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33 INTRODUCTION

34 Disproportionate collapse is defined as the final collapse of a building is disproportionate to the
35 initial local damage due to the development of local damage in a domino manner (Ellingwood
36 2006). Catastrophes occasionally occurred in the past decades, such as the recently collapse of a
37 12-story residential building in Miami on June 24, 2021. It is realized that the partial loss of load
38 resistance in the ground column due to foundation settlement or reinforcement corrosion is the
39 possible causes. Partial or entire loss of the load resistance of the column can also be caused by
40 many other threats such as vehicle impact, terrorist attack, gas explosion, extreme environment,
41 construction mistake, and so on.

42 In the existing design guidelines for disproportionate collapse (GSA 2013, DoD 2016), both
43 threat-dependent and non-threat dependent design approaches are proposed. The former required
44 to predict the possible abnormal load, which may bring difficulties in practical design. The latter,
45 as known as alternate load path (ALP) approach, assumes hypothetical local damage by the
46 removal of one or several critical vertical load bearing members, but ignores all other potential
47 damage to adjacent structural elements, the non-threat specific nature allows researchers to
48 perform experimental program conveniently.

49 Based on the ALP approach, extensive studies have been carried out to understand the load-
50 resisting mechanisms of RC structures (Sasani et al.2007, Yi et al. 2008, Orton et al. 2009, Su
51 2009, Sheffield et al. 2011, FarhangVesali et al. 2013, Yu and Tan 2013 a, Yu and Tan 2013b, Pham
52 and Tan 2014, Yu et al. 2014, Xiao et al. 2015, Qian et al. 2017, Peng et al. 2018, Ma et al. 2020;

53 Deng et al. 2020, Yu et al. 2020, Zhou et al. 2021) and precast concrete structures (Nimse et al.
54 2014, Qian and Li 2019, Zhou et al. 2019, Qian et al. 2021). The Vierendeel action was found to
55 be a viable load-resisting mechanism to resist disproportionate collapse from a test on an actual
56 10-story RC building (Sasani et al. 2007). Compressive arch action (CAA) and tensile catenary
57 action (TCA) developed in beams were also investigated extensively (FarhangVesali et al. 2013,
58 Yu and Tan 2013 b, Deng et al. 2020, Qian et al. 2021). Conversely, the membrane actions
59 developed in RC slabs were relatively insufficient (Pham and Tan 2014, Lu et al. 2017, Yu et al.
60 2020). The mobilization of CAA and TCA corresponds to compressive and tensile axial force
61 developed in RC beams (Yu and Tan 2013a, Yu and Tan 2013b, Su et al. 2009, Vali pour et al.
62 2015, Deng et al. 2020).

63 Currently, few studies on prestressed concrete structures were reported in literature (Keyvani
64 and Sasani 2015, Keyvani and Sasani 2016, Qian et al. 2018, Qian et al. 2019, Tian et al. 2020,
65 Qian et al. 2021, Husain et al. 2021). And also, most of those studies use unbonded posttensioned
66 strands (UPS). They concluded that the UPS was able to enhance structural robustness effectively,
67 while the enhancement was mainly attribute to increased total area of reinforcement regardless of
68 the prestressing magnitude (Husain 2021). The parametric study on profile of the strand shown
69 that straight and parabolic profiles resulted in similar structural resistance but different failure
70 modes (Husain 2021, Qian et al. 2021). Those studies helped the practitioners to understand load-
71 resisting mechanisms of precast concrete structures; but all of them didn't reproduce the actual
72 boundary condition because the boundary of specimens in those tests were simplified by enlarged
73 column to provide sufficient boundary stiffness. The conclusions drawn by studies based on
74 different boundary conditions could be inconsistent.

75 To fill this gap, six specimens consist of four posttensioned concrete (PC) specimens and two
76 RC counterparts were tested to understand the structural behavior of PC frames subjected to

77 various column removal scenarios. Other than the previous tested beam-column sub-assemblies,
78 in this paper, the side columns and joints were reproduced to reflect the boundary condition more
79 realistic.

80 **Experimental Programme**

81 *Specimen Detailing*

82 To explore the behavior of posttensioned concrete (PC) frames under the column removal
83 scenarios, four PC beam-column sub-assemblies with different strands profiles and boundary
84 conditions were fabricated. The prototype building is a large commercial PC moment-resisting
85 frame, which was designed according to ACI 318-14 (2014). The dead load and live load are taken
86 as 5.5 kPa and 2.0 kPa, respectively. The PC specimens with different strand profiles are designed
87 to have same level of bending moment capacity. The specimens were 1/2 scaled from the prototype
88 frame due to the limitation of Lab. facility capacity. The main details between prototype and scaled
89 models are compared in Table 1. The design variables include the position of column removal
90 (middle or penultimate) and strand profile (straight or parabolic). To quantify the effects of the
91 strands, two additional RC specimens with identical dimension and reinforcement details as the
92 PC specimens were constructed for reference. The detailed characteristics of the specimens are
93 tabulated in Table 2. The naming criterion follows: Specimen PCM-S indicates a PC specimen
94 subjected to Middle column removal, while the strand profile is Straight. Similarly, Specimen
95 PCP-P indicates a PC specimen under a Penultimate column removal, while the strand profile is
96 Parabolic.

97 Fig. 1 shows the design details of specimens under a middle column removal scenario, the
98 specimens include one removed column stub, two side columns, two beams, and two overhanging
99 beams. The clear beam span is 2750 mm. The beam and column cross-section is $250 \times 150 \text{ mm}^2$

100 and $250 \times 250 \text{ mm}^2$, respectively. The beam was reinforced by 2T12 at the bottom and 3T12 at the
101 top, while the curtailment of reinforcement was considered in the design. The transverse
102 reinforcement of R6 with a spacing of 50 mm and R6 with a spacing of 100 mm was installed in
103 the reinforced zone and non-reinforced zone, respectively. T12 and R6 represent deformed rebars
104 with diameters of 12 mm and round rebar with diameter of 6 mm, respectively. Two UPS with 7-
105 wire and nominal diameter of 12.7 mm were installed in parallel with the axis of beam of PCM-S,
106 whereas only one UPS with parabolic profile was installed in PCM-P. The UPS was designed with
107 effective prestress of $0.65 f_{pu}$, where f_{pu} is nominal ultimate strength of the UPS of 1860 MPa. It
108 should be noticed that the RC details of the corresponding specimens subjected to penultimate
109 column removal were identical to those subjected to middle column removal except without the
110 overhanging beam on the right side.

111 ***Material Properties***

112 Based on the compressive concrete test, average cylinder compressive strengths of RCM and
113 RCP were 39 MPa while for PCM-S, PCM-P, PCP-S, and PCP-P were 36 MPa. The properties of
114 reinforcement and strand are listed in Table 3.

115 ***Instrumentation Layout and Test Setup***

116 Fig.2a shows the experimental setup. Figs. 2b and c show the instrumentations layouts. The
117 pin support and horizontal restraints on the top of side columns were applied to simulate contra-
118 flexural points of the side column. As illustrated in Fig. 2, the top of the side columns and the
119 overhanging beams were connected to an A-frame by horizontal rollers. The concentrated load
120 was applied by a hydraulic jack (Item 1 in Fig. 2a). As only planar beam-column sub-assemblies
121 were constructed, to prevent out-of-plane failure, a steel assembly (Item 3 in Fig. 2a) was installed.
122 To simulate axial force applied on the side column, a self-equilibrium system (In Fig. 2b) was

123 designed. To measure the applied concentrated load, a load cell (Item 2 in Fig. 2a) was installed
124 beneath the jack. The horizontal reaction force was measured by several tension/compression load
125 cells (Item 5 in Fig. 2a) and load pin (Item 8 in Fig. 2a). The deflection of the beam and column
126 was measured by a series of linear variable displacement transducers (LVDTs).

127 **Experimental Results**

128 Four PC beam-column sub-assemblies and two RC specimens (for reference) were tested by
129 push-down loading regime. The comparison analysis was conducted to quantify the influences of
130 location of column removal and strand profile on the disproportionate collapse resistance of PC
131 frames. The key results were listed in Table 4 and discussed in the following sections.

132 *Global Performance*

133 *Nonprestressed Specimen RCM*

134 Fig. 3 shows the vertical load resistance versus the vertical removed column displacement
135 (RCD). For RCM, at RCD of 30 mm, the yield load (YL), which was defined as the load when
136 the first yielding start in longitudinal reinforcement, of 42 kN was obtained. Increasing the RCD
137 to 70 mm, the first peak load (FPL) of 53 kN was recorded, which was 126% of that of YL. After
138 FPL, because of concrete crushing, a load softening occurred with the increase of RCD. However,
139 the re-ascending of load resistance was observed when the RCD reached 300 mm due to the
140 mobilization of TCA. At RCD of 320 mm and 370 mm, rebar fracture was observed at the right
141 side of the removed column, causing decrease of the load resistance by 15% and 23%, respectively.
142 When the RCD reached 538mm, the load resistance sharply decreased by 28% due to rebar fracture.
143 As the hydraulic jack reached its stroke capacity, test had to be stopped at RCD of 659 mm. The
144 ultimate load (UL) at this stage was 79 kN.

145 As shown in Fig. 4, the rebar fracture and wide cracks were occurred in the beam end near

146 the removed column (BERC) while the compression zone of BERC suffered severe concrete
147 crushing or spalling. Several penetrating cracks occurred in the beams while few cracks were
148 observed in the joint.

149 *Nonprestressed Specimen RCP*

150 Specimen RCP has identical dimensions and reinforcement details as RCM, but no
151 overhanging beam on the right side. As shown in Fig. 3, the YL of RCP was measured as 40 kN
152 at a displacement of 27 mm. When the RCD further increased to 76 mm, the FPL of 51 kN was
153 recorded, which was 96% of that of RCM. It indicates that the effects of boundary conditions on
154 load resistance of RC frame is inconspicuous at the small deformation stage. The rebar fracture
155 occurred in the beam end near the right side of the removed column at a RCD of 409 mm, but no
156 rebar fracture occurred at the left side. The fracture of rebars resulted in a 28% reduction in the
157 load resistance. The remaining rebars contributed to further development of TCA, resulting in re-
158 raising of the load resisting capacity. Test was stopped when the RCD reached 665 mm, the UL of
159 RCP was measured as 74 kN, which was lower than that of RCM only by 6%.

160 Fig. 5 shows the failure mode of RCP. In general, the failure mode of RCP was similar to
161 RCM but more cracks formed in the right-side column.

162 *PC Specimen PCM-S*

163 Specimen PCM-S has identical details of nonprestressed rebar as RCM, but include two
164 straight UPSs parallel to the beam axis (straight profile). As illustrated in Fig. 3, at a RCD of 30
165 mm, the YL of 68 kN was recorded. When the RCD reached 56 mm, the FPL of 79 kN, which was
166 49% higher than that of RCM, was recorded. When the RCD reached 179 mm, the applied load
167 re-raised due to the involvement of TCA. With further increasing RCD to 463 mm, the load
168 resistance increased again until rebar fracture. The UL of 228kN was measured at a RCD of 614
169 mm, which was 289% of that of RCM. Beyond this point, load resistance dropped sharply due to

170 the bottom strand fractured in the BERC.

171 Fig. 6 gives the failure mode of PCM-S. The fracture of rebars and the partial fracture of the
172 bottom strand was observed in BERC. In the compression zone of the beam ends, severe concrete
173 crushing was observed. A number of small flexural cracks and slight concrete crushing appeared
174 in the side column without significant deformation. The penetrated flexural cracks were distributed
175 along the beams, which indicated that the whole beam section was in tension at the stage of TCA.

176 ***PC Specimen PCP-S***

177 As shown in Fig. 3, at the beginning of the test, the vertical load-RCD relationship of PCP-S
178 is familiar to that of PCM-S. However, due to inadequate axial restraints, TCA in PCP-S could not
179 be fully mobilized. The structural resistance increased gradually when the RCD exceeded 329 mm.
180 The UL of 99 kN was obtained at a RCD of 499 mm. Thus, the UL and deformation capacity of
181 PCP-S were 43% and 81% of those of PCM-S, respectively.

182 Unlike the PCM-S, the failure of PCP-S was governed by the pre-mature flexural-tension
183 failure of the side column due to high lateral tensile load for side column. Thus, no strand was
184 fractured. As shown in Fig. 7, the right-side column was subjected to severe inward deformation
185 accompanied by an enormous number of flexural cracks. The bottom of the beam end near the
186 right-side column was subjected to great compressive force, which resulted in the buckling of the
187 rebar. Moreover, severe flexural/shear failure happened in the beam end near the right-side column.
188 However, no penetrated cracks were formed in the beam, which indicates that majority of the
189 tensile force of the beam was attributed to the strands, rather than the non-prestressed rebars.

190 ***PC Specimen PCM-P***

191 Specimen PCM-P has similar reinforcement details as PCM-S, but only one UPS with
192 parabolic profile was installed. As shown in Fig. 3 and Table 4, increasing the load to 43 kN,
193 yielding was first observed in the BERC at a RCD of 27 mm. When the RCD reached 90 mm, the

194 FPL of 63 kN, which was 119% of that of RCM, was recorded. In conventional design, the
195 parabolic UPS is expected to increase the hogging moment capacity of the beam ends. However,
196 after removal of a column, the direction of bending moment at the beam end near the missing
197 column changes from hogging into sagging. To this end, the parabolic UPS will induce additional
198 sagging moment. In this test, the additional sagging moment led to pre-mature fracture of two
199 bottom rebars at a RCD of 283 mm. The third fracture of the rebar occurred at a RCD of 567 mm,
200 resulting in a 25% reduction in load resistance. When the MDC was further increased to 680 mm,
201 the UL of 154 kN was measured, which was 195% of that of RCM.

202 Fig. 8 gives the failure mode of PCM-P, due to the additional sagging moment induced by
203 parabolic strand, the damage at the BERC was more severe than that of PCM-S. However, damage
204 at the beam end near the side column (BESC) was slighter comparing to PCM-S, which can be
205 explained as the increased hogging moment capacity due to the parabolic UPS.

206 ***PC Specimen PCP-P***

207 As shown in Fig. 3, the variation in trend of the load-displacement curve of PCP-P was similar
208 to that of PCM-P in the test beginning. The FPL of the specimen was measured as 61 kN at a RCD
209 of 66 mm. When the RCD increased to 353 mm, the first rebar fracture was observed in BERC,
210 resulting in the decreasing of the applied load. When RCD was beyond 480 mm, the greater lateral
211 deformation of the right column without overhanging beam slowed down the rise of the load
212 resistance. When RCD increased to 600 mm, the UL of 86 kN was measured, which was 56% of
213 that of PCM-P.

214 Fig. 9 demonstrates the failure mode of PCP-P. Similar to PCP-S, the right-side column was
215 failed by eccentric tension with severe concrete crushing and flexural cracks. However, the main
216 differences were the rebar fracture occurred in the BERC due to the additional sagging bending
217 moment produced by the parabolic strand. Extensive tensile cracks developed over the whole

218 beam span, and some cracks even penetrated the beam cross-sections. Moreover, no shear failure
219 was observed in the beam end due to the parabolic strand increased the compressive zone of the
220 beam end section.

221 *Horizontal Reaction Force*

222 Fig. 10 shows the horizontal reaction force-RCD relationship. The horizontal reaction forces
223 at each side are the summation of the horizontal reactions measured in the tension/compression
224 load cells and load pin (shown in Fig. 2). Table 4 lists the maximum horizontal compressive and
225 tensile reaction force. As shown in Fig. 10a, the maximum compressive reaction force of RCM
226 was -99kN. The maximum compressive reaction forces on the left and right sides of RCP were -
227 81kN and -69 kN, respectively. As shown in Fig. 10b, for PC specimens with the straight UPS,
228 the compressive reaction force was reversed to tensile reaction force at a RCD much earlier than
229 that of specimens with parabolic UPS, indicating that TCA was mobilized earlier in PC specimens
230 with straight UPS.

231 The reaction of each horizontal restraint was denoted in Fig.11, in the small deformation
232 stage, the majority of horizontal reaction was transferred from the bottom of the side column.
233 However, in large deformation stage, the majority of the horizontal reaction force was provided
234 by the overhanging beam. Moreover, the horizontal tension at the overhanging beam was most
235 sensitive to the beam rebar fracture and the failure of the side column. Fig 11d shows the horizontal
236 reaction at the right side of PCP-P, at the large deformation stage, the horizontal tension at the top
237 constraint was greater than that at bottom one, which implicitly indicated that hogging moment
238 still actively developed in the BENS.

239 *Beam and Column Deformation*

240 Fig. 12 illustrates the deformation of the beams in PCM-S and PCP-P. As shown in Fig. 12a,

241 the beams of PCM-S kept straight during the test, which agreed with the chord rotation well. For
242 PCP-P, the deformation of beams was almost symmetric before the first fracture of the rebar at
243 BERC. In the large deformation stage, the beam segment near the BERC experienced larger
244 rotation than that near the BESC.

245 The lateral drift of the right-side column of the specimens was plotted in Fig. 13. As given in
246 this figure, outward movement was measured at the initial stage due to the development of CAA
247 in the beams. It can be found that the specimens with the straight UPS had larger inward movement
248 than the specimens with the parabolic UPS for a given RCD. Due to absence of the overhanging
249 beam, the right-side column of PCP-S and PCP-P experienced large inward movement in large
250 deformation stage.

251 *Strain Gauge Reading*

252 Fig. 14 shows the strain gauge results. As shown in the figure, for Specimen PCM-S, initially,
253 the longitudinal reinforcements experienced compressive strain. The bottom rebar near the
254 removed column yielded first. Thus, plastic hinges were formed at each beam end at the CAA
255 stage. The maximum compressive strain was recorded at the top rebar near the removed column
256 and the bottom rebar near the side column, which agreed with the failure mode (refer to Fig. 6).
257 At the TCA stage, the compressive strain of bottom reinforcement gradually decreased and finally
258 transferred into tensile. At the ultimate load stage, no compressive strain was recorded at either
259 the top or the bottom reinforcement, which indicates that all non-prestressed reinforcements
260 contributed to TCA. In general, the strain gauge reading of PCM-P and PCP-P was similar to that
261 of PCM-S. However, for PCP-S, compressive strain was measured at longitudinal reinforcements
262 even at large deformation stage.

263 *Variation of Prestressing Force in Strands*

264 Fig. 15 illustrates the variation of the prestressing force of strands of the four specimens. As
265 described in the previous section, the effective prestressing force of $0.65 f_{pu}$ (119 kN) was applied
266 in each strand. However, due to the prestressing force loss, the effective prestressing force of PCM-
267 S, PCP-S, PCM-P, and PCP-P was respectively measured as 230 kN, 228 kN, 111 kN, and 111kN,
268 respectively, at the beginning of the test. As shown in Fig. 15a, the strand in PCM-P yielded at a
269 RCD of 520 mm. However, the strand in PCP-P did not yield during the loading process, indicating
270 that the strand was not fully utilized when the loss of a penultimate column was focused on. As
271 shown in Figs. 15b and c, for PCM-S and PCP-S, the prestressing force of the bottom strand was
272 similar to that of top strand. The bottom strand in PCM-S fractured at a RCD of 614 mm, and the
273 maximum prestressing force was measured as 172 kN at this displacement. Moreover, it was found
274 that the fracture of strand was observed before reaching its ultimate strength. This is because the
275 strand was subjected to complex stress during the tests, rather than the pure tensile stress. In
276 general, the fracture of strand occurred at the position with great stress concentration, such as the
277 beam-column interfaces.

278 **Discussion of the Results**

279 *The Effects of the Profile of UPS*

280 As illustrated in Fig. 3 and Table 4, the measured FPL resistance of RCM, PCM-S, PCM-P,
281 RCP, PCP-S, and PCP-P were 53 kN, 79 kN, 63 kN, 51 kN, 77 kN, and 61 kN. Compared to RCM,
282 the FPL of PCM-S and PCM-P was increased by 49% and 19%, respectively. Compared with RCP,
283 the FPL of PCP-S and PCP-P was increased by 51% and 20%, respectively. It was found that both
284 straight and parabolic strand profiles can effectively increase the FPL of RC frames regardless the
285 position of column removal. The UL resistance of RCM, PCM-S, and PCM-P was 79 kN, 228 kN,

286 and 154 kN, respectively. Compared with RCM, the UL resistance of PCM-S and PCM-P was
287 increased by 189% and 95%, respectively. Similarly, compared with RCP, the FPL resistance of
288 PCP-S and PCP-P was increased by 34% and 16%, respectively. It was found that both strand
289 profiles can effectively increase the UL resistance, especially for the specimens subjected to the
290 loss of an interior column scenario.

291 As given in Fig. 3, PC specimens with parabolic UPS achieved greater deformation capacity
292 (the displacement at UL) than those with straight UPS. Under scenario of middle column removal,
293 the boundary condition allowed the UPS to sufficiently develop tensile force; the straight UPS
294 further produced larger elongation compared with the parabolic one at the same displacement,
295 resulting in earlier fracture of the UPS. Therefore, PCM-S had the lower deformation capacity
296 compared with PCM-P. In comparison, the failure of PC specimen under penultimate column
297 removal scenario was controlled by eccentric tension failure of the side column. Thus, the lower
298 deformation capacity of PCP-S compared with PCP-P can be attributed to the greater tensile forces
299 developed in the straight UPS, which aggravates the second order effect in the side column.

300 *The Effects of the Position of Column Removal*

301 As presented in Fig. 3 and Table 4, the FPL resistance of RCM and RCP was 53 kN and 51
302 kN, respectively. The UL resistance of RCM and RCP was 79 kN and 74 kN. Thus, compared with
303 RCP, the FPL and UL of RCM increased by 4% and 7%, respectively. Moreover, RCM and RCP
304 had similar deformation capacity. Therefore, the position of column removal had limited
305 influences on the performance of RC frame to resist disproportionate collapse.

306 The FPL of PCM-S, PCP-S, PCM-P, and PCP-P was 79 kN, 77 kN, 63 kN, and 61 kN.
307 Therefore, at relatively small deformation stage, the position of column removal had little
308 influences on the load resistance of the PC specimens. However, the UL of PCM-S, PCP-S, PCM-
309 P, and PCP-P was 228 kN, 99 kN, 154 kN, and 86 kN, respectively. The UL of PCM-S was 130%

310 higher than PCP-S, while the UL of PCM-P was 79% higher than PCP-P. Thus, the UL capacity
311 of the PC specimen was significantly influenced by the position of column removal. In addition,
312 due to absence of the overhanging beam, the right-side column of PCP-S and PCP-P suffered
313 severe flexural tension failure due to large eccentricity, resulting in lower deformation capacity
314 compare with PCM-S and PCM-P.

315 In summary, the position of column removal not only affected the UL capacity but also
316 deformation capacity of the PC specimens.

317 *Dynamic Resistance*

318 As discussed above, the UPS effects on the quasi-static response of PC frame in resisting
319 disproportionate collapse had been captured by the experimental results. However,
320 disproportionate collapse is a dynamic event, and therefore, it is important to investigate the
321 dynamic behavior of these specimens. An energy-based method proposed by Izzuddin et al. (2008)
322 was adopted in describing the dynamic evaluation. In their method, the external work is assumed
323 to be totally converted to strain energy in the remaining building if a new balance can be achieved.
324 This method is mathematically expressed as

$$325 \quad P_d(u_d) = \frac{1}{u_d} \int_0^{u_d} P_{qs}(u) du \quad (1)$$

326 where $P_d(u)$ and $P_{qs}(u)$ are the dynamic load resistance and the quasi-static load resistance at
327 specific displacement demand u .

328 Fig. 16 illustrates the dynamic capacity curves of the specimens with and without UPS. The
329 dynamic ultimate load of Specimen RCM, RCP, PCM-S, PCM-P, PCP-S, and PCP-P were 48 kN,
330 44 kN, 113 kN, 79 kN, 80 kN, and 62 kN, respectively. Thus, the straight and parabolic UPSs
331 increased the ultimate dynamic load of RCM by 135% and 65%, respectively. Similarly, the
332 straight and parabolic UPSs increased the dynamic ultimate load of RCP by 82% and 41%,

333 respectively.

334 ***Bending Moment of the Right-Side Column***

335 To better understand the failure mode of the right column, the bending moment of critical
336 section E-E in the right column was determined by Eq. (2) and shown in Fig. 17.

$$337 \quad M_E = H_4 L_0 + V_1 \Delta \quad (2)$$

338 where H_4 is the horizontal reaction force in the top horizontal constraint; L_0 is the length from the
339 top horizontal constraint to section E-E; V_1 is the designed axial compressive force of 703 kN on
340 the side column; Δ is horizontal movement in Section E-E.

341 Fig. 17 shows the variation of bending moment in right-side column of the PC frame under
342 a penultimate column removal scenario while Fig. 18 presents the theoretical M-N curve of E-E
343 section. As shown in Fig. 17, the bending moment at Section E-E was negative (clockwise
344 direction) first and then converted to positive (counter-clockwise direction). When the RCD
345 reached 329 mm, the bending moment of E-E section was 76 kN·m and then began to decrease.
346 Theoretically, as shown in Fig. 18, the E-E section reached eccentric tension failure at this stage.
347 However, the re-ascending behavior was observed for the bending moment. This is because the
348 designed axial compression force in the side column was assumed to be constant in calculation,
349 but actually it kept decreasing after damage in the side column. Similar observation was found in
350 PCP-P.

351 ***De-composition of the Load Resistance***

352 Fig. 19 illustrates the static equilibrium of a section of a deformed beam. As given in the
353 figure, the vertical load resistance consists of the vertical component of axial force and shear force,
354 which can be mathematically expressed by:

$$355 \quad P = \sum_{j=1}^2 (N_j \sin \theta_j + V_j \cos \theta_j) \quad (3)$$

356 where P is the applied load; N_j and V_j are the axial force and shear force transferred from the beams
357 to the beam-column interfaces, respectively; θ_j is the rotation of the beam section.

358 Fig. 20 shows the de-composition of the load resistance at the critical section (beam-removed
359 column interface) of the PC specimens. All those PC specimens had similar load resistance
360 component at the beginning of the test. At this stage, the shear force (bending moment) contributed
361 majority of the load resistance, the axial force made negative but marginal contribution. At large
362 deformation stage, the contribution from the shear force of PCM-S and PCM-P decreased quickly
363 and even became negative at the end of the tests, while the axial force contributed majority of the
364 load resistance. Thus, the TCA from strand was the main load-resisting mechanism at the large
365 deformation stage. In comparison, the contribution from the shear force of PCP-S is always greater
366 than that from the axial force, indicating that bending moment still actively developed in the
367 BENM (no rebar fracture occurred). Regarding PCP-P, due to rebar fracture at the BENM, the
368 contribution from the shear force was much lower compared with PCP-S.

369 In general, two major load-resisting mechanisms were found from the PC specimens to resist
370 the applied load: beam action and TCA. The beam action can be further categorized as the flexural
371 action and CAA depend on whether axial compressive force developed in the beams. Firstly, the
372 beams deformed within elastic range without axial forces developed in the beams, the applied load
373 was resisted by the bending of beam ends. Subsequently, the plastic hinges began to form in the
374 beam ends due to increased deflection, while the axial compressive force began to develop in the
375 beams because the beam ends prone to move outward but were constrained by boundary. With the
376 help of the induced axial compressive forces, the bending moment capacity of the beam ends
377 exceeded yield bending moment. This is the so call "CAA". Therefore, the enhancement of the
378 flexural capacity due to CAA was inherently attributed to additional plastic moment caused by the
379 axial compressive forces in the beams. When the beams undergo the deformation of approximate

380 one beam depth, the axial compressive force began to transfer to axial tensile force. After that, the
381 TCA began to progress to resist the applied load.

382 **Conclusions**

383 In this study, four posttensioned concrete (PC) frames and two referential reinforced concrete
384 (RC) specimens were tested subjected to push-down loading regime. Based on experimental and
385 analytical results, the conclusions were drawn as follows:

- 386 1. The unbonded posttensioning strand (UPS) can significantly increase the load resistance,
387 comparing to conventional RC specimen. However, the UPS induced considerable tensile
388 force to side column may lead to flexural tension failure due to large eccentricity of the side
389 column. Thus, the potential enlarged collapse zone for PC frames due to greater horizontal
390 tensile force for side columns should be considered seriously.
- 391 2. The position of column removal had a minor effect on the performance of RC frame. For PC
392 specimens, the position of column removal had limited effects on the first peak load (FPL).
393 However, it had considerable effects on their UL capacity. This is mainly because considerable
394 tensile catenary action (TCA) could develop in PC beams with the loss of a middle column.
395 Conversely, TCA could not be fully developed in PC beams when the loss of a penultimate
396 column was considered as the side column prone to occur eccentric tension failure.
- 397 3. PC specimen with straight strand profile achieved greater load resistance compared with those
398 with parabolic strand profile due to greater strand area. When consideration of the loss of a
399 penultimate column, PC specimen with straight strand profile may accumulate the internal
400 damage of column due to greater tensile force required at identical displacement stage. When
401 the loss of a middle column was considered, the straight strands were fractured earlier than the
402 parabolic ones, since the straight strands experienced lager elongation than the parabolic one

403 at the same vertical displacement.

404 4. The load resistance de-composition analysis shows that the load resistance component of each
405 PC specimen at small deformation stage was similar; meanwhile, the shear forces (bending
406 moments) contributed most of the load resistance while axial force made negative contribution.
407 However, the load resistance from axial forces dominated the load resistance at large
408 deformation stage except PCP-S. In other words, for PC specimens, the beam action (flexural
409 action together with CAA) and TCA are the main load-resisting mechanism at small and large
410 deformation stage, respectively.

411 **Data Availability**

412 Some or all data, models, or code that support the findings of this study are available from the
413 corresponding author upon reasonable request.

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504

505 **FIGURE CAPTIONS**

506 **Fig. 1.** Specimen detailing: (a) RCM; (b) PCM-S; (c) PCM-P

507 **Fig. 2.** Experimental setup: (a) photo of PCM-S; (b) drawing of PCM-S; (c) drawing of PCP-P

508 **Fig. 3.** Comparison of load-displacement curves

509 **Fig. 4.** Failure mode of Specimen RCM

510 **Fig. 5.** Failure mode of Specimen RCP

511 **Fig. 6.** Failure mode of Specimen PCM-S

512 **Fig. 7.** Failure mode of Specimen PCP-S

513 **Fig. 8.** Failure mode of Specimen PCM-P

514 **Fig. 9.** Failure mode of specimen PCP-P

515 **Fig. 10.** Horizontal reaction versus the RCD: (a) RC specimens; (b) PC specimens

516 **Fig. 11.** Contribution of the horizontal reaction of different measuring points: (a) RCM; (b) PCM-
517 S; (c) Left side of PCP-P; (d) Right side of PCP-P

518 **Fig. 12.** Deformation of beams at various stages: (a) PCM-S; (b)PCP-P

519 **Fig. 13.** Horizontal drift in right-side column: (a) PCM-S; (b)PCP-S; (c) PCM-P; (d)PCP-P

520 **Fig. 14.** Strain of beam longitudinal rebar: (a) top rebar in PCM-S; (b) bottom rebar in PCM-S; (c)
521 top rebar in PCP-S; (d) bottom rebar in PCP-S; (e) top rebar in PCM-P; (f) bottom rebar in PCM-
522 P; (g) top rebar in PCP-P; (h) bottom rebar in PCP-P

523 **Fig. 15.** Prestressing force of tendons versus RCD: (a) Total prestressing force of the PC specimens;
524 (b) PCM-S; (c) PCP-S

525 **Fig. 16.** Dynamic resistance of tested specimens

526 **Fig. 17.** The varying of bending moment in E-E section of side column

527 **Fig. 18.** Determination of the failure mode of PC specimens under penultimate column removal

528 **Fig. 19.** Determination of internal forces

529 **Fig. 20.** De-composition of the vertical resistance: (a) PCM-S; (b) PCM-P; (c) PCP-S; (d) PCP-P

530

531 **Table 1.** Details of Prototype Building and Corresponding Test Model

Test Specimen	Prototype Building			Test model		
	Beam (mm ²)	Column (mm ²)	Strand Size (mm)	Beam (mm ²)	Column (mm ²)	Strand Size (mm)
RCM	500×300	500×500	N/A	250×150	250×250	N/A
RCP	500×300	500×500	N/A	250×150	250×250	N/A
PCM-S	500×300	500×500	17.8	250×150	250×250	12.7
PCM-P	500×300	500×500	17.8	250×150	250×250	12.7
PCP-S	500×300	500×500	17.8	250×150	250×250	12.7
PCP-P	500×300	500×500	17.8	250×150	250×250	12.7

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Table 2. Specimen Characteristics

Test Specimen	Effective prestressing	Axial compressive ratio	Beam reinforcements				Position of removed column	Posttensioning strands profile
			End section		Mid-span section			
			Top	Bottom	Top	Bottom		
RCM	N/A	0.31	3T12	2T12	2T12	2T12	Middle	N/A
RCP	N/A	0.31	3T12	2T12	2T12	2T12	Penultimate	N/A
PCM-S	0.65 f_{pu}	0.31	3T12	2T12	2T12	2T12	Middle	Straight
PCM-P	0.65 f_{pu}	0.31	3T12	2T12	2T12	2T12	Penultimate	Parabolic
PCP-S	0.65 f_{pu}	0.31	3T12	2T12	2T12	2T12	Middle	Straight
PCP-P	0.65 f_{pu}	0.31	3T12	2T12	2T12	2T12	Penultimate	Parabolic

533 Note: f_{pu} equals to 1860 MPa, is the nominal ultimate strength of the tendons. T12 denotes deformed rebar with
534 diameter of 12 mm.

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Table 3. Material Properties of Tendon and Rebar

Item	Nominal diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)	Elongation (%)
Strands	12.7	1649	1970	213000	6.3
R6	6	368	485	162000	20.1
T12	12	462	596	171000	14.7
T16	16	466	604	182000	17.0

541 Note: R6 denotes plain rebar with diameter of 6 mm while T12 and T16 denotes deformed rebar with diameter of 12
542 mm and 16 mm, respectively.

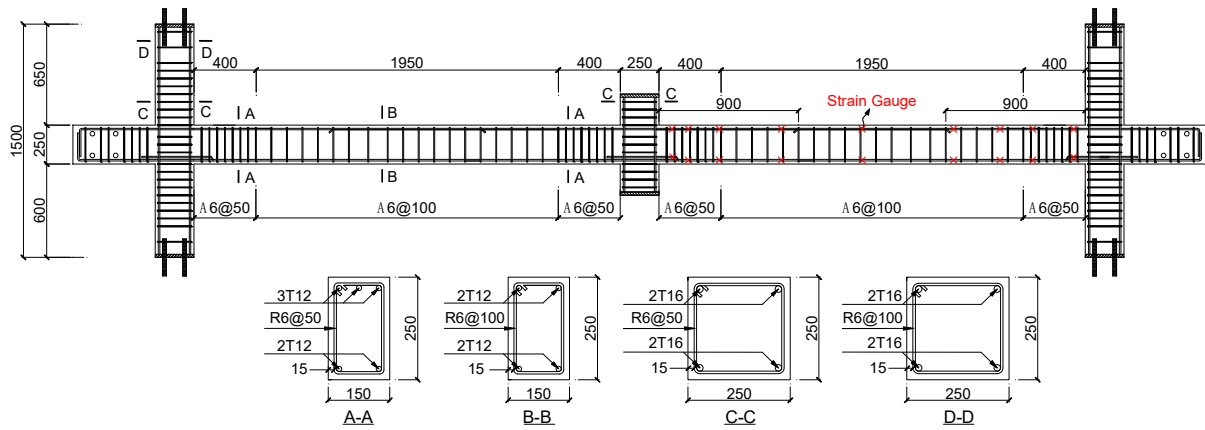
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Table 4. Critical Results

Test ID	Critical displacement (mm)			Critical load (kN)			MHCF in the left/ right side (kN)	MHTF in the left/ right side (kN)
	Yield load	First peak load	Ultimate load	Yield load	First peak load	Ultimate load		
RCM	30	70	659	42	53	79	-99	167
RCP	27	76	665	40	51	74	-81/-69	153/143
PCM-S	30	56	614	68	79	228	-62	488
PCM-P	27	90	680	43	63	154	-80	298
PCP-S	25	48	499	64	77	99	-61/-61	162/122
PCP-P	19	66	600	39	61	86	-87/-78	166/152

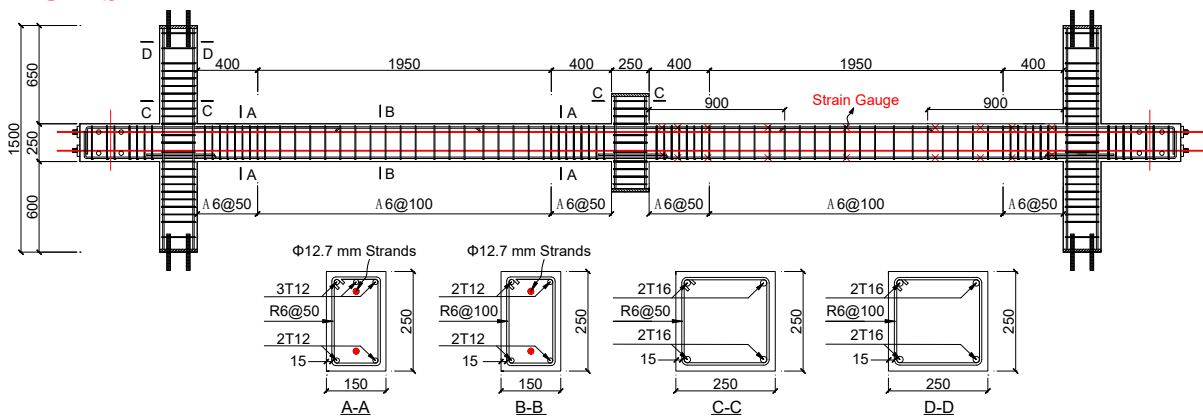
551 Note: MHCF and MHTF denote maximum horizontal compressive force and maximum horizontal tensile force,
552 respectively.

RCM



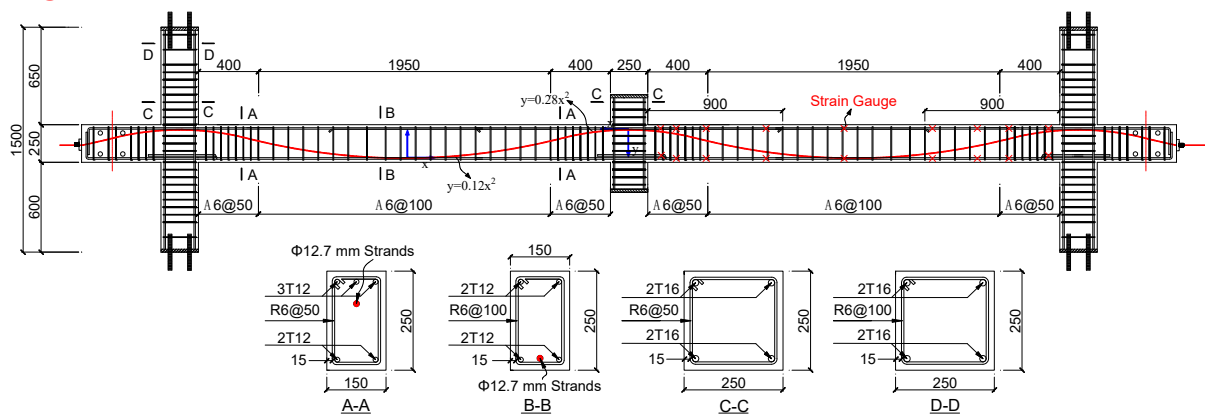
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PCM-S

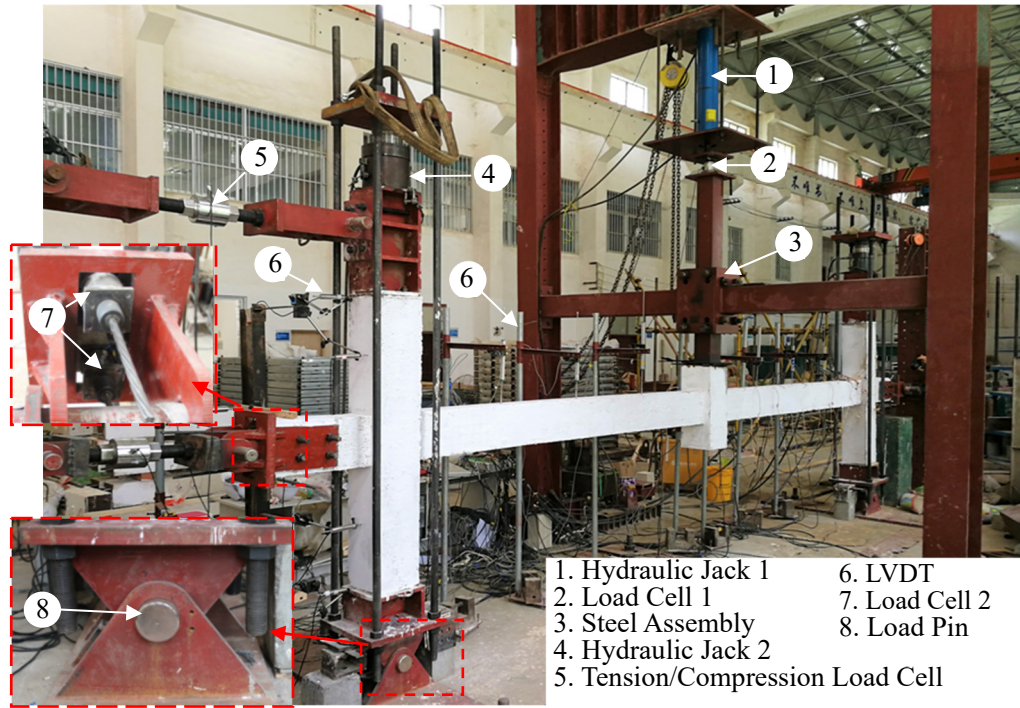


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PCM-P

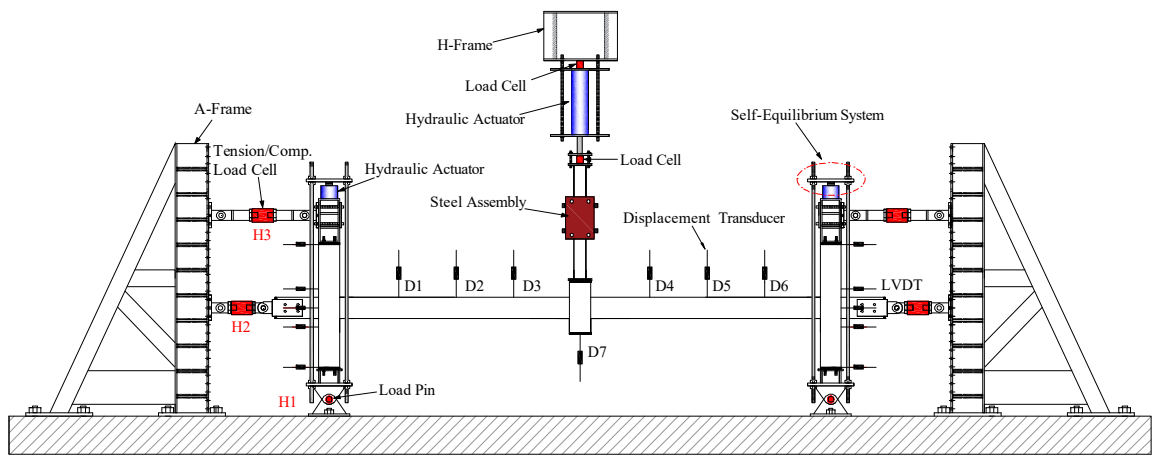


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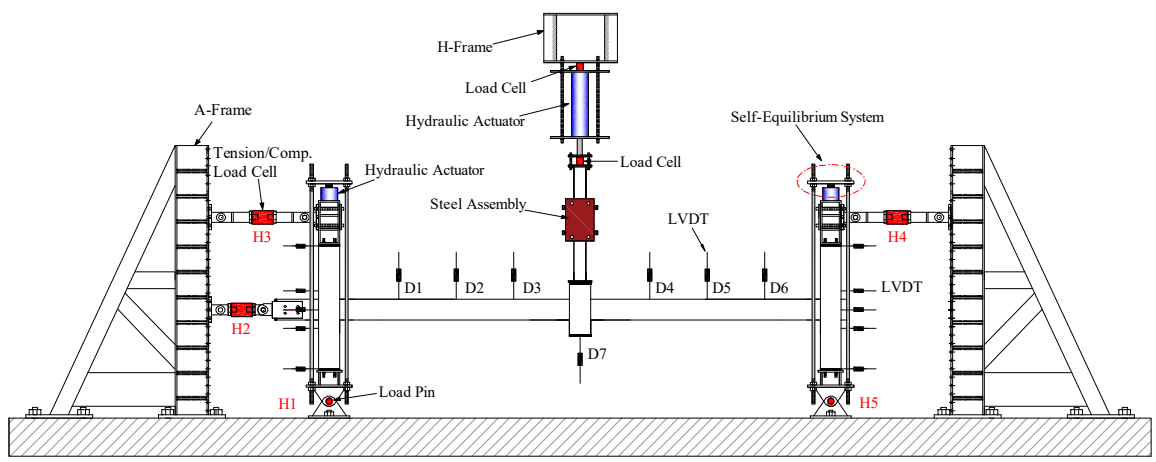


- 1. Hydraulic Jack 1
- 2. Load Cell 1
- 3. Steel Assembly
- 4. Hydraulic Jack 2
- 5. Tension/Compression Load Cell
- 6. LVDT
- 7. Load Cell 2
- 8. Load Pin

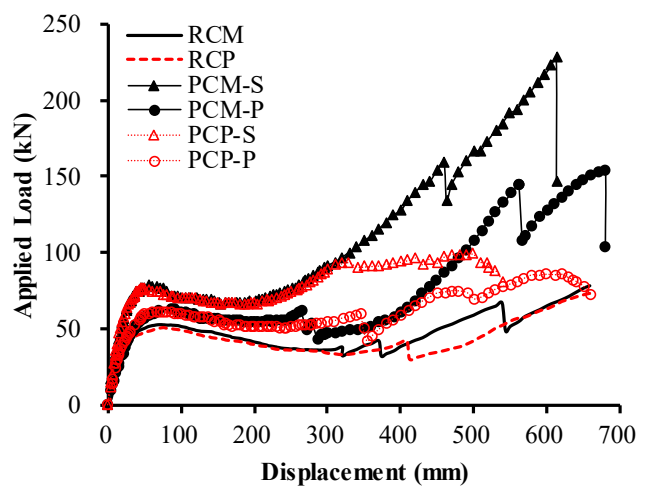
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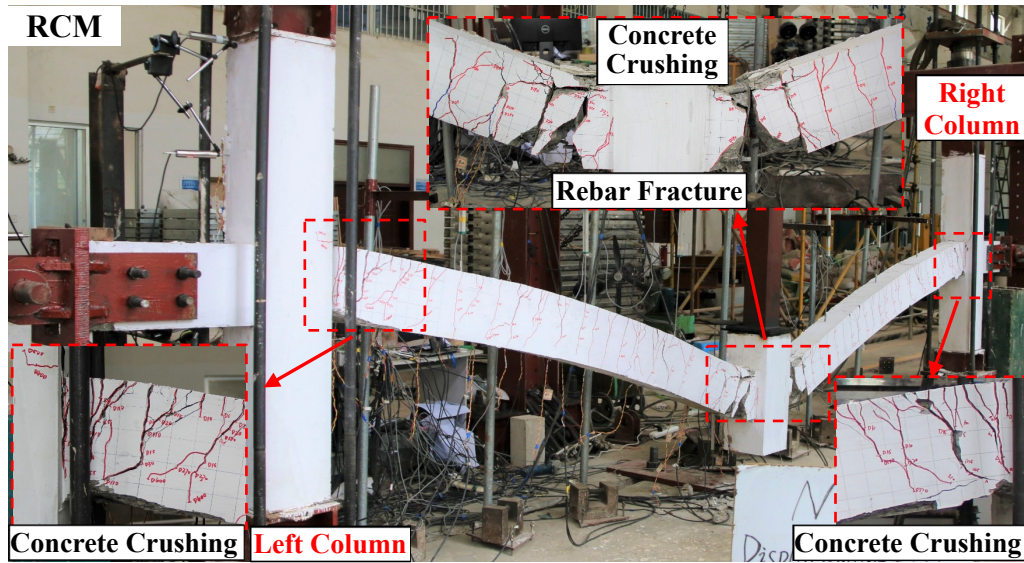


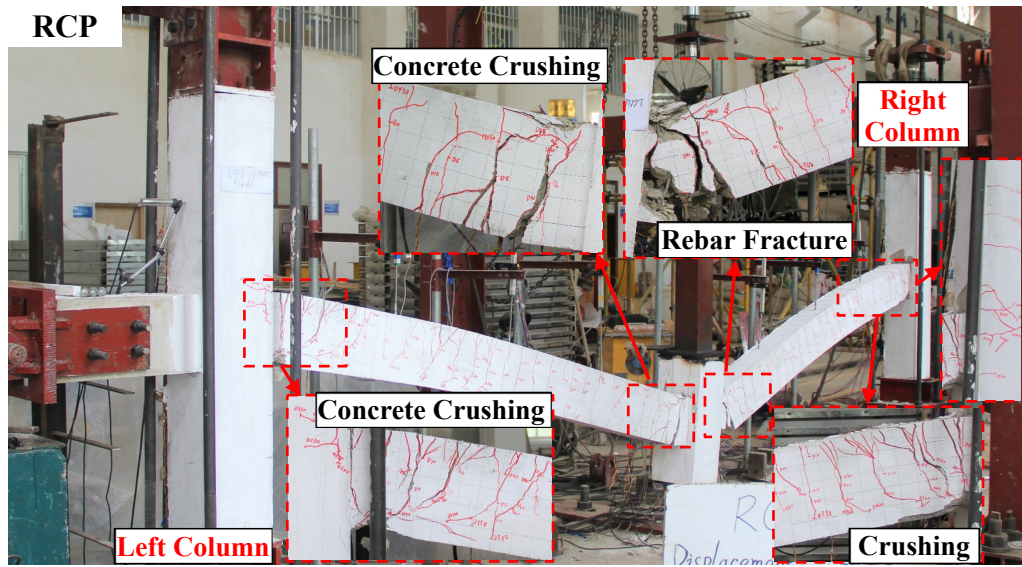
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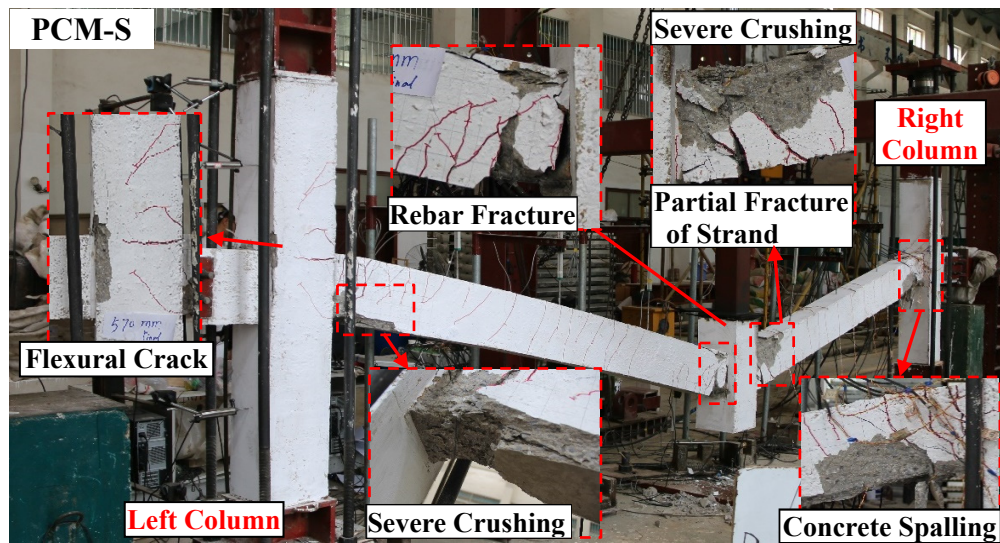


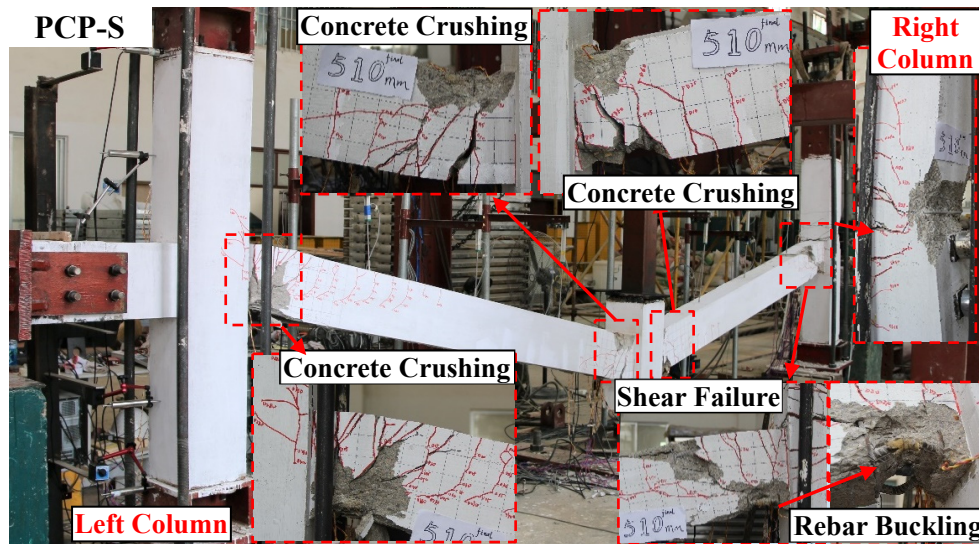
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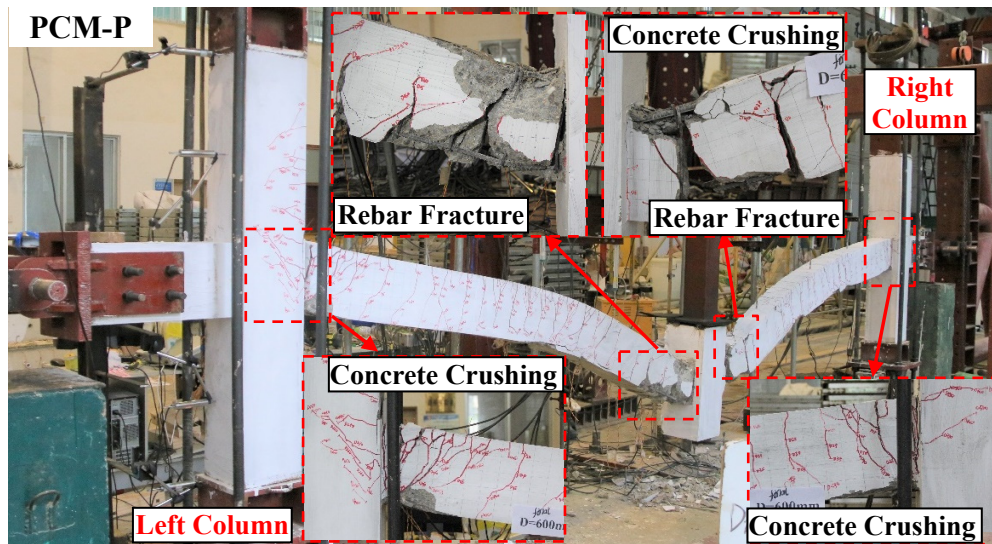


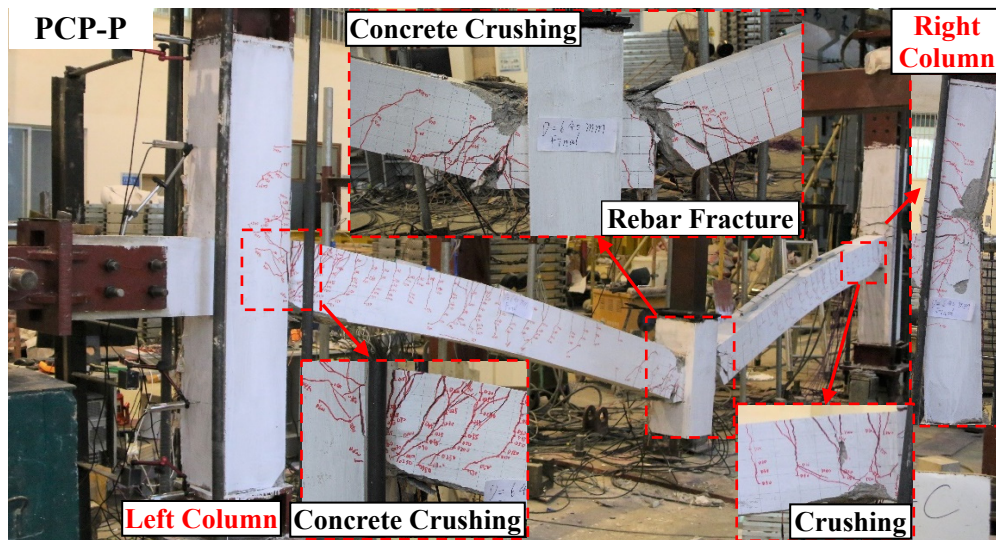


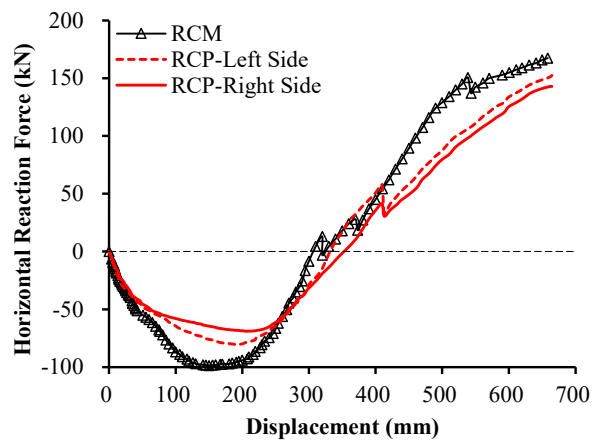




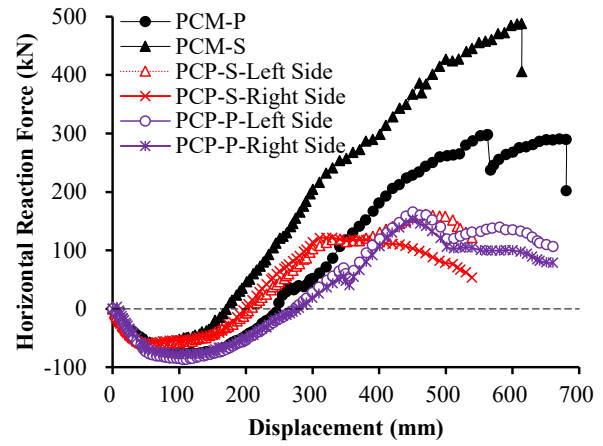




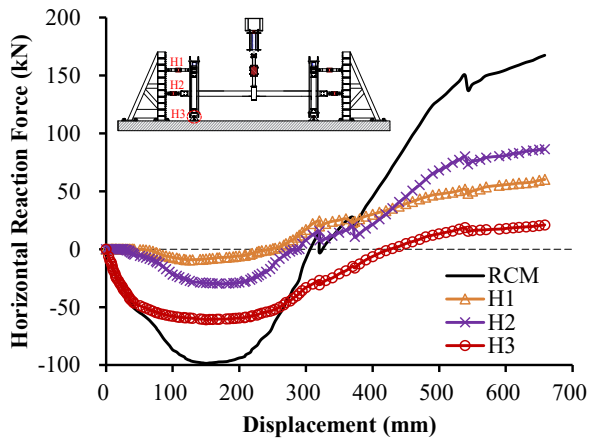




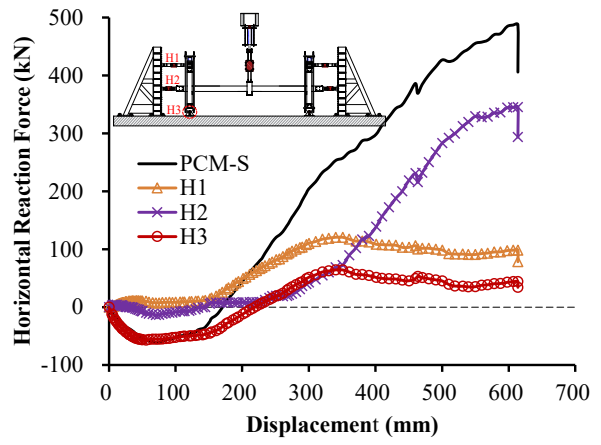
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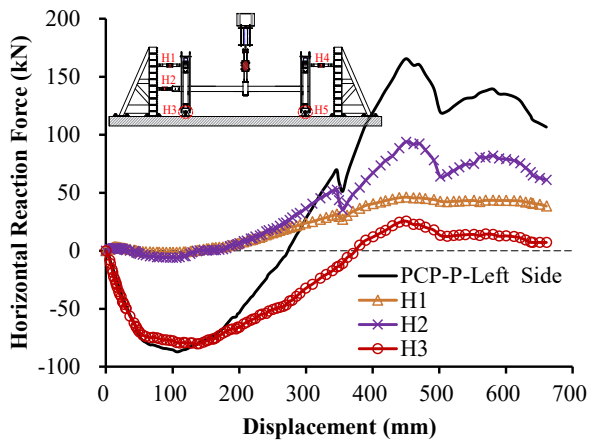
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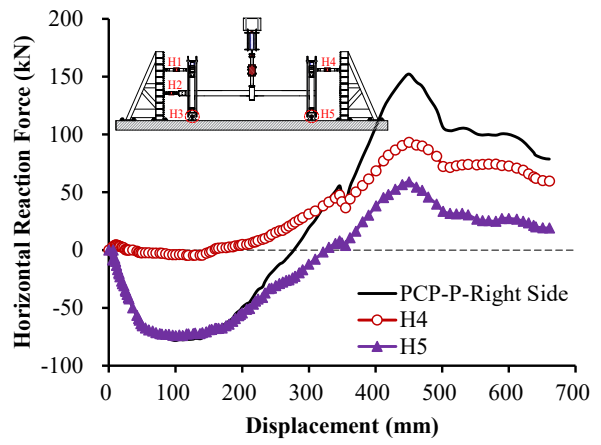
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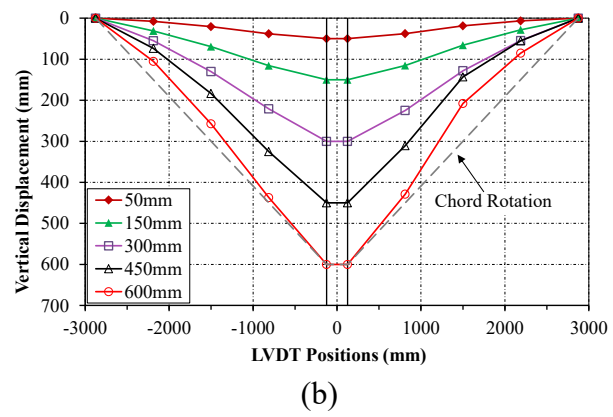
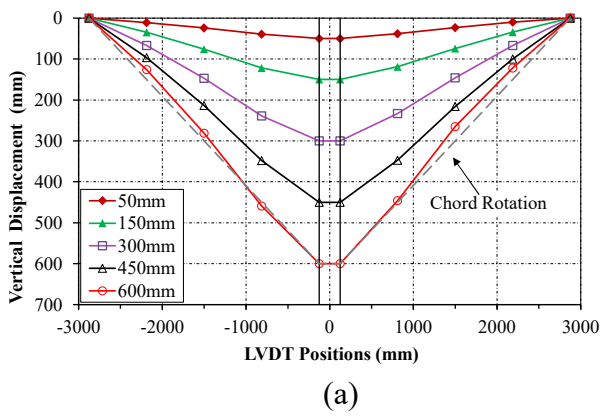
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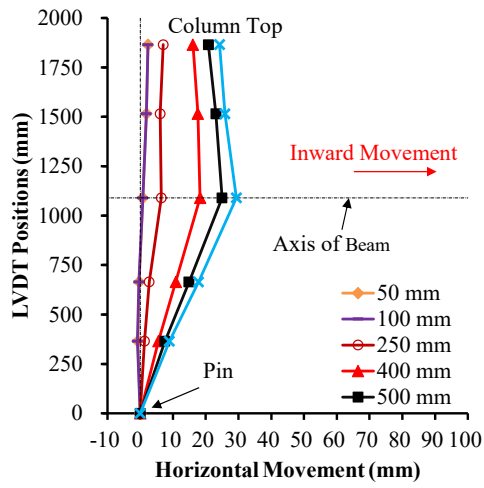


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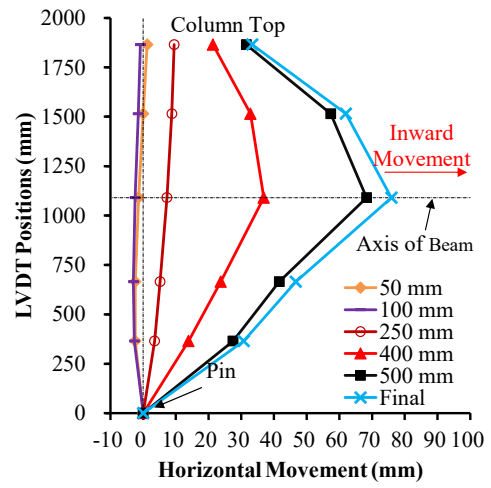


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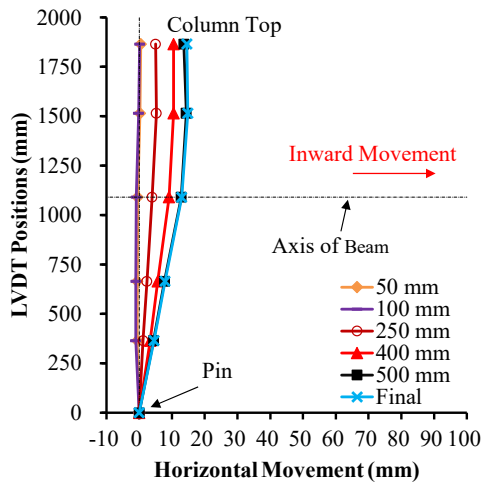




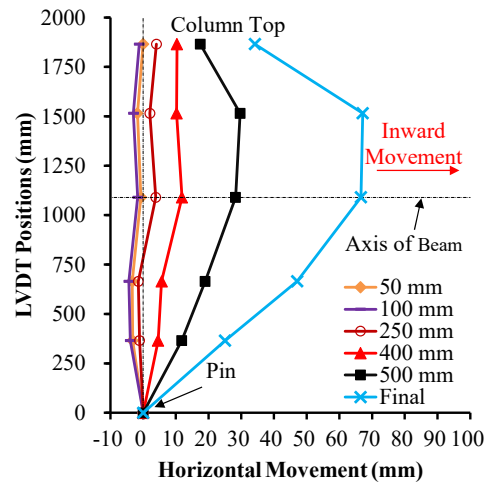
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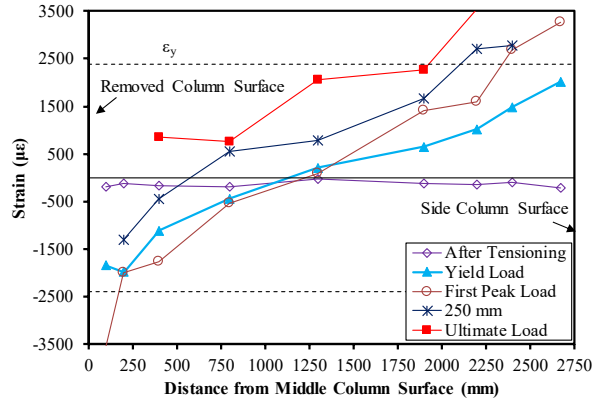
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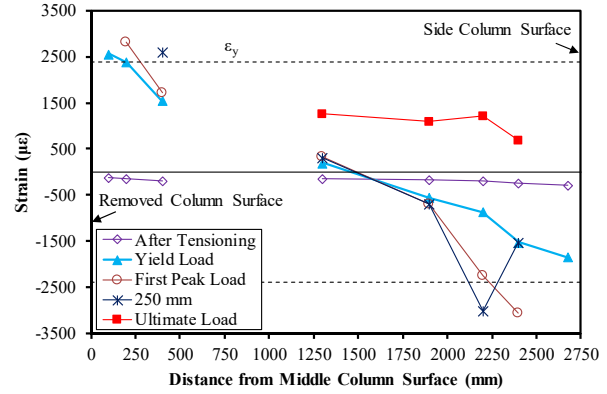
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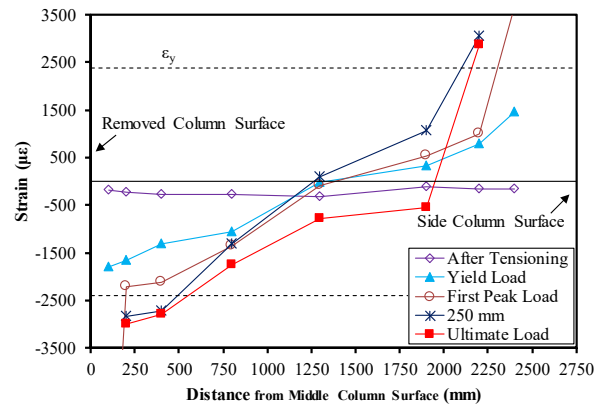
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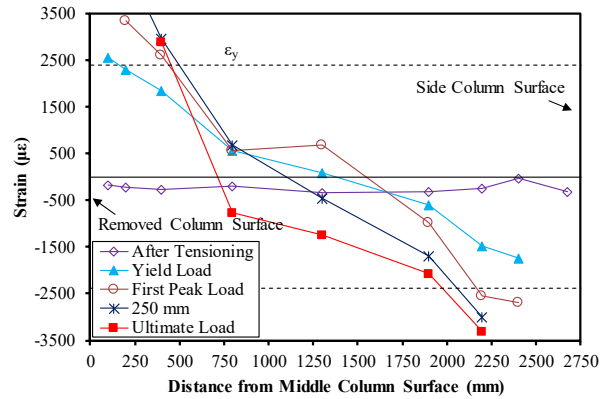
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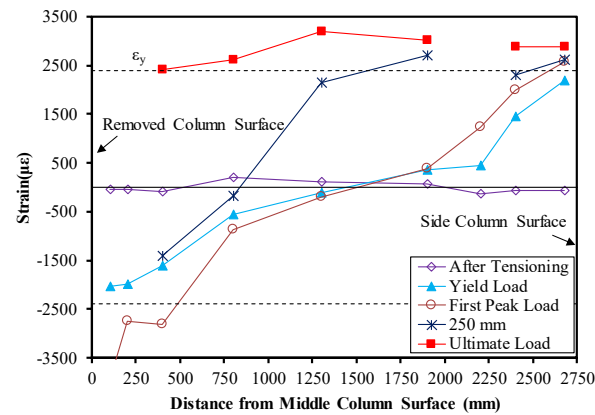
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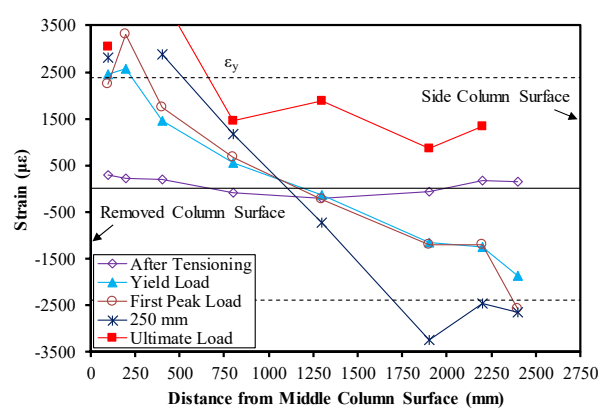
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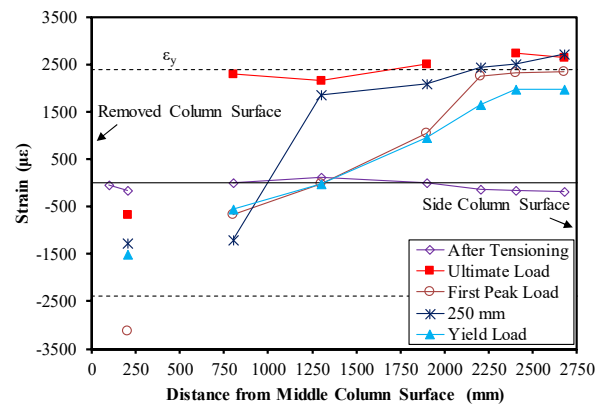
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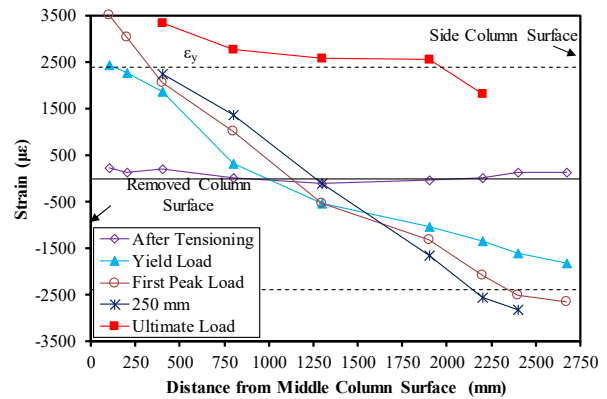
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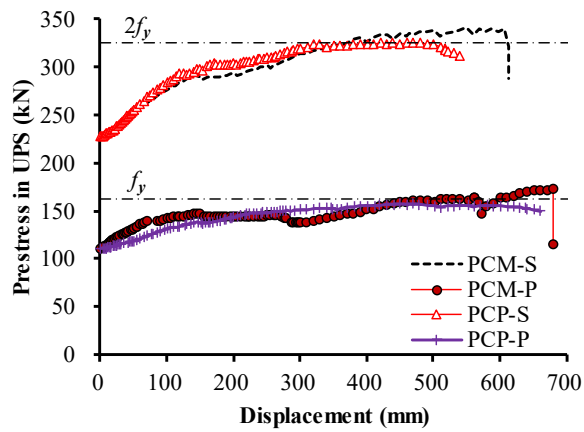
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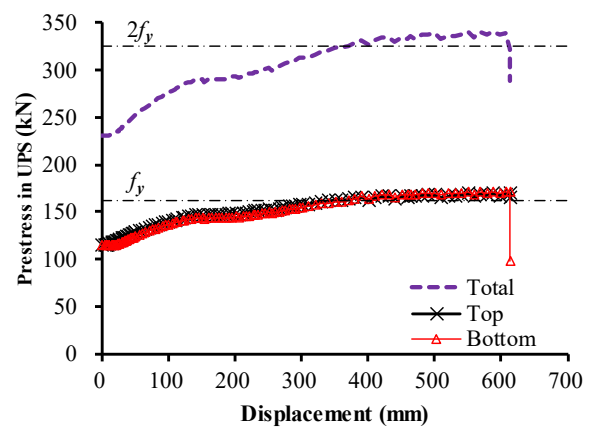
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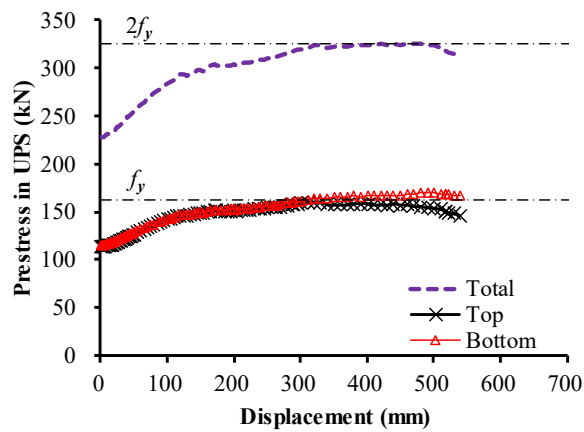
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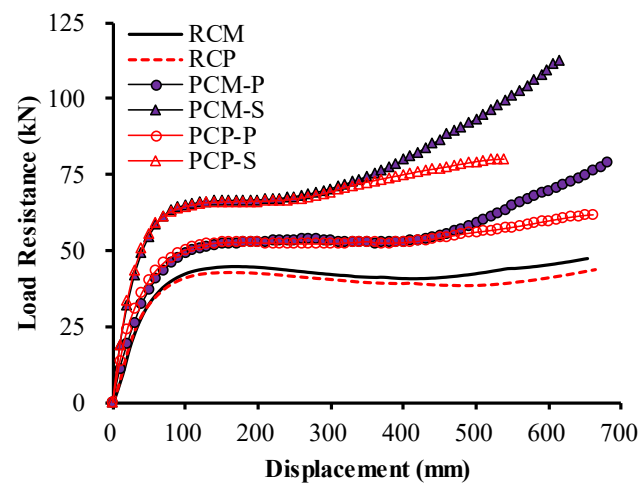
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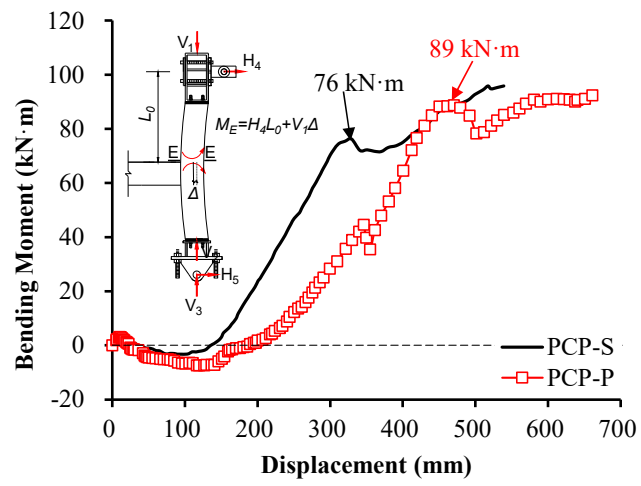


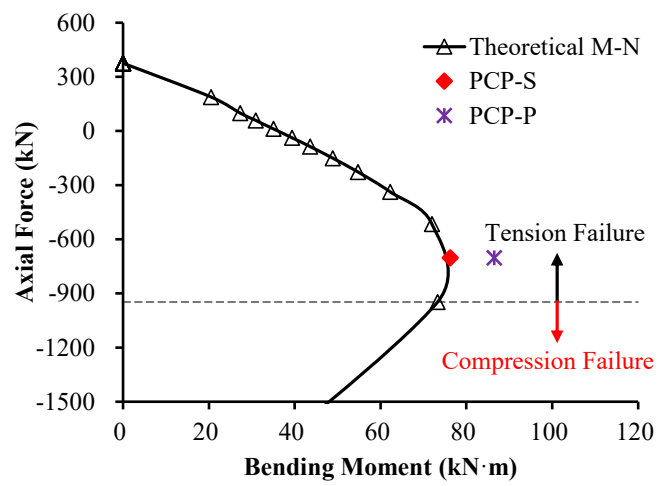
(b)

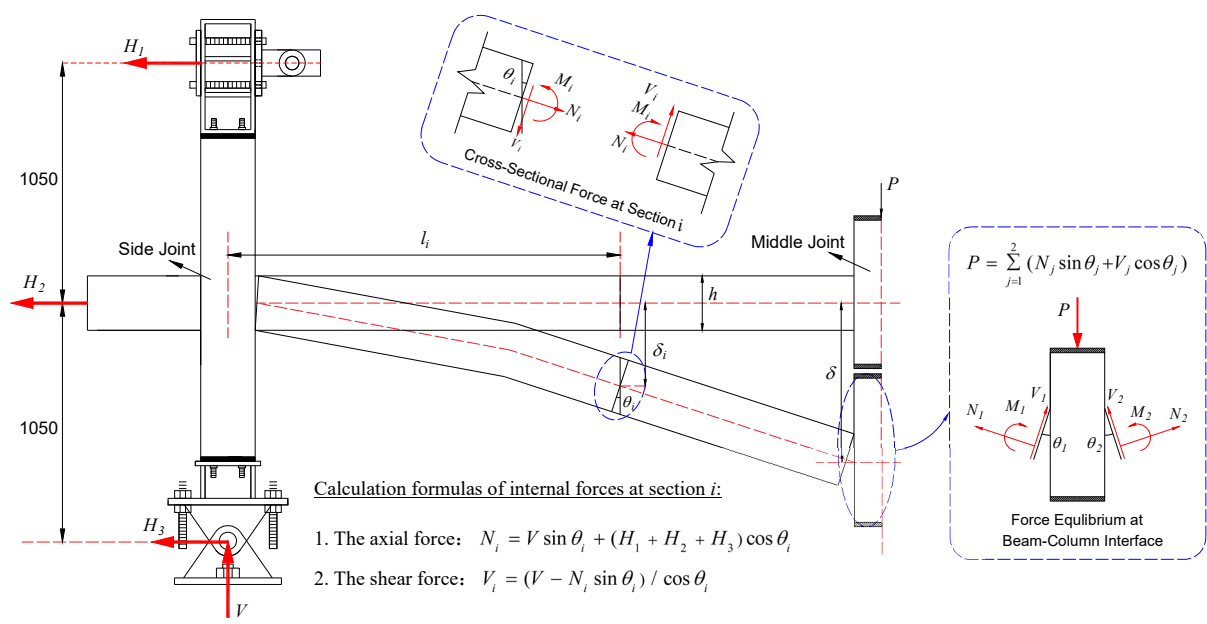


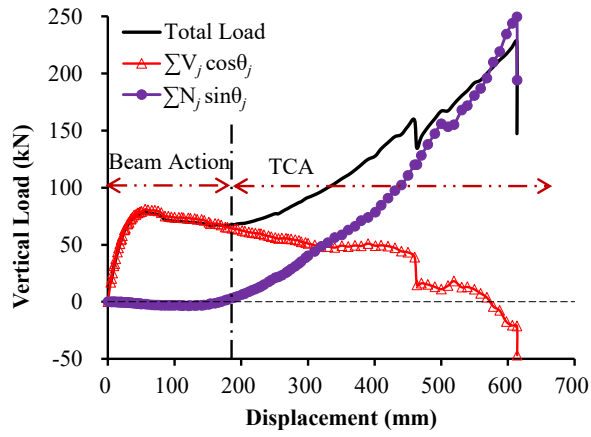
(c)



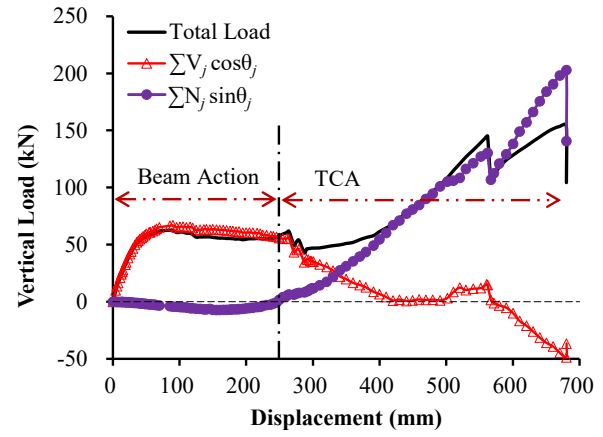




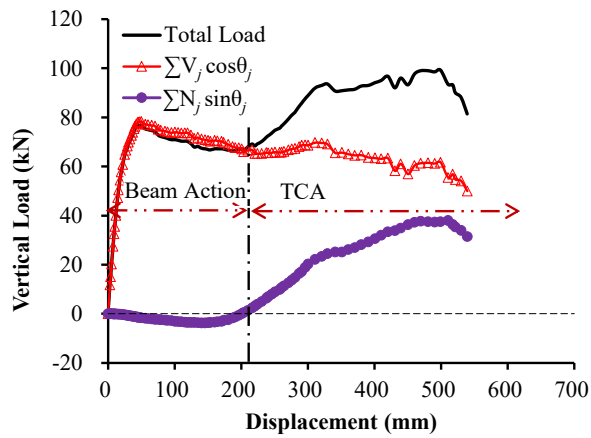




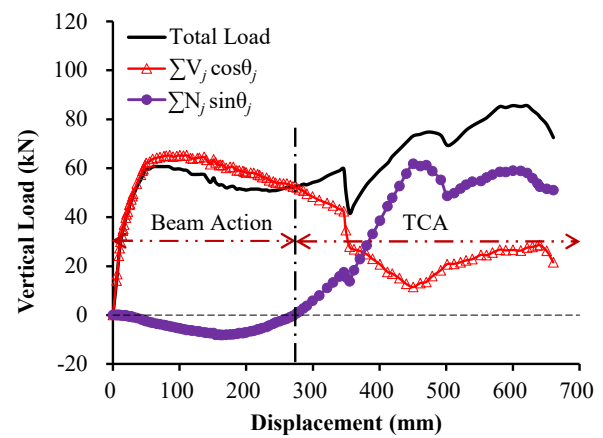
(a)



(b)



(c)



(d)