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Suggestion of Reinforcement Detailing for Hybrid Precast Concrete Wall-Steel Link Beam Systems

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ABSTRACT

Given the gap that there are suggested guides or codes for reinforcement detailing in either precast concrete (PC) or monolithic concrete walls of steel link beam systems, experimental and analytical studies of hybrid PC wall-steel link beam systems were undertaken. For this, cyclic tests of the connections of the system were carried out. Seismic behavior of test specimens with different reinforcement details was investigated. Based on the analytical studies along with experimental data, seismic detailing was proposed. The reinforcement detailing in the PC wall showed a significant effect on the overall seismic behavior and the proposed reinforcement detailing turned out to be adequate under cyclic inelastic deformations.

1. INTRODUCTION

The use of precast concrete (PC) systems is popular for building and bridge construction. PC shear walls have a merit of easier assembly in low- to mid-rise buildings and/or tilt-up construction. The seismic resistance can be maximized if the PC walls are coupled each other using a link beam. In this study, an innovative PC wall and steel link beam system is presented. As shown in **Fig. 1**, the coupled PC wall system comprises a steel link beam, PC walls with embedded steel section, hexagonal nuts anchored in the concrete, top-seat angles and high-tension bolts (Lim et al., 2016). This system can be used for low- to mid-rise tilt-up and precast concrete buildings. All the parts of a steel link beam, top-seat angles and PC walls are fabricated in the factory, and are transported to and assembled on a job-site without emulated connection. However, there are no guidelines for specific detailing that would be necessary for reinforcing the embedded steel section region subject to combined pull-out, push-in

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and shear forces (see **Fig. 1**). Given this gap, the authors studied several reinforcement detailing in the steel beam anchorage region in the PC wall. A total of four, half-scale specimens of a PC wall and half portion of a steel link beam were subjected to under reversed cyclic loads. Next, based on the test results, an analytical model for the design of reinforcement in the PC wall was attempted to be developed.

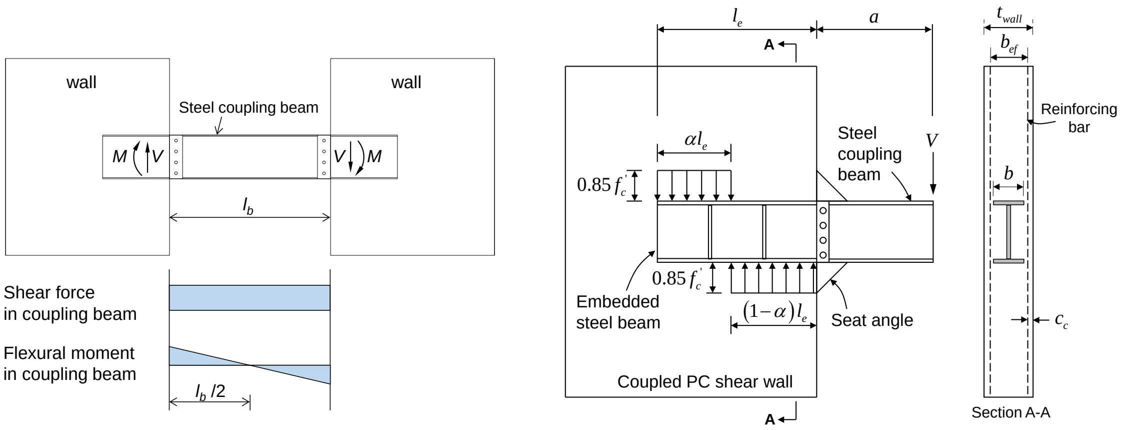


Fig. 1 Coupled PC wall-steel link beam system and its ultimate limit state

2. TESTING

Cyclic tests were carried out on four PC wall-steel link beam connections with several reinforcement detailing. The steel link beam was connected to the embedded steel beam by a bolted connection. The protruded portion (connection) of the embedded steel beam had a dimension of 120 × 400 × 20 mm. The protruded portion had four circular holes in the web. Four M24 hex-head bolts with a diameter of 24 mm were used. The precast wall portion had dimensions of 300 × 1,500 × 1,800 mm. Thickness of the concrete cover was 40 mm. The perimeter of the PC wall was reinforced by four D19 or D22 bars. The specified compressive strength of concrete (f_c') was 35 MPa. **Fig. 2** shows the detailing for each specimen. For all specimens, the embedment length (l_e) of the beam was 600 mm and the angles with dimensions of 200 × 200 × 20 mm were used above and below the link beam at the wall-beam interface. Four high-tensile bolts with a diameter of 24 mm were used to anchor each steel angle to the embedded nuts in the PC wall. The control specimen (EL600A-C) had regular reinforcement detailing in the PC wall, as shown in **Fig. 2(a)**. The transverse and longitudinal reinforcement ratios (ρ_t and ρ_l) were 0.005 and 0.0054, respectively (Ten D13 & four D19 bars or d_b = 13 & 19 mm; and ten D13 bars or d_b = 13 mm) hoops, where d_b is the diameter of bars. The second specimen (EL600A-LH) was additionally reinforced with two long D16 closed hoops located just beside the embedded steel beam, that is, above and below the embedded beam (in **Fig. 2(b)**, left and right of the beam). Also, the center D16 U-shaped transverse reinforcement was replaced by a D19 reinforcing bar.

The third specimen (EL600A-SH) was provided by a series of closed hoops above and below the embedded beam with the same length as that of the embedded beam. Ten D13 closed hoops were provided at intervals of 60 mm above or below the embedded steel section (i.e., total 20 hoops; see **Fig. 2(c)**). The EL600A-LH and EL600A-SH specimens' reinforcement detailing was determined based on the previously developed detailing by other researchers (Harries et al., 1993; Gong and Shahrooz, 2001). The fourth specimen (EL600A) was the prototype specimen with the reinforcement detailing proposed by the authors. Here, three D16 closed hoops with a length of 620 mm were provided perpendicular to the embedment length of the steel beam at intervals of 200 mm, as illustrated in **Fig. 2(d)**. Additionally, long D16 closed hoops were provided along the beam length just outside the embedded nuts for top-seat angles.

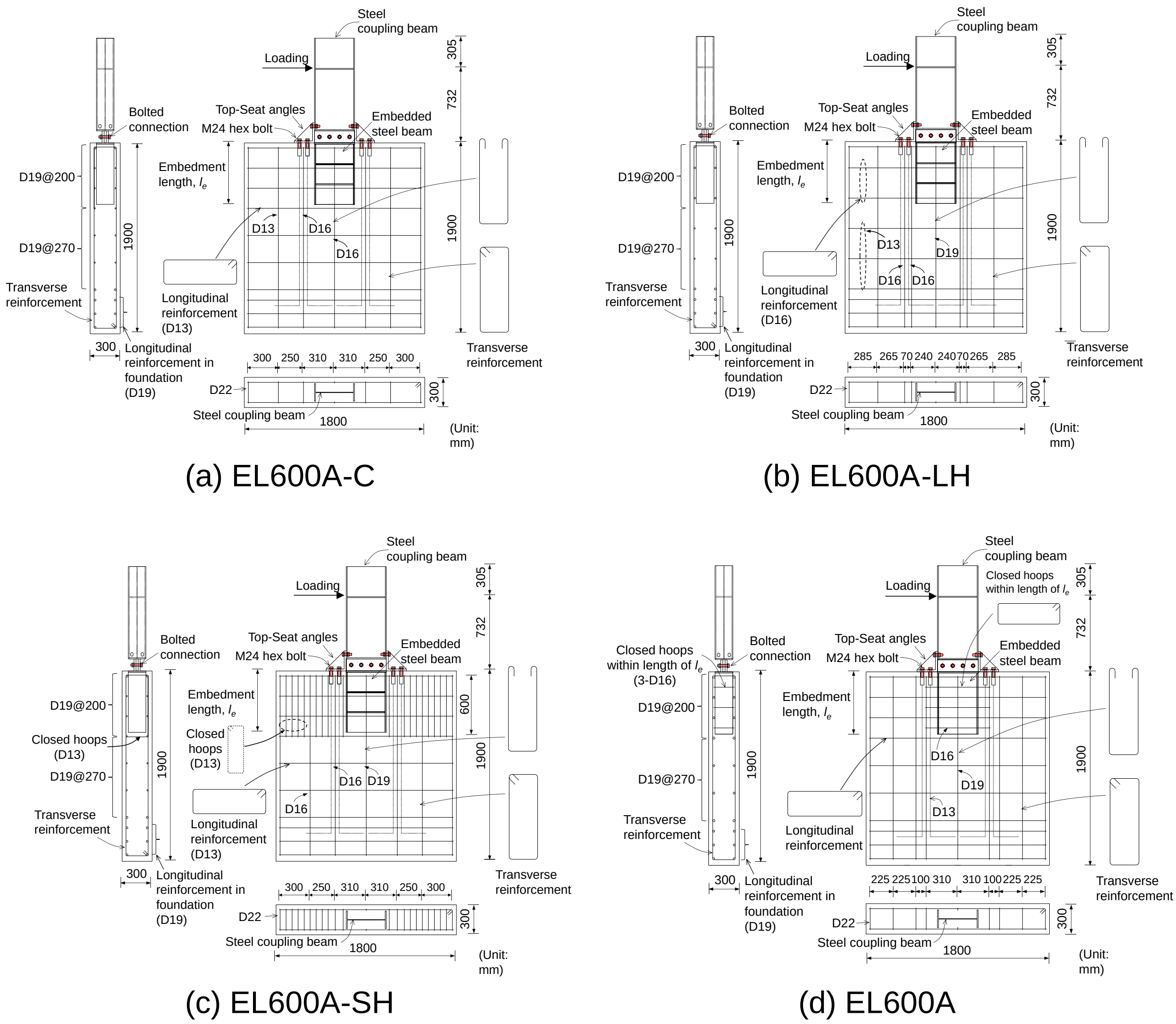


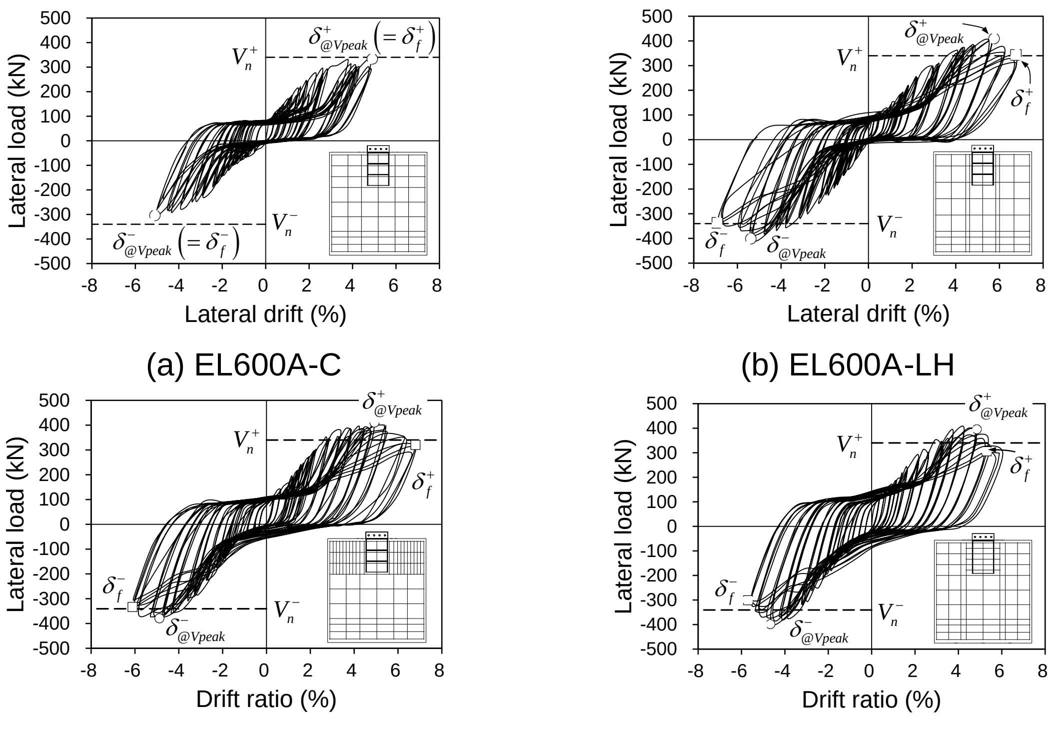
Fig. 2 Test specimens

The measured yield and tensile strengths of reinforcing bars used in the specimens ranged from 354 to 418 MPa. The average compressive strength at the testing day was 38 MPa.

Test specimens were loaded by a 2,000 kN actuator using displacement control until the failure. The length between the wall-link beam interface and the loading point was 732 mm, which represents the half of the clear link beam span. The drift ratio increased from 0.25% (1.5 mm) to 2% (12 mm) in increments of 0.25%, and subsequently in increments of 0.5% until ultimate failure.

3. RESULTS

Figure 3 shows the lateral load-drift relationship of the test specimens subjected to cyclic loading. The dotted line indicates the plastic shear strength (V_p) of the steel link beam. The ratios of the measured maximum shear to the plastic shear strength (V_{peak}/V_p) were 0.98, 1.19, 1.18, and 1.18, respectively, for EL600A-C, EL600A-LH, EL600A-SH, and EL600A. The three specimens with supplementary reinforcement in the PC wall performed as designed in a failure mode of plastic shear yielding. The measured plastic shear strengths were similar between these three specimens of EL600A-LH, EL600A-SH and EL600A; however, the energy dissipation and pinching were different depending on the provided reinforcement detailing.



(a) EL600A-C (b) EL600A-LH

(c) EL600A-SH (d) EL600A

Fig. 3 Test results

The strain of the steel link beam of EL600A-C did not reach the yield strain until the end of the tests, whereas the steel link beams of EL600A-LH, EL600A-SH, and EL600A yielded at the drift ratios (δ_y) of 6.2%, 6.5%, and 5.3% for positive loading and -5.9%, -6%, and -4.7% for negative loading, respectively. Particularly, significant extent of yielding at the web was clearly shown for EL600A, likely due to the better anchorage of the beam in the wall, resulting in the maximum web strain of 1800 μs. Unlike the specimens with supplementary reinforcement in the PC wall, the control specimen of EL600A-C had only modest strains in the web during the cyclic test, because EL600A-C experienced apparent damage of the bearing concrete just inside the link beam at approximately 4% drift ratio.

The strains of longitudinal reinforcement were measured by strain gauges at four different locations. The strains showed a tendency to increase rapidly for the longitudinal reinforcements closer to the face of the wall. All test specimens (EL600A-C, EL600A-SH, and EL600A) excluding EL600A showed the yielding of outermost longitudinal reinforcement, which occurred at the rotation angle of 4%. In contrast, all the reinforcements of EL600A did not yield until the end of the tests due to the confinement reinforcement within the embedment length of the steel beam. These results indicate that reinforcement detailing in the hybrid link beam system greatly affected the damage extent in the vicinity of the top surface of the wall. The confinement reinforcement along the beam embedment length was effective in preventing premature failure of concrete in that region, which delayed the yielding of longitudinal reinforcement when the beam and concrete were subjected to tension during cyclic loading.

4. SUGGESTION OF REINFORCEMENT DETAILING

The longitudinal reinforcement ratio over the embedment length (l_e) can be determined as the following procedures based on the assumption in **Fig. 1**, where the coefficient of α is determined from the force and moment equilibrium (Lim et al., 2016). For the tested specimens, the value of α is calculated to be 0.43. The bearing forces near the interface and at the end of the embedded section are then determined as $0.85f'_c\alpha l_e b_{ef}$ and $0.85f'_c(1 - \alpha)l_e b_{ef}$, respectively, where b_{ef} is the effective width of the wall. The hypothesis in the present study is that approximately 25% of the bearing force is resisted by "tie-back" longitudinal reinforcement located just outside the steel beam and that the rest portion is resisted by the concrete in front of the steel beam. The 25% assumption is adopted from the portion of the prestressing force resisted by bonded reinforcement in the vicinity of anchorage devices located away from the end of a member as recommended by ACI 318-14, R25.9.4.4.3. As such, the design tensile strength ($T_{sf} = A_{sf}f_y$) of longitudinal reinforcement near the wall-beam interface (front part) is set equal to the bearing force of ($0.21f'_c(1 - \alpha)l_e b_{ef}$) of concrete, where A_{sf} is the longitudinal reinforcement along the length of $(1 - \alpha)l_e$, and f_y is the specified yield strength of mild steel bars.

Similarly, the area of the longitudinal reinforcement (A_{sb}) for the region along the length of αl_e (back part) is determined to be the same as A_{sf}. Therefore, the longitudinal reinforcement ratios in the region of $(1 - \alpha)l_e$ and αl_e are specified as $[\rho_{lf} = A_{sf} / ((1 - \alpha)l_e t_{wall})]$ and $[\rho_{lb} = A_{sb} / (\alpha l_e t_{wall})]$, respectively, where t_{wall} is the wall thickness. The calculated values of ρ_{lf} and ρ_{lb} are turned out to be the same, though the total amount of longitudinal reinforcement for each region is different.

The use of closed hoops with 135-degree hooks is recommended to confine the embedded steel beam along the length, as demonstrated from the test results. The closed hoops surrounding the embedment length can be determined as the following procedures: First, the same uniform stress distribution is assumed above and below the embedded steel beam as shown in **Fig. 1** and as described in the earlier subsection and reference (Lim et al., 2016). The following vertical force equilibrium and the shear-friction design method can be applied in accordance with Section 22.9.4 of ACI 318-14 (2014), except that the angle between shear-friction reinforcement (closed hoops) and shear plane is considered to be 90°. Thus, the area of the closed hoops (A_{ch}) is determined to $(0.85f'_c(1 - 2\alpha)l_e b_{ef})/(\phi_y \mu)$, where ϕ is the strength reduction factor and is recommended as 0.75 (ACI 318-14, Section 22.9.4), and μ is the coefficient of friction (= 1.4). It is noted that the total area (or reinforcement ratio ρ_{ch}) of closed hoops provided in EA600A is equal to 1173.6 mm^2 (or ρ_{ch} = 0.0089) and similar to the value of 1083.2 mm^2 (or ρ_{ch} = 0.0082) obtained from the suggested closed-hoop equation.

Transverse reinforcement in PC walls can be provided in accordance with ACI 318-14, Section 18.10 (2014), where the ratio of distributed transverse reinforcements should be at least 0.0025 and their spacing (s) should not exceed 450 mm. The tested bolted steel link beam system used D16 bars as transverse reinforcement at a spacing of 225 mm, which was equivalent to 450 mm for full-scale systems. Additionally, transverse reinforcements were placed just above and below the embedded beam to engage closed hoops placed along the beam (see **Fig. 4**). Furthermore, a D19 U-shaped tie with 135-degree hooks was placed at the mid-height of the embedded beam. Similar detailing is recommended for actual size of PC walls with some adjustment of the bar size of transverse reinforcement.

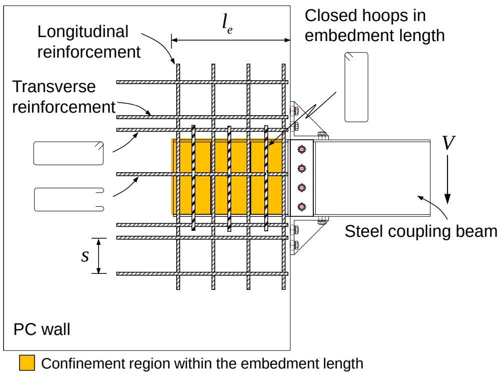


Fig. 4 Suggested reinforcement detailing for hybrid PC wall-steel link beam systems

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