Computers and Concrete, *Vol. 25, No. 1 (2020) 75-81*
DOI: https://doi.org/10.12989/cac.2020.25.1.075

Flexural and shear behavior of large diameter PHC pile reinforced by rebar and infilled concrete

Jin-Wook Bang[1a], Bang-Yeon Lee[2b] and Yun-Yong Kim*[3]

[1]TongYang Construction Materials R&D Center, 2822-1, Gimpo-daero, Gyeonggi-do 10024, Republic of Korea
[2]School of Architecture, Chonnam National University, 77, Yongbong-ro, Buk-gu, Gwangju 61186, Republic of Korea
[3]Department of Civil Engineering, Chungnam National University, 99, Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea

(*Received September 18, 2019, Revised December 25, 2019, Accepted January 10, 2020*)

Abstract. The purpose of this paper is to provide an experimental and analytical study on the reinforced large diameter pre-tensioned high strength concrete (R-LDPHC) pile. R-LDPHC pile was reinforced with infilled concrete, longitudinal, and transverse rebar to increase the flexural and shear strength of conventional large diameter PHC (LDPHC) pile without changing dimension of the pile. To evaluate the shear and flexural strength enhancement effects of R-LDPHC piles compared with conventional LDPHC pile, a two-point loading tests were conducted under simple supported conditions. Nonlinear analysis on the basis of the conventional layered sectional approach was also performed to evaluate effects of infilled concrete and longitudinal rebar on the flexural strength of conventional LDPHC pile. Moreover, ultimate strength design method was adopted to estimate the effect of transverse rebar and infilled concrete on the shear strength of a pile. The analytical results were compared with the results of the bending and shear test. Test results showed that the flexural strength and shear strength of R-LDPHC pile were increased by 2.3 times and 3.3 times compared to those of the conventional LDPHC pile, respectively. From the analytical study, it was found that the flexural strength and shear strength of R-LDPHC pile can be predicted by the analytical method by considering rebar and infilled concrete effects, and the average difference of flexural strength between experimental results and calculated result was 10.5% at the ultimate state.

Keywords: LDPHC pile; flexural strength; shear strength; ultimate strength design method

1. Introduction

Soil has characteristics such as high moisture content, high voids, high settlement, and low load-bearing capacity (Maedeh *et al*. 2018). Therefore, it may not be possible for soil to meet engineering design requirements as a natural foundation system (Canakci and Hamed 2017, Ghiasi and Mobin 2018, Zhou *et al*. 2018). As a safe foundation, it needs to be treated to improve its stability and load-bearing capacity. A PHC (prestressed high strength concrete) pile foundation is characterized by having a high pile load bearing capacity, reliable stability, good penetration, and low construction cost. Because of these advantages, the PHC pile foundation has been mainly applied to heavy infrastructures and high-rise buildings in the Republic of Korea. PHC pile was introduced from Japan in 1992 and began to replace existing PC piles (Choi 2002). In the early 1990s, small-diameter piles of 300 to 400 mm were used, and then mid-diameter piles of 500 to 600 mm in diameter were mainly applied since the 2000s.

Recently, a large diameter PHC pile of 700 mm ~ 1200 mm has been applied to construction sites, which can resist heavy static loads in mega-construction systems. However, it has been reported that PHC pile used in soft soil strata could be seriously damaged by lateral loadings because the flexural and shear strength and ductility of PHC pile is lower than those of steel pile. Kisida *et al*. (1998) investigated the shear strength of PHC pile with large diameter experimentally and analytically. In their studies, the effects of prestressing force, shear span to depth ratio (a/d), axial force, and thickness to diameter ratio (t/d) were investigated. Moreover, they reported that brittle failure with small deformation in the large diameter PHC pile by the lateral loading was observed. Mitsuyoshi (2012) also reported that the brittle failure of the PHC pile by the shear failure of concrete could occur when the flexural strength of the PHC pile is increased. Therefore, sufficient flexural strength as well as shear strength simultaneously should be ensured for the PHC pile when PHC pile is used to soft soil.

Most PHC piles are secondary concrete products manufactured at the factory through precast casting and steam curing. The common way to increase the flexural and shear strength of the PHC pile is to increase the compressive strength of the concrete used for PHC pile and area of prestressing tendons, the dimension of the pile. However, Ozden (2009) reported that the increase in the reinforcement area or the dimension of the pile may not be a proper precautionary measure to resist the heavy lateral loads. Therefore, it is necessary to study for verifying the

*Corresponding author, Professor
E-mail: yunkim@cnu.ac.kr
[a]Manager
E-mail: best6516@naver.com
[b]Professor
E-mail: bylee@jnu.ac.kr

ISSN: 1598-8198 (Print), 1598-818X (Online)

Fig. 1 Reinforcement of LDPHC pile

structural integrity of PHC pile. In order to overcome this problem, Bang *et al*. (2014a) suggested a novel reinforcement system of the conventional PHC pile with a diameter of 500 mm. In order to improve the flexural strength of the pile without changing the dimension of the pile, longitudinal reinforcement was reinforced in the hollow area of the PHC pile, and shear strength also was increased through infilled concrete and transverse reinforcement. The transverse reinforcement was designed not only to contribute to the increase of shear strength but also to serve as a shear connection between the interface of the infilled concrete and the PHC pile concrete. Bang *et al*. (2014b) investigated the cyclic behavior of connection between the PHC pile reinforced by infilled concrete and transverse reinforcement and footing. Test results showed that the reinforced PHC pile-footing connection has improved cyclic performance in terms of ductility, load carrying capacity, stiffness, and energy dissipation capacity compared to the conventional PHC pile-footing connection. The purpose of this study is to provide an experimental and analytical investigation on the flexural and shear behavior of a large diameter pre-tensioned high strength concrete (LDPHC) pile reinforced with infilled concrete, longitudinal rebar, and transverse rebar.

2. Materials and fabrication specimens

2.1 Materials

2.1.1 LDPHC pile

Concrete with a compressive strength of 80 MPa was used for the main body of the LDPHC pile. Prestressing tendons with a tensile strength of 1,450 MPa and a diameter of 11.2 mm were used in the LDPHC pile. The initial prestressing stress was 70% of the yield strength of the tendon, and it was applied before the concrete casting process. The rebar with a yield strength of 400 MPa and a diameter of 16 mm was used as a transverse rebar. Fig. 1 shows the installation of transverse rebar. The shape of the transverse rebar was hexagonal, and the effective spacing between the transverse rebars was 150 mm. The diameter and thickness of the LDPHC pile was 1,000 mm and 130 mm, respectively.

2.1.2 Longitudinal rebar and infilled concrete

The deformed rebar with a yield strength of 400 MPa and a diameter of 29 mm was used as a longitudinal rebar to increase the flexural capacity of the LDPHC pile. The longitudinal rebars were installed inside the hollow area of the LDPHC pile. The stirrup with a diameter of 10 mm was used to keep the position of longitudinal rebars. Highly workable concrete with a slump value of 210 mm and a compressive strength of 27 MPa was used for infilled concrete in order to avoid aggregate segregation. The mixture proportion of the concrete was determined based on the procedure described in KS F 4009. Ordinary Portland Cement was used for the infilled concrete. A crushed sand and coarse aggregate with a maximum size of 19 mm were used as aggregates.

2.2 Manufacturing specimen

The LDPHC pile specimens were fabricated through the first stage, in which transverse reinforcing bars were arranged in the pile, and the second stage, in which LDPHC pile was reinforced with infilled concrete and longitudinal rebar. For the first stage of the fabricating process, a total of nineteen prestressing tendons were fixed in the cage, followed by the hexagonal shaped transverse rebar fixed in a cage with effective spacing of 150 mm. The cage setup was then placed in the mold and the mold was filled with a high strength concrete. After placing the concrete, prestressing force was applied to the tendons, and centrifugal force was applied. All specimens were subjected to steam curing for 12 hours. After steam curing, the LDPHC pile was removed from the mold, and it was subsequently cured under air dry conditions. After the first step, the LDPHC piles were placed in a vertical position, and sixteen longitudinal rebars were installed inside of the LDPHC pile. The hollow portion of the LDPHC pile was filled with concrete, and the concrete was compacted using a vibrator. The R-LDPHC piles were then cured for 28 days under air dry conditions. All R-LDPHC piles have a diameter of 1,000 mm. Two R-LDPHC pile specimens with a length of 10,000 mm were prepared for bending tests, and two R-LDPHC pile specimens with a length of 7,000 mm were prepared for shear tests.

2.3 Experimental program

2.3.1 Bending test

In order to evaluate the flexural capacity of the R-LDPHC piles, four-point bending tests were performed in accordance with KS F 4306. Fig. 2 shows the test setup. A hydraulic jack with a capacity of 10,000 kN was used to apply the vertical load to the specimen, and the load was applied at a loading rate of 1.0 mm/min under the displacement control. Two linear variable-differential

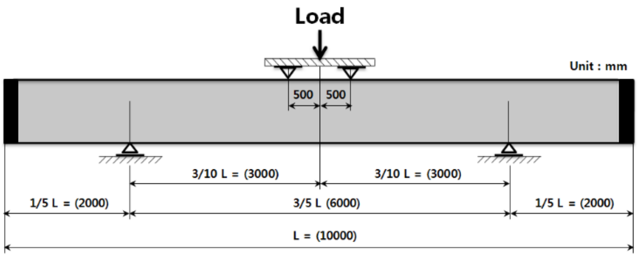


Fig. 2 Flexural bending setup

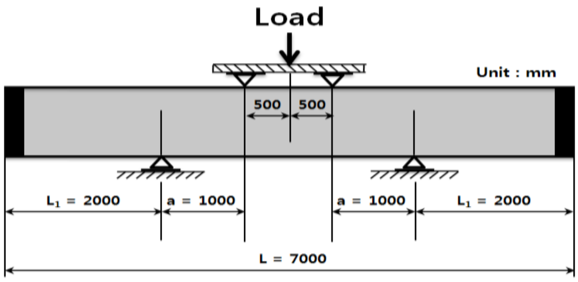


Fig. 3 Shear test setup

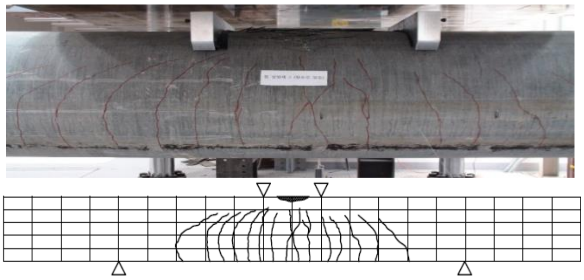


Fig. 4 Cracks pattern of R-LDPHC pile

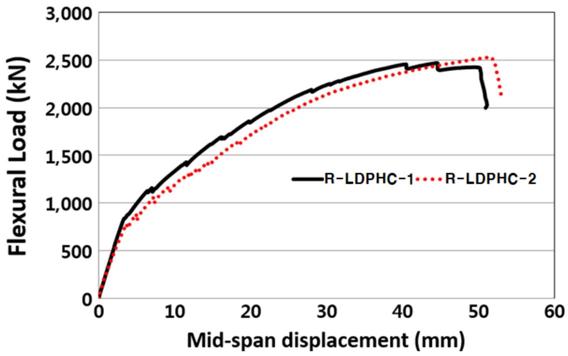


Fig. 5 Relationship between the flexural load and the mid-span deflection

transducers (LVDTs) were installed at the bottom center of the specimen to measure the mid-span deflection of the specimen. All data including load and displacement were recorded using the data acquisition system. Cracking and failure patterns were observed during the test.

The flexural strength of the R-LDPHC piles were obtained from Eq. (1) as follows.

$$M = \frac{W_{LDPHC}+W_{con}}{40}L + \frac{P_v}{4}\left(\frac{3}{5}L - 1\right) \tag{1}$$

where, W_{LDPHC} and W_{con} are weights of LDPHC pile and infilled concrete, respectively. L and P_v are the length of the specimen and the maximum vertical load, respectively.

2.3.2 Shear test

According to the shear testing method recommended in KS F 4306, the shear test was performed until failure and the experimental setup is shown in Fig. 3. A hydraulic jack with a capacity of 10,000 kN was used to apply the vertical load to the specimen, and the loading rate was maintained as 1.0 mm/min displacement. The mid-span deflection of the specimen was measured through two LVDTs which were installed at the bottom center of the specimen. The shear strength of specimen was calculated from Eq. (2).

$$Q_c = \frac{P_c}{2} \tag{2}$$

where, Q_c is shear strength of the piles, and P_c is maximum vertical load.

3. Experimental test results

3.1 Flexural behavior

The initial cracks in the specimen were developed at the 774.3 kN loading level. After the initial cracking state, the number of flexural cracks as well as the width of the cracks increased. However, no shear crack was observed in the R-LDPHC pile, which could be due to the presence of the transverse rebar. Loading further, the specimen failed by crushing the concrete at the top compressive zone of specimens. Fig. 4 shows the failure mode and the crack pattern of the specimen. As shown in Fig. 4, no shear cracks are observed and the width of flexural-shear cracks was effectively controlled. The transverse rebar prevented the shear crack of the specimen, and the longitudinal rebar increased the compressive zone area which led to an increase in the compressive force of the concrete. Fig. 5 shows the relationship between the flexural load and mid-span displacement. All specimens exhibited flexible flexural behavior up to maximum load after initial cracking as the load increased. The maximum flexural load was measured at an average of 2,499 kN.

3.2 Shear behavior

The initial flexural crack was observed in the mid-span of the specimen at the load of 2,297 kN and 2,040 kN, respectively. Loading further, a few more shear cracks were observed across the specimen, consequently, the flexural cracks were propagated upwards with steeper inclination. A few shorter cracks were also observed near the supports at higher loading and propagated upwards with gentle inclination. At higher loading, it was observed that the bending cracks open widely. In the fractured state, the specimen showed a fewer number of cracks and exhibited a very symmetric crack distribution, which is shown in Fig. 6. It can be inferred that the installation of the transverse rebar effectively controlled the development of shear cracks opening and consequently leads to an increase in the shear capacity of the high flexural capacity R-LDPHC pile.

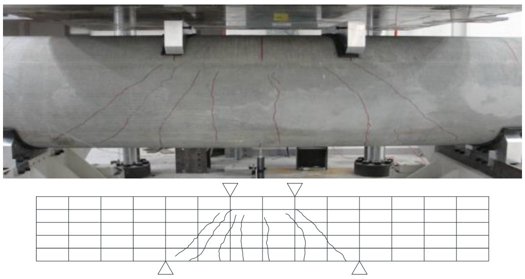


Fig. 6 Cracks pattern of R-LDPHC pile

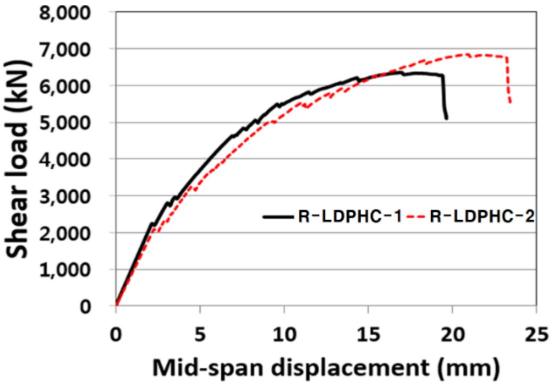


Fig. 7 Relationship between the shear load and the mid-span deflection

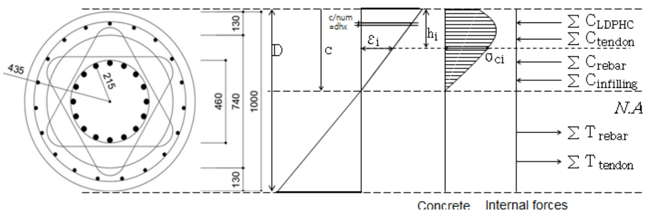


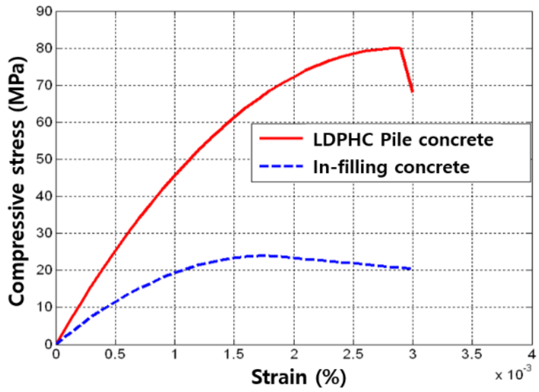
Fig. 8 Schematic diagram of layered sectional approach for nonlinear analysis

Fig. 7 shows the relation curve between the shear load and mid-span deflection. After the initial crack load, the maximum load of 6,467 kN and 6,830 kN was measured without abrupt fracture with increasing load. The transverse rebar installed in the LDPHC pile prevented abrupt fractures occurring and contributed to the increase of shear resistance. The shear strength of the LDPHC pile calculated based on Eq. (2) is 3,234 kN and 3,415 kN, respectively. It can be seen that the experimental average shear strength was 1.32 times higher than the design shear strength.

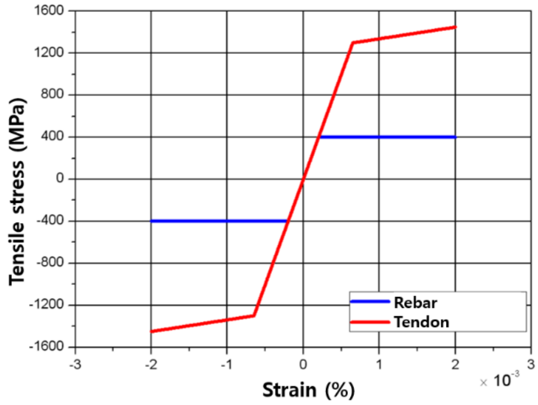
4. Analytical investigation of R-LDPHC pile

4.1 Flexural strength

The nonlinear analysis based on a layered section approach was performed to analyze theoretically the moment-curvature curve and nominal axial compression and bending moment (P-M) interaction of the R-LDPHC pile and to investigate effects of infilled concrete and the reinforcement of the longitudinal rebar on the P-M interaction behavior. Fig. 8 shows the schematic diagram of



(a)



(b)

Fig. 9 Stress and strain curves of materials; (a) LDPHC pile concrete and infilled concrete and (b) Rebar and tendon

the layered sectional approach for nonlinear analysis and Fig. 9 shows the relation curves between stress and strain of materials used in this study for the analysis. The initial prestressing force of tendons was taken into account in the analysis. Fig. 10 indicates the flow chart of nonlinear section analysis.

The maximum axial compressive force (P_0) of the R-LDPHC pile was calculated by Eq. (3).

$$P_0 = \sigma_{LDPHC}(\varepsilon_{LDPHCini} + \varepsilon_\Delta)A_{LDPHC} + \sigma_t (\varepsilon_{tTENDONini} + \varepsilon_\Delta)A_t + \sigma_c(\varepsilon_\Delta)A_c + \sigma_s(\varepsilon_\Delta)A_s \quad (3)$$

where, $\varepsilon_{LDPHCini}$ and ε_Δ are an initial strain of pile concrete and a strain of infilled concrete and longitudinal rebar corresponding to the maximum axial compression, respectively. $\sigma_{LDPHC}(\varepsilon_{LDPHCini} + \varepsilon_\Delta)$ is a stress of pile concrete when the strain of LDPHC concrete is a strain of $\varepsilon_{LDPHCini} + \varepsilon_\Delta$. A_{LDPHC} is a total area of pile concrete. $\varepsilon_{tTENDONini}$ and $\sigma_t(\varepsilon_{tTENDONini} + \varepsilon_\Delta)$ are an initial strain of the tendon and a stress of the tendon when the strain of the tendon reaches $\varepsilon_{tTENDONini} + \varepsilon_\Delta$, respectively. A_t is a total area of tendons. $\sigma_c(\varepsilon_\Delta)$ is a stress of infilled concrete corresponding to a strain of ε_Δ, and A_c is an area of infilled concrete. $\sigma_s(\varepsilon_\Delta)$ is a stress of longitudinal rebar corresponding to a strain of ε_Δ, and A_s is a total area of longitudinal rebar. An axial force (P) was assumed and an initial neutral axis (c) is assumed to be positioned at the center of the pile. The internal force in the R-LDPHC pile was calculated using Eq. (4).

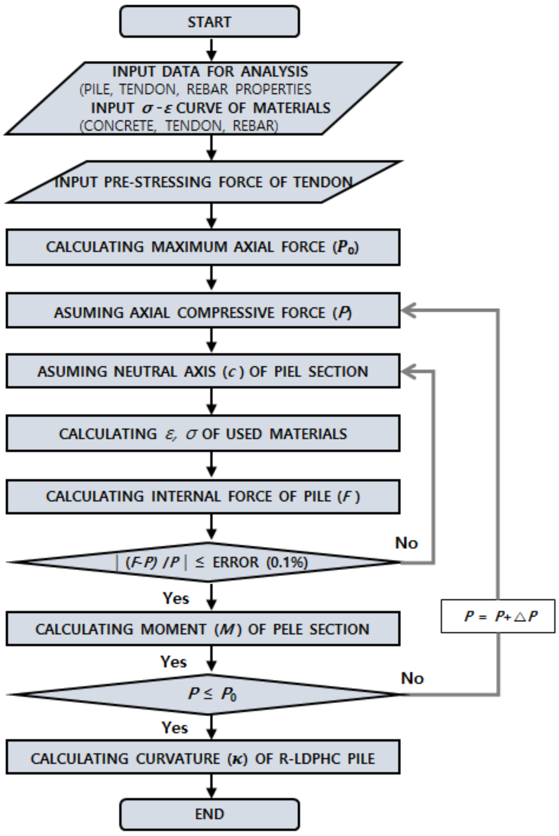


Fig. 10 Flow chart of nonlinear section analysis

$$F = \int_0^D [\sigma_{LDPHC}(\varepsilon(h_i)) \times w_{LDPHC}(h_i) + \sigma_{tendon}(\varepsilon(h_i)) \times w_{tendon}(h_i) + \sigma_c(\varepsilon(h_i)) \times w_c(h_i) + (\varepsilon(h_i)) \times w_s(h_i)]dh_i \tag{4}$$

where, D is a diameter of LDPHC pile, h_i is a distance of neutral axis from the compressive zone of the pile concrete, and $\varepsilon(h_i)$ is a strain corresponding to the h_i. The w_{LDPHC}, w_{tendon}, w_c, and w_s are the width of used materials corresponding to the h_i. The neutral axis was adjusted by a force equilibrium between an internal force and an external force. The allowable error was set to be 0.1%. Based on the calculated neutral axis (c_i) and the compressive strain (ε_{ci}) of pile concrete, a curvature (κ) can be obtained as shown in Eq. (5).

$$\kappa_i = \frac{\varepsilon_{ci}}{c_i} \tag{5}$$

The bending moment (M) was calculated based on Eq. (6) when the force equilibrium was satisfied, and the P increased. This process was repeated until an assumed P reaches P_0.

$$M = \int_0^D [\sigma_{PHC}(\varepsilon(h_i)) \times w_{PHC}(h_i) \times h_i + \sigma_{tendon}(\varepsilon(h_i)) \times w_{tendon}(h_i) \times h_i + \sigma_c(\varepsilon(h_i)) \times w_c(h_i) \times h_i + \sigma_s(\varepsilon(h_i)) \times w_s(h_i) \times h_i]dh_i \tag{6}$$

4.2 Shear strength

A total shear strength (V_n) of the R-LDPHC pile reinforced with transverse rebar and infilled concrete shall be calculated by Eq. (7) based on the ultimate strength design method.

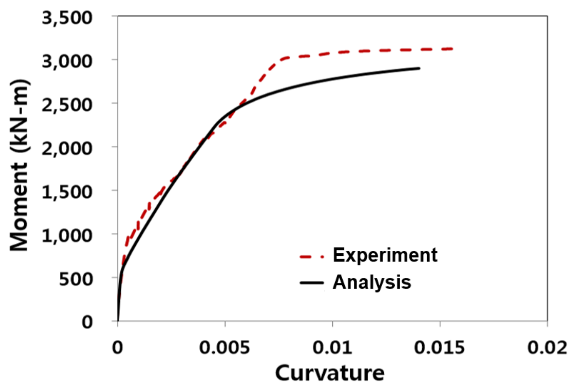


Fig. 11 Moment-curvature curves of R-LDPHC pile

$$V_n = V_{LDPHC} + V_c + V_s \tag{7}$$

The shear strength of R-LDPHC pile concrete (V_{LDPHC}) is calculated using Eq. (8) in accordance with KS F 4306 considering prestressed forces of the tendons.

$$V_{LDPHC} = \frac{2tI}{S_0} \times \frac{1}{2}\sqrt{(\sigma_{ce} + 2\phi\sigma_t)^2 - \sigma_{ce}^2} \tag{8}$$

where, t is a diameter of the LDPHC pile (mm), I is a transformed geometrical moment of inertia of pile concrete, S_0 is a transformed geometrical moment of pile concrete area, σ_{ce} is an effective prestressing force of pile concrete (3.92 MPa), σ_t is a tensile strength of LDPHC pile concrete (5.39 MPa), and the value of ϕ is 0.5.

The shear strength of infilled concrete (V_c) and transverse rebar (V_s) shall be computed by Eq. (9) and Eq. (10), respectively.

$$V_c = \frac{1}{6}\sqrt{f_{ck}}b_w d \tag{9}$$

$$V_s = \frac{A_v f_y d}{s} \tag{10}$$

where, f_{ck} is a compressive strength of infilled concrete, b_w is width of infilled concrete section, and d is an effective depth. A_v is a total area of the transverse rebar, f_y is a yielding strength of the transverse rebar, and s is a spacing between the transverse rebar.

4.2 Comparison between experimental and analytical results

Fig. 11 shows the moment-curvature curves of R-LDPHC pile specimen, and Table 1 compares the flexural loads between the experimental results and calculated predictions based on Eq. (6). The average difference of bending moment between the experimental results and calculated result was 10.5% at the ultimate state. Although the difference between the experimental and the analytical results was about 10% because of manufacturing conditions such as the concrete strength and the position error of the longitudinal rebar, the analysis based on the P-M interaction and moment curvature can consider the effect of infilled concrete and reinforcements of LDPHC pile and flexural

Table 1 Comparison of the moment-curvature results

Specimens	Experimental maximum bending moment		Calculated pure bending moment		Difference
	Flexural load (kN)	Bending moment (kN·m)	Flexural load (kN)	Bending moment (kN·m)	Bending moment (%)
Conventional LDPHC pile (Bang *et al.* 2014)	1089.1	1,365	962.2	1,206	13.2
R-LDPHC-B1	2,491	3,161	2,262	2,870	10.1
R-LDPHC-B2	2,506	3,181			10.8

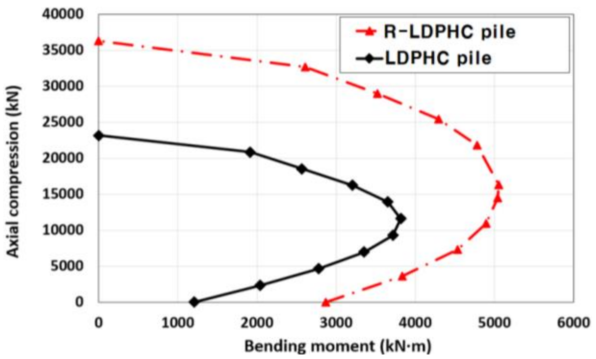


Fig. 12 Theoretical P-M interaction of pile specimens

Table 2 Analytical bending moment of pile specimens

	Designed bending moment results of reinforcing materials (kN·m)				
	LDPHC pile body	Tendons	Infilled concrete	Longitudinal rebar	Total
Conventional LDPHC pile	1,098	108	-	-	1,206
R-LDPHC pile	2,310	148	81	331	2,870

behavior effectively.

Fig. 12 shows the theoretical P-M interaction curves for conventional LDPHC pile and R-LDPHC pile, and analytical bending moment values of pile specimens are listed in Table 2. The pure bending moment values of the LDPHC pile and R-LDPHC pile designed by P-M interaction are 1,206 kN·m and 2,870 kN·m, respectively. Based on the design results, it is predicted that the reinforcement using infilled concrete and longitudinal rebar can improve the pure bending moment of the conventional LDPHC pile by 238%. The contribution of each reinforcing material to the flexural strength of R-LDPHC pile was calculated as 81% for the LDPHC pile body, 5% for the tendons, 3% for the infilled concrete, and 12% for the longitudinal rebar. Analytical results indicate that the longitudinal rebar and the infilled concrete independently contribute to the increase of the flexural strength. This is attributed the fact that the installed reinforcing materials keep the neutral axis of the pile significantly close to the centroidal axis of the pile, and increase the compression zone of the conventional LDPHC pile.

The shear strength design results of R-LDPHC pile based on Eq. (7) are summarized in Table 3. The shear strength of the LDPHC pile body was calculated to be 766 kN. From the design results, it was found that the shear strength of LDPHC pile body can be increased by about 3.28 times by reinforcing with concrete and rebar. Among the increased shear strength of 1,748 kN, infilled concrete and transverse rebar contribute 23.2% and 76.8% to the increased shear strength, respectively.

Table 3 Shear strength result of pile specimen

	Shear strength design results of reinforcing materials (kN)			
	LDPHC pile body	Infilled concrete	Transverse rebar	Total
R-LDPHC pile	766	406	1,342	2,514

5. Conclusions

This current paper conducted experimental and numerical analysis studies on the shear and flexural characteristics of R-LDPHC pile reinforced with transverse and longitudinal rebar and infilling concrete and made comparisons with conventional LDPHC pile. A series of shear and bending specimens were manufactured, and structural tests and sectional analysis for shear and flexural strength enhancement were performed to evaluate the effect of reinforcement. Based on the result the following conclusions were reached.

• The presence of the longitudinal and transverse rebar contributed to the flexural behavior of LDPHC pile by controlling the width of the flexural-shear cracks and enhancing the shear strength capacity under high flexural strength state after the initial cracking of the LDPHC pile. The installed transverse rebar in the R-LDPHC pile prevents the shear failure of the LDPHC concrete and yields a symmetric crack pattern; in addition, the crack width was also very small.

• Using a conventional layered sectional approach, the numerical analysis was performed to predict the theoretical strength capacity of the R-LDPHC pile. From the results, it was found that the reinforcement using infilled concrete and longitudinal rebar increases the flexural capacity of LDPHC pile. As a result, the flexural strength of the R-LDPHC pile with reinforcing materials was increased by 231% compared to the conventional LDPHC pile. The average difference of flexural strength between experimental results and calculated result by nonlinear analysis was 10.5% at the ultimate state.

• By reinforcing LDPHC pile with infilled concrete and rebar, the shear strength of LDPHC pile can be increased 3.28 times higher than that of conventional LDPHC pile. Among the increased shear strength of 1,748 kN, infilled concrete and transverse rebar contribute 23.2% and 76.8% to the increased shear strength, respectively.

• Reinforcing the LDPHC pile with longitudinal rebar and transverse rebar and infilled concrete can effectively improve the flexural and shear strength that is similar to previous studies but without increasing the dimension of the pile.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science and ICT (No. 2015R1A5A1037548).

References

Akiyama, M., Abe, S., Aoki, N. and Suzuki, M. (2012), "Flexural test of precast high-strength reinforced concrete pile prestressed with unbonded bars arranged at the center of the cross-section", *Eng. Struct.*, **34**, 259-270. https://doi.org/10.1016/j.engstruct.2011.09.007.

Bang, J.W., Hyun, J.H., Lee, B.Y. and Kim, Y.Y. (2014b), "Cyclic behavior of connection between footing and concrete-infilled composite PHC pile", *Struct. Eng. Mech.*, **50**(6), 741-754. https://doi.org/10.12989/sem.2014.50.6.741.

Bang, J.W., Lee, B.Y., Lee, B.J., Hyun, J.H. and Kim, Y.Y. (2014a), "Effects of infilled concrete and longitudinal rebar on flexural performance of composite PHC pile", *Struct. Eng. Mech.*, **52**(4), 843-855. https://doi.org/10.12989/sem.2014.52.4.843.

Canakci H. and Hamed M. (2017), "Experimental study on axial response of different pile materials in organic soil", *Geomech. Eng.*, **12**(6), 899-917. https://doi.org/10.12989/gae.2017.12.6.899.

Choi, S.S. (2002), "A suggestion of high quality concrete for PHC pile", *J. Korea Concrete Inst.*, **14**(6), 41-48.

Ghiashi, V. and Moradi, M. (2018), "Assessment the effect of pile intervals on settlement and bending moment raft analysis of piled raft foundations", *Geomech. Eng.*, **16**(2), 187-194. https://doi.org/10.12989/gae.2018.16.2.187.

Gurkan, O. and Cihan, T.A. (2009), "Lateral load response of steel fiber reinforced concrete model piles in cohesionless soil", *Constr. Build. Mater.*, **23**, 785-794. https://doi.org/10.1016/j.conbuildmat.2008.03.001.

Kishida, S. (1998), "Experimental study on shear strength of the phc pile with large diameter", *J. Struct. Constr. Eng.*, **510**, 123-130.

KS F 4009 (2016), Ready-Mix Concrete Design, Korea.

KS F 4306 (2014), Pre-Tensioned Spun High Strength Concrete Piles, Korea.

Maedeh, P.A., Wu, W., da Fonseca, A.V., Irdmoosa, K.G., Acharya, M.S. and Bodaghi, E. (2018), "A new approach to estimate the factor of safety for rooted slopes with an emphasis on the soil property, geometry and vegetated coverage", *Couple. Syst. Mech.*, **3**(3), 269-288. https://doi.org/10.12989/acd.2018.3.3.269.

Mitsuyoshi, A., Satoshi, A., Nao, A. and Motoyuki, S. (2012), "Flexural test of precast high-strength reinforced concrete pile prestressed with unbonded bars arranged at the center of the cross-section", *Eng. Struct.*, **34**, 259-270. https://doi.org/10.1016/j.engstruct.2011.09.007.

Zhou, C., Chen, A. and Zhang, B. (2018), "Composite foundation bearing characteristics of PHC pile", *Adv. Eng. Res.*, **170**, 251-255. https://doi.org/10.2991/iceep-18.2018.43.

HK