Dynamic Behavior of Precast Concrete Beam-Column Sub-assemblages with High Performance Connections Subjected to Sudden Column Removal Scenario

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ABSTRACT

Unbonded posttensioned precast concrete (UPPC) structure has shown its excellent aseismic performance in laboratory tests and earthquake investigation. However, the progressive collapse behavior of UPPC subjected to column removal scenario is still unclear. To fill this knowledge gap, two 1/2 scaled UPPC beam-column sub-assemblages were tested under a penultimate column removal scenario. The dynamic test results indicated that UPPC sub-assemblages have desirable load redistribution capacity to mitigate progressive collapse. The failure modes of the sub-assemblages observed in dynamic test were quite similar to that in static counterparts.

INTRODUCTION

Progressive collapse was defined as the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it (ASCE 7-11 2011). It was first obtained attention after the collapse of Ronan Point Apartment in 1968. However, extensive studies carried out on vulnerability of structures against progressive collapse after the collapse of Twin Towers of the World Trade Center in 2001. Alternate load path (ALP) method was frequently used to evaluate the ability of structures to resist progressive collapse. ALP method was mainly focused on the bridge ability of the remaining structures after removal of one or couple columns or partial of walls. Qian and Li (2012) designed an innovated sudden column removal device to simulate suddenly column removal scenario in laboratory. It was found that seismically design and detailing succeeded in increasing the resistant capacity of the structures against progressive collapse. Structures with longer length exhibited a higher vulnerability for progressive collapse compared to structures with shorter span length. It was found that the dynamic load increase factor of the specimen could be less than 1.38. Qian and Li (2013) evaluated the slab effects on dynamic response of beam-slab substructures after suddenly removal of a corner column. It was found that the first peak displacement could increase up by 264.4 % in absence of reinforced concrete (RC) slab to redistribute the initial corner column's axial force. Yu et al. (2014) studied the dynamic behavior of beam-column sub-assemblages after explosively removal of a middle column. It was found that initially the middle column achieved upward displacement at the beginning 2ms-20ms. After the shock wave stage, the sub-assemblage started falling down due to applied gravity loads in the time range of 100-500 ms. Qian et al. (2018) investigated the effects of multi-column removal on the dynamic behavior of flat slab substructures experimentally. It was found that missing a single interior column achieves larger dynamic response than that of the loss of a single corner or an exterior column. For missing two-column scenarios, the substructures under the loss of both a corner column and an adjacent exterior column simultaneously may experience more severe damage than that of the substructures subjected to the combined loss of an interior column and an adjacent exterior column. Orton and Kirby (2014) found that there is a very fine tipping point at which the structure is pushed past the compressive arch or flexural range of response into the catenary action range of response.

Although a number of dynamic tests were carried out for evaluation of the dynamic response of RC frames subjected to column missing scenarios, little studies had been carried out on dynamic behavior of precast concrete (PC) frames due to suddenly column removal, especially for PC frames with high performance dry connections.

PC frames were popular used in practice due to its high-construction speed, low labour requirements, and less pollution. The performance of PC frames with emulating connections subjected to the loss of column scenarios was investigated by Kang and Tan (2015) and Qian et al. (2019). Kang and Tan (2015) indicated that PC frame with emulating connections was able to develop much higher rotation compared to the requirements in DoD (2009) if catenary action in the beam is considered. Qian et al. (2019) found that precast slab together with topping layer could ensure the integrity of the slab system. However, as the wire mesh in the topping layer is the source of tensile membrane action, the tensile membrane action in PC beam-slab substructures is much less than that in cast-in-place substructures. The progressive collapse behavior of PC frames with dry connections was studied by Lew et al. (2017), Qian and Li (2018). Lew et al. (2017) found that the fracture of bottom anchorage bars at the welded connection prevents the mobilization of tensile catenary action. Qian and Li (2018) indicated that the gap existing between beam and column interfaces for bolted connected specimens prevented the development of compressive arch action and catenary action. However, due to large rotational capacity of bolted connected specimens, the tensile membrane action due to wire mesh of topping layer could be developed significantly. However, for welded connected specimens, due to fracture at the weld anchorage, no reliable compressive arch action, catenary action, and tensile membrane action were developed. Therefore, comparing to cast-in-place RC frames (Su et al. 2009; Orton et al. 2009; Choi and Kim 2011; Qian and Li 2012a; Yu and Tan 2013; Li et al. 2014; Lew et al. 2014; Ren et al. 2016; Lu et al. 2017) or PC frames emulating connections, PC frames with welded or bolt connections has poor behavior to resist progressive collapse. Thus, it was necessary to found high performance dry connections to resist progressive collapse. Based on seismic investigation, it was found that unbonded post-tensioning precast concrete (UPPC) frames performed well in resisting seismic load. Therefore, the progressive collapse behavior of UPPC, one of dry connections, frames was evaluated in the present study. Moreover, it was well known that the column loss normally was suddenly due to terrorist attack or vehicular impact. Therefore, the sudden column loss device, which was commonly used in previous studies, was also used to conduct dynamic test of UPPC beam-column sub-assemblages subjected to the loss of a penultimate column scenario.

EXPERIMENTAL STUDY

Specimen design

In this study, two 1/2 scaled UPPC beam-column substructures, which were extracted from the prototype structure at the inflection points, were tested subjected to dynamic loading regimes: UPPC-DL and UPPC-DH. The designation “UPPC” represents Unbonded Posttensioned Precast Concrete frame. The letter “D” represents dynamic test. In addition, the last letter “L” and “H” denote axial compression ratio of 0.2 and 0.4 at the side column, respectively. It should be noted that all specimens have identical reinforcement detailing and dimensions. As shown in Fig. 1, the specimen consists of two beams, two side columns, one middle column stub, and an overhanging beam beyond one of the side columns as a penultimate column removal was assumed. The side column with overhanging beam represents interior side column (to simulate horizontal restraints from surrounding bays).

Conversely, the side column without overhanging beam represents exterior side column where no additional horizontal restraints.

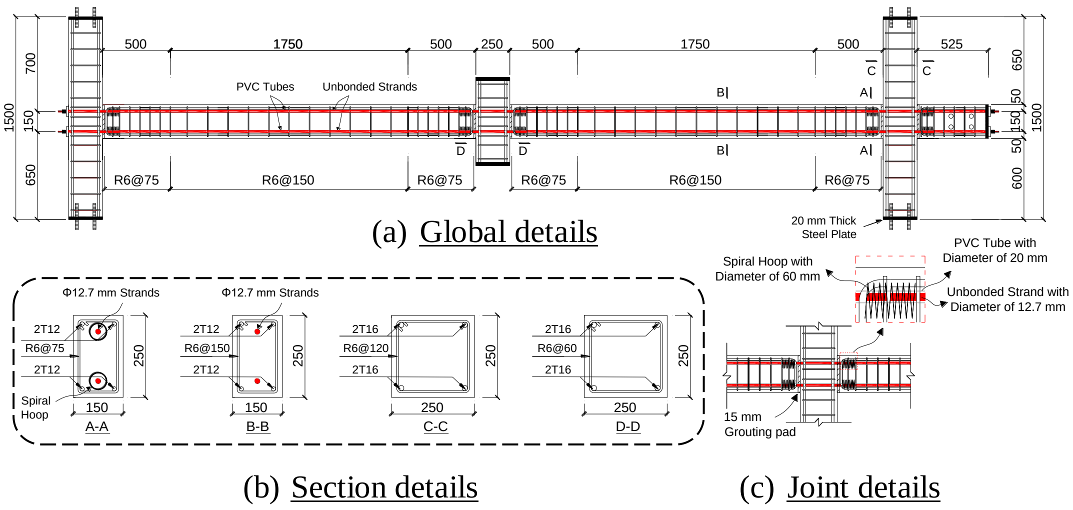


Figure 1. Dimensions and reinforcement details of test specimen

At the day of tests, the concrete compressive strength of UPPC-DL and UPPC-DH were 37.5 MPa and 38.1 MPa, respectively. The yield strength of R6, T12, and T16 were 368 MPa, 462 MPa, and 466 MPa, respectively. The nominal diameter of the strand was 12.7 mm. The yield strength and ultimate strength of the strand were 1649 MPa and 1970 MPa, respectively.

Test setup and instrumentation

The test setup is shown in Figure 2. For interior column (with extending beam), the top column and the extending beam connected with the A-shaped frame by rollers. Each roller installed a tension/compression load cell for measuring the reaction force. The column bottom was seated on a pin connection. For measuring the reaction force of the pin connection, a load pin was installed. For exterior column (without extending beam), only the top column connected to the A-shaped frame by a roller and bottom column seated on the pin support. The penultimate column was replaced by a sudden column removal device (SCRD), which was used frequently in previous studies (Qian and Li 2012; Qian et al. 2018). To prevent undesired out-of-plane failure, a steel box with steel column (Item 3 in Figure 2) was specially designed.

Before test, the SCRD was erected. Then, the weights were hung below the beams. After that, the SCRD was knocked down by impact load.

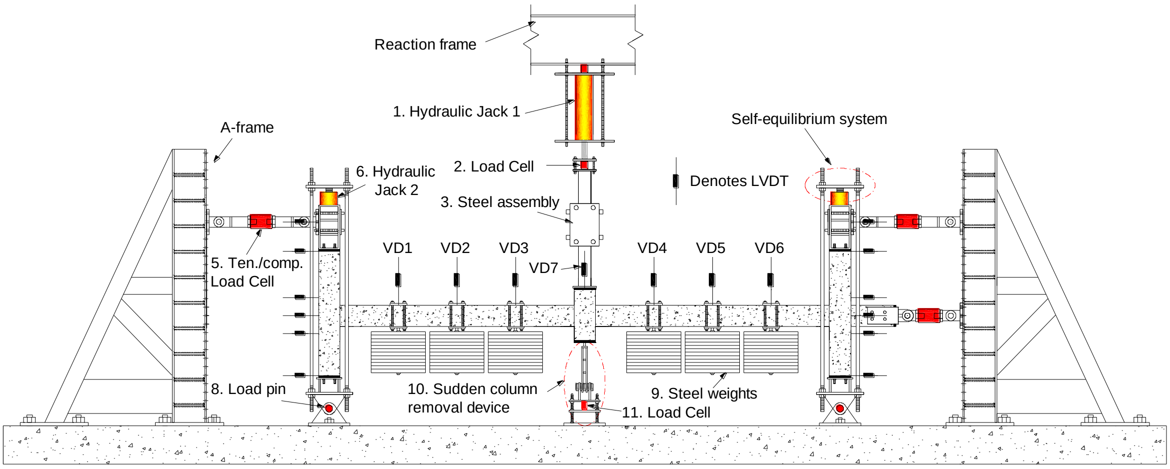


Figure 2. Test setup

PRELIMINARY RESULTS

Varying of axial force in SCRD

Figure 3 presents the varying of axial force in SCRD after removal of SCRD suddenly. It can be seen that, for UPPC-DL, the initial axial force was 40.5 kN before column removal at a time of 0.01 s and it reduced to 0.0 kN at a time of 0.018 s. Thus, the duration was 0.008 s, which is about 1.1 % of its natural period of vibration. Similarly, the duration of UPPC-DH was 0.005 s, which is about 0.9 % of its natural period. Thus, the reliability of the SCRD was ensured.

Dynamic displacement responses

Figures 4a and b illustrate the displacement response of UPPC-DL and UPPC-DH, respectively. For UPPC-DL, the maximum displacement was 320 mm at a time of 2.1 s. The maximum displacement of VD1, VD2, VD3, VD4, VD5, and VD6 were 88 mm, 170 mm, 253 mm, 250 mm, 168 mm, and 86 mm, respectively. For UPPC-DH, the maximum displacement was 295 mm a time of 1.99 s. The maximum displacement of VD1, VD2, VD3, VD4, VD5, and VD6 were 76 mm, 160 mm, 235 mm, 230 mm, 153 mm, and 73 mm, respectively. Regarding the position of LVDTs, please refer to Figure 2.

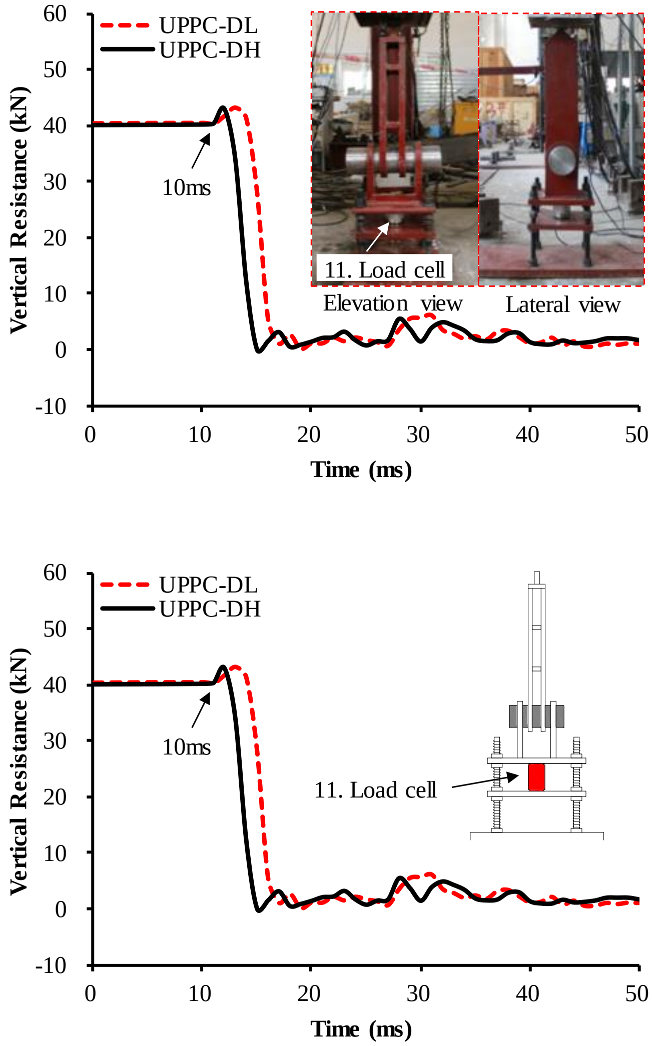
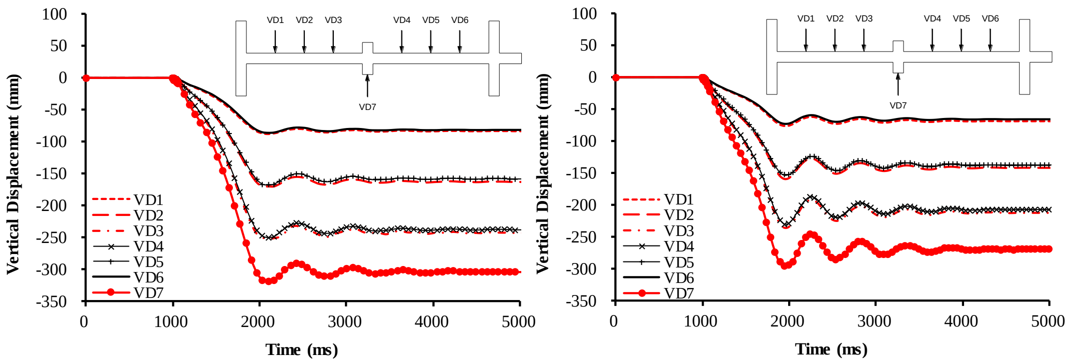


Figure 3. Varying of axial force in SCRD



(a) **(b)**

Figure 4. Displacement response: (a) UPPC-DL, (b) UPPC-DH

Failure mode

The crack pattern and local damage of UPPC-DL and UPPC-DH were illustrated in Figures 5 and 6, respectively. The differences caused by different axial compression ratio were mainly reflected in the crack pattern of the side columns. It could be found that the cracks observed in the side columns of UPPC-DH were much fewer than that in UPPC-DL. Moreover, the cracks formed in the interior column were milder than that in the exterior one for both specimens.

Figure 5 Crack pattern and local damage of UPPC-DL (from the author)

Figure 6 Crack pattern and local damage of UPPC-DH (from the author)

Horizontal reaction force

Figure 7 illustrates the total horizontal reaction force at each side of tested specimens. For exterior side (without overhanging beam) of UPPC-DL, after removal of the column over 1.0 s, total horizontal reaction force reached maximum compressive force of -71 kN a time of 1.388 s, but then the compressive reaction force began to decrease. When the time is over 1.71 s, the horizontal reaction force changed from compression to tension. The maximum tensile force of 110 kN was measured at a time of 2.15 s. After vibration, the residual force of 89 kN was measured. For interior side (with overhanging beam), the maximum horizontal compressive and tensile force were measured to be -84 kN and 185 kN at times of 1.323 s and 1.97 s, respectively. Therefore, the interior side achieved larger compressive and tensile reaction force due to stronger horizontal restraints. For UPPC-DH, the maximum horizontal compressive force at exterior side and interior side were -75 kN and -96 kN, respectively, whereas the maximum horizontal tensile forces were 104 kN and 148 kN, respectively. Therefore, both compressive arch action and tensile catenary action were able to develop in dynamic tests.

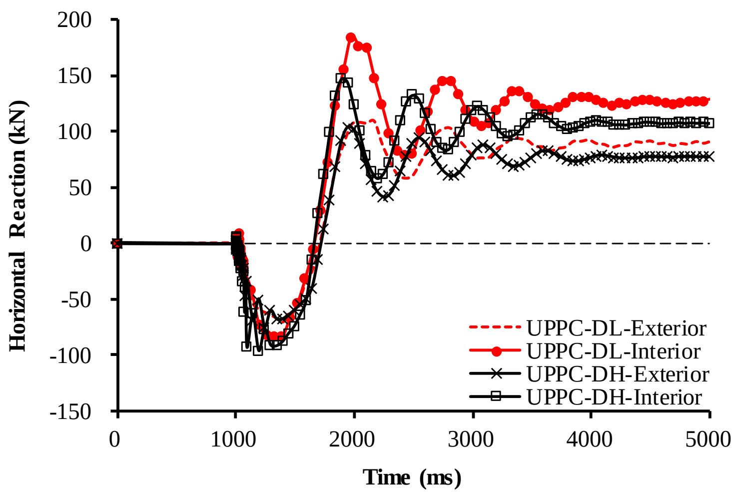


Figure 7 Total horizontal reaction-time curves

CONCLUSIONS

1. Unbonded post-tensioning precast concrete (UPPC) frames exhibited excellent resilience and integrity to resist progressive collapse caused by the loss of a penultimate column.

2. Exterior joint suffered more severe damage than that of interior joint due to less horizontal constraints from surrounding beam. The rotation and damage of the beam concentrated in the beam-column interfaces and little damage was observed in the beam itself.

3. Test results indicated that even sudden column removal was considered, compressive arch action and tensile catenary action were able to develop in UPPC frames to resist progressive collapse.

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