Structural Engineering and Mechanics, *Vol. 50, No. 6 (2014) 741-754*
DOI: http://dx.doi.org/10.12989/sem.2014.50.6.741

Cyclic behavior of connection between footing and concrete-infilled composite PHC pile

Jin-Wook Bang[1a], Jung Hwan Hyun[1b], Bang Yeon Lee[2c] and Yun Yong Kim[*1]

[1]*Department of Civil Engineering, Chungnam National University, 220 Gung-dong Yuseong-gu, Daejeon, 305-764, Republic of Korea*
[2]*School of Architecture, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju, 500-757, Republic of Korea*

(Received November 11, 2013, Revised March 26, 2014, Accepted April 3, 2014)

Abstract. The conventional PHC pile-footing connection is the weak part because the surface area and stiffness are sharply changed. The Composite PHC pile reinforced with the transverse shear reinforcing bars and infilled-concrete, hereafter ICP pile, has been developed for improving the flexural and shear performance. This paper investigates the cyclic behavior and performance of the ICP pile-footing connection. To investigate the behavior of the connection, one PHC and two ICP specimens were manufactured and then a series of cyclic loading tests were performed. From the test results, it was found that the ICP pile-footing connection exhibited higher cyclic behavior and connection performance compared to the conventional PHC pile-footing connection in terms of ductility ratio, stiffness degradation and energy dissipation capacity.

Keywords: PHC pile; transverse shear reinforcing bar; cyclic behavior; pile-footing connection

1. Introduction

Foundation piles such as hollow pre-tensioned spun high-strength concrete (PHC) pile, steel pipe pile and reinforced concrete pile play an important role in securing stability of the structure as they transfer large superstructure loads through deeper soils (Meyerhof 1976, FHWA 2006, Iskander and Hassan 1998). In particular, PHC piles have continuously made quantitative and qualitative growth, since it was firstly introduced in 1992, and more than 4 million tons of PHC have been applied to the construction sites in the early 2,000's in Korea. At present, they account for 99.5% of the concrete based piles (Chun *et al*. 2010). PHC piles are manufactured by centrifugal casting method and prestressed by high strength reinforcing steel bars, which results in excellent resistance to bending, compression and impact (JIS A 5335). Therefore, PHC piles can be applied to hard ground. In addition, PHC piles are economical and have higher corrosion

∗Corresponding author, Associate Professor, E-mail: yunkim@cnu.ac.kr
[a]Ph.D. Candidate, E-mail: best6516@cnu.ac.kr
[b]Ph.D. Candidate, E-mail: mildface@cnu.ac.kr
[c]Assistant Professor, E-mail: bylee@jnu.ac.kr

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

resistance compared to steel pipe piles (Choi 2002).

The application of PHC piles, however, is constrained in the cases of civil structure where the high shear force is required, such as abutments, because the shear force of PHC piles is 1/5-1/4 of that of steel pipe piles (Song 2008). Concrete infill was one of the most well-known strengthening methods, particularly improving the stability and load-carrying capacities of hollow piles (Mirmiran *et al*. 2002, Guades *et al*. 2012, Kishida *et al*. 2000). Hyun *et al*. (2012), Bang *et al*. (2013) has developed the composite PHC pile reinforced with the transverse shear reinforcing bars and infilled-concrete, hereafter ICP pile, for the improvement of strength and deformation capacity in the shear, flexure and compression compared to the conventional PHC piles. The pile foundation is mainly composed of three elements: the main pile body, the pile-footing connection, and the footing. These three elements should be safely designed with respect to the external loads including the axial force, bending moment, and shear force. Particularly, the pile-footing connection, which transfers footing loads through pile body, is critical because the sudden area and stress change occurs in the region. Hence, it should not only have sufficient load transferring capacity but also satisfy the ductility and the energy dissipation capacity with regard to the cyclic load. For these purposes, the rigid connection between pile and footing is recommended. The Korean Highway Bridge Design Code (2008) suggests two connection methods for rigid connection. In Method A, the pile is inserted into the footing with the depth of pile diameter. In Method B, the pile is inserted minimum 100 mm into the footing with longitudinal reinforcing bars placed in hollow section of the pile for the purpose of pile head reinforcement. In both methods, the footing concrete is placed into the hollow section of the pile. However, there have been only few studies on the structural behavior of connection between pile and footing.

Therefore, the objective of this study is to investigate the pile-footing connection performance, hereafter connection performance, which is represented by load-carrying capacity, ductility (deformation capacity), stiffness degradation and energy dissipation capacity of the PHC pile and ICP pile. A series of cyclic tests under cyclic lateral load was performed to investigate the connection performance and the effects of transverse reinforcing bar installed in the pile on the connection performance were discussed. This study would provide basic data for on-site application.

2. Manufacturing specimen and experimental program

In this study, cyclic load tests were performed in order to evaluate the structural behavior of the connection between the ICP piles and the footing, developed by increasing the shear resistance capacity of PHC piles having weak shear performance. Specimens were manufactured using the conventional PHC piles without transverse shear reinforcing bars in order to compare and evaluate the effect of the ICP piles on the performance of the connection. Fig. 1 shows the manufacturing processes of the PHC and ICP pile. A stage in the process of installation of transverse shear reinforcing bars was added in the manufacturing processes of the PHC pile before the concrete placement. After the concrete placement, the remaining processes are identical to the process of PHC pile. The pile head reinforcing was designed by the rigid connection Method B so that the pile could be fixed on the footing according to the Korean Highway Bridge Design Code (2008). Fig. 2 shows comparative schematics of pile-footing connection between PHC and ICP pile. Both piles are inserted into the footing, and then the footing concrete is placed into the hollow section of the pile down to the required depth. Due to the presence of transverse shear rebar, ICP pile is

(a) Preparation of the spiral steel cage (in case of PHC and ICP)

(b) Installation of shear reinforcing bar (in case of ICP)

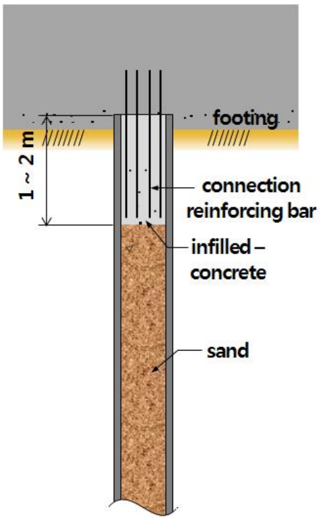
(c) Concrete placement

(d) Prestressing

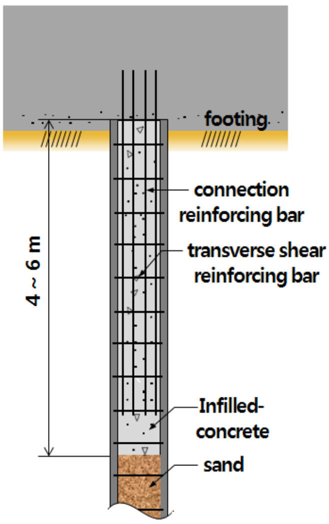
(e) Centrifugal casting

(f) Curing

Fig. 1 Manufacturing procedures of PHC and ICP pile



(a) Conventional PHC pile



(b) ICP pile

Fig. 2 Comparative schematics of pile-footing connection between conventional PHC and ICP pile

Table 1 Physical properties of PHC pile (φ450-70t)

	Diameter (mm)	Thickness (mm)	Compressive strength (MPa)	Effective prestress (MPa)	Transformed sectional area (mm2)
PHC pile	450	70	86.8	4.0	86,13

Table 2 Physical properties of concrete

	Specified slump (mm)	Maximum size of coarse aggregate (mm)	Compressive-strength (MPa)
Concrete	120	20	25.3

Table 3 Physical properties of reinforcing bars

	Nominal diameter (mm)	Nominal section area (mm2)	Tensile strength (MPa)	Yield strength (MPa)
D10	9.53	71.33	618	505
D19	19.1	286.5	601	483
D22	22.4	387.1	607	492

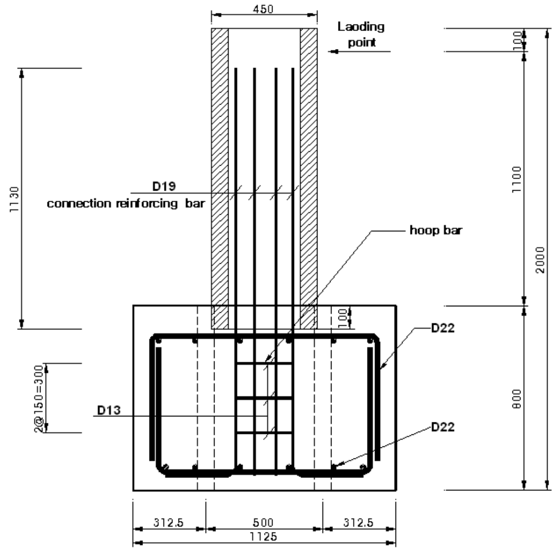
expected to provide enhanced composite action between PHC pile and infilled-concrete, compared to conventional PHC pile.

2.1 Material

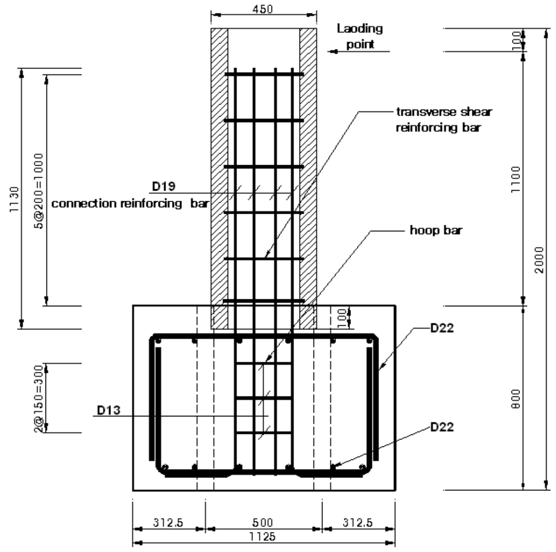
The specifications of PHC pile used for the manufacture of the pile-footing connection specimens in this study are listed in Table 1. The concrete with the compressive strength of 80 MPa was used and prestressing was applied to the concrete with eight high strength reinforcing steel bars with the nominal diameter of 8.2 mm, and the tensile strength of 1,450 MPa. The D10 deformed reinforcing bars were installed before placing the concrete in the PHC pile manufacturing procedure as transverse shear reinforcing bars for manufacturing the ICP piles. The concrete from the same batch was used for the infilled-concrete and the footing. The physical properties of the concrete are listed in Table 2. The D22 and D19 deformed reinforcing bars were used for the footing and the connection between the pile and footing, respectively, and their physical properties are listed in Table 3.

2.2 Manufacture of the specimens

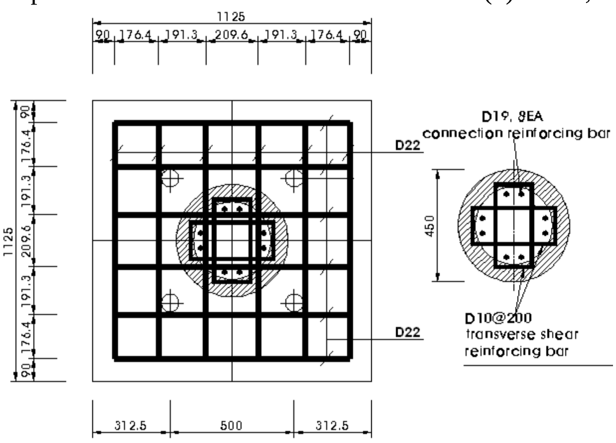
For the cyclic test of the pile-footing connection, one specimen of the conventional PHC piles (PHC-1) and two specimens of the ICP piles (ICP-1, ICP-2), in which transverse shear reinforcing bars were arranged, were manufactured. As shown in Fig. 3, the size of the footing was determined to be 800 mm in height and 1,125 mm×1,125 mm for providing embedment length of the connection reinforcing bars between the pile body and the footing. PVC pipes were inserted into the footing to install the bolts that fixed the cyclic loading test specimens to the strong floor. The pile height was determined to be 1,300 mm to satisfy the structural specification of the head part infilled-concrete placement depth specified in the Korean Highway Bridge Design Code (2008) Eight D19 deformed reinforcing bars were arranged in the pile head part, symmetrically two



(a) PHC-1 specimen



(b) ICP-1, 2 specimen



(c) Footing

Fig. 3 Configuration and dimension of the cyclic test specimens

reinforcing bars on each side. Three closed hoop bars with D13 deformed reinforcing bars were arranged in the 150 mm spacing in the footing of all specimens for fixing the connection reinforcing bars in the footing during concrete placement.

2.3 Experimental program

Fig. 4 shows the test set-up. For the practical purposes, the test setup represents an inverted orientation of the pile foundation. To provide cantilever-type loading conditions, the footing of each specimen was fixed to the strong floor in order to achieve full fixity at the base (Cho *et al*. 2012, Kim *et al*. 2012). Lateral loading without axial force on the piles was applied through a reaction wall equipped with a 500 kN capacity actuator according to a predetermined displacement-controlled loading sequence. Fig. 5 illustrates the unidirectional lateral displacement history followed in the testing specimens. The cyclic lateral load was controlled by the top-displacement of the pile. The specimens were equipped with a displacement transducer at the top of the pile to measure and control the lateral displacement of the pile. Two cycles at each step according to the drift ratio were programmed in order to evaluate the decrease of the strength and stiffness at the constant drift ratio. After the loading was over the maximum load, the test was finished when the load was less than 80% of the maximum lateral load.

As shown in Fig. 6, to measure the strain of the longitudinal connection reinforcing bars and evaluate the performance of the connection, a total of 8 steel gauges were attached to the reinforcing bars at the end, where the bending moment was the greatest, and the locations 100 mm, 200 mm, and 400 mm away from the footing. To measure the strain of the transverse shear reinforcing bars of ICP-1 and ICP-2 specimens, the two steel gauges were attached to them that were located the nearest to the footing and the direction of the steel gauges was the same with lateral loading direction.

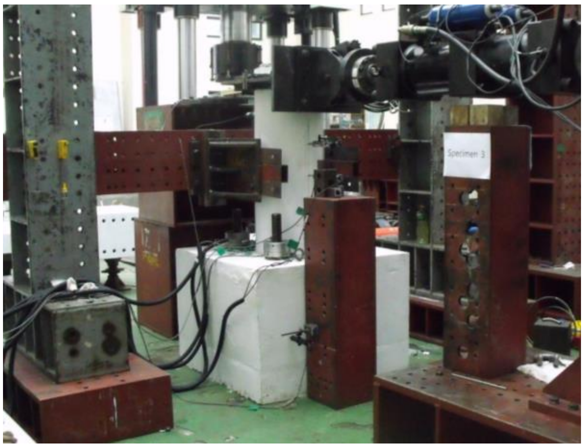


Fig. 4 Laboratory test set-up

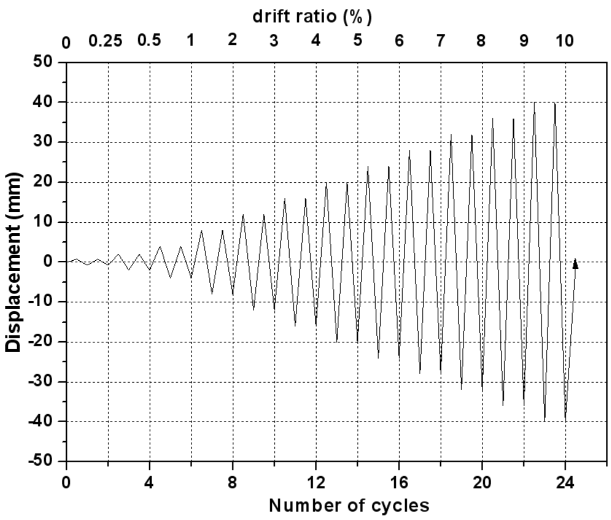
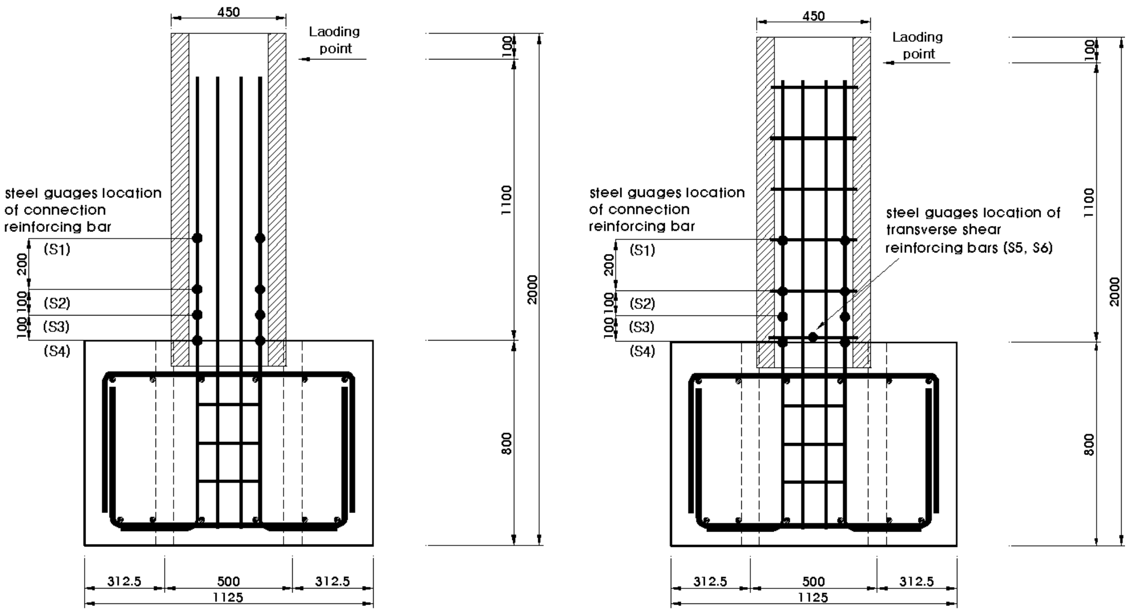


Fig. 5 Cyclic lateral loading history by displacement control



(a) PHC-1 specimen (b) ICP series specimen

Fig. 6 Reinforcing bar strain gauges locations

3. Results and discussion

3.1 Crack and failure patterns

Fig. 7 shows the cracking patterns of each specimen from the frontal view. The initial cracks in the concrete of the connection on the tensile side appeared for all specimens as the lateral load increased. As the cyclic loading continued, vertical and horizontal cracks and inclined cracks with respect to the axis of the member progressed from the end of the piles to the top. The width of the cracks in the connection gradually augmented according to the increase of the cyclic loading, and finally the connection failed.

For the specimen PHC-1 the first crack on the connection appeared at the load level of 0.5% drift ratio (four cycles). At the load level of 1% drift ratio (five cycles), the first crack at the bottom end of the main pile body appeared. Beginning with these cracks, X-shaped inclined cracks were observed with the vertical and horizontal cracks up to the point 900 mm away from the connection as the cyclic loading increased until the load level of 5% drift ratio (thirteen cycles). After thirteen cycles, the width of the cracks was notably increased and simultaneously, the PHC pile concrete was partially crushed. Then, the connection failed at the fifteenth cycle finally.

For the specimen ICP-1 and ICP-2 the first crack on the connection appeared at the load level of 0.5% drift ratio (four cycles) as the PHC-1 specimen. Thus, it seems that the transverse shear reinforcing bars did not significantly affect the cracking strength of connection. Unlike the PHC-1 specimen, the first crack at the bottom end of the main pile body appeared at the load level of 2.0% drift ratio (seven cycles). Until the load level of 5% drift ratio (fourteen cycles), concrete crushing as well as connection failure was not observed. The width of the cracks, the crack spacing, and the slope and length of the inclined cracks at each loading level were smaller than those of the PHC-1

(a) PHC-1 specimen

(b) ICP-1 specimen

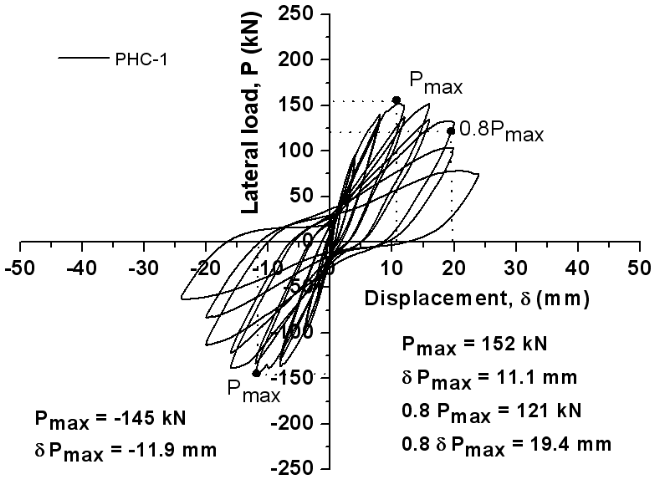
(c) ICP-2 specimen

Fig. 7 Crack and failure patterns of the each specimen

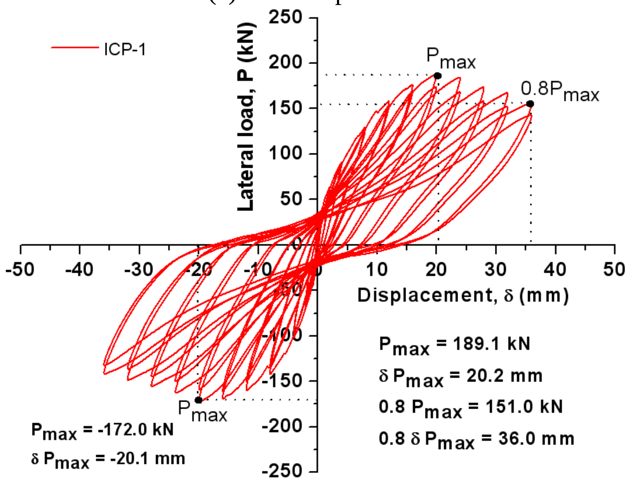
specimen, which means that the shear resistance capacity of ICP specimens was increased. The improved crack control performance is mainly attributed to the integrity of the outer pile concrete and the inner filled concrete such as a shear connector by the transverse shear reinforcing bars. The tests with the ICP series specimens were terminated at the load level of drift ratio 10% (twenty four cycles), at which the load was 80% of the maximum load. As shown in Fig. 7 (b) and (c), the two ICP specimens showed similar crack and failure patterns.

3.2 Load-displacement hysteresis

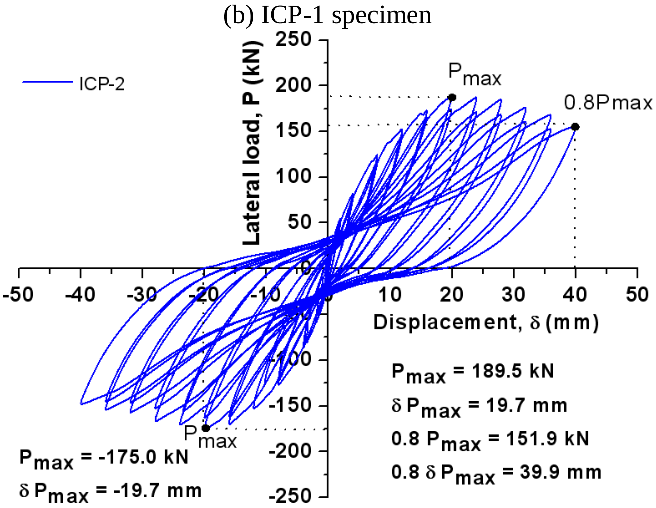
In order to evaluate the cyclic responses of the pile foundation under severe loading conditions



(a) PHC-1 specimen



(b) ICP-1 specimen



(c) ICP-2 specimen

Fig. 8 Lateral load and displacement hysteresis curve of the each specimen

Table 4 Cyclic loading test results of the each specimen

	Reinforcing bars yielding				80% of $P_{\max}$				Ductility ratio	
	Positive		Negative		Positive		Negative			
	P_y (kN)	δ_y (m)	P_y (kN)	δ_y (mm)	P_u (kN)	δ_u (m)	P_u (kN)	δ_u (mm)	Positive	Negative
PHC-1	151	11.9	146	12.1	121	19.4	116	14.9	1.63 (100%)	1.23 (100%)
ICP-1	159	11.9	160	12.1	151	36.0	138	35.9	3.02 (185%)	2.97 (241%)
ICP-2	153	11.8	154	12.8	152	39.9	140	40.1	3.38 (207%)	3.13 (254%)

such as earthquake, it is necessary to understand the cyclic performance characteristics of the pile foundation, such as ductility, energy dissipation capacity, strength deterioration, and stiffness degradation. Therefore, the hysteretic behavior of the members should be thoroughly investigated. Fig. 8 shows the load-displacement hysteresis curves of the individual specimens on the basis of the cyclic loading test results. The ductility and energy dissipation capacity of the individual specimens were quantitatively evaluated through the curves.

The PHC-1 specimen showed the maximum load of 152 kN (displacement: 11.1 mm) at the nine cycles. After that, it showed an abrupt load drop and then showed the load of 121 kN (displacement: 19.4mm), which is 80% of the maximum load, at the thirteen cycles. On the other hand, the ICP-1 and ICP-2 specimens showed the maximum load of 189.1 kN (displacement: 20.2mm) and 190 kN (displacement: 19.7mm), respectively, at the thirteen cycles (drift ratio: 5%). After that, the loads decreased gradually with the increase of drift ratio. The test was terminated when the loads were 80% of the maximum loads which were 151 kN (displacement: 36.0 mm) at twenty two cycles for ICP-1 specimen and 152 kN (displacement: 39.9 mm) at twenty three cycles for ICP-2. In comparison to the PHC-1 specimen, the ICP specimens could provide excellent cyclic responses in improving the load-carrying and deformation capacities of pile and connection during cyclic load reversals.

The envelop curve of each specimen as shown in Fig. 9 can be obtained from the lateral load–top displacement hysteretic behavior of each specimen and Table 4 provides a summary of the measured overall envelop responses of each specimen. The P_y and δ_y, which are the load and displacement when the connection reinforcing bars between pile and footing were yielded, denote the yielding load and corresponding yielding displacement, respectively. The 80% load of the maximum load was denoted as P_u, and the corresponding displacement was denoted as δ_u. The ductility ratio was denoted as δ_u/δ_y and the results are listed in Table 4. The ductility of ICP specimens were greatly improved approximately by 196% under the positive loading and by 247% under the negative loading compare to the PHC-1 specimen. From these test results, it was verified that the ductility of pile foundation can be improved by applying the ICP piles.

3.3 Stiffmess degradation characteristics

Fig. 10 shows the average stiffness value of each specimen for two cycles of each step. In all the specimens, the stiffness decreased with the increase of the loading cycle. The decrease in the stiffness is mainly attributed to the cracks in the connection and the pile body. The degree of the

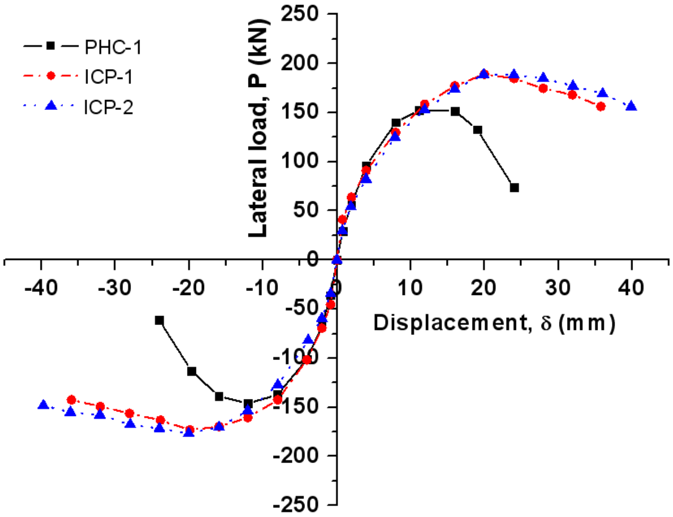


Fig. 9 Envelop curve of each specimen

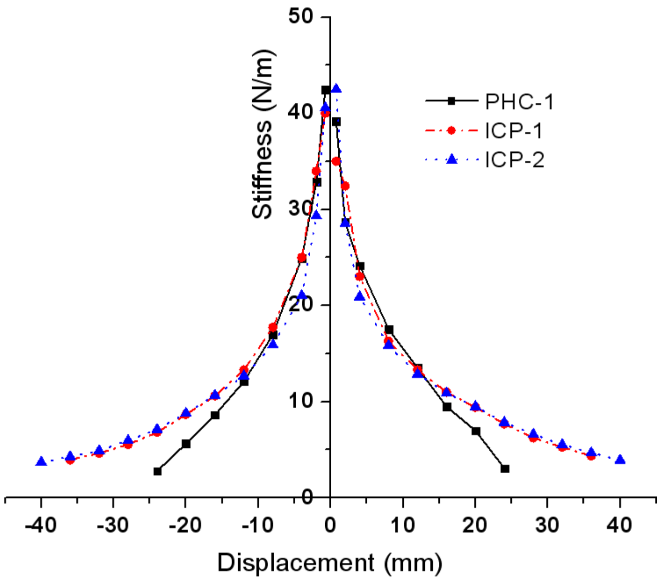


Fig. 10 Cyclic stiffness degradation of each specimen

stiffness degradation was similar for all the specimens before the yielding of the connection reinforcing bars (nine cycles (drift ratio: 3.0%)). After the yielding of the connection reinforcingbars, however, the stiffness of the PHC-1 specimen decreased abruptly, while the stiffness of ICP specimens was higher than that of the PHC-1 specimen for each of the loading cycle and decreased gradually. The stiffness of the ICP specimens was about 2.5 times higher than that of the PHC-1 specimen at fifteen cycles when the PHC-1 specimen failed.

3.4 Energy dissipation capacity

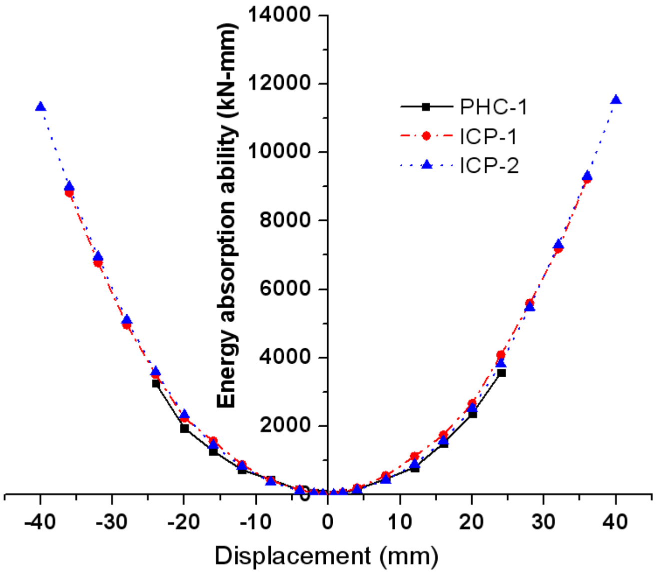


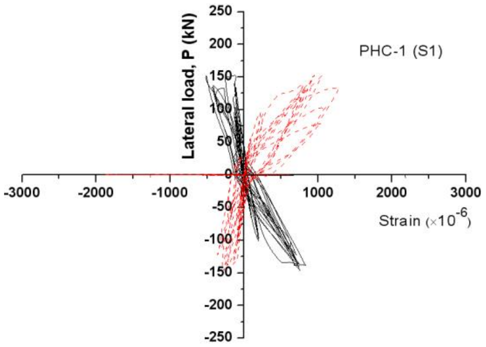
Fig. 11 Cumulative dissipated energy of each specimen

Fig. 11 shows the average value of cumulative dissipated energy calculated by integrating the area of the lateral load-displacement hysteresis curve of two cycles. The cumulative dissipated energy of the PHC-1 specimen was almost same with that of the ICP specimens until the cycle when the PHC-1 specimen failed. After that, the cumulative dissipated energy of the ICP specimens increased continuously until twenty cycles. The cumulative dissipated energy of the ICP specimens was approximately 2.9 times higher than that of the PHC-1 specimen when the test was terminated.

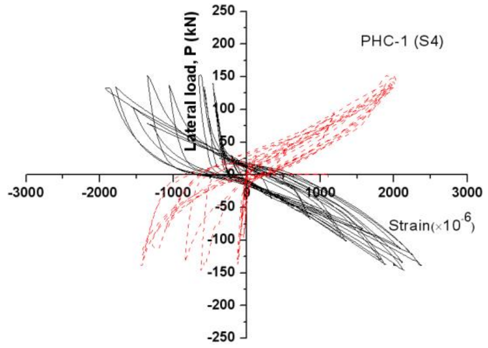
In the case of the hysteretic response of each specimen, in comparison to PHC-1, the ICP specimens showed improved and stable hysteretic responses in increasing the energy dissipation capacity and reducing the strength deterioration and stiffness degradation of the pile-footing connection during the reversed cyclic load.

3.5 Evaluation of the rebar strain

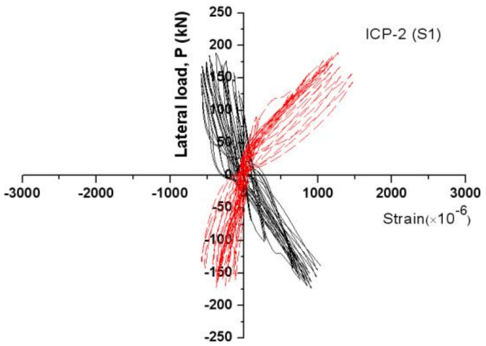
Fig. 12 shows the strain distribution of the connection reinforcing bars in the PHC-1 and ICP-2 specimens according to the lateral load. In both of the specimens, a greater strain was measured at the gauge closer to the pile-footing connection, and the strain increased as the lateral loading increased. Except the S1 gauge that was the farthest from the connection, the strain exceeded the yielding strain of 0.002 when the test was terminated. As expected, the strain of connection reinforcing bars of the ICP-2 specimen was higher than that of the PHC-1 at the same locations. This is mainly attributed to the higher deformation capacity and ductility of the ICP-2 specimen compared to the PHC-1 specimen. The strain of the transverse shear reinforcing bars in Fig. 12(e) also increased step by step as the lateral loading stage was increased, eventually reaching the yield strain. This indirectly verifies that the transverse shear reinforcing bars were sufficiently settled in the piles body and effectively combined between the piles body and the infilled-concrete.



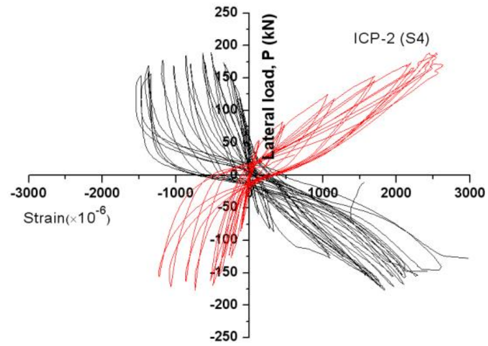
(a) PHC-1 (S1)



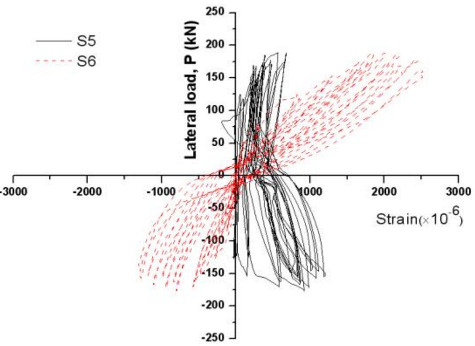
(b) PHC-1 (S4)



(c) ICP-2 (S1)



(d) ICP-2 (S4)



(e) ICP-2 (S5, S6)

Fig. 12 Measured reinforcing bar strains of the PHC-1 and ICP-2 specimen

4. Conclusions

This paper presents an experimental investigation on the cyclic behavior and connection performance of the PHC pile-footing connection and the ICP pile-footing connection. A series of cyclic loading test was performed to investigate the effects of transverse shear rebar installed in the pile on the connection performance such as ductility ratio, stiffness degradation and energy dissipation capacity. It was shown that the ICP specimens have the improved and stable hysteretic responses in terms of increasing the load-bearing capacity, ductility, energy dissipation capacity and reducing stiffness degradation during the reversed cyclic load compared to the PHC-1 specimen. Although the presence of transverse shear reinforcing bars does not affect the cracking strength of the connection between pile and footing, it was found that the transverse shear reinforcing bars decrease the width of the cracks, the crack spacing, and the slope and length of the inclined crack. From the strain distribution, it was indirectly verified that the transverse shear reinforcing bars were sufficiently settled in the piles body and effectively combined two elements, enhancing composite action between the hollow PHC pile and the infilled-concrete.

Acknowledgements

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology(No. 2011-0024924)

References

Bang, J.W., Hyun, J.H., Lee, B.Y., Lee, S.S. and Kim, Y.Y. (2013), “Flexural strength of PHC pile reinforced with infilled concrete transverse and longitudinal reinforcements”, *J. Korea Concrete Ins.*, **25**(1), 91-98.

Cho, C.G., Kim, Y.Y., Feoc, L. and Huid, D. (2012), “Cyclic responses of reinforced concrete composite columns strengthened in the plastic hinge region by HPFRC mortar”, *Compos. Struct.*, **94**(7), 2246-2253.

Choi, S.S. (2002), “A suggestion of high quality concrete for PHC pile”, *Mag. Korea Concrete Ins.*, **14**(6), 41-48.

Chun, Y.S., Park, J.B. and Sim, Y.J. (2010), “Mechanical properties of PHC pile head connection with foundation slab and field application”, *Mag. Korea Concrete Ins.*, **22**(5), 71-77.

Gary, L.H. (2006), *Behavior of Fiber-Reinforced Polymer Composite Piles Under Vertical Loads*, Federal Highway Administration, Mclean, VA, USA.

Guades, E., Aravinthan, T., Islam, M. and Manalo, A. (2012), “A review on the driving performance of FRP composite piles”, *Compos. Struct.*, **94**(6), 1932-1942.

Hyun, J.H., Bang, J.W., Lee, S.S. and Kim, Y.Y. (2012), “Shear strength enhancement of hollow PHC pile reinforced with infilled concrete and shear reinforcement”, *J. Korea Concrete Ins.*, **24**(1), 71-78.

Iskander, M. and Hassan, M. (1998), “State of the practice review in FRP composite piling”, *J. Compos. Constr., ASCE*, **2**(3), 116-120.

JIS A 5335 (1987), Pretensioned Spun Concrete Pile, Japan.

Kishida, S., Horii, M., Kuwabara, F. and Hayashi, S. (2000), “Experimental study on shear strength of the PHC pile with large diameter”, *Proceedings of World Conference on Earthquake Engineering*, Auckland, January.

Kim, T.H., Seong, D.J. and Shin, H.M. (2012), “Seismic performance assessment of hollow reinforced concrete and prestressed concrete bridge columns”, *Int. J. Concrete Struct. Mater.*, **6**(3), 165-176.

Korean Highway Bridge Design Code (2008), Seoul, Korea.

Meyerhof, G.G. (1976), “Bearing capacity and settlement of pile foundations”, *J. Geotech. Eng. Div., ASCE*, **102**(3), 195-228.

Mirmiran, A., Shao, Y. and Shahawy, M. (2002), “Analysis and field tests on the performance of composite tubes under pile driving impact”, *Compos. Struct.*, **55**(2), 127-135.

Song, T.E. (2008), “Decision procedure in applying PHC piles instead of steel plies”, *Technical Mag. Ssangyong Eng. Constr.*, September.