

Development of Aseismic Column with Self-Centering Capacity Only During Restoration

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Abstract: Self-centering columns (SC), while attracting interest for their high recoverability, do not dissipate seismic energy as efficiently as conventional reinforced concrete or steel columns, potentially leading to a more significant seismic response. This study proposes a concept aimed at enhancing both energy dissipation during earthquakes and post-earthquake restoration performance. This is achieved by exhibiting an SC capacity only during restoration. The proposed aseismic column consists of a central component, the SC core constructed from steel tubes filled with high-strength mortar, and energy-dissipation (ED) components made from steel plates. This SC core generates a moderate SC force sufficient to counteract the P - Δ effect. Given the minimal SC force from the SC core, the plasticization effect of the ED components becomes more conspicuous during large earthquakes, resulting in the emergence of a spindle-shaped lateral load capacity, leading to residual displacement in the columns. During restoration after earthquakes, the SC force emerges when the ED components are removed. The residual displacements of the columns can be gradually reduced during this process. Cyclic loading tests are conducted on the proposed column prototype followed by removal tests of the ED components with vertical axial forces acting on the column with residual displacement. In the cyclic loading tests, we confirmed the superior ED performance of the proposed

column prototype, although residual displacement occurred in the column. In the ED component removal tests, a substantial reduction in the residual displacement of the column was observed when the ED components were removed. Specifically, the residual displacements were reduced by up to 96.2%, to a value of only 0.13% of the column height. In conclusion, the proposed concept can achieve superior energy absorption during earthquakes and high restoration performance afterward.

Introduction

Conventional reinforced concrete (RC) and steel columns have been designed to absorb energy and mitigate seismic responses by allowing plasticization of the column base during moderate to large earthquakes. However, significant seismic damage could necessitate the reconstruction of these conventional column structures owing to large residual displacements, thereby obstructing restoration efforts. Recently, self-centering (SC) columns exhibiting flag-shaped hysteresis behavior have gained attention. In SC columns, the bottom edge of the column is not connected to the footing, allowing for a rocking behavior during earthquakes. The incorporation of unbonded post-tensioning (PT) tendons within the columns, coupled with the addition of energy-dissipating (ED) components, facilitates a flag-shaped hysteresis response. This particular behavior can present a certain level of ED capacity and mitigate residual displacement in the event of earthquakes.

In SC columns, it is extremely important to protect the base where the rocking behavior occurs. Therefore, several studies have been conducted on SC columns reinforced with steel jackets at their bases. Chou and Chen (2006) proposed an SC column using a precast concrete-filled tube and experimentally demonstrated that the external ED component increased its equivalent viscous damping by approximately a factor of 1.5. Wang et al. (2019a) proposed an SC concrete-filled square steel tubular column and conducted experimental studies on the arrangement of external ED and PT materials as parameters. They confirmed that all cases exhibited an acceptable flag-shaped hysteresis loop. Zhang et al. (2021) developed an SC column featuring an ED bar either inside or outside a precast concrete-filled tube column, achieving a reduction in the residual displacement of

53 approximately 94.4% compared with conventional RC columns. Yang et al. (2022) proposed an SC
54 column protected by jacketing the base with a steel plate, which enabled energy dissipation through
55 easily replaceable dampers. Sun et al. (2023) experimentally investigated the seismic performance of
56 circular concrete columns restrained with spiral reinforcement or steel plates using low-bond ultra-
57 high strength (LBUS) rebars as longitudinal bars. They confirmed that the LBUS rebar provided a
58 strong restoring force and that the columns exhibited high drift hardening and SC behaviors up to a
59 drift ratio of 5.0%.

60 Furthermore, different studies on SC columns have been conducted using high-performance
61 materials such as ultra-high-performance concrete (UHPC), engineered cementitious composite
62 mortar, and polyurethane (PU). Yang et al. (2017) conducted cyclic loading tests on precast post-
63 tensioned concrete segment columns made of UHPC, confirming its superior SC capacity and
64 demonstrating that UHPC is effective in preventing damage at the base of SC columns. Wang et al.
65 (2018a) developed an SC column using UHPC for both core and cover plates. The ED components
66 were positioned inside the cover plates; experimental studies confirmed the excellent SC capacity of
67 the structure. After an earthquake, rapid repair was possible by replacing the damaged cover plates
68 and ED components. Wang et al. (2018b) proposed precast segmental unbonded post-tensioned SC
69 columns made of ultra-high-performance fiber-reinforced concrete. Experimental studies
70 investigated the influence of ED bars and PT forces inside the column on the SC capacity and damage
71 condition of the proposed structure. Additionally, Wang et al. (2019b) introduced a numerical model
72 to evaluate the seismic performance of this SC column in addition to a simple formula for assessing
73 residual displacements. Shen et al. (2022) proposed an SC column using ultrahigh-strength concrete
74 and placed engineered cementitious composite (ECC) mortar beds on the footing surfaces. In the
75 proposed structure, the column was restrained with a steel tube to prevent performance degradation
76 owing to damage at the base. Motaref et al. (2014) conducted shaking table tests on segmental bridge
77 columns using different materials at the column base and confirmed that the use of ECC at the column
78 base suppressed damage and demonstrated excellent SC capacity. Nikoukalam and Sideris proposed

SC columns based on PU reinforced rocking columns. In a series of studies, the feasibility of the proposed structure was numerically examined (Nikoukalam and Sideris 2017) and followed by experimental studies (Nikoukalam and Sideris, 2021a, 2021b). The proposed structure used PU-made segments at the column base and high-performance steel buckling-restrained bars as ED components, and achieved damage suppression at the base, superior SC capacity, and ED performance.

In addition, different types of SC columns such as double-shell and steel SC columns have been proposed. Guerrini et al. (2014) proposed a precast hollow SC column composed of two cylindrical steel shells and high-performance concrete placed between them to facilitate erection by reducing the concrete volume by hollowing out the column. Moustafa and ElGawady (2020) conducted a shaking table test on a dual-shell SC column (SC-HC-FCS) consisting of an outer glass fiber-reinforced polymer (GFRP) tube and inner steel tube. They confirmed the excellent SC capacity of the column, which was characterized by minimal residual drift and negligible damage. Shi et al. (2023) developed an SC-HC-FCS comprising an outer fiber-reinforced polymer (FRP) tube and inner steel tube, with concrete filling the space between them. The SC-HC-FCS column equipped with external ED components and unbonded post-tensioned tendons demonstrated sufficient SC and ED capacities through experiments and numerical analysis. Lin et al. (2023) conducted cyclic loading tests on SC columns with multiple joints in the column height direction using concrete-filled double-skin steel tube segments. Their results indicated that the application of ED devices at multiple joints efficiently enhanced the ED performance. Freddi et al. (2020) proposed a post-tensioned steel SC column using friction devices as ED components. The column consisted of a circular steel plate with rounded edges at the rocking interface. In addition to conducting cyclic loading tests on the proposed structure, they developed a three-dimensional nonlinear finite-element (FE) model that could be used for the design of the proposed structure. Rahmzadeh et al. (2021) conducted cyclic loading tests on a post-tensioned rocking steel bridge pier and demonstrated that the proposed structure exhibited a stable hysteresis response and excellent SC capability up to a lateral displacement of 4.3% of the column height. Moreover, the installation of a base plate at the column–base interface effectively

105 suppressed base damage. In addition, they developed an FE model of the structure to elucidate the
106 influence of key factors such as the material model, base plate size, column diameter-to-thickness
107 ratio, initial axial force, and ED location on the lateral cyclic response (Rahmzadeh et al. 2022). Chen
108 et al. (2022) proposed a steel SC column combining composite combination disc springs
109 demonstrating nonlinear elastic member force and buckling restrained braces with excellent ED
110 capacity, and demonstrated its superior SC and ED capacity through numerical analysis. Sun et al.
111 (2022) proposed a steel SC column using replaceable ED steel components. The SC column
112 incorporated post-tensioned strands and friction energy dissipation via brass plates.

113 Diverse ED components paired with SC columns have been the subject of different studies.
114 Palermo et al. (2007) proposed using post-tensioned precast SC columns with mild steel bars as ED
115 members. They experimentally demonstrated the superior performance of this structure and outlined
116 the methods for its modelling and design. Marriott et al. (2009) conducted quasi-dynamic experiments
117 to study the dynamic response characteristics of this structure. Ou et al. (2010a) employed
118 Enduramet32 (S24100), a high-performance steel bar, as the ED element to achieve exceptional
119 energy dissipation. Guo et al. (2015) introduced a precast SC column jacketed with GFRP at the base
120 and incorporated aluminium rods with enhanced material properties as the external ED components.
121 Kamperidis et al. (2018) developed elements termed hourglass-shaped steel yielding devices (WHPs),
122 which were incorporated into SC columns as ED materials. Other studies explored SC columns
123 utilizing steel angles (ElGawady and Sha'lan 2011) and superelastic shape memory alloy (SMA) bars
124 (Roh and Reinhorn 2010; Nikbakht et al. 2015) as the ED materials.

125 Moreover, several studies have been conducted into adding SC forces to columns using
126 members other than PT tendons in consideration of the issues concerning the repair ability and
127 durability posed by the application of PT tendons. Akbarnezhad et al. (2022) proposed the use of
128 superelastic SMA bars. Wang et al. (2019c) and Chen and Zhu (2022) suggested implementing
129 superelastic SMA bolts to incorporate SC forces into the columns. Furthermore, numerical analysis
130 models of SC columns have been proposed to optimize different parameters. Ou et al. (2007)

131 developed a simplified analytical model that accurately predicted the lateral force-displacement
132 response (pushover curve), maximum strain in ED bars, and stress in tendons for SC columns using
133 precast unbonded posttensioned concrete. A three-dimensional FE model for this SC column was
134 developed, enabling the reproduction of the hysteretic behavior of this column and evaluation of the
135 effect of ED components on the column's lateral load capacity. Rahmzadeh et al. (2018) proposed an
136 FE model capable of predicting the reduction in SC capacity and decrease in lateral load and
137 deformation capacity in steel SC columns owing to local buckling at the base, and demonstrated the
138 usefulness of base plates at the rocking interface and axial ED components. Furthermore, an array of
139 studies have been conducted including shaking table test investigations of frame structures
140 comprising multiple SC columns (Cheng 2008; Manzo et al. 2022), experiments with large SC
141 column specimens approximately 6 m high (Ou et al. 2010b), and performance evaluations under
142 different loading directions or simultaneous two-direction loading (Marriott et al. 2011; Li et al. 2019;
143 Jia et al. 2020).

144 As described above, considerable knowledge has been accumulated regarding SC columns
145 as an effective structural strategy for enhancing post-earthquake recoverability. SC columns are
146 characterized by their flag-shaped hysteresis loops, which are effective in dissipating seismic energy.
147 However, the ED performance of the flag-shaped loops in SC columns is not as great as the hysteresis
148 loops of conventional RC and steel columns. Fig. 1 compares the equivalent damping ratios of SC
149 columns exhibiting a typical flag-shaped hysteresis loop, as proposed in previous studies, with those
150 of columns featuring spindle-shaped hysteresis loops. The figure demonstrates that the equivalent
151 damping ratio of the SC columns is approximately half that obtained in columns with spindle-shaped
152 hysteresis loops. Thus, despite their high restoration performance, SC columns pose the risk of larger
153 seismic responses than conventional RC or steel columns. Considering the risk of extreme
154 earthquakes in earthquake-prone zones is crucial. Ideally, structures should exhibit superior energy
155 dissipation during extreme earthquakes and high restoration performance. However, SC columns with
156 flag-shaped hysteresis loops pose the risk of significant seismic responses to extreme earthquakes,

157 whereas conventional RC or steel columns with spindle-shaped hysteresis loops exhibit poor
158 restoration performance after earthquakes. Therefore, achieving both high SC column restoration
159 performance and an ED performance similar to that of conventional RC or steel columns remains a
160 challenge.

161 This study proposes a concept to both enhance energy dissipation during an earthquake and
162 provide effective restoration performance. This concept is achieved by exhibiting an SC capacity only
163 during restoration, leading to the proposal of a novel SC column structure. The proposed aseismic
164 column consists of a central component, referred to as the SC core, constructed from steel tubes filled
165 with high-strength mortar, and ED components made from steel plates. The SC core generates a
166 moderate SC force sufficient to counteract the $P-\Delta$ effect. Fig. 2 illustrates the expected behavior of
167 the proposed aseismic column. Given the minimal SC force from the SC core in the proposed structure,
168 the plasticization effect of the ED components becomes more conspicuous during large earthquakes,
169 resulting in the emergence of a spindle-shaped lateral load capacity, leading to residual displacement
170 in the columns. During restoration, the SC force emerges when the ED components are removed. The
171 residual displacements of the columns gradually decrease during this process. Unlike conventional
172 SC columns, which can be immediately usable post-earthquake, the proposed aseismic column
173 exhibits temporary residual displacements, making them less readily restorable compared to SC
174 columns. However, they can diminish seismic response compared to conventional SC columns and
175 exhibit superior restoration performance compared to conventional RC and steel columns. Therefore,
176 this proposed aseismic column offers an effective structural strategy in regions prone to severe
177 seismic activity. It is important to note that if the residual displacement following an earthquake
178 exceeds the radius of the SC core, the line of action of the axial force deviates from the bottom of the
179 SC core, thus negating the SC force, even when the SC core is undamaged. Consequently, the SC
180 core must have an adequate surface area. In the proposed aseismic column, the SC force of the SC
181 core is only required to counteract the $P-\Delta$ effect of the column, eliminating the requirement for PT
182 tendons, which are commonly used in other conventional SC columns. Although PT tendons can be

used to enhance structural stability, the PT force applied to the PT tendons should not be overly significant, to prevent the hysteresis behavior of the column from becoming flag-shaped.

Previous studies on SC columns have primarily focused on evaluating the performance of the SC columns during earthquakes without considering the behavior of SC columns during the detailed removal of ED components. However, in this study, we investigate not only the performance of the columns during seismic events but also their behavior during the removal of ED components. Specifically, cyclic loading tests were conducted on the proposed column prototype, followed by removal tests of the ED component. These removal tests were carried out on the prototype column that had residual displacements while under axial force. Such experiments, removing plasticized members from a column with residual displacement under axial force, have not been previously conducted, representing a significant novel aspect of our study. It should be noted that the concept proposed in this study is adaptable to the majority of previously proposed SC columns by adjusting the required SC force. Thus, the primary objective of this study is to verify the feasibility of emerging SC only during restoration while presenting an exemplary structure that could embody this proposed concept. It is crucial to emphasize that this study does not propose an optimal structure or member-joining method to actualize this concept.

Experimental Protocol

Experimental Specimens

Fig. 3 displays the configuration and dimensional drawing of the specimen. This experiment primarily focused on the restoring force characteristics of the proposed aseismic column and its behavior when the ED elements were removed. Thus, in this experiment, we modeled only the plastic hinge region of the proposed column as an experimental specimen, with the upper segment and footing of the column designed to function as a rigid body.

The SC core of the specimen comprised a 254 mm diameter steel tube (SS400) with a

209 thickness of 8.0 mm filled with non-shrink mortar (with a uniaxial compressive strength of 58.1 MPa).
210 The SC core was individually designed to support axial forces and provide SC to avoid column
211 collapse due to the $P-\Delta$ effect. The SC cores also had shear pins at their bottom to restrict shear
212 displacement. These pins, inserted through the bottom steel component that formed the footing, could
213 prevent shear misalignment without vertical action.

214 U-shaped cross-sectional steel members were selected for the ED components because of
215 their convenience of installation. This design was selected because it resembled a typical box-shaped
216 steel column. Joining U-shaped ED components to create a closed section and incorporating stiffeners
217 are effective methods for improving the seismic performance of a column. However, in this study,
218 the U-shaped ED members were not interconnected and stiffeners were not installed because the focus
219 was on the least seismic-resistant condition. Two varying plate thicknesses (4.5 mm and 6.0 mm)
220 were employed to investigate the restoring force characteristics of the column post-installation of the
221 ED components. The steel grade used for all components, including weldments, was SS400, with
222 square welding executed on both sides through full penetration bevel welding. Table 1 lists the
223 material properties of the steel members. The specification values listed in Table 1 are based on the
224 Japanese Industrial Standard (2020), whereas the other values were obtained from coupon tests.
225 Triangular ribs were installed at the terminations of the ED components to avoid abrupt alterations in
226 the cross section, ensuring that both ends were entirely fixed. Moreover, this specimen is considered
227 a scaled-down experimental model rather than a full-scale one. As the columns are elevated, the
228 bending moments exerted on the ED components vary, necessitating appropriate design adjustments.

229 In practical applications of the proposed structure, high-strength bolted mechanical joints or
230 welded joints can be used to interconnect the SC core and ED components. However, this study did
231 not comprehensively explore the members' joints; instead, it concentrated on the restoring force
232 characteristics of the proposed column and the behaviors during the removal of the ED components
233 for restoration. Therefore, for simplicity, the SC core and ED components were connected using high-
234 strength bolts via tension bonding (Fig. 4).

Experimental Procedure

The sequencing of the experiments is illustrated in Fig 5, while Figs. 6 and 7 depict the lateral loading protocol and setup of the cyclic loading tests. The experiment utilized displacement-based control for lateral loading and force-based control for vertical loading.

Initially, an axial force of 200 kN was exerted on the SC core, followed by a cyclic loading test exclusively on this core (termed as SCC-1-Loading). Subsequently, ED components, each with a plate thickness of 4.5 mm, were installed while the axial force was directed onto the SC core, facilitating lateral cyclic loading (SCC-ED4.5-Loading). Upon completing SCC-ED4.5-Loading, residual displacement was generated to bring the lateral load on the columns to zero, initiating the removal of the ED components (ED4.5-Removal). Post-removal of the ED components, cyclic loading tests were conducted solely on the SC core (SCC-2-Loading) to determine the remaining seismic performance of the SC core. Afterward, ED components with a plate thickness of 6.0 mm were installed, and a cyclic loading test was performed (SCC-ED6.0-Loading). The lateral load capacity evaluation of the specimen during SCC-ED6.0-Loading was limited to a displacement amplitude of 45 mm due to the ED components rupturing at their connections. Thus, SCC-ED6.0-Loading created a situation in which the self-centering capacity of the specimen could be fully evaluated in subsequent removal tests of the ED components. Specifically, a pushover loading test was performed, gradually increasing the displacement amplitude from 50 mm to 80 mm to induce residual displacements in the column. Subsequently, the removal test of the ED component was carried out (ED6.0-Removal). Finally, a cyclic loading test was conducted solely on the SC core (SCC-3-Loading). All experiments were conducted with a vertical axial force of 200 kN applied to the specimens to generate an initial axial compressive stress of approximately 4.0 MPa (3.95 MPa) on the SC core. For the cyclic loading tests exclusively on the SC core (SCC-1-Loading, SCC-2-Loading, and SCC-3-Loading), the reference lateral amplitude (drift) was set to 1/150, the drift value at which the maximum load was exhibited by the specimen on the positive side during the SCC-1-Loading test. A reference lateral amplitude (drift) of 1/300 for SCC-ED4.5-loading and SCC-ED6.0-

loading was selected to investigate, in detail, the behavior of the specimens in regions where the lateral load capacity was linear.

The removal tests of the ED components (ED4.5-Removal and ED6.0-Removal) began with residual displacement in the test specimens. The lateral actuators were operated under displacement control to ensure safety. Nevertheless, the displacement was adjusted to nullify any lateral restoring force that arose on the columns to closely replicate the conditions of the onsite restoration work. A plausible method for removing the ED components is gas cutting. However, in these experiments, the midsections of the ED components were cut using a grinder for simplicity.

Measurement Data

Load cells affixed to both lateral and vertical actuators were used to measure the lateral and vertical loads, respectively. The horizontal displacement was evaluated using a wire-drawn displacement sensor at a point subjected to a lateral load. The vertical displacement was appraised at the position of the vertical force application using an integrated displacement transducer in the vertical actuator.

The strains of the steel tubes in the SC core were measured using strain gauges. Strain gauges were attached to the front and back surfaces of the ED components to determine their curvatures. Multiple points on the steel segment connected to the SC core were equipped with strain gauges to evaluate the axial forces exerted on the SC core. However, owing to missing data, the axial force on the SC core could not be calculated for SCC-ED6.0-Loading. Consequently, evaluations of the axial forces on the SC core were conducted exclusively for the SCC-ED4.5-Loading. Fig. 8 indicates the positions of the strain gauges attached to each component.

Experimental Results

This study defined any displacement that occurred when the actuator pulled the specimen as a positive displacement. For example, the second loading cycle with a displacement of +20 mm is referred to

287 as “+20mm-2”.

288

289 ***Hysteretic Behavior***

290 Fig. 9 (a–c) illustrates the hysteretic responses of the specimens obtained under SCC-1-Loading,
291 SCC-2-Loading, and SCC-3-Loading. These figures illustrate that the SC core in the specimen
292 exhibits the hysteresis behavior characteristic of an SC column, wherein the displacement reverts to
293 zero as the load reaches zero. In addition, the SC force of the SC core is positive relative to the
294 displacement, confirming the adequate SC force to avert column collapse due to the $P-\Delta$ effect.
295 However, the initial stiffness and maximum lateral load of the SC core decreased with each cyclic
296 load test implemented in conjunction with the ED components. Fig. 9 (d) displays the hysteretic
297 responses of the specimen after offsetting the load reduction due to the $P-\Delta$ effect. The magnitude of
298 the $P-\Delta$ effect was calculated by multiplying the axial force with the column drift value. The figure
299 indicates a negligible difference in the maximum load across each experiment, with only the initial
300 stiffness experiencing a reduction. Specifically, the initial stiffness in SCC-1-Loading was 1.75
301 kN/mm, SCC-2-Loading was 0.99 kN/mm, and SCC-3-Loading was 0.90 kN/mm. These results
302 indicate a 48.6% reduction in the initial stiffness over the series of experiments. (The initial stiffness
303 in each experiment was determined using the lateral load values at displacements of ± 5 mm after
304 removing the load reduction due to the $P-\Delta$ effect.) This finding indicates that despite damage to the
305 bottom surface of the SC core and reduction in its initial stiffness due to the cyclic loading tests on
306 the specimen with ED components, the maximum lateral load capacity of the SC core was preserved.

307 Figs. 9 (e) and (f) illustrate the hysteretic responses of the specimens obtained in SCC-
308 ED4.5-Loading and SCC-ED6.0-Loading, respectively. In SCC-ED4.5-Loading, hysteresis loops
309 with residual displacement can be observed, indicating acceptable ED performance. Buckling
310 deformation was visually observed in the ED components on the compression side at a displacement
311 of +20 mm-3. However, the buckling does not lead to a decrease in lateral load, with the peak load
312 achieved at 35 mm-1. Further buckling deformation of the ED components was subsequently

noticeable, yet no abrupt decrease in the lateral load can be observed. It is anticipated that incorporating stiffeners into the ED components and jointing the U-shaped ED components could further enhance the ED performance and delay the buckling of the ED components.

In the case of SCC-ED6.0-Loading, the welds of the ED components fractured at -50 mm-1, causing an abrupt reduction in lateral load. This made it difficult to accurately evaluate the lateral load capacity of a specimen beyond this point. Nevertheless, until the breakage of the welds, the columns exhibit a greater lateral load capacity than the SCC-ED4.5-Loading. Specifically, the maximum load in SCC-ED4.5-Loading was 174.5 kN on the positive side and -177.8 kN on the negative side, whereas the maximum load in SCC-ED4.5-Loading is 240.1 kN on the positive side and -239.4 kN on the negative side. Thus, the seismic performance of a column can be enhanced by altering the thickness of the ED component. However, no significant change was observed in the initial stiffness of the specimen under SCC-ED6.0-Loading compared with SCC254-ED4.5-Loading, despite the expectation that the initial stiffness of the columns would increase with an increase in the thickness of the ED component. These results suggest that damage to the welds of the ED members could have been initiated at small displacement amplitudes, which could have influenced the initial stiffness of the specimen.

329

330 ***Deformation Behavior of ED components***

Fig. 10 displays the calculated curvatures of the ED components at a height of 100mm in SCC-ED4.5-Loading plotted against the lateral displacement of the specimen. The curvature of the ED component was calculated by taking the difference between the strain values obtained from the strain gauges attached to the front and back of the ED component, and dividing by the thickness of the ED component. This indicates a sharp increase in the curvature following a displacement exceeding +10 mm. This trend suggests that although buckling was visually noticeable at a displacement of 20 mm, it is more precise to state that the ED components begin to exhibit signs of buckling at a displacement of approximately 10 mm.

Fig. 11 indicates the deformed shape of the ED components at ± 50 mm-3 in SCC-ED4.5-

Loading. This figure reveals that despite buckling under compression, the ED component exhibit adequate deformation in tension upon reversal of the lateral loading direction. Fig. 12 indicates the height distribution of the strain within the ED component for each displacement amplitude. These strains represent the average values at each height of the strain of the ED component located on the negative side. The graph reveals that in the case of SCC-ED4.5-Loading, the tensile strain progressively increases with the displacement amplitude, even after the buckling of the ED component. This result also suggests that in SCC-ED4.5-Loading, the ED component persists in exerting a tensile force even after buckling. Conversely, in SCC-ED6.0-Loading, the tensile strain that emerged within the ED component is relatively minimal because of the early onset of damage in the weld.

Axial force support by SC core

The relationship between the axial load carried by the SC core and lateral displacement of the specimen in SCC-ED4.5-Loading is displayed in Fig. 13. The axial force was calculated using the strain values of the steel segment connected to the SC core. The figure indicates that when the displacement due to loading exceeds ± 10 mm, an increase in the axial force carried by the SC core is observed. This suggests that the ED components begin to buckle at a displacement of approximately 10 mm, leading to an increased axial force sustained by the SC core. These results imply that the SC core is capable of carrying an axial force even when the ED components buckle. Moreover, the axial force support provided by the SC core enables the ED components to continue exerting a tensile force during the tensile deformation following the occurrence of buckling, which consequently helped mitigate the reduction in the lateral load capacity of the column.

Fig. 14 displays the relationship between the steel tube strain of the SC core at a height of 25 mm and lateral displacement of the specimen derived from SCC-ED4.5-Loading. It should be noted that in the specimen, the axial force was carried by the mortar that was confined by the steel

365 tube. This section focuses on indirectly evaluating the behavior of mortar by observing the strain in
366 the steel tube. The relationship between the vertical strain of the steel tube and lateral displacement
367 reveals that vertical compressive strain on the E- and W-sides of the tube grew after reaching a
368 displacement range of ± 20 mm, a point at which visual buckling of ED components was noticeable.
369 This suggests that the axial compressive force on the mortar containing the steel tube increased after
370 buckling of the ED components. Conversely, no variation in the steel-tube strain was observed when
371 the strain measurement point was located on the tensile side. This observation indicates that the SC
372 core was rocking at the end, with only a minimal amount of vertical tensile force being transferred to
373 the steel tube.

374 The relationship between the circumferential strain of the steel tube and lateral displacement
375 reveals that tensile strain emerged in the circumferential direction of the tube. Notably, the tensile
376 strain increases significantly beyond a displacement amplitude of ± 20 mm. The increase in the
377 circumferential tensile strain within the steel tube is likely a direct consequence of the augmenting
378 compressive force applied to the internal mortar. These observations indicate that as the displacement
379 amplitude increased, the axial compressive force on the mortar confined by the steel tube also
380 increased, thus demonstrating the restraining effect of the steel tube.

381

382 ***Removal test of ED components***

383 The lateral load-displacement relationship during the removal test of the ED components is displayed
384 in Fig. 15. Upon completion of the removal process, residual displacements in ED4.5-Removal
385 decreased from 27.0 mm to 5.9 mm, and in ED6.0-Removal, it reduced from 52 mm to 2.0 mm. These
386 final residual displacement values correspond to 0.39% and 0.13% of the column height, respectively.
387 These results imply that the SC capacity of the specimen emerged as the ED components were
388 removed, demonstrating the actualization of the SC capacity only during restoration.

389 Figs. 16 and 17 display the correspondence between the behavior of the specimen and
390 specific process of removing the ED components in ED4.5-Removal and ED6.0-Removal,

391 respectively. In these experiments, the ED component on the side with residual tensile deformation
392 was initially cut and entirely removed, followed by the cutting of the ED component on the
393 compression side. The sequence for both the tensile and compressive ED components was to first cut
394 the lateral sections (N- and S-sides), followed by the E- or W-side.

395 In ED4.5-Removal, despite the removal of the ED component on the side with the residual
396 tensile deformation, there was no noticeable change in the residual displacement of the specimen (Fig.
397 16 (b), Work 1–6). However, the commencement of the removal of the last face of the ED component
398 on the compression side generated a restoring force that reduced the residual displacement, making
399 SC behavior evident. Specifically, the residual displacement reduced by 20.0% from Works 7 to 8,
400 and further decreased by 53.7% from Works 8 to 9. Finally, at the end of Work 10, the residual
401 displacement was diminished by 78.1%. A similar behavior was observed in ED6.0-Removal (Fig.
402 17), where the residual displacement of the specimen started to decrease upon the removal of the final
403 face of the compression-side ED component. Specifically, the residual displacement was reduced by
404 24.8% from Works 7 to 8, and further decreased by 67.5% from Works 8 to 9. Finally, at the end of
405 Work 10, the residual displacement decreased by 96.2%. A temporary negative restoring force against
406 the column displacement was observed; however, there was no remarkable increase in the residual
407 displacement, signifying the stable SC behavior of the specimens.

408 Fig. 18 illustrates the relationship between the axial force exerted by the SC core and lateral
409 displacement of the specimen during ED4.5-Removal. The figure indicates that as the residual
410 displacement begins to decrease, the borne axial force of the SC core initially decreases before
411 gradually increasing. As indicated in Fig. 19, the removal of the ED component on the tension side
412 led to a decrease in the axial force on the SC core by 77.4 kN, which is equivalent to 38.7% of the
413 external axial force. Subsequently, the axial force on the SC core began to increase when the ED
414 component on the compression side was cut. Finally, the total axial force of 200 kN on the specimen
415 was transferred to the SC core.

416 In conclusion, the results of a series of ED-component removal tests replicating post-

earthquake restoration work demonstrated the feasibility of the proposed concept, in which the SC capacity is exhibited only during restoration.

Considerations for application to full-scale columns

The specimen utilized in cyclic loading tests is not full-scale but a scaled-down experimental model. This chapter offers examples of how this specimen's SC core and ED components can be applied to a full-scale column. Specifically, a simplified approach for evaluating the SC capacity of the SC core and for calculating the ultimate flexural strength of the column is described. Finally, examples of the application of the proposed aseismic column to a bridge pier are presented.

Method for evaluating the self-centering capacity of SC core

When designing the proposed aseismic columns for seismic performance, it is necessary to calculate the limit drift at which the SC core can perform its SC capacity. Essentially, as long as the position of the axial force loading is located within the bottom of the SC core, the SC core will exhibit a self-centering capacity when the ED components are removed (Fig. 20). Consequently, the limit drift at which the SC capacity is activated can be calculated using the following equation.

$$\theta_{csl} = D_{cs}/2H \quad (1)$$

where θ_{csl} is the limit drift at which the SC core can perform its SC capacity, D_{cs} is the diameter of SC core, and H is the column height. Applying Eq. (1) to the experimental specimen results in $\theta = 8.43\%$. Considering the shape of the lateral load-displacement relationship exhibited by the SC cores in a series of experiments, it is inferred that the positive lateral load is sustained up to $\theta_{csl} = 8.43\%$ (Fig. 20). Therefore, Eq. (1) is a valid method for calculating the limit drift at which the SC capacity of SC core can be demonstrated. It is noted that accurately calculating the residual drift following earthquakes at the time of seismic design is challenging. Therefore, in applying the proposed aseismic columns to real-life structures, it is prudent to adopt a conservative design approach by ensuring the ultimate drift of the columns remains below the limit drift as calculated from Eq. (1).

443

444 ***Method for evaluating the ultimate flexural strength of the proposed aseismic column***

445 This section describes the method for evaluating the ultimate flexural strength of the proposed
 446 aseismic column. It is essential to clarify that this section aims not to introduce a numerical model
 447 for the aseismic column. Instead, the aim is to simplify the resistance mechanism of the column and
 448 provide a conservative estimate of its ultimate flexural strength.

449 As illustrated in Fig. 21, the SC core is assumed to support the axial force at the compression
 450 edge during ultimate drift. Additionally, the resisting force of the ED component on the compression
 451 side is disregarded. Consequently, the ultimate flexural strength of the proposed aseismic column can
 452 be calculated by using the compression edge of the SC core as the fulcrum and considering the
 453 resisting moment generated by the ED component on the tension side.

$$454 \quad P_u \cdot H_{cf} = \int_{\frac{D_s}{2}}^{L-t} \sigma \cdot (2t) \cdot x \, dx + \int_{L-t}^L \sigma \cdot D_{ed} \cdot x \, dx \quad (2)$$

$$455 \quad L = (D_{ed} + D_{cs})/2 \quad (3)$$

456 where P_u is the ultimate flexural strength of the proposed aseismic column, H_{cf} is the distance from
 457 column base to point of contraflexure, σ is the stress of ED component on the tension side, t is the
 458 thickness of ED component, D_{ed} is the cross-sectional height of ED component, x is the distance of
 459 the compression edge of SC core. For the sake of simplicity, the strain and curvature of the ED
 460 component on the tension side are assumed to be uniform along its height as follows:

$$461 \quad \varepsilon_{ed} = L \cdot \theta_u / H_{ed} \quad (4)$$

462 where θ_u is the ultimate drift and H_{ed} is the height of ED component. Upon applying the equations
 463 above to the experimental specimens, the calculated ultimate flexural strength was found to be 164.4
 464 kN for SCC-ED4.5-Loading and 219.0 kN for SCC-ED6.0-Loading (Fig. 21). These calculated
 465 values generally agree well with the experimental results. Therefore, Eqs. (2-4) that simplify the
 466 resistance mechanism provide a reasonable evaluation for estimating the ultimate flexural strength of
 467 the proposed aseismic column. Given that the evaluation method discussed in this section is simplified,

it is recommended that a more detailed investigation with a numerical model should be conducted based on this method, especially when applying the proposed aseismic column to real-life structures.

Example of application to full-scale columns

This section presents examples of applying the proposed aseismic column to a bridge pier. Table 2 details the specifications of the full-scale column used for reference. The column and cross-sectional heights of the full-scale bridge pier were 12180 mm and 2400 mm, respectively, based on the concrete-filled rectangular steel tube pier (CFT-R-pier) cited in the reference on seismic retrofitting of existing road bridges (Japan Road Association, 2003). The ED component's thickness was set to 36 mm, consistent with the steel tube thickness used in CFT-R-pier. For the designed bridge pier, the maximum required drift was set at 4%. The diameter of the SD core was then calculated to ensure that the limit drift of the SC core, derived from Eq. (1), would align with the maximum drift. This means the minimum SC core diameter necessary to retain the self-centering capacity during restoration was selected. The height of the ED component was determined using Eq. (4) to ensure its strain did not exceed 3% at maximum drift. The Young's modulus of the ED component was established at 206,000 MPa. Yield strength was set at 240 MPa, consistent with the steel used for CFT-R-pier. A fully elastoplastic bilinear model was used as the material constitutive law.

Fig. 22 (a) illustrates the full-scale bridge pier designed under the conditions mentioned above, indicating the column dimensions and the ultimate flexural strength calculated from Eq. (2). According to the figure, the designed full-scale bridge pier's ultimate flexural strength was 4638 kN, approximately 30% lower than that of CFT-R-pier. This suggests that the proposed aseismic column with the minimum SC core diameter might result in a reduced ultimate flexural strength compared to standard concrete-filled rectangular steel pipe piers of similar dimensions. However, increasing the diameter of the SC core to 2171 mm can enhance the ultimate flexural strength of the proposed aseismic column to 6645 kN, matching that of CFT-R-pier (Fig. 22 (b)). Therefore, it is found that an appropriately sized SC core diameter can achieve a flexural strength comparable to that of standard

concrete-filled rectangular steel pipe piers. It is important to note that achieving the same level of flexural strength as conventional rectangular CFT piers with the proposed aseismic column necessitates increasing not only the diameter of the SC core but also the height of the ED component. This is because a larger diameter SC core causes greater deformation in the ED component when the drift reaches its limit value. Consequently, the height of the ED components must be increased to ensure that their strain remains below the limit value.

Moreover, a larger SC core diameter might increase the likelihood of contact between the buckled ED component and the SC core during seismic events. Although such contact does not compromise the column's energy dissipation capacity—by restraining the buckling deformation of the ED component and enhancing its compressive resistance—it may subject the ED component's joints to unexpected impact forces. Therefore, maintaining a suitable gap between the ED component and the SC core is essential to prevent contact during earthquakes. Incidentally, in SCC-ED4.5-Loading, the inward deflection of the ED component was about 23 mm at a displacement amplitude of 50 mm (a drift of 3.3%), which was less than the 50 mm gap between the SC core and the ED component, ensuring no contact occurred during the experiment.

Conclusion

This paper proposed a concept to enhance both energy dissipation during an earthquake and post-earthquake restoration performance. This concept was achieved by exhibiting SC capacity only during the restoration. Cyclic loading tests were conducted on the proposed aseismic column prototype, followed by ED component removal tests with vertical axial forces acting on columns with residual displacements.

In the cyclic loading tests, acceptable performance in terms of energy dissipation in the proposed structure was confirmed by the plasticization effects of the ED components. Moreover, the axial force support provided by the SC core allowed the ED components to maintain their tensile forces, even after buckling. This mitigated the reduction in the lateral load capacity of the column.

520 During the ED component removal tests, removing the plasticized ED elements led to an incremental
521 exertion of the SC force by the SC core. When all the ED components were removed, a significant
522 reduction in the residual displacement of the column was achieved. Specifically, as the final face of
523 the ED component on the compression side was removed, the column exhibited an SC force that
524 reduced the residual displacement by up to 96.2%. This decreased it to 0.13% of the column height.
525 The proposed concept, in which the SC capacity is exhibited only during restoration, achieved
526 superior ED performance during an earthquake and high restoration performance afterward.
527 Furthermore, the experimental results facilitated the presentation of a simplified approach to
528 evaluating the SC capacity of the SC core and calculating the ultimate flexural strength of the column.
529 Finally, examples illustrating the application of the proposed aseismic column to a full-scale bridge
530 pier are provided.

531 The primary goal of this study was to examine the feasibility of the proposed concept while
532 presenting an exemplary structure that could potentially implement this proposed concept. Future
533 studies should examine the optimal sequence for removing the ED components, investigate more
534 efficient materials, and consider specific structural components to propose an optimal structure for
535 actualizing the proposed concept. Additionally, numerical studies to confirm the reliability of the
536 proposed concept and macro models to simplify the modeling of the proposed structure are also
537 necessary for future studies. Furthermore, while it is theoretically feasible to implement the proposed
538 concept even with ED components installed at the top and bottom ends of columns, the stability of
539 self-centering behavior during the removal of the ED component at both ends of the column remains
540 underexplored. Experimental studies are necessary to demonstrate that a stable self-centering capacity
541 only during restoration can be maintained, even with ED components at both ends of the column.

542

543 **Data Availability Statement**

544 All data that support the findings of this study are available from the corresponding author upon
545 reasonable request.

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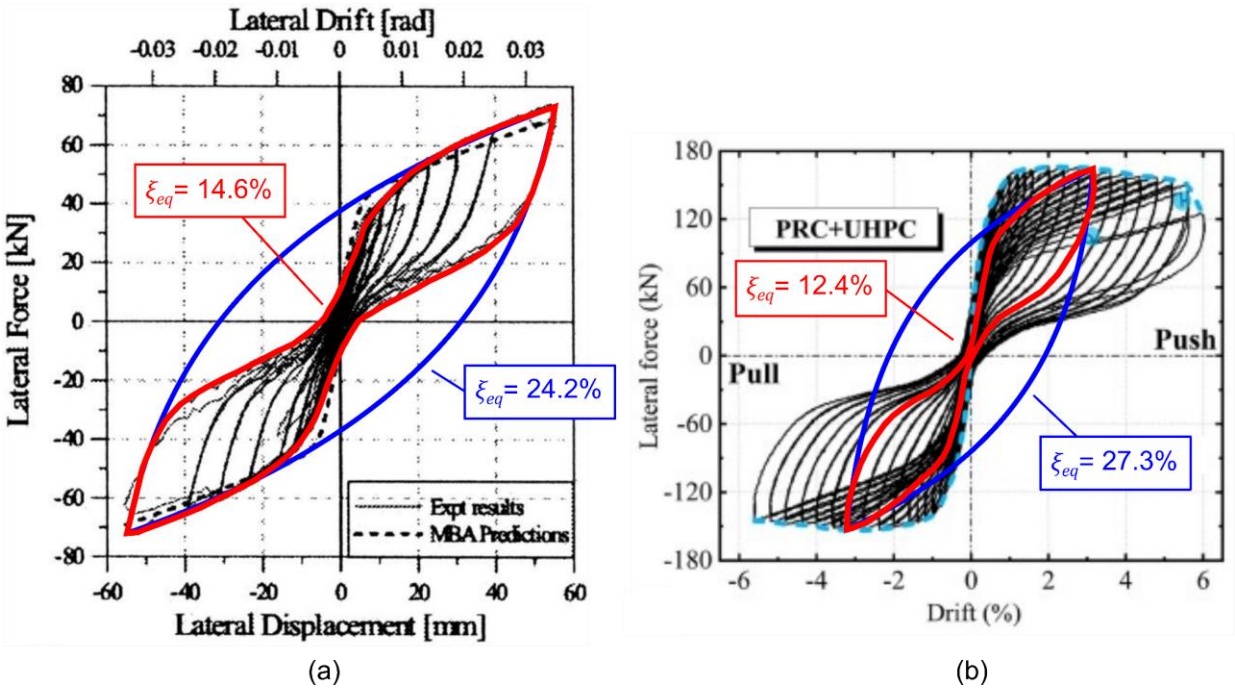
Tables and Figures

Table 1. Material properties of steel members (* specification values based on the Japanese Industrial Standard (2020)).

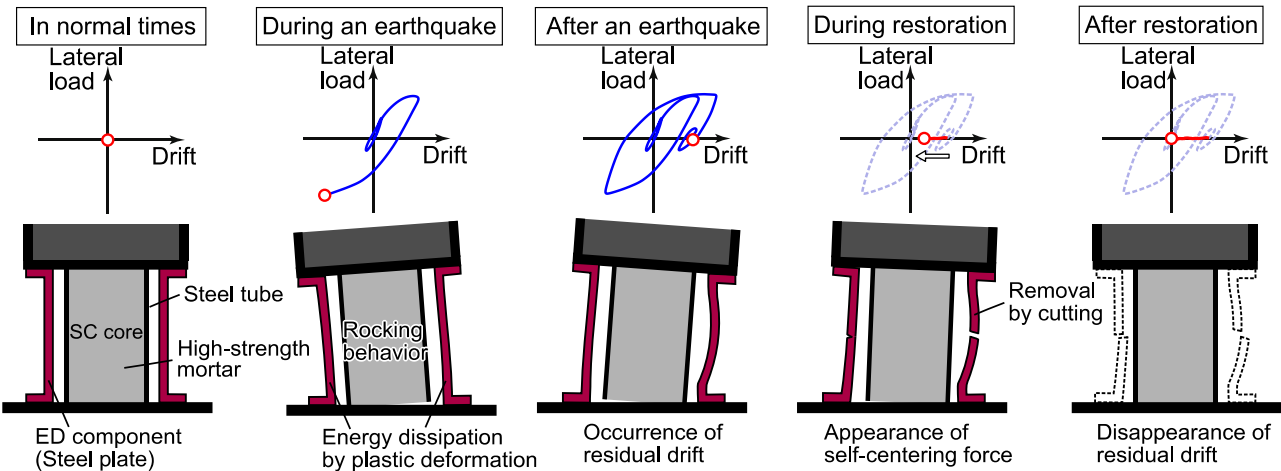
	ED component		Steel pipe of SC core	Upper and Lower segment, Steel segment for axial force measurement
	Thickness: 4.5mm	Thickness: 6.0mm		
Steel Grade	SS400	SS400	SS400	SS400
Yield strength (MPa)	309	309	245 or higher*	235 or higher*
Tensile strength (MPa)	451	436	400-510*	400-510*
Young’s modulus (GPa)	206*	206*	206*	206*
Elongation at Break (%)	42	27	17 or higher	21 or higher

695 **Table 2.** Specifications of full-scale bridge pier used for reference.

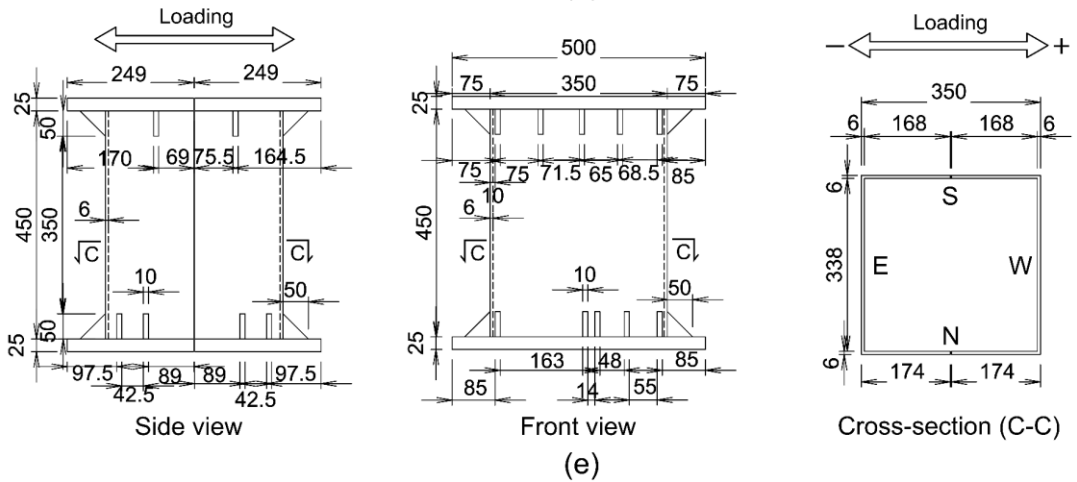
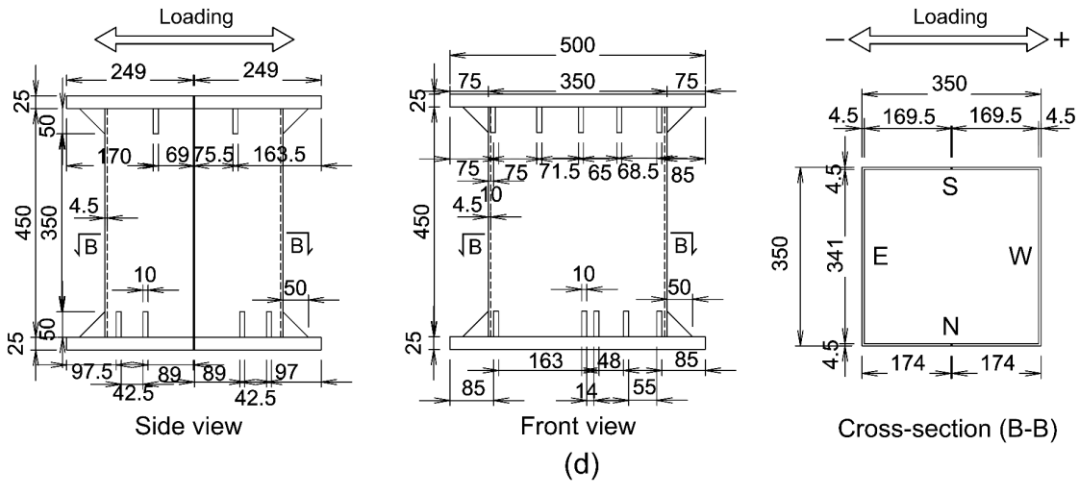
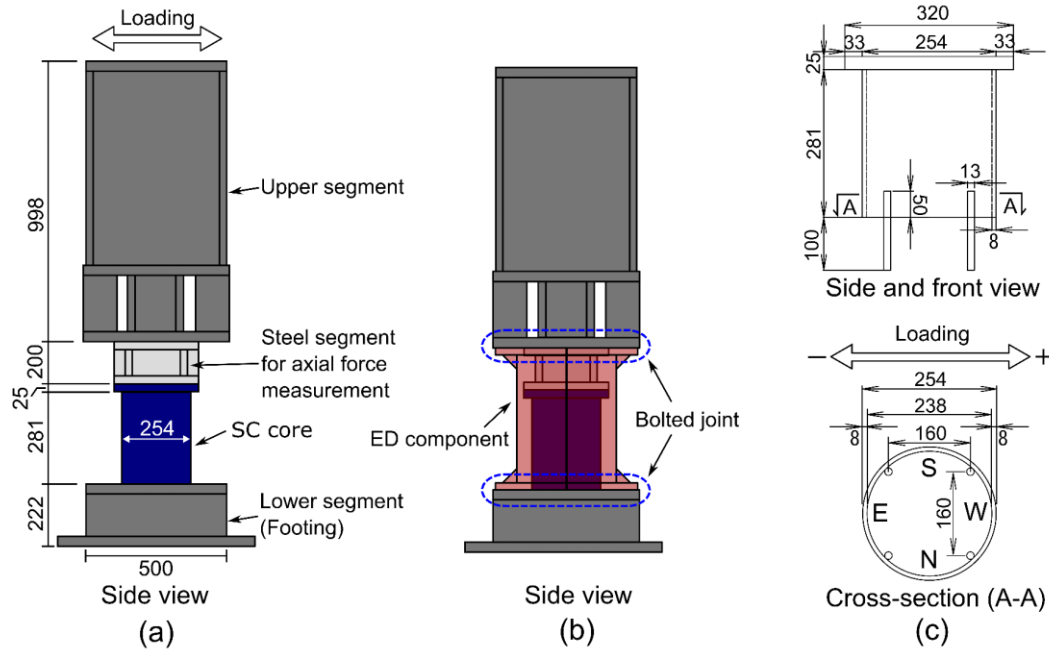
Reference	Column type	Column height	Cross-sectional height	Steel member		Ultimate flexural strength
				Thickness	Yield strength	
CFT-R-pier (JRA 2003)	Concrete-filled rectangular steel tube pier	12180 mm	2400 mm	36 mm (steel tube)	240 MPa (steel tube)	6645 kN



699 **Fig. 1.** Equivalent damping ratio ξ_{eq} for SC columns at approximate drift ratio of 3%: (a) Palermo et
700 al. (2007); (b) Shen et al. (2022).



703 **Fig. 2.** Expected behavior of proposed aseismic column.



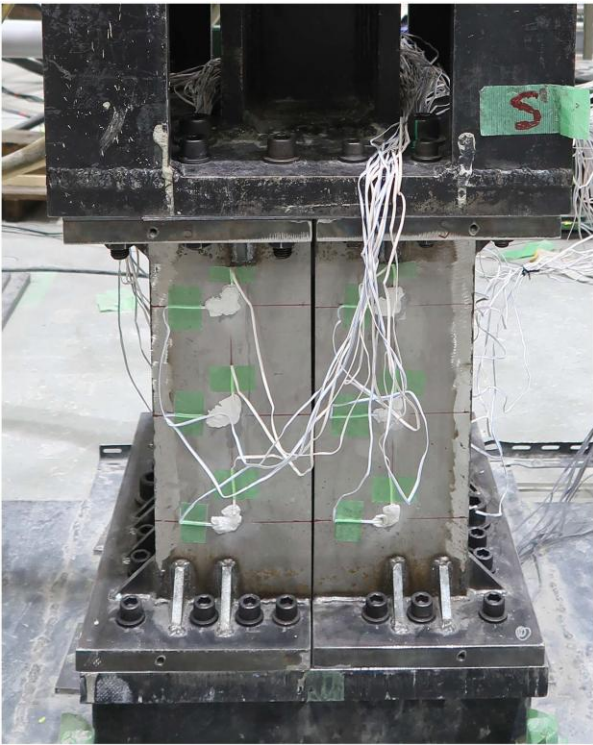
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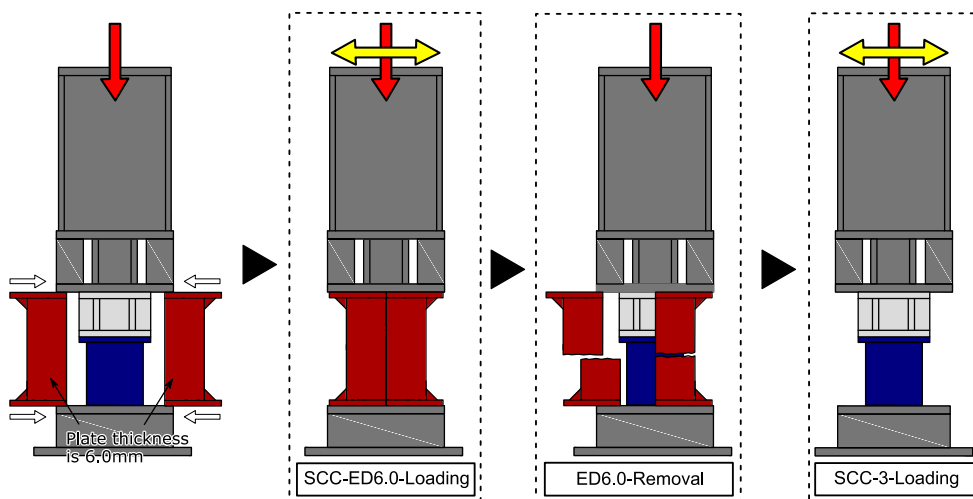
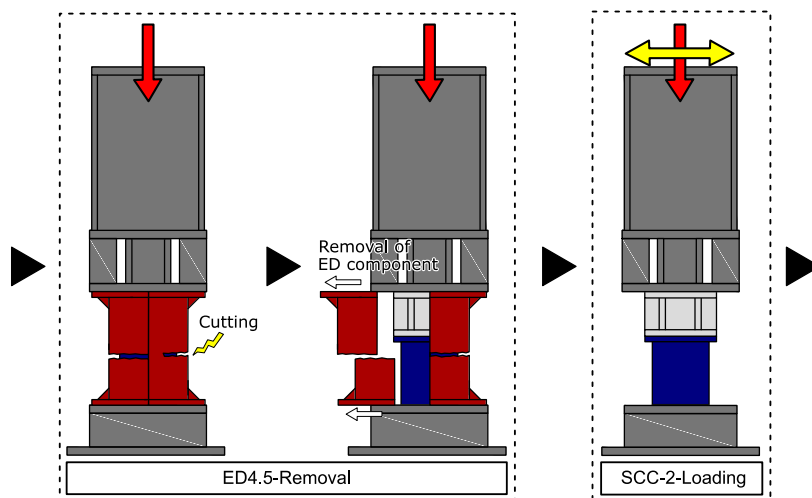
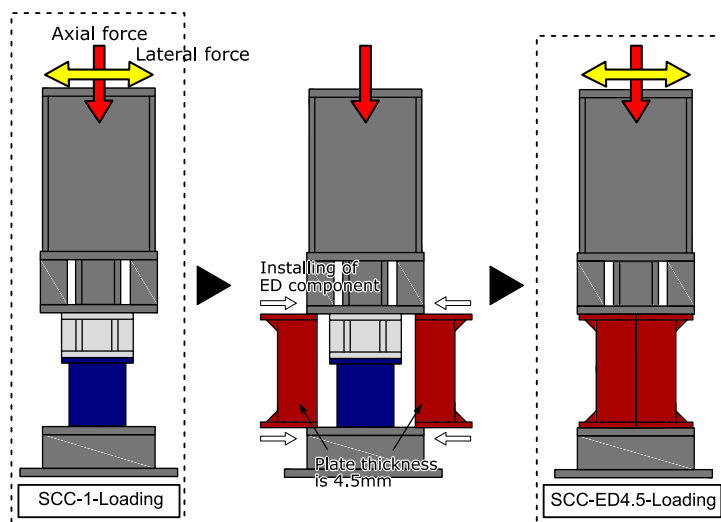
Fig.3. Configuration and dimensional drawing of specimen (dimensions in mm): (a) specimen without ED components; (b) specimen with ED components; (c) SC core; (d) ED component with plate thickness of 4.5mm; and (e) ED component with plate thickness of 6.0mm.



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709 **Fig. 4.** View of ED components connection.

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711

712 **Fig. 5.** Sequencing of experiments.

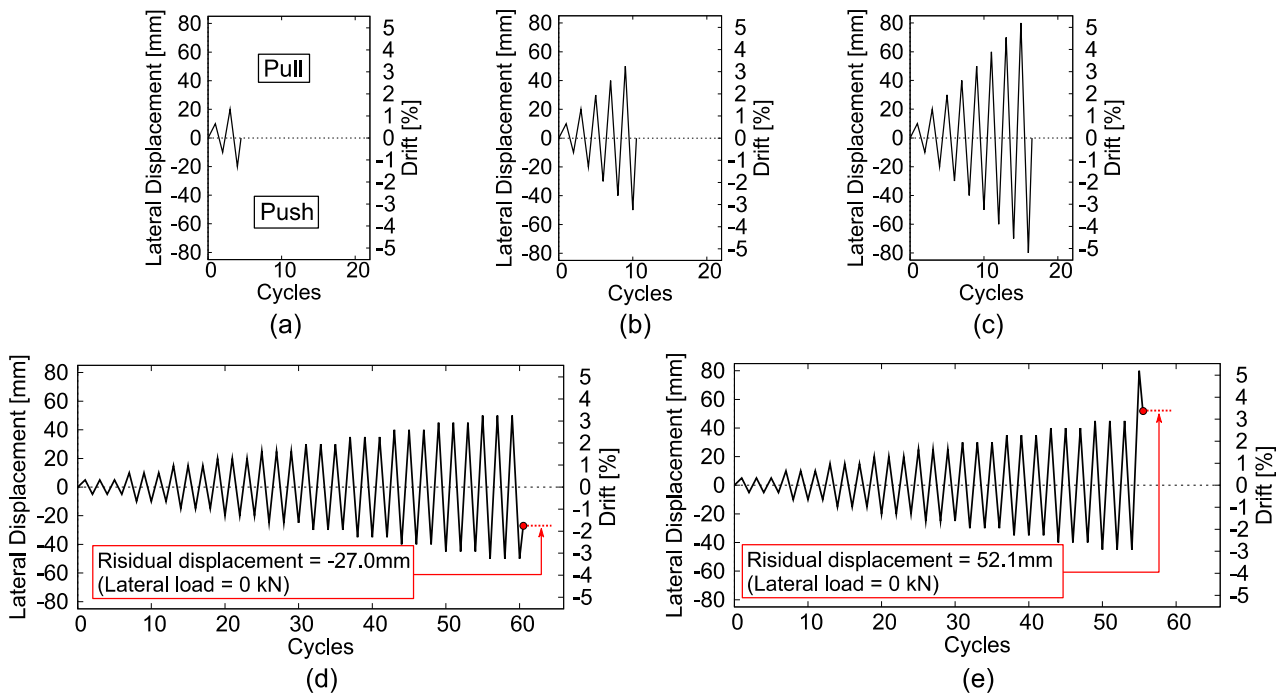


Fig. 6. Lateral loading protocol: (a) SCC-1-Loading; (b) SCC-2-Loading; (c) SCC-3-Loading; (d) SCC-ED4.5-Loading; and (e) SCC-ED6.0-Loading.

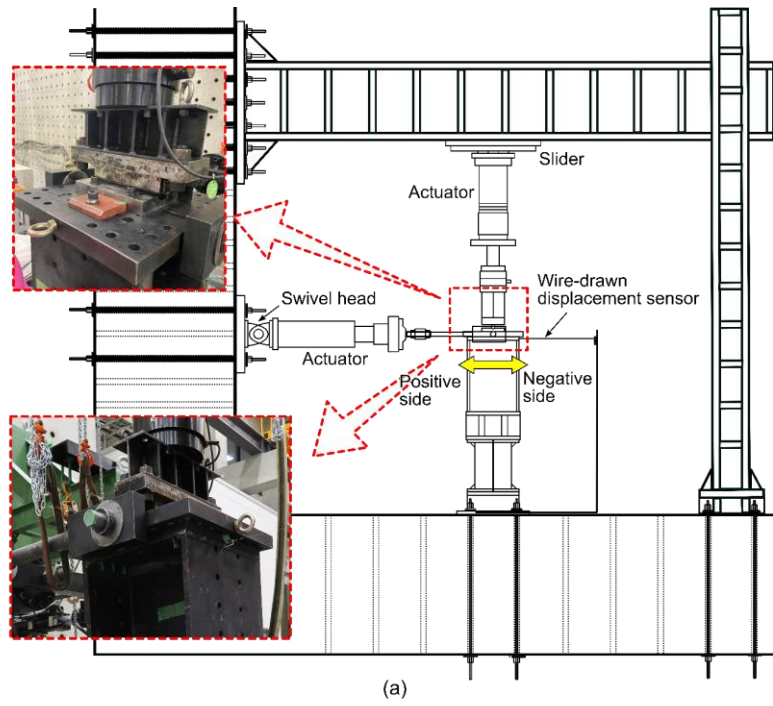


Fig. 7. Experimental setup: (a) schematic view; and (b) actual images.

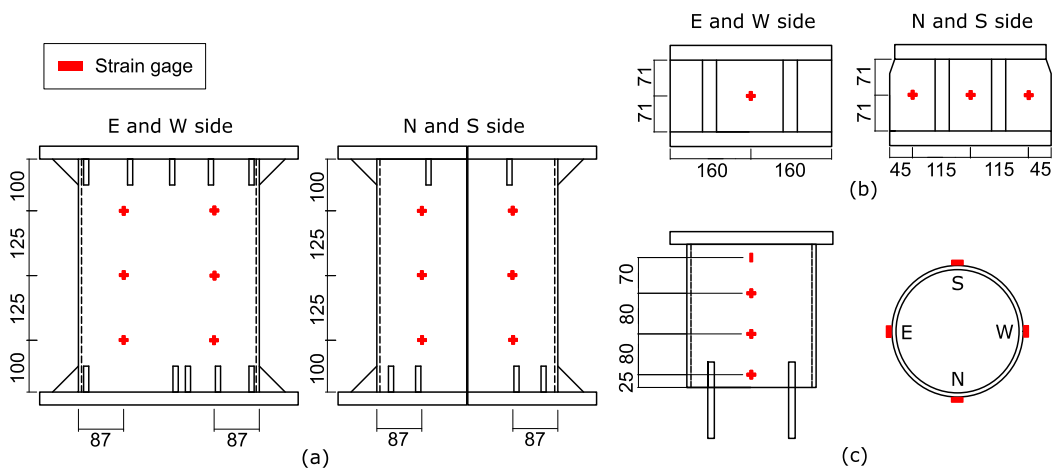
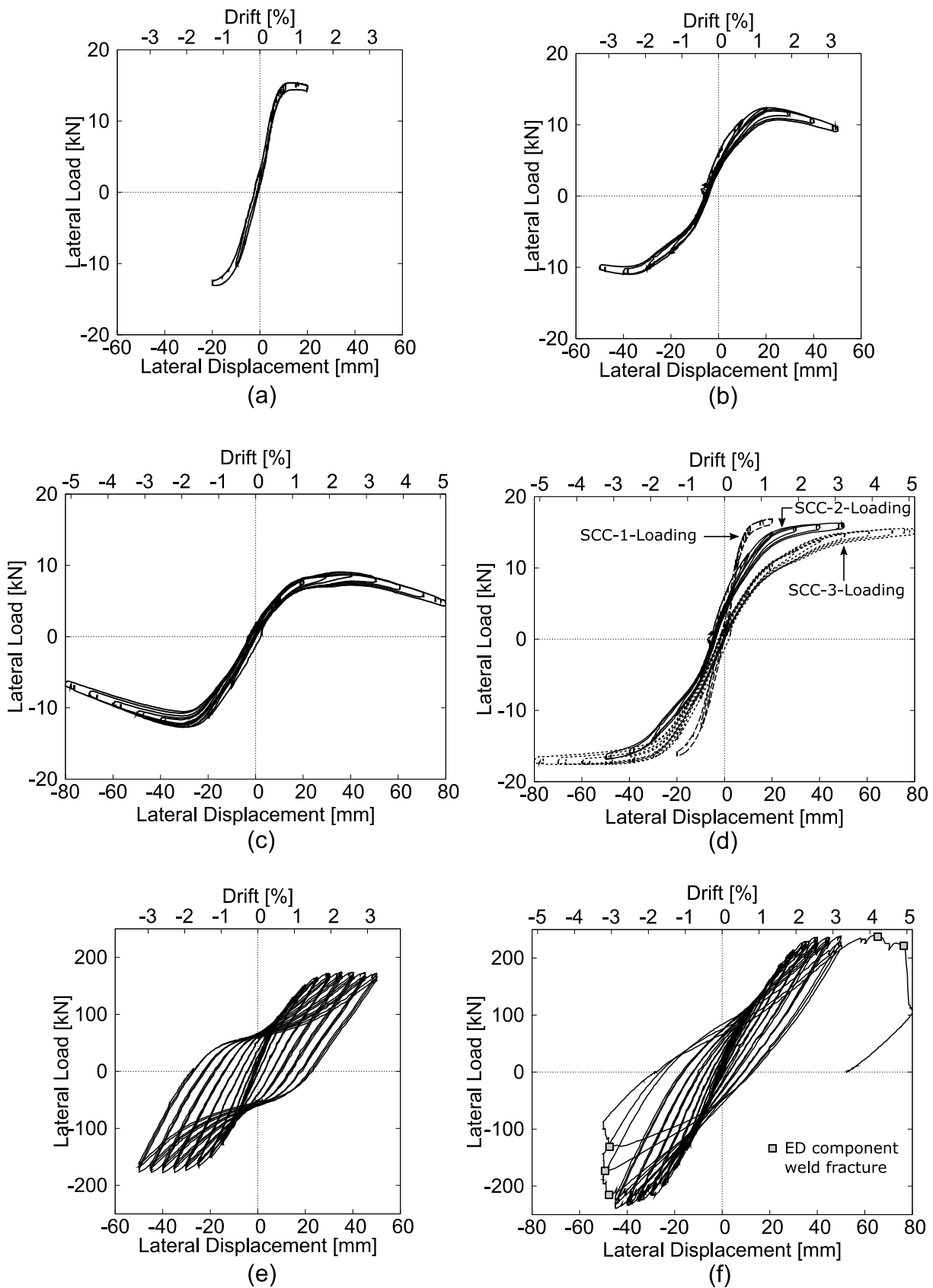


Fig.8. Location of strain gauges attached to each component (dimensions in mm): (a) ED components; (b) steel segment for axial force measurement; and (c) SC core.



721

722 **Fig. 9.** Hysteretic responses of specimen: (a) in SCC-1-Loading; (b) in SCC-2-Loading; (c) in SCC-
 723 3-Loading; (d) without $P-\Delta$ effect in SCC-1-Loading, SCC-2-Loading, and SCC-3-Loading; (e) in
 724 SCC-ED4.5-Loading; and (f) in SCC-ED6.0-Loading.

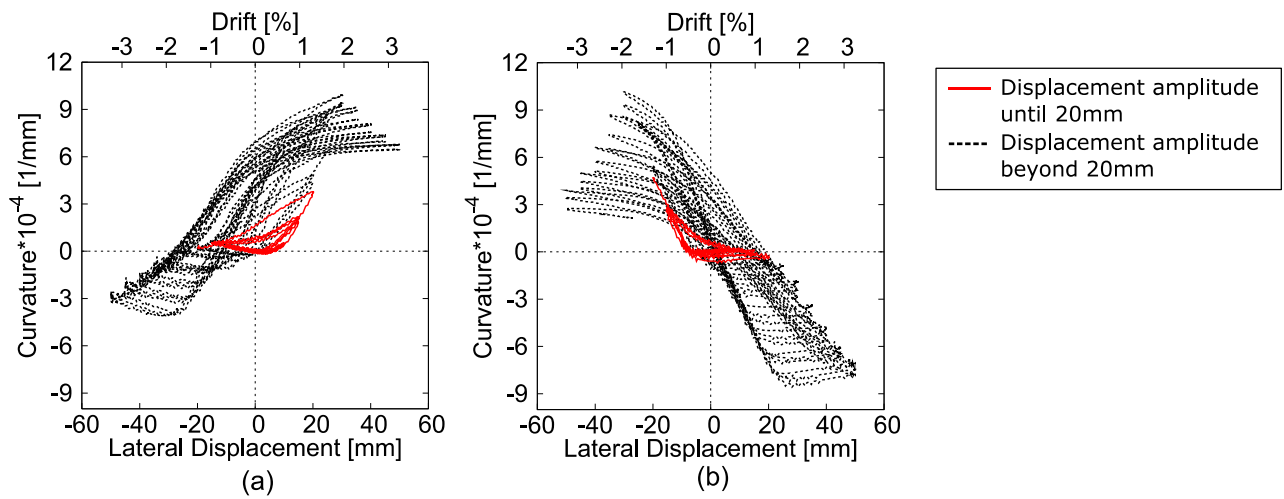


Fig. 10. Relationship between curvature of ED components at height of 100mm and lateral displacement of the specimen in SCC-ED4.5-Loading: (a) positive side; and (b) negative side.

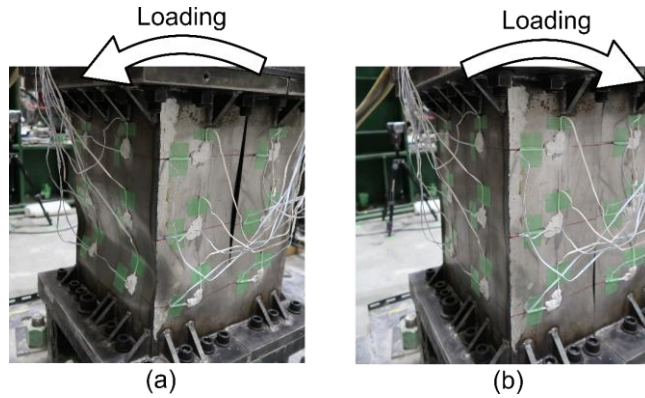


Fig. 11. Deformed shape of ED components at ± 50 mm-3 in SCC-ED4.5-Loading: (a) during compressive deformation; and (b) during tensile deformation.

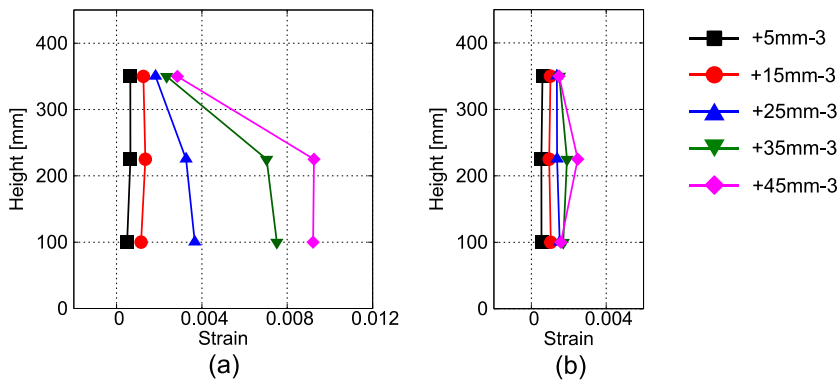
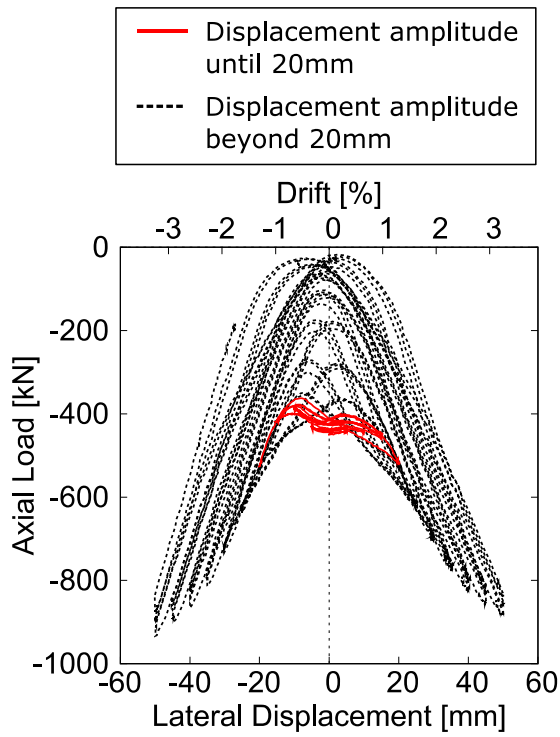


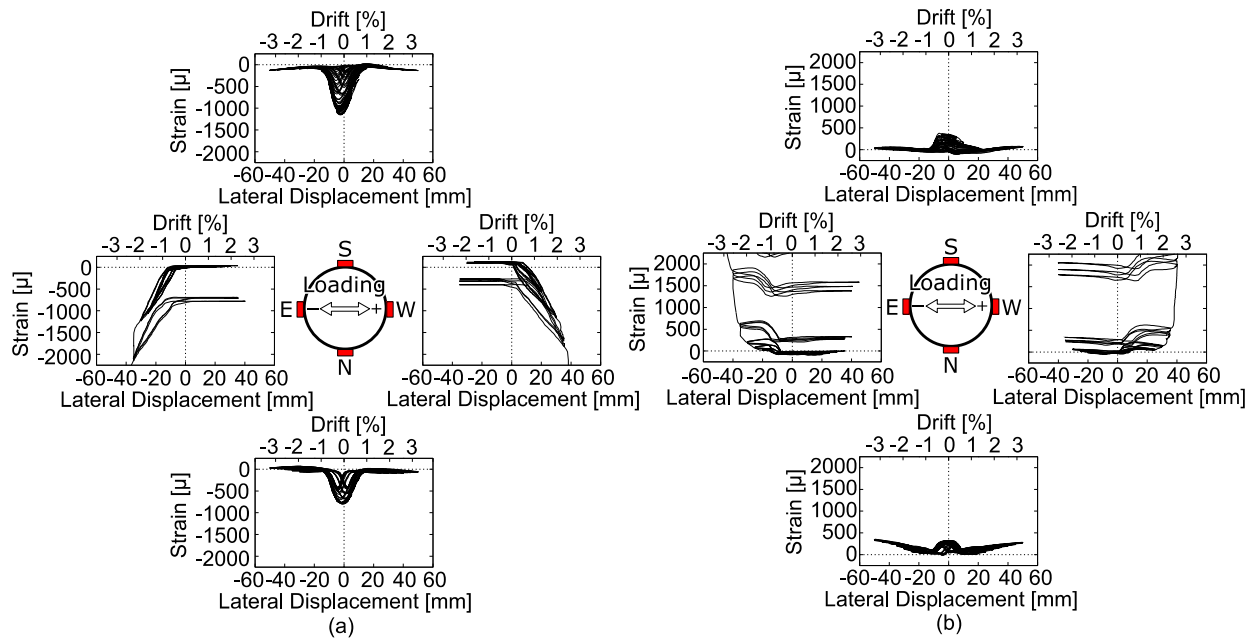
Fig. 12. Height distribution of strain within ED components: (a) in SCC-ED4.5-Loading; and (b) in SCC-ED6.0-Loading.



736

737 **Fig. 13.** Relationship between axial load carried by SC core and lateral displacement of specimen
 738 in SCC-ED4.5-Loading.

739



740

741 **Fig. 14.** Relationship between steel tube strain of SC core at height of 25mm and lateral displacement
 742 of specimen in SCC-ED4.5-Loading: (a) axial strain; and (b) circumferential strain.

743

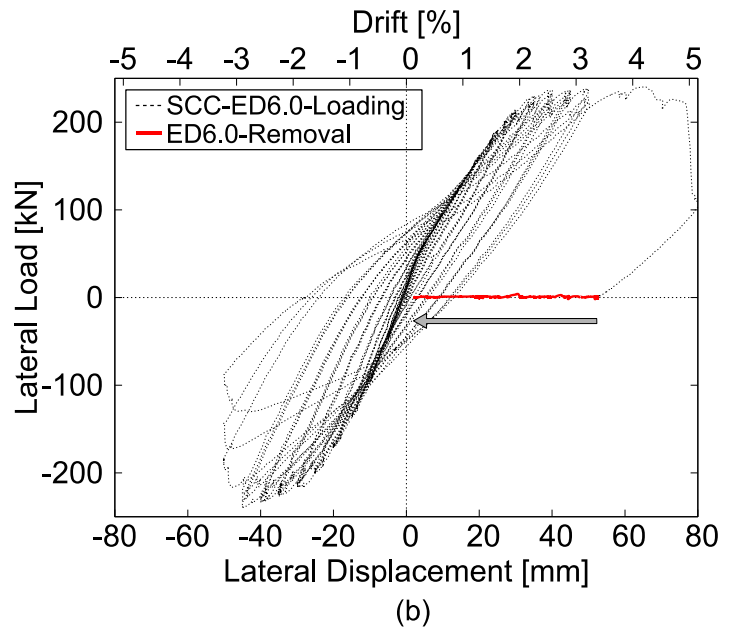
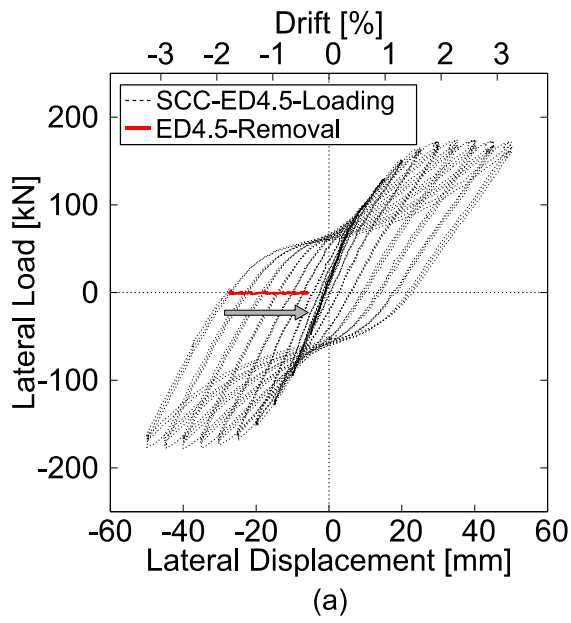


Fig. 15. Lateral load-displacement relationship during removal of ED component: (a) in ED4.5-Removal; and (b) in ED6.0-Removal.

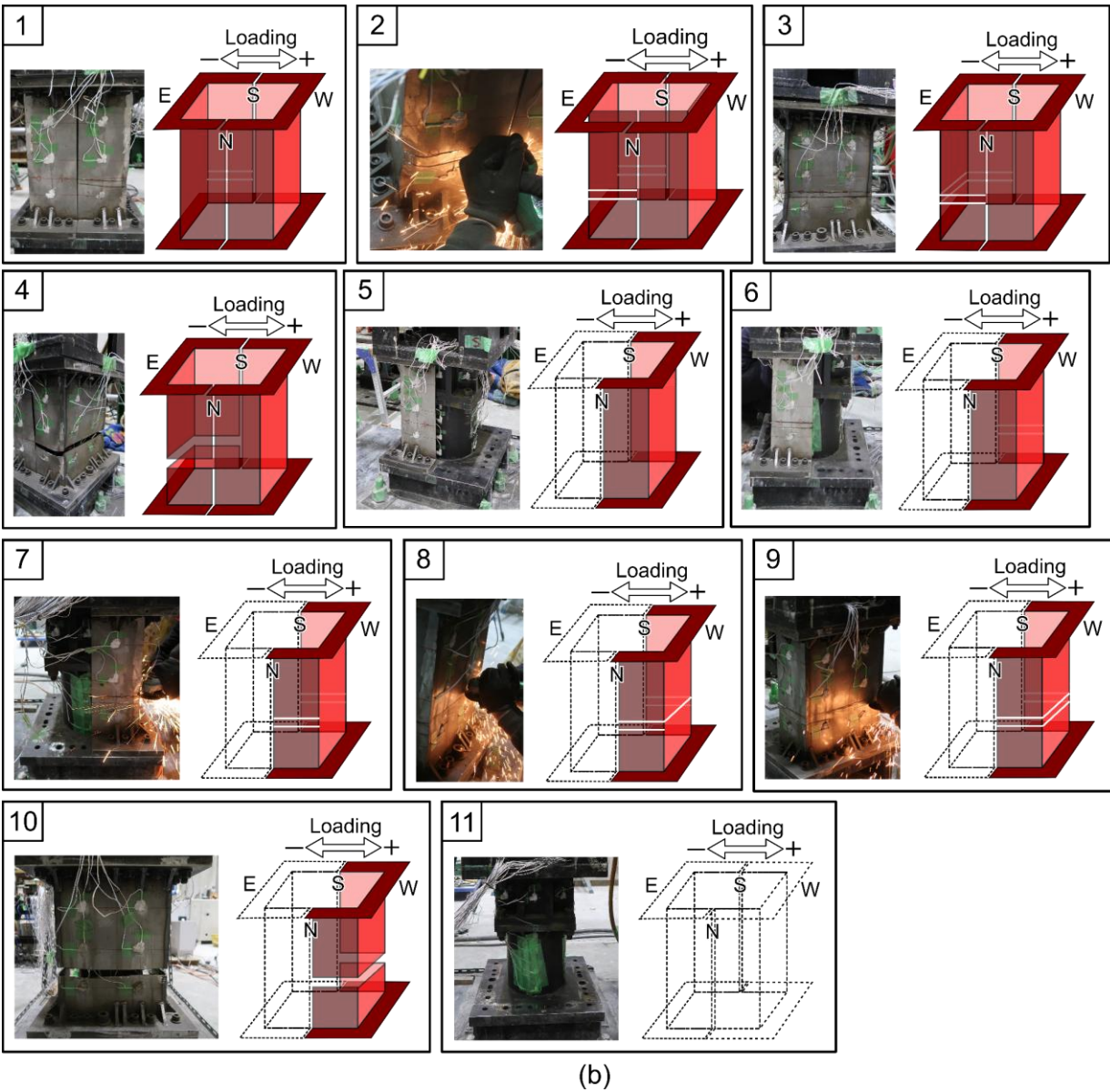
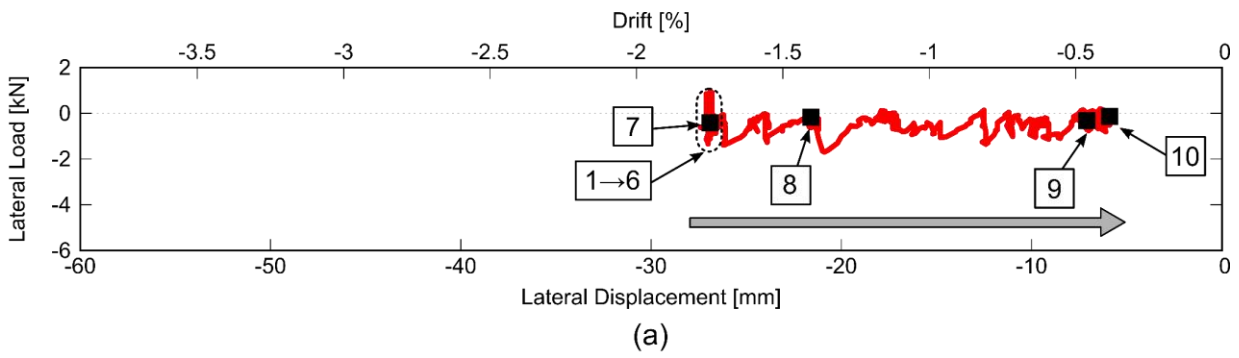


Fig. 16. Correspondence between specimen behavior and specific process of removing ED components in ED4.5-Removal: (a) lateral load-displacement relationship; and (b) specific process of removing ED components.

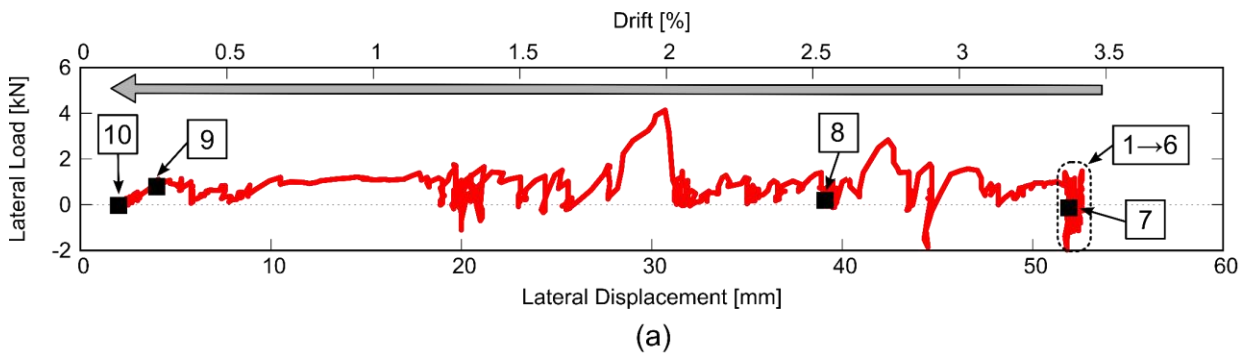
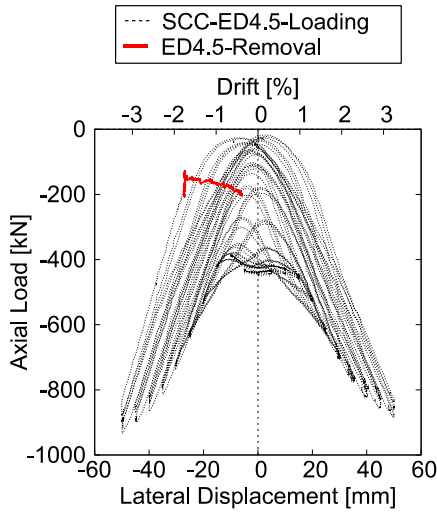


Fig.

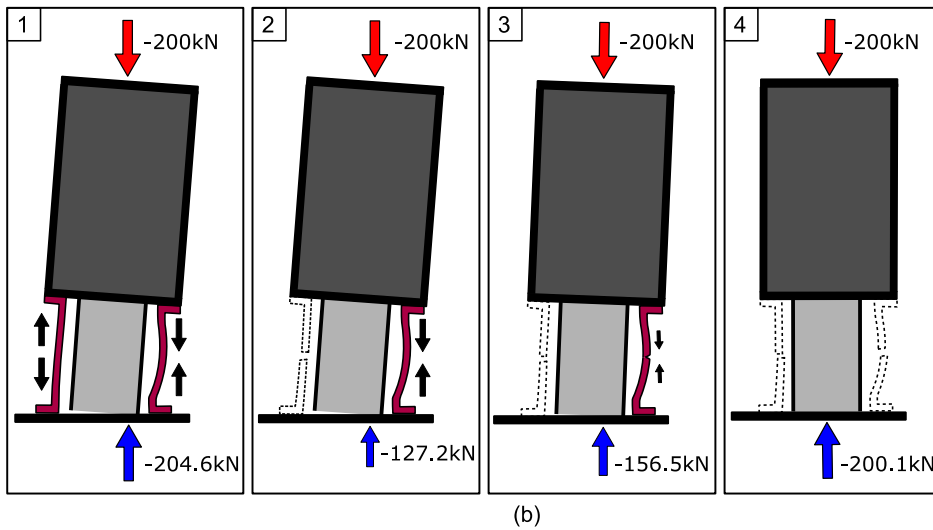
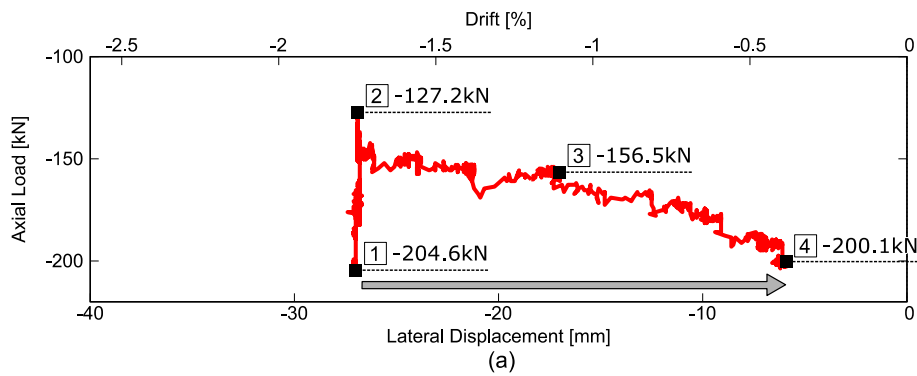
17. Correspondence between specimen behavior and specific process of removing ED components in ED6.0-Removal: (a) lateral load-displacement relationship; and (b) specific process of removing ED components.



758

759 **Fig. 18.** Relationship between axial force carried by SC core and lateral displacement during ED4.5-
760 Removal.

761



762

763 **Fig. 19.** Correspondence between axial force carried by SC core and process of removing ED
764 components in ED4.5-Removal: (a) relationship between axial force carried by SC core and lateral
765 displacement of specimen; and (b) process of removal of ED components.

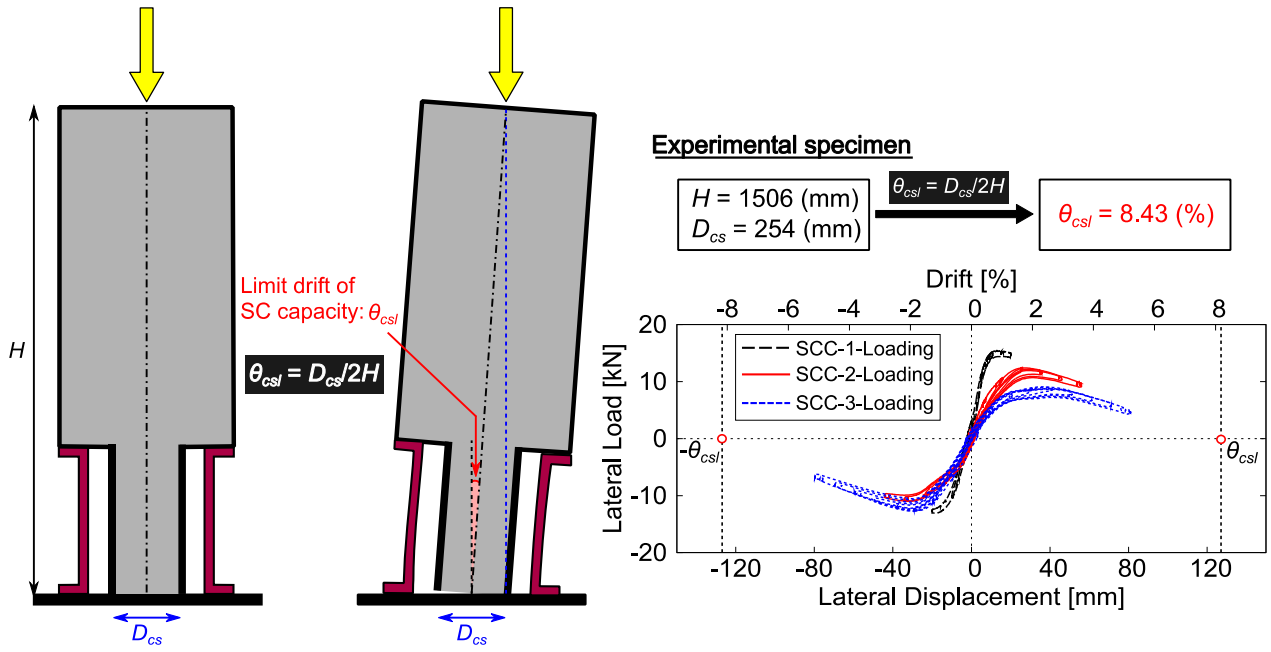


Fig. 20. Evaluation of limit drift of SC core indicating SC capacity.

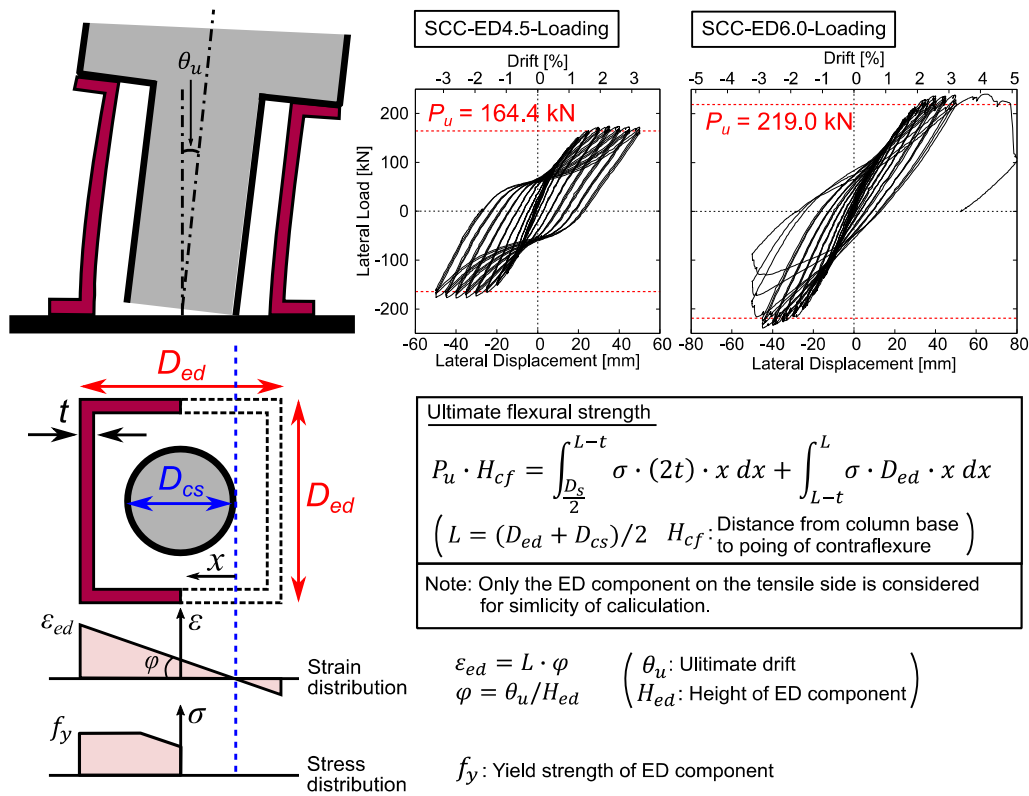
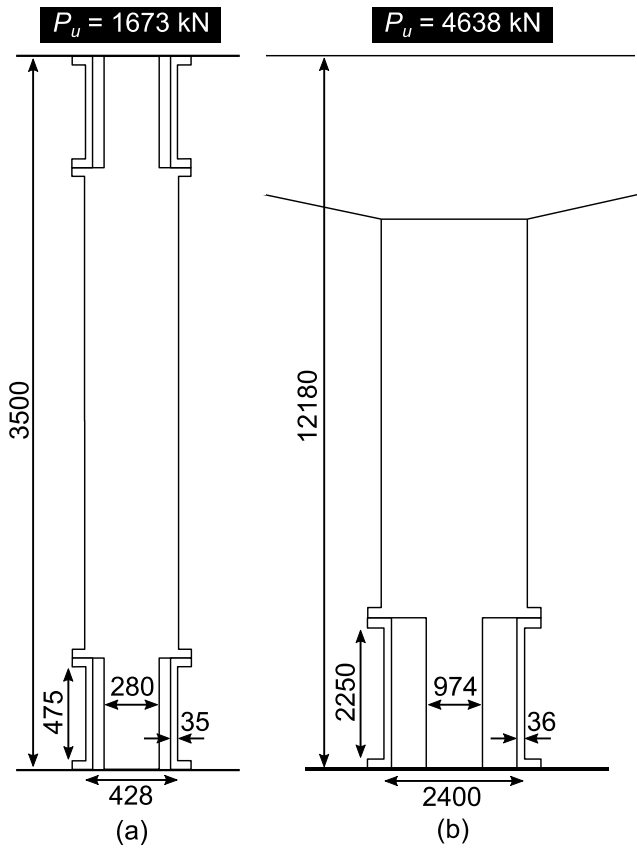


Fig. 21. Evaluation of ultimate flexural strength of proposed aseismic column.



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Fig. 22. Examples of applying the proposed aseismic column to full-scale bridge pier (Unit: mm):
 (a) design with a minimum SC core; and (b) design matching the flexural strength of CFT-R-pier.