RC-SB. Additionally, horizontal cracks were evident in the filled portion, indicating that the filled portion behaved separately from the existing portion.
- In H-RC, the inward buckling of the inner longitudinal bars caused significant axial settlement and a decrease in the lateral load capacity of the column. In contrast, in H-RC-FB, concrete-filling retrofitting suppressed the inward buckling of the inner longitudinal bars, thereby enhancing the flexural deformation performance to a certain extent. However, this did not prevent a pronounced reduction in the lateral load capacity or axial settlement of the column when the inner longitudinal bars buckled. This is because the filled portion cannot resist axial forces when the filled and existing portions behave separately.
- The results indicate that concrete-filling retrofitting can delay the decrease in the lateral load capacity of hollow RC columns. However, it has been observed that when the filled and existing

portions behave separately, owing to inadequate treatment of the internal surfaces of hollow RC columns, there is no improvement in the flexural failure behavior and axial load-bearing capacity after the onset of lateral load reduction.

- The plastic lengths derived from the equations in the JRA specification (2012) and Priestley et al. (1996) generally aligned with the column heights at which significant damage was observed in the experiments. This alignment suggests that these equations are reliable for estimating the plastic hinge lengths of hollow RC columns retrofitted with concrete filling, as well as solid or fully hollow RC columns.

- The stirrup strain in H-RC increased with the displacement amplitude, reaching the yield strain at multiple measurement points. In H-RC-SB, although the stirrup strain increased gradually with an increase in the displacement amplitude, the strain values were lower than those observed in H-RC. In contrast, H-RC-FB exhibited an increase in the stirrup strain as the displacement amplitude increased, similar to H-RC. At the end of the experiment, the stirrup strain reached the yield strain values at multiple measurement points.

- The shear deformation component in relation to the total horizontal displacement of the column was more significant in H-RC and H-RC-FB than in H-RC-SB. This suggests that concrete-filling retrofitting measure does not substantially enhance the shear resistance of the hollow RC column when the filled portion behaves separately from the existing portion. Consequently, concrete-filling retrofitting might not be the optimal strategy for increasing the shear capacity of hollow RC columns with low shear strength, particularly when it is not feasible to strengthen the bond between the filled and existing portions.

- Future research should focus on developing methods to enhance the effectiveness of concrete-filling retrofitting, particularly in cases where internal surface treatment is not feasible. For instance, future work could investigate a method to strengthen the bond between the filled and existing portions by externally applying post-construction anchors to the columns. Moreover,

although the hollow RC columns examined in this study featured square cross-sections, it is important to evaluate the effectiveness of concrete-filling retrofitting in hollow RC columns with cross-sectional side length ratios exceeding 1.

Appendix. Completion of Vertical Displacement Data

In H-RC-SB, the displacement transducers on the W side at both the lowest section (column height: 0–77 mm) and the second-lowest section (column height: 77–186 mm), as well as on the W side of the second-lowest section (column height: 65–190 mm) in H-RC-FB, failed to provide data owing to measurement anomalies. The missing displacement data for these measurement points were supplemented using data from the displacement transducers on the E side, which were positioned at identical cross-sectional heights. The methods used to complete the data are described below. For reference, **Fig. 24** shows the history of the vertical displacement at the lowest section (column height: 0–69 mm) and the second-lowest section for H-RC, where no measurement anomaly was observed. **Fig. 24** illustrates that although slight differences existed, the compression and tension peak values on the W and E sides were largely comparable at every displacement amplitude. Based on the observed patterns, it was hypothesized that both H-RC-SB and H-RC-FB would exhibit similar trends. Specifically, the curvature of each cross-section was determined by equating the peak value of the vertical displacement on the W side (from which data were missing) to the peak value on the E side observed in the previous cycle. Although this data completion method may not perfectly replicate the lost data, it provides a general trend of column deformation, which is deemed sufficient for the discussions in this paper.

Note that the data presented in **Fig. 24** do not represent the vertical displacements of the columns themselves, but rather the readings from the vertical displacement transducers mounted on the W and E sides, referred to as Vd_w and Vd_e , respectively. The actual vertical displacement of the columns within the measured section is determined by averaging these values: $(Vd_w + Vd_e)/2$. **Fig.**

25 illustrates the vertical displacement, calculated as $(Vd_w + Vd_e)/2$, for column heights ranging from 0–69 mm and 69–117 mm. The figure reveals that significant axial settlement of the columns began after reaching $7 \delta y_0$.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author on reasonable request.

Acknowledgments

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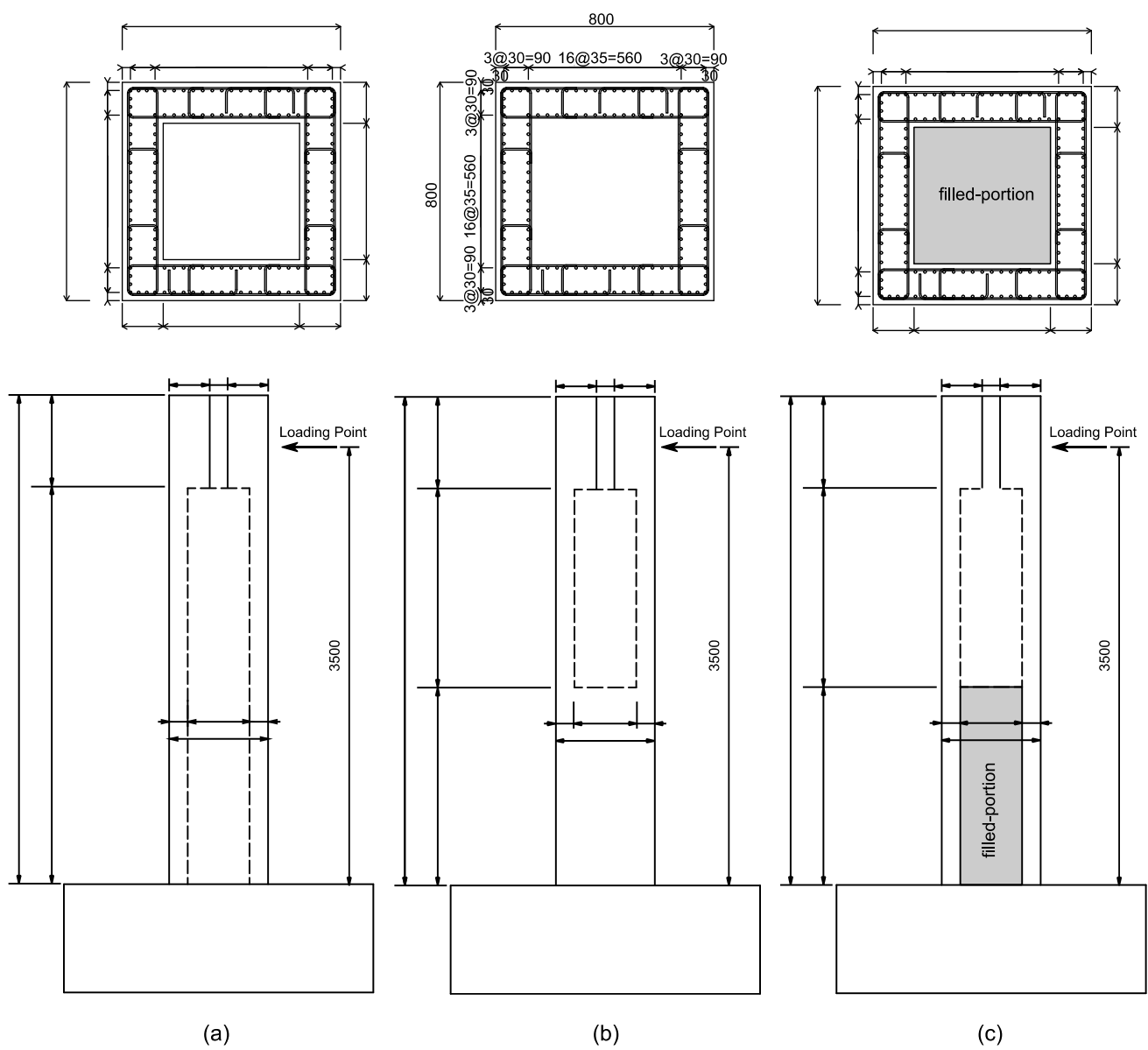
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612 **Fig. 1.** Dimensions of specimens and details of rebar arrangement (Unit: mm): (a) H-RC; (b) H-RC-
613 SB; and (c) H-RC-FB.

(a), (b): Only for hollow RC piers with a cross-sectional side length ratio of 1.5 or less

● Real-life hollow RC pier ● Experimental specimen (H-RC)

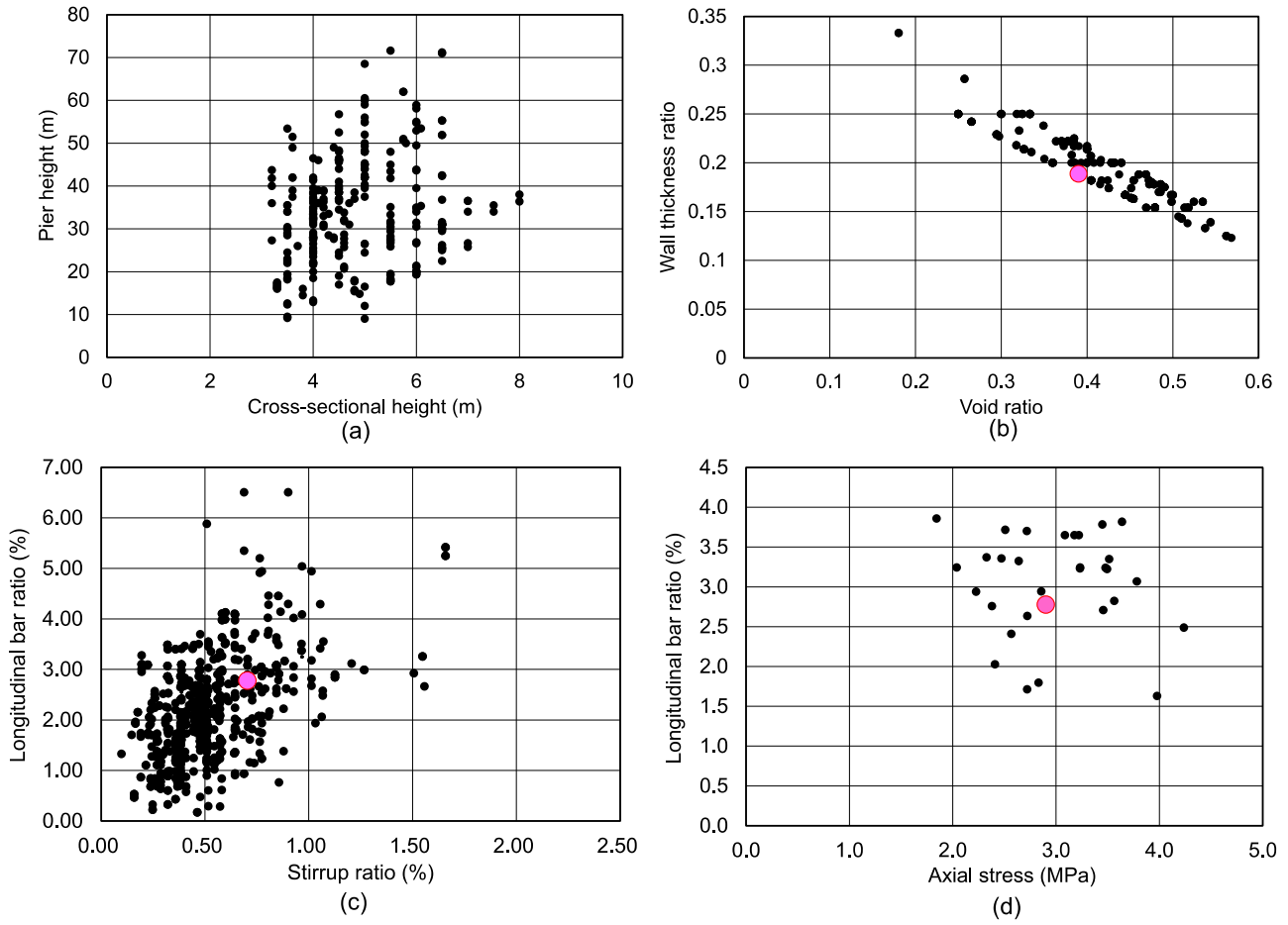


Fig. 2. Structural specifications of real-life hollow RC bridge piers managed by West Nippon Expressway Company Limited: (a) Correlation between pier and cross-sectional heights; (b) Correlation between wall thickness and void ratios; (c) Correlation between longitudinal bar and stirrup ratios; and (d) Correlation between longitudinal bar ratio and axial stress.

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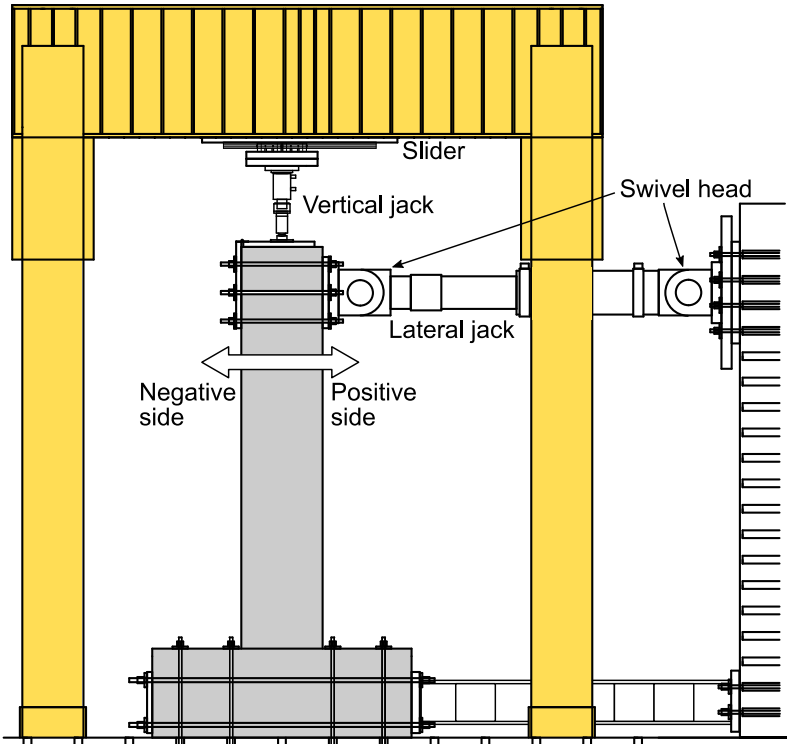


Fig. 3. Experimental setup.

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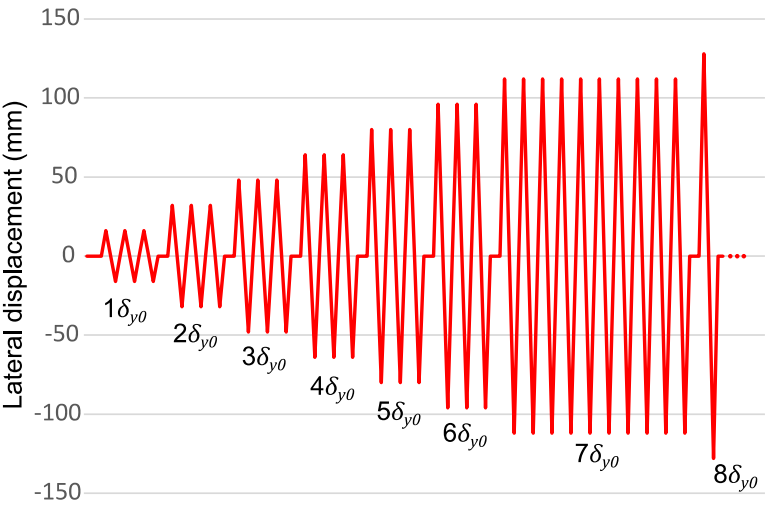


Fig. 4. Lateral loading protocol.

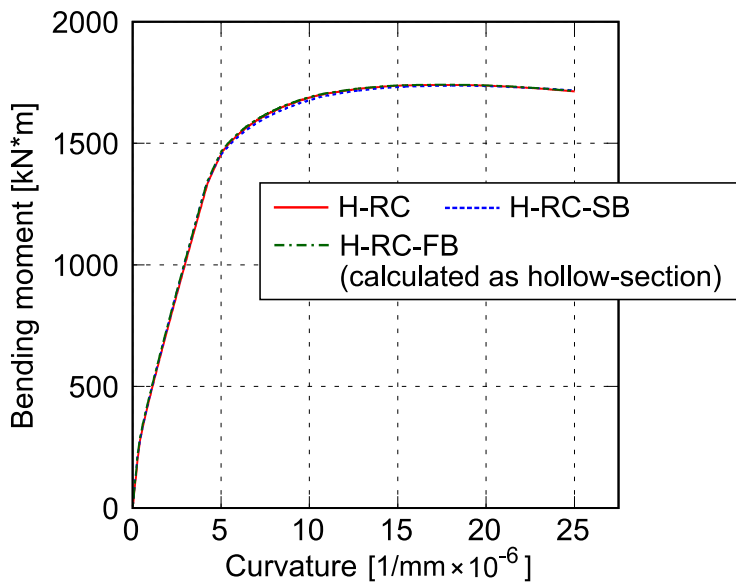


Fig. 5. Cross-sectional analysis result for the column bases of the specimens.

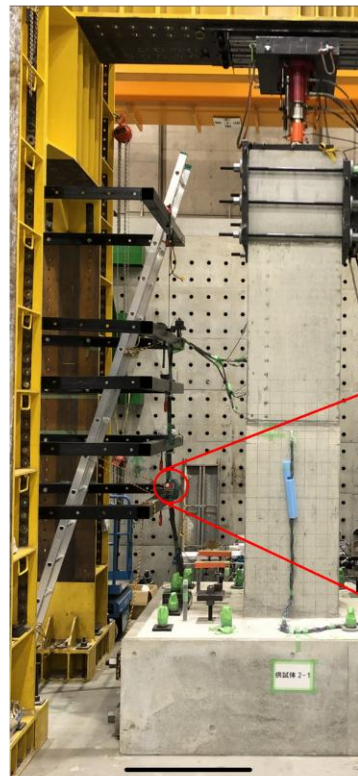
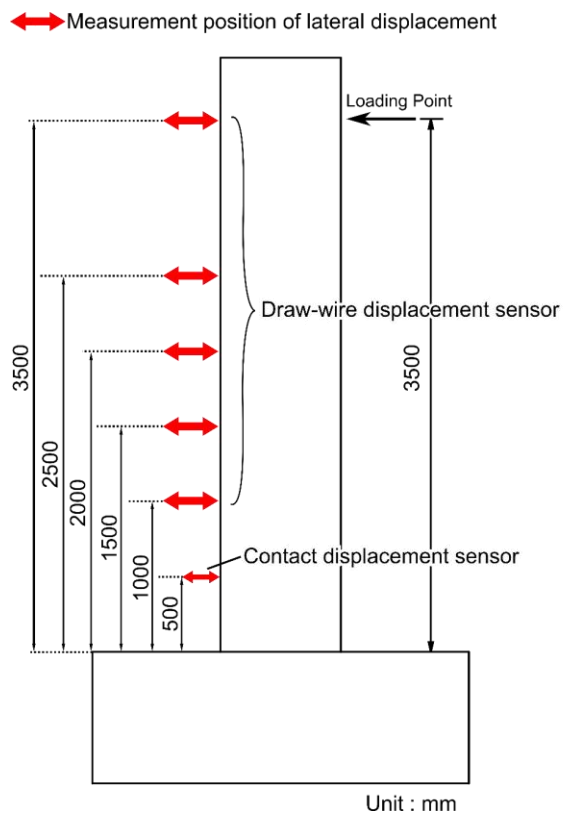
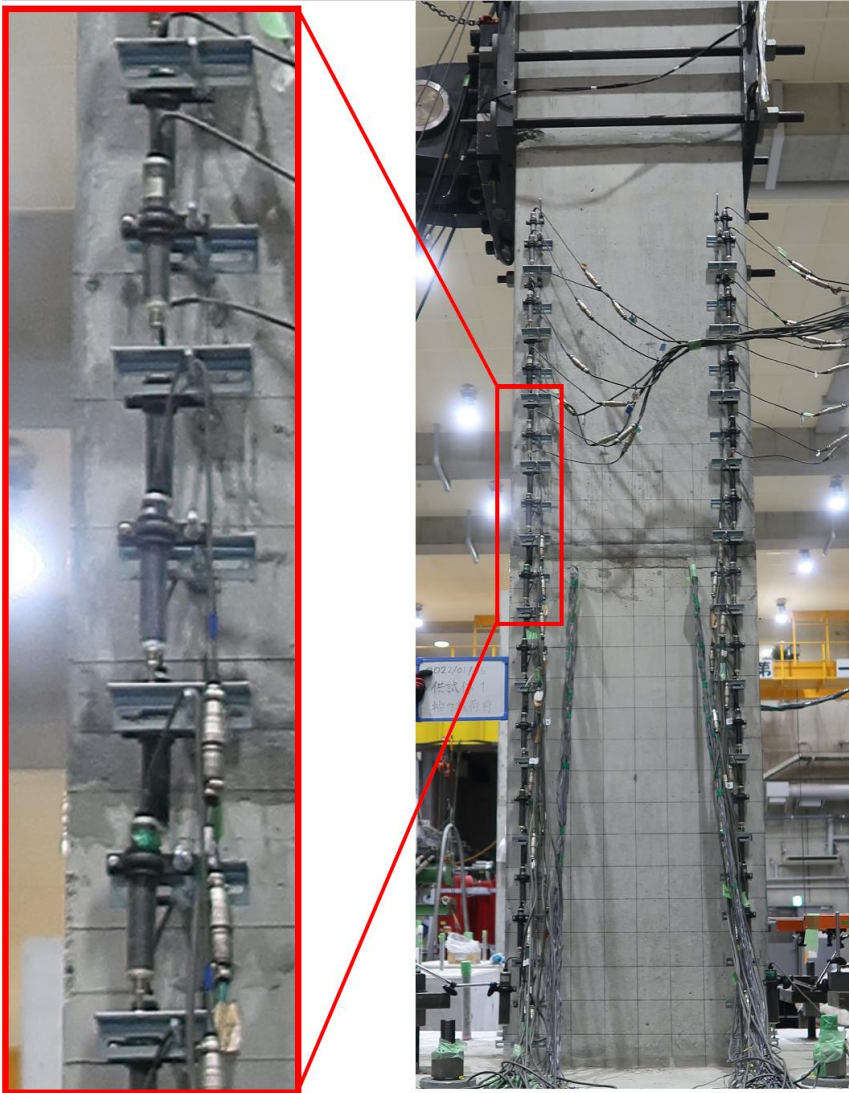


Fig. 6. Measurement points of lateral displacement.



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631 **Fig. 7.** Measurement points of vertical displacement.

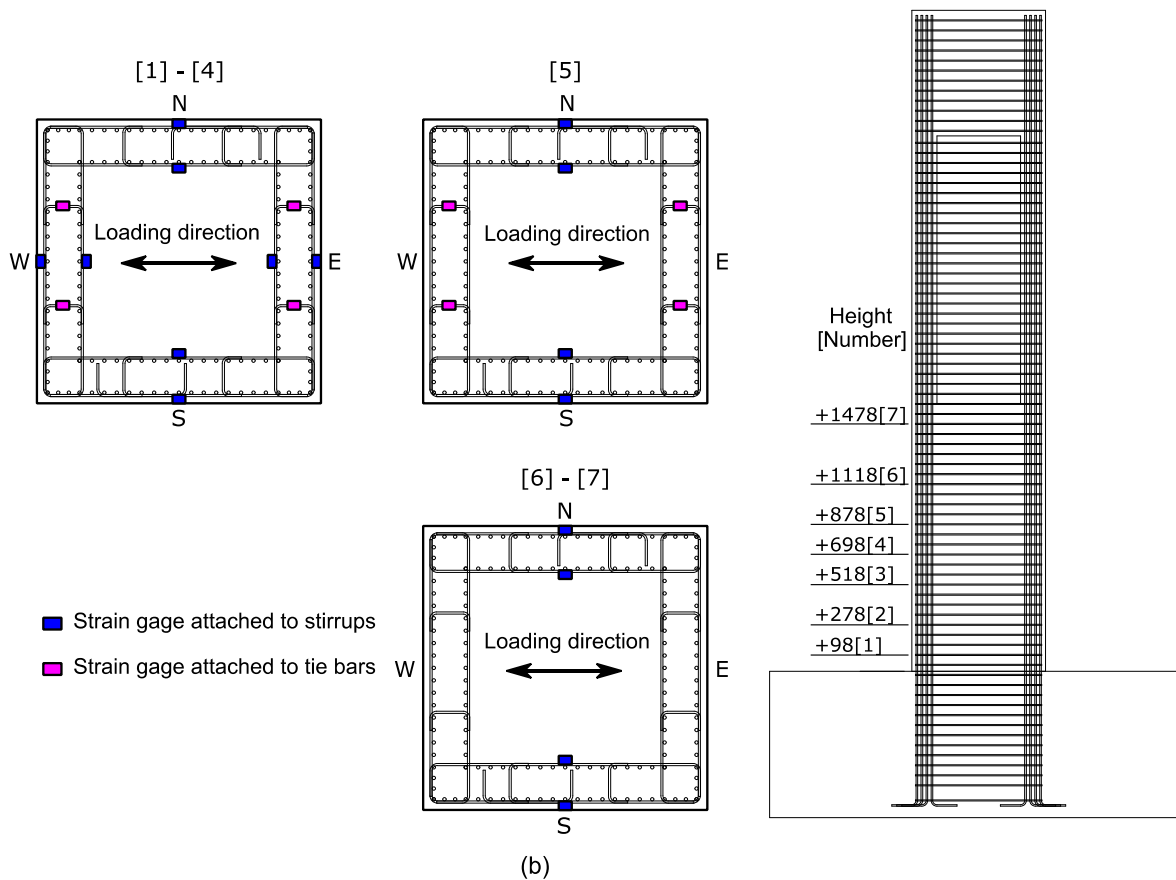
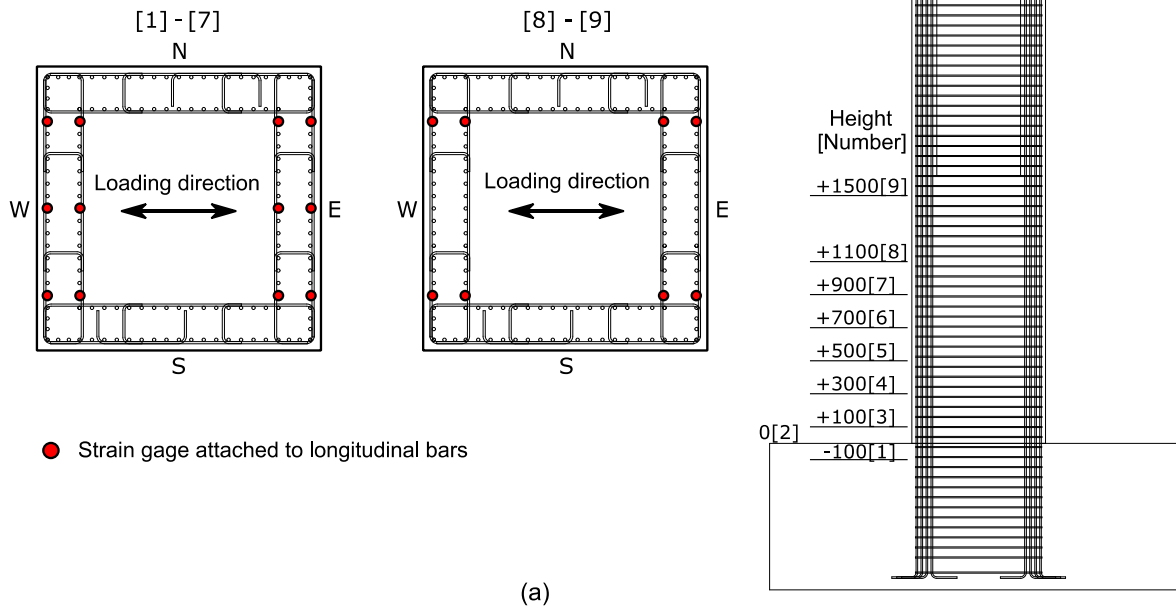


Fig. 8. Position of strain gauges: (a) longitudinal bars; and (b) stirrups and tie bars.



Fig. 9. Cutting at the center of the cross-section to examine internal damage.

Fig. 10. Crack patterns on column side (N side): (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

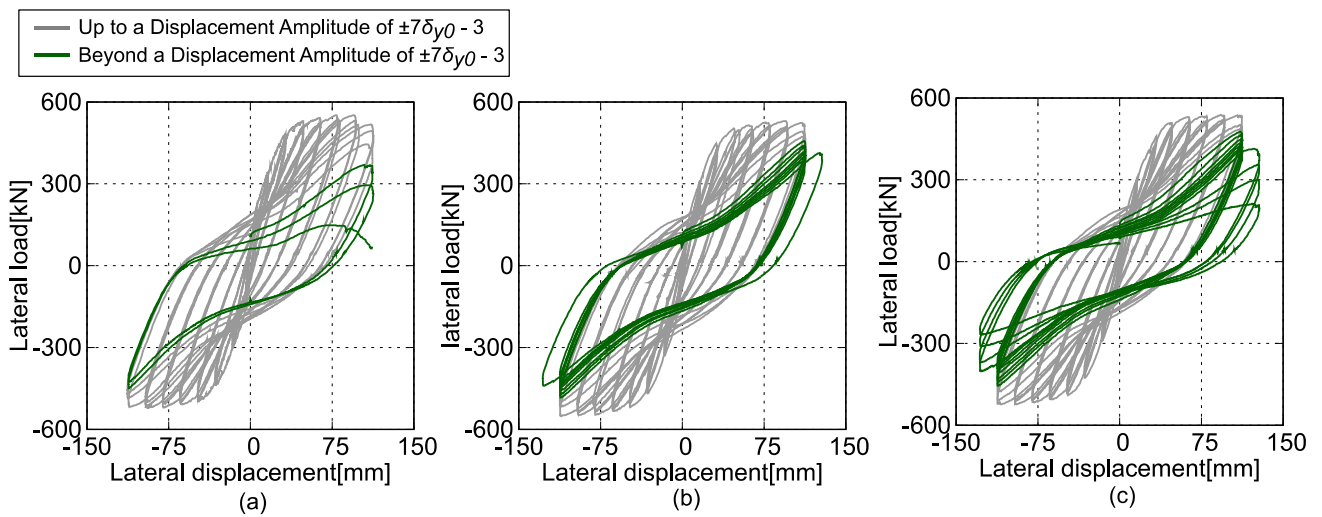


Fig. 11. Lateral load-displacement relationship: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

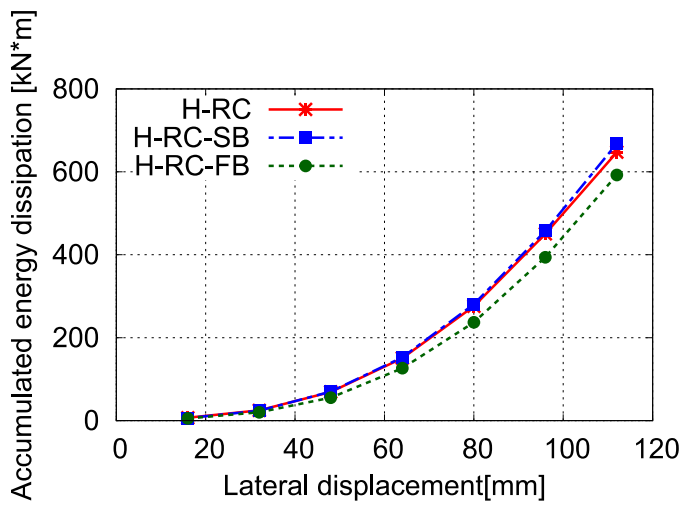


Fig. 12. Accumulated energy dissipation.

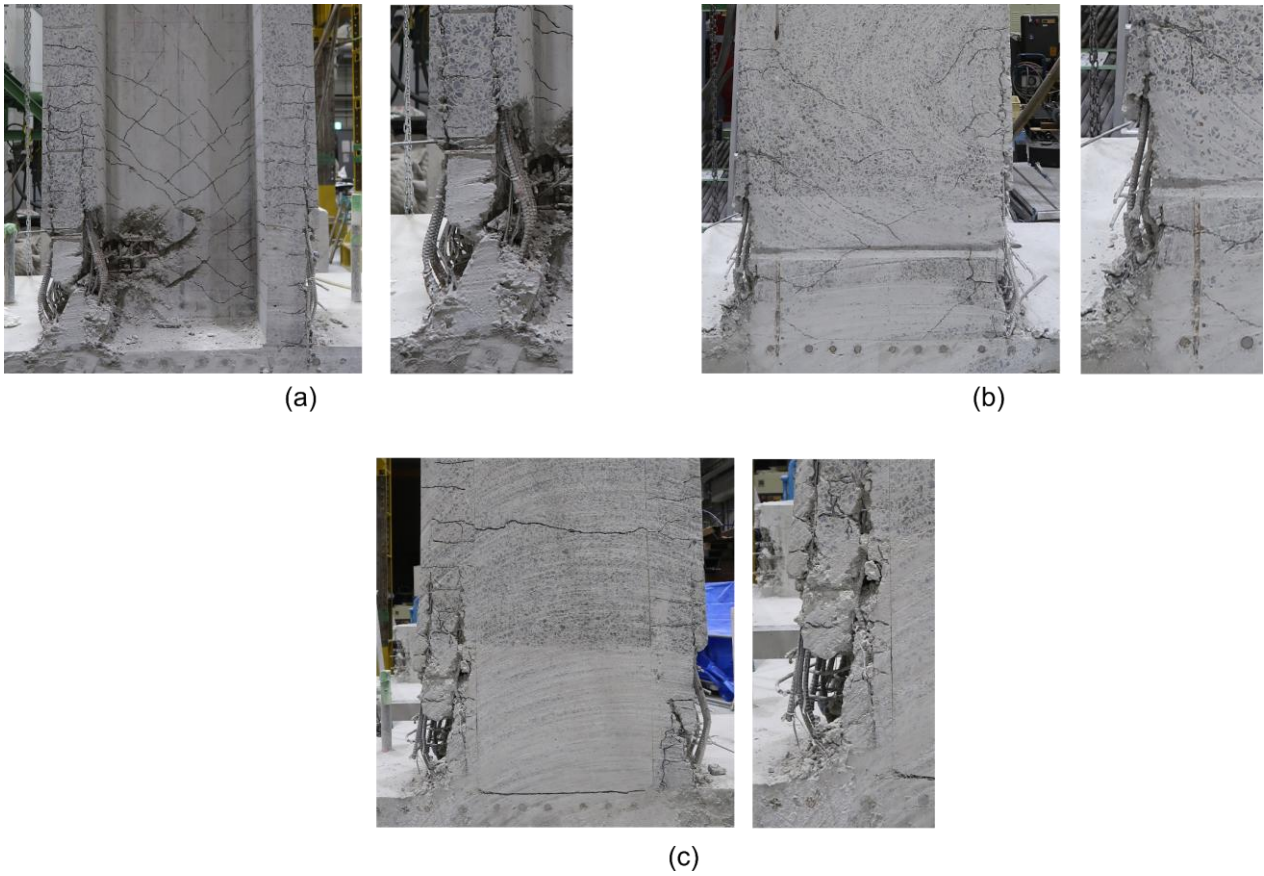


Fig. 13. Damage state of column after cutting at the center of the cross-section: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

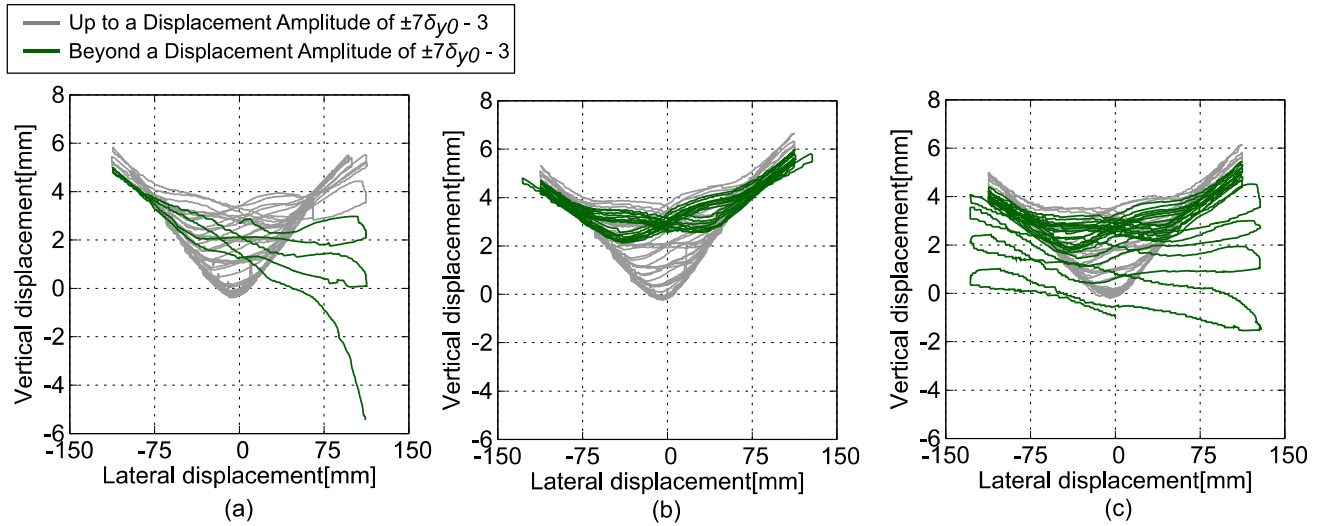


Fig. 14. Relationship between vertical and lateral displacement: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

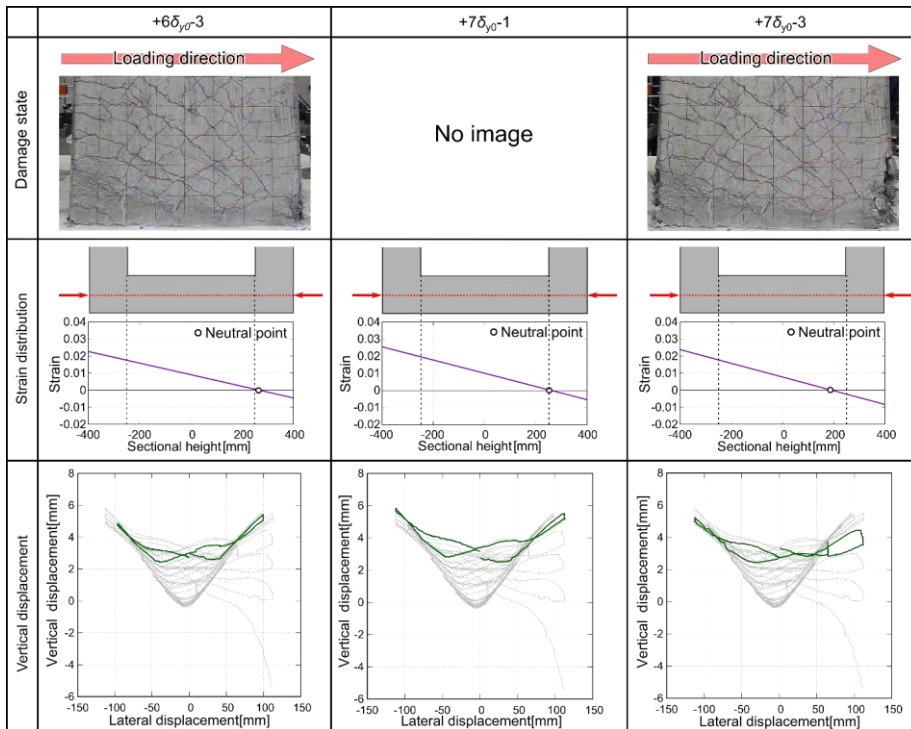


Fig. 15. Relationships among damage state at column base, strain distribution across its cross-section, and the extent of axial settlement (H-RC).

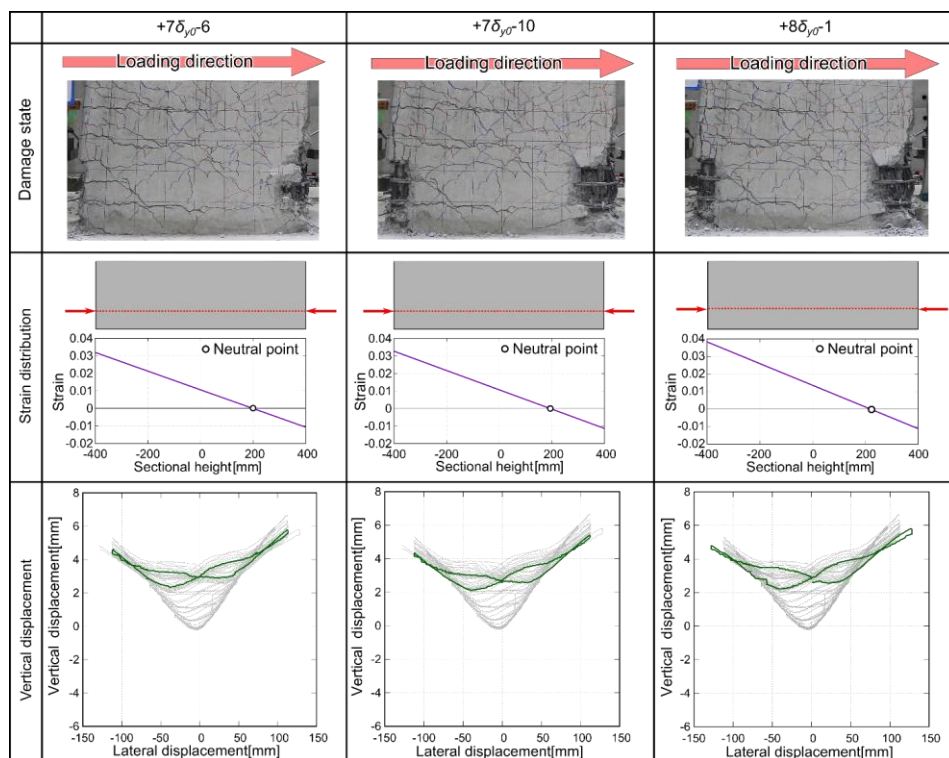


Fig. 16. Relationships among damage state at column base, strain distribution across its cross-section, and the extent of axial settlement (H-RC-SB).

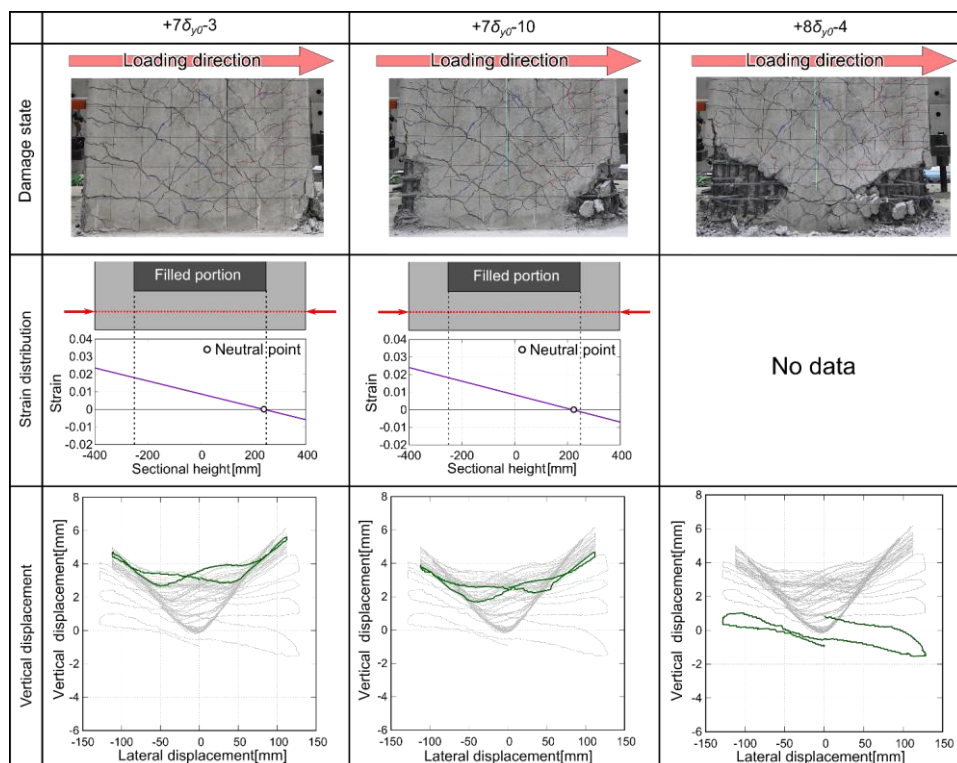


Fig. 17. Relationships among damage state at column base, strain distribution across its cross-section, and the extent of axial settlement (H-RC-FB).

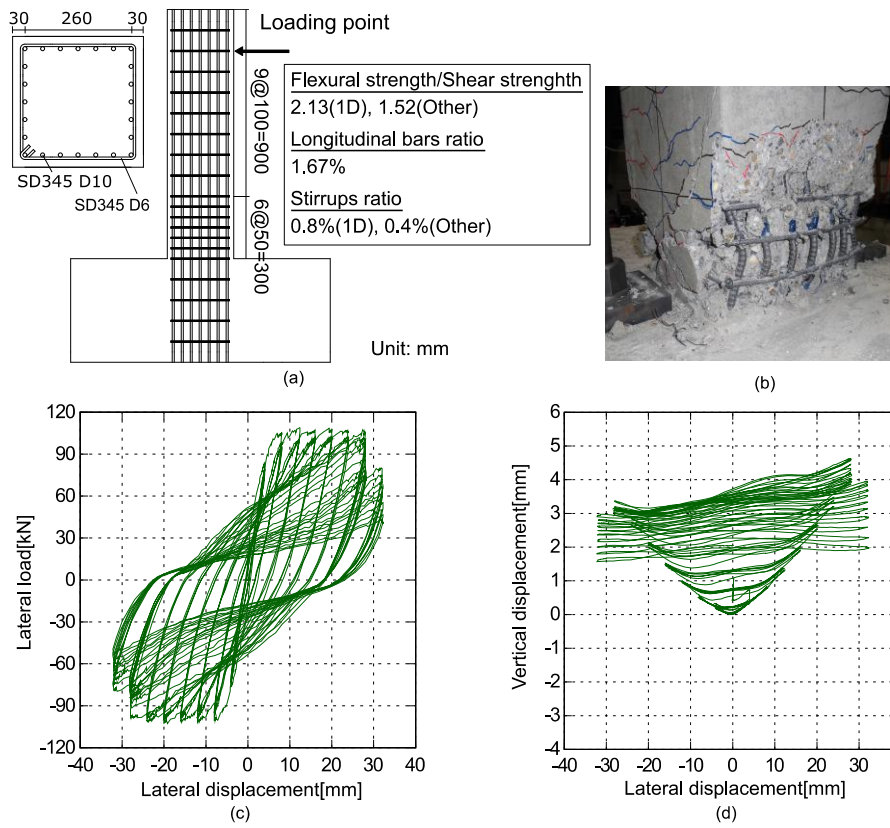


Fig. 18. Past cyclic loading tests on a medium-sized RC column with a solid section.

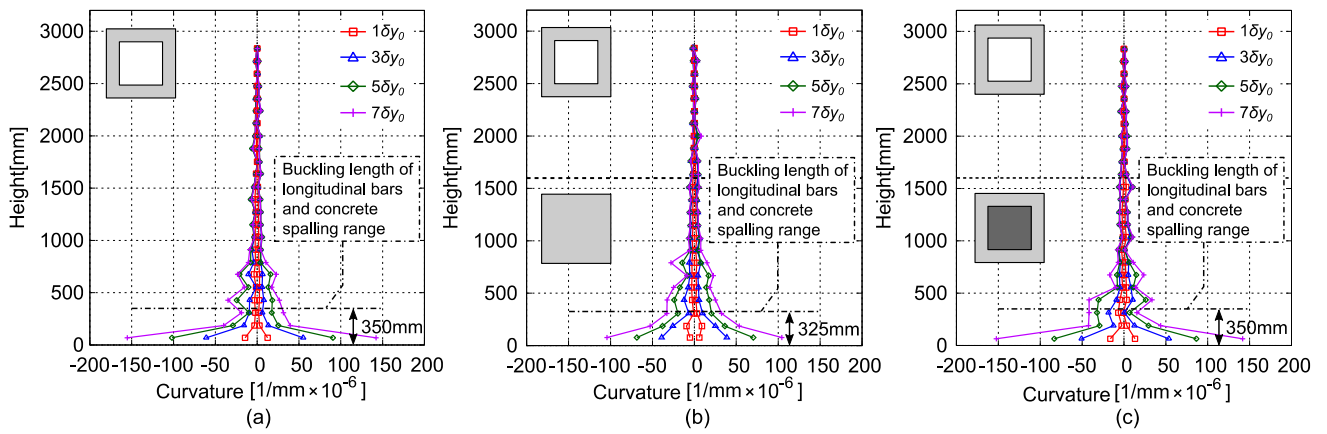


Fig. 19. Height distribution of curvature: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

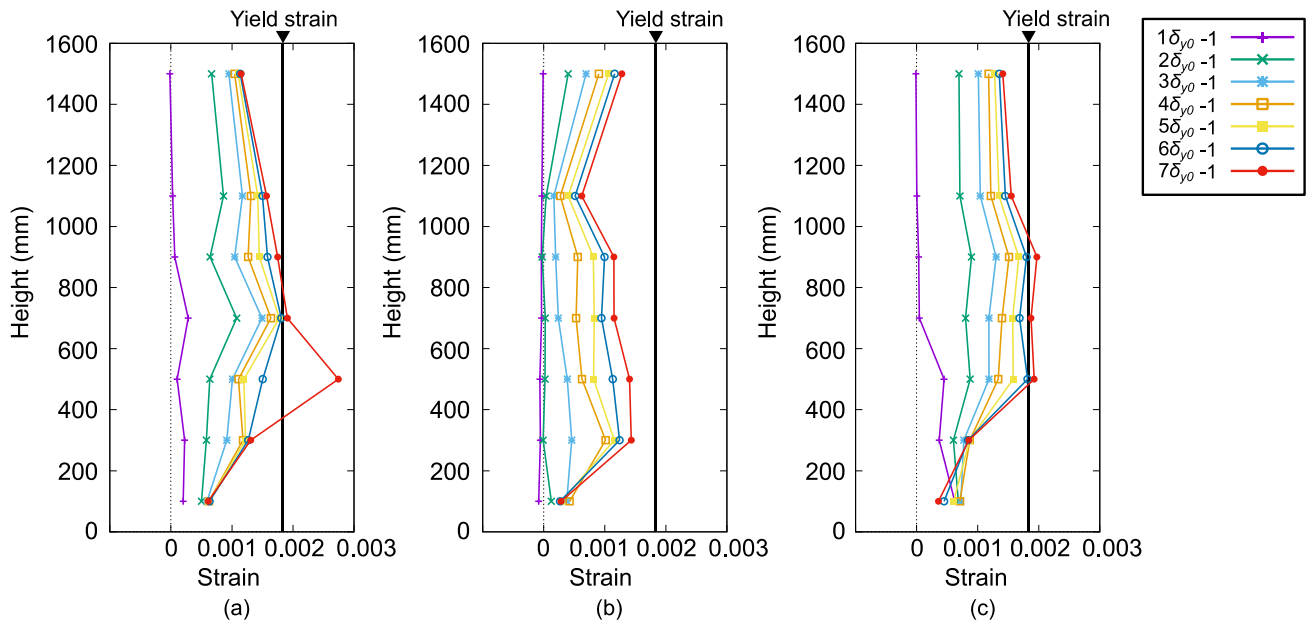


Fig. 20. Height distribution of stirrup strain: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

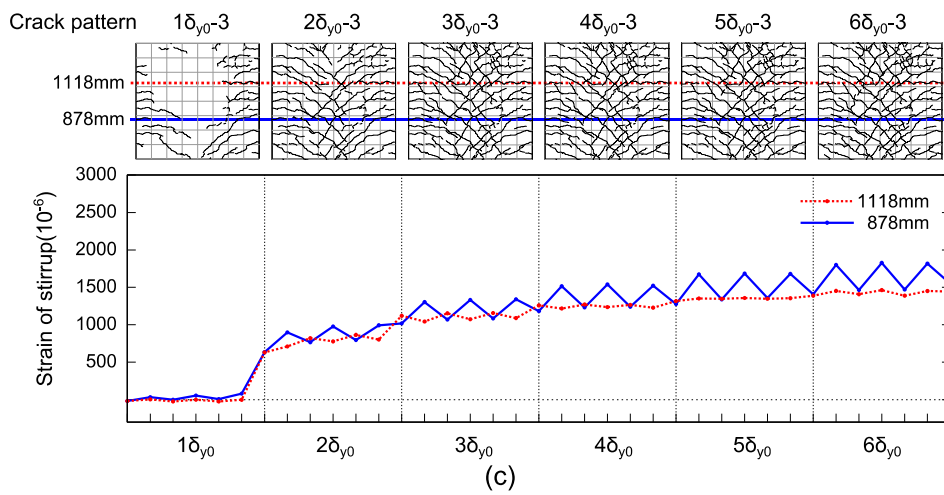
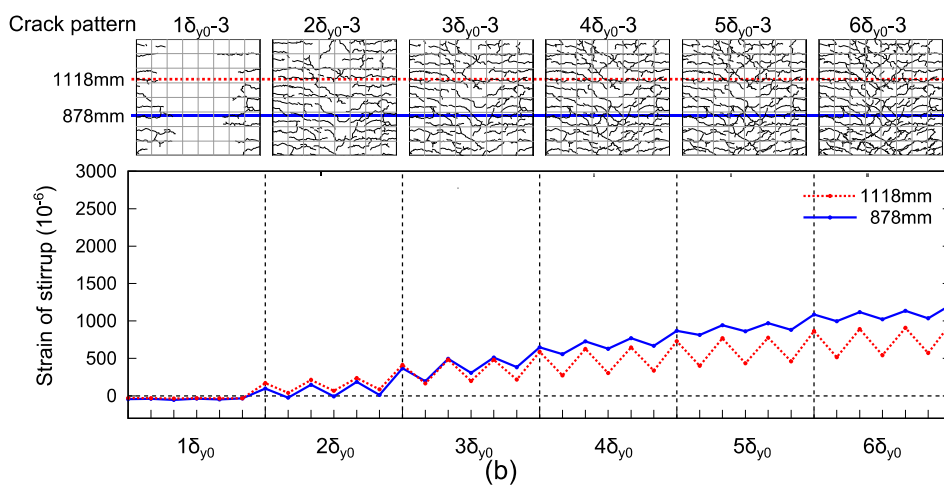
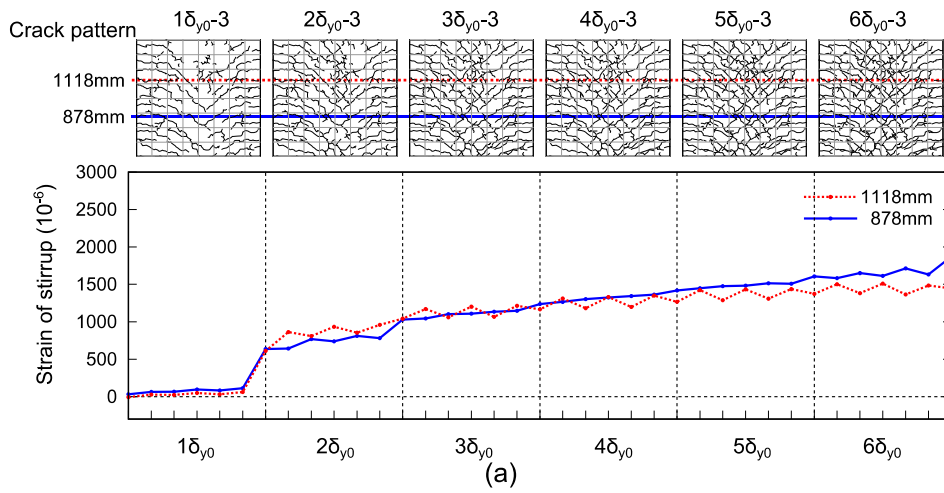
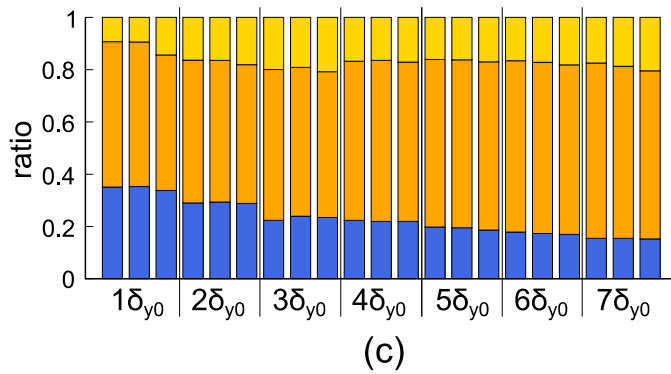
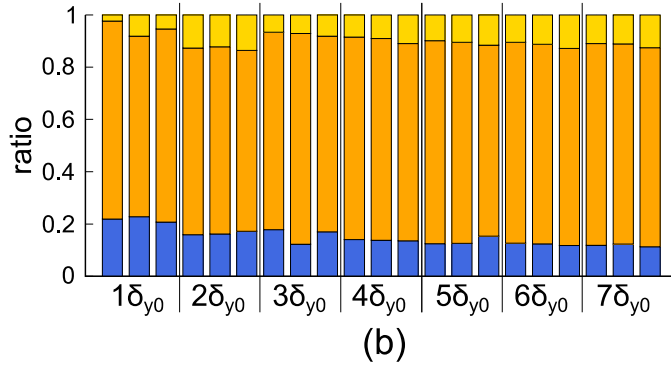
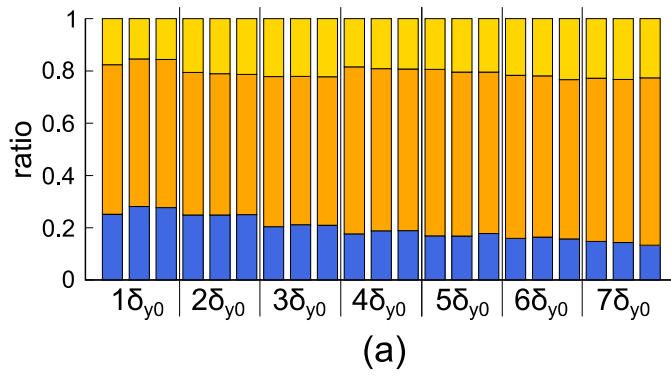
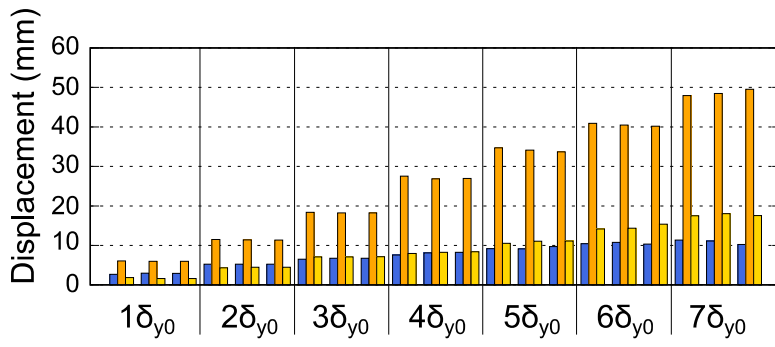


Fig. 21. Strain histories of outer stirrups at 878 mm and 1118 mm column heights: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

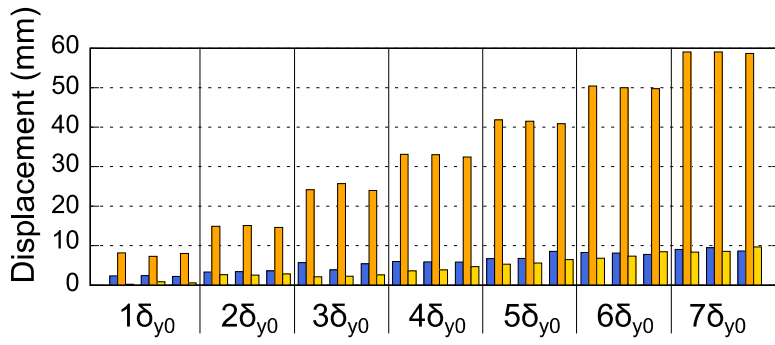


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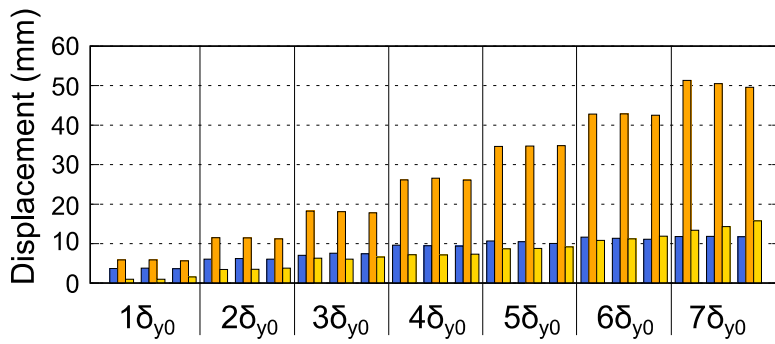
670 **Fig. 22.** Proportion of horizontal displacement attributable to bending, shear, and rotation in relation
 671 to the total horizontal displacement of the column: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.



(a)



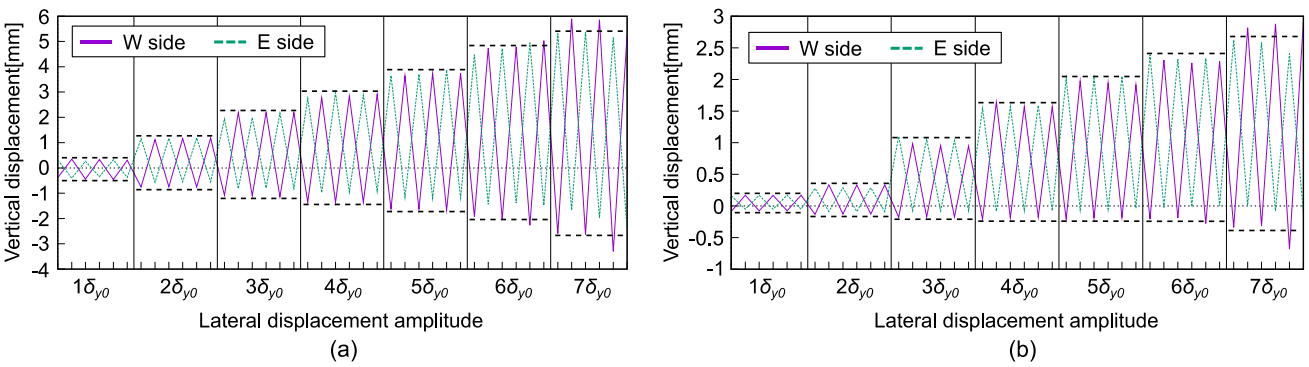
(b)



(c)

Fig. 23. Absolute horizontal displacements due to bending, shear, and rotation for each specimen: (a) H-RC; (b) H-RC-SB; and (c) H-RC-FB.

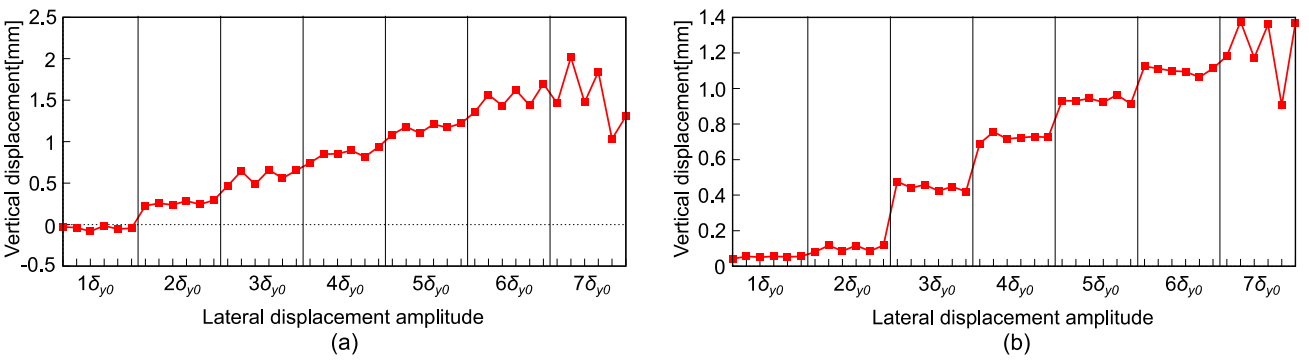
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678 **Fig. 24.** History of vertical displacement in H-RC measured by the vertical displacement transducers,
679 illustrated for two height ranges: (a) 0–69 mm; and (b) 69–117 mm.

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682 **Fig. 25.** History of vertical displacement of H-RC, illustrated for two height ranges: (a) 0–69 mm; and
683 (b) 69–117 mm.

684 Table 1. Material properties of rebars

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Usage	Type	Yield strength (N/mm ²)	Tensile strength (N/mm ²)	Young's modulus (N/mm ²)
Stirrup and tie bar	D6-SD345	367	587	2.0×10 ⁵ *
Longitudinal bar	D10-SD345	396	660	2.0×10 ⁵ *

686 Note: * specification values

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691 Table 2. Material properties of concrete

Specimen	Compressive strength (N/mm ²)				Tensile strength (N/mm ²)				Young's modulus (N/mm ²)			
	1st Lift	2nd Lift	3rd Lift	Filled portion	1st Lift	2nd Lift	3rd Lift	Filled portion	1st Lift	2nd Lift	3rd Lift	Filled portion
H-RC	23.7	30.8	33.5	-	2.20	2.42	-	-	19596	22952	28888	-
H-RC-SB	23.2	30.7	35.1	-	2.64	2.77	-	-	18202	20526	21534	-
H-RC-FB	23.7	26.4	31.9	35.7	2.69	2.75	-	2.45	22934	23888	25556	

692 Note: 1st Lift: Column height less than 1600 mm, 2nd Lift: Column height from 1600 mm to 3200 mm,

693 3rd Lift: Column height from 3200 mm to 3950 mm

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699 Table 3. Comparison between calculated and experimental values of plastic hinge length.

	Priestley et al. (1996)	JRA specification (2012)	Paulay and Priestley (1993)
Calculation value (mm)	364	363	302
H-RC	1.04	1.04	0.86
Calc./Exp. ratio	H-RC-SB	1.12	-
	H-RC-FB	1.04	0.86

700 Note: The equation proposed by Paulay and Priestley (1993) is not applicable to H-RC-SD, as it was intended for structural walls.

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