- Technical Paper -

ANALYSIS ON SHEAR FAILURE BEHAVIOR OF PHC-PILE CONSIDERING CONFINEMENT EFFECT

Cheng JU*1, H. NAKAMURA *2, S. KOUMURA*3 and Y. SHIRATORI*4

ABSTRACT

Shear failure behaviors of pre-stressed high-strength concrete pile were investigated by 3D-RBSM which is a discrete numerical model and can describe crack development accurately. The applicability of 3D-RBSM was confirmed by comparing with test results such as load-displacement relationship, crack development, deformation performance. Moreover, the effects of passive internal (spiral stirrups) and active external confinement effect was investigated. Several analysis were carried out with stirrups ratio by varying space of stirrups and cross section area and with different external active confinement pressure around pile body under monotonic and cyclic loading. It was revealed that external active confinement pressure is more effective to improve the deformation performance.

Keywords: PHC-Pile, Shear Failure, Confinement Effect, Soil Pressure, 3D-RBSM

1. INTRODUCTION

As a foundation structural member, pre-stressed high-strength concrete (PHC) pile has been used for various structures such as power plant, bridge, building and so on. The pile is important member to insure the stable condition for whole structure, and high ductility is required for structure to prevent the fatal brittle collapse. Recently, earthquake wave motions in design become large which was considered by measured data when big earthquakes happen, such as Kobe earthquake (1995), East Japan earthquake (2011). Since, large soil deformation in a soft layer is predicated under big earthquake wave motion, the deformation performance of pile is required to prevent brittle local shear behaviors.

The deformation performance of PHC pile including the several phenomenon have been evaluated experimentally and analytically, especially the load carrying capacity and macro behavior have been studied. Kisida, et al., investigated shear strength of PHC-pile experimentally and analytically [1]. In their studies, the effect of pre-stress, a/d ratio, axial force and t/d ratio were investigated. Moreover, they modeled PHC-pile by 3D Finite element method (3D-FEM) to investigate its maximum loading carrying capacity. By 3D-FEM, Yamamoto, et al., obtained very well corresponding results in macro behaviors such as maximum load carrying capacity and its load-displacement relationship until peak-load [2]. However, the problems are how to realistically demonstrate the deformation behaviors, evaluating the post-peak behavior of shear failure considering the several conditions under grounds.

On passive confinement effect, the focus is mainly concentrated on internal confinement like spiral stirrups and external confinement like FRP sheet, which both can effectively enhance the deformation performance and ductility. Kisida et al. evaluate the pile's seismic performance due to spiral stirrups ratio [3]. Abe et al. investigated the effect from the reinforcement of CFRP around RC pile [4]. In their experimental research, notable ductility improvement and spalling suppression effect were confirmed. We have to consider another confinement effect for pile structure, which is active external confinement by soil pressure. Although a few researches have been investigated for flexural failure considering active external confinement, the effect on shear failure has not been revealed [5] [6] [7].

In this study, 3D-Rigid Body Spring Method (3D-RBSM) is used to simulate the shear failure behaviors of PHC-piles and its results is compared with experiments results to confirm its applicability. Then, passive internal confinement effect due to stirrups and active external confinement effect due to low soil pressure are investigated to evaluate the load carrying capacity, the deformation performance, the cracking propagation and the failure pattern.

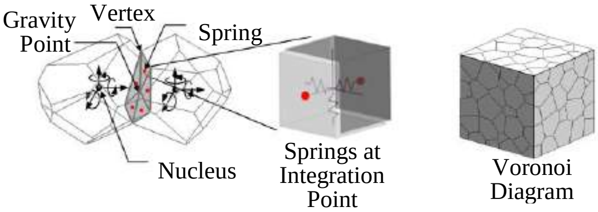


Fig.1 Concept of Rigid-Body Springs Model

*1 Master Student, Department of Civil Engineering, Nagoya University, JCI Student Member
*2 Prof., Dept. of Civil Engineering, Nagoya University, Dr.E., JCI Member
*3 Civil Engineer Division, Cyubu Electric Power
*4 Civil Engineer Division, Cyubu Electric Power

2. OUTLINE OF 3D-RBSM

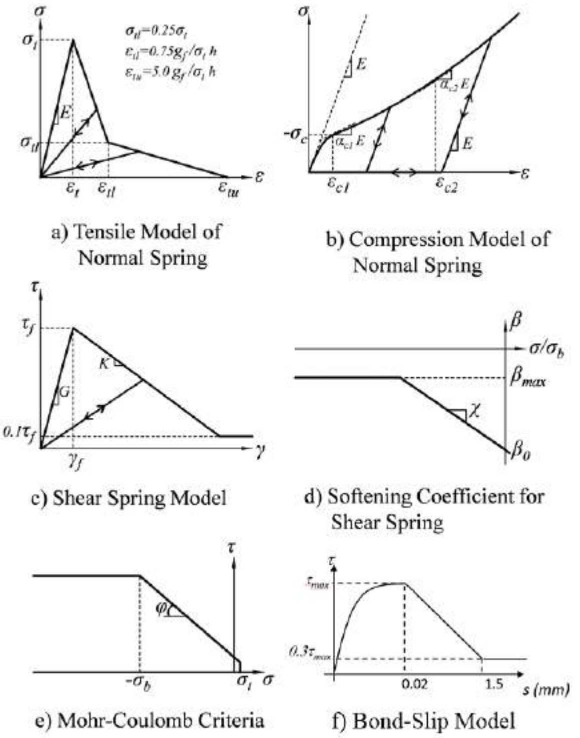


Fig.2 Constitutive Law of 3D-RBSM

3D-RBSM is used to analyze in this study. In the model, concrete is modeled as an assemblage of rigid particles interconnected by springs along their boundary surfaces, as shown in Fig.1. The feature of RBSM is that concrete behavior is expressed by deformation of springs between particles and it can show realistic cracking behaviors. The crack pattern is strongly affected by the initial mesh design as the cracks initiating and propagating through the interface boundaries of particles. Therefore, a random geometry of rigid particles is generated by a Voronoi-diagram, which reduces mesh bias on the initiation and propagation of potential cracks. These springs' constitutive laws follow the relationships as Fig.2. The model of each kind of springs is simple one dimension relationship. The applicability of RBSM has been confirmed by simulation of several members with several loading conditions [7] [8].

Reinforcement is modeled as truss elements that can be freely located within the structure, regardless of the concrete mesh design. The truss element is attached to the concrete particles by means of zero-size link elements that provide a load-transfer mechanism due to bond effect between the truss node and the concrete particles. Fig.2.(f) shows the element model around reinforcement and its bond-slip model.

3. OUTLINE OF TEST AND APPILICABILITY OF ANALYSIS

3.1 Test Outline

The dimension of specimens is shown in Fig.3, which has 300mm diameter, 60mm thickness and 450mm shear span (a/d=1.5). High strength concrete (f_c'=125Mpa) was used in this test. Regarding reinforcement arrangement, 12 pre-stressing steel bars with 7mm diameter are used as longitudinal reinforcement and pre-stressed of 8MPa is introduced. 100mm pitch spiral stirrups with 4mm diameters are also arranged in specimen.

Monotoic and cyclic loading tests are carried out to invetigate its behaviors. For monotonic loading test, the axial force is not loaded, and additional 6Mpa axial force is loaded for cyclic loading test. Their results are shown in Fig.6 to Fig.9, both show typical shear faliure which is confirmed by load-displacement curves and crack patterns.

3.2 Applicability of Analysis

The analytical mesh is modeled as shown in Fig.4, which is meshed by voronoi-diagram with 20mm size elements. The reinforcement arrangement is shown in Fig.5. All reinforcements are modeled by truss elements. In the analysis, a stub is fixed all direction as boundary condition, axial force is applied to another stub and the lateral displacement is controlled.

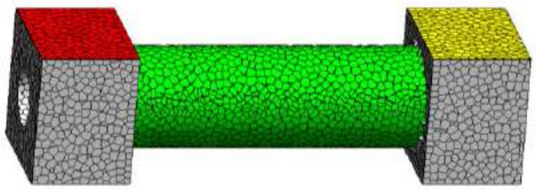


Fig.4 Concrete Mesh

Fig.5 Reinforcement Arrangement

The test and analytical results under monotonic loading are shown in Fig.6 and Fig.7. The load-displacement relationships coincide well from initial to

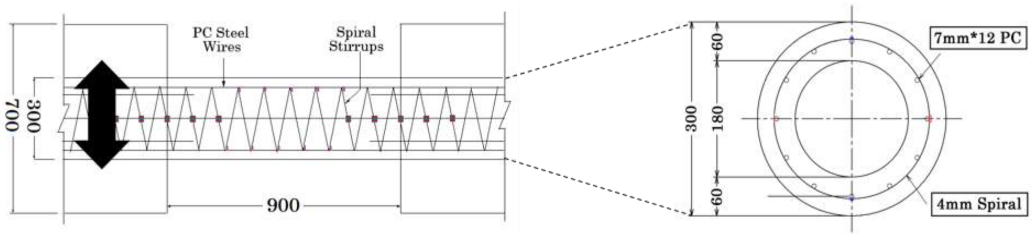


Fig.3 Specimen's Dimension

failure stage. Fig.7 shows the deformation and crack pattern at the same displacements of test and analytical results in Fig.6. At point-A, flexural crack initiate at the boundary of stubs. At point-B, the diagonal crack with about 45 degree is observed at an end in test and the diagonal cracks at both ends are observed in analysis due to symmetric condition. The diagonal cracks at both ends propagate at point-C in test and analysis. At point-D, main shear crack through whole part occur and the load capacity decrease rapidly in test and analysis. All crack events of test and analytical results coincide well.

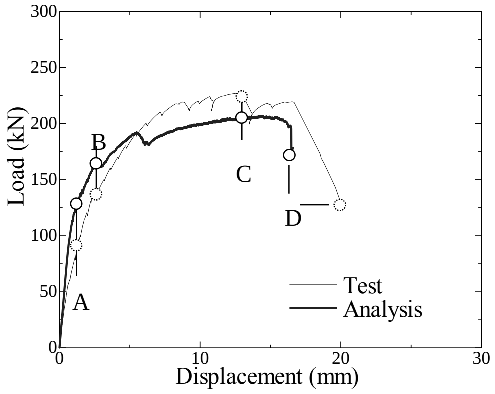
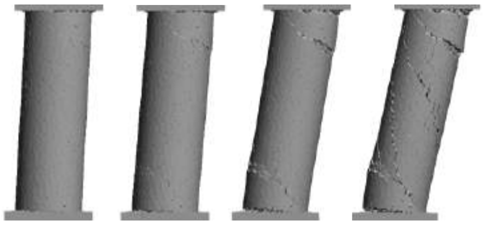
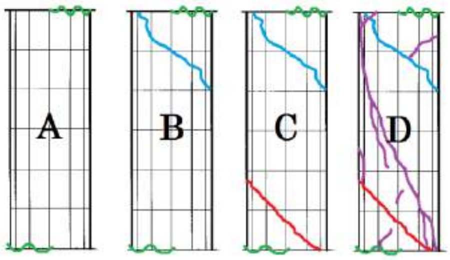


Fig.6 Load-Displacement Curve under Monotonic Loading



(a) Analytical results



(b) Test results

Fig.7 Crack Propagation at Different Displacement

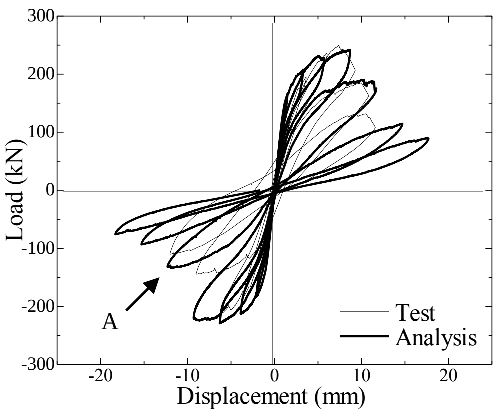


Fig.8 Load-Displacement Curve under Cyclic Loading

(a) Analytical (b) Test

Fig.9 Crack Comparison under Cyclic Loading

The cyclic feature is also investigated with test and analysis. Reversed cyclic loading with R=1/500, 1/250, 1/150, 1/100, 1/75, 1/67.5 and 1/50 is loaded to same specimen until failure. Well agreements are obtained in Fig.8 on its load capacity, deformation performance and post-peak behaviors. On the crack propagation at point-A, it is compared with test's photo as shown in Fig.9. Main shear crack and complex diagonal crack at both end can be confirmed that 3D-RBSM has enough applicability to simulate the shear failure of PHC-pile till post-peak phase under cyclic loading.

4. EVALUATION OF CONFINEMENT EFFECT

4.1 Passive Internal Confinement Effect

Reinforcement effect due to spiral stirrups can be considered as passive confinement from inner part. Stirrups' space and cross-section area are varied to achieve the same stirrups ratio by 1.5, 2 and 4 times from the standard specimen, to investigate the effect of the stirrups ratio. The standard specimen has the same dimension with test specimen as shown in Fig.3 in which axial force is not loaded. Each specimens' confinement stress level at yielding of stirrups obtained as Eq.1 is about 0.5MPa, 0.75MPa, 1.0MPa and 2.0MPa.

$$\sigma_r = \frac{2 f_{ysp} \cdot A_{sp}}{d_{sp} \cdot s} \tag{1}$$

where,

f_{ysp} : Yielding strength of stirrups

A_{sp} : Cross-section area of stirrups

d_{sp} : Diameter of cross section surrounded by spiral reinforcement

s : Space of stirrups

Fig.10 and 11 show load displacement relationship for different stirrup's space and section area under monotonic loading, respectively. As increasing stirrups ratio, both obtain remarkable ductility and deformation improvement. Fig.12 shows the deformation captured from ○, △ and □ in Fig.10 and Fig.11. ○ correspond the final stage of standard specimen, □ is the final stage of specimen with 4 times stirrup section area, and △ is captured from the same displacement of □ for 25mm space specimen. The main shear crack through whole part are suppressed due to stirrups ratio increasing.

Moreover, the stirrup's space is effective to improve deformation performance and prevent main shear crack when stirrups ratio is same.

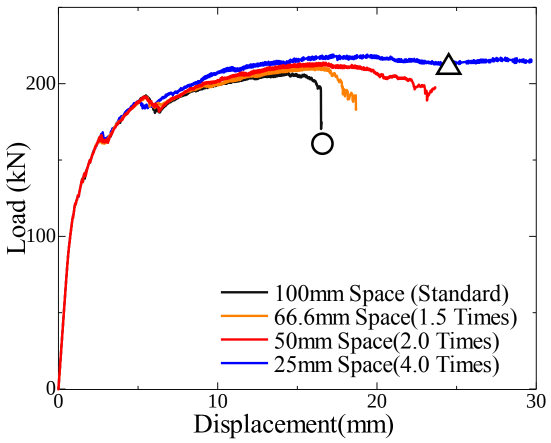


Fig.10 Load-Displacement Curve in Different Stirrup Space under Monotonic Loading

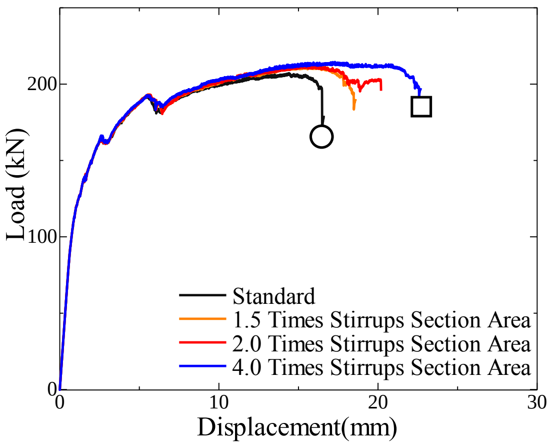


Fig.11 Load-Displacement Curve in Different Stirrups Section Area under Monotonic Loading

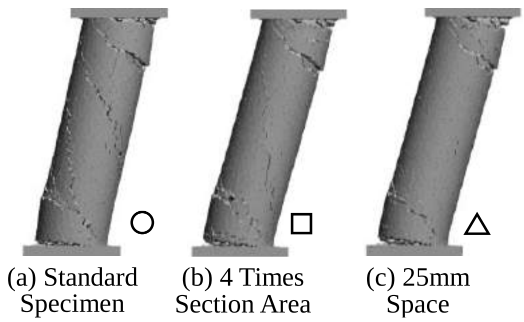


Fig.12 Deformation Comparison under Monotonic Loading

The effect of passive internal confinement under cyclic loading is also evaluated as shown in Fig.13. The cyclic loading history is same with tested case in chapter 3. Before peak load, the inner loop of loading history is same and no remarkable load increasing can be confirmed. The reinforcement effect is mainly reflected in post-peak stage by suppressing the losing of load-capacity. Fig.14 shows the deformation at maximum displacement. The main shear crack through whole part of pile is vanished at the same displacement level with the increasing of stirrups ratio.

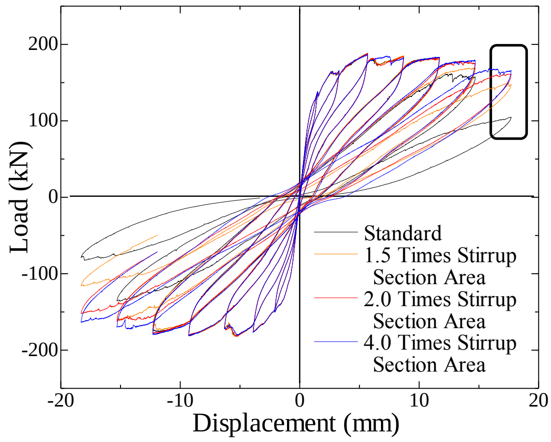


Fig.13 Load-Displacement Curve in Different Stirrups Section Area under Cyclic Loading

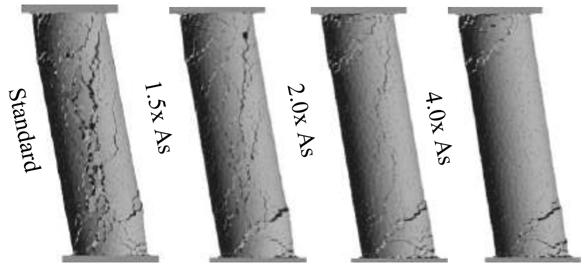


Fig.14 Deformation Comparison under Cyclic Loading

4.2 Active External Low Confinement Effect

It is reported that even the low level external active confinement such as soil pressure has positive effect for ductility of PHC-Pile failed in flexure mode. Imamura et al., investigated the actual behavior of piles, which is show greater ductility than these experimental results in air, because pile embedded in the ground are subjected to confining pressure from the subgrade [6]. Therefore, the effect of the active external confinement pressure on shear failure is interesting to discuss about what phenomenon would be caused.

The active external confinement pressure is modeled by distributed load from radius. The load is subjected on the green area of pile-body surface as shown in Fig.4. The confinement pressure of 0MPa, 0.05MPa, 0.15MPa and 0.3Mpa are assumed, which are corresponding the soil pressure of 0m to 12m underground in normal condition. The stress level is smaller than the one from stirrups, which is 0.5MPa of standard specimen discussed in chapter 4.1.

From the load-displacement curve of monotonic load as shown in Fig.15, the deformation capacity is remarkably improved by the increasing of confinement pressure and load carrying capacity slightly increase. Furthermore, from the deformation in Fig.16 which is captured at the position with circle mark in Fig.15, it is confirmed that shear crack through whole part of pile body are gradually vanished with the increasing of confinement pressure. The sudden failure in shear can be avoided with the increasing confinement pressure. Comparing with varying stirrups, about 0.15MPa active external confinement can obtain similar reinforcement effect with 2~4 times stirrups ratio varying (1.0~2.0 Mpa passive internal confinement) at ductility and crack suppression.

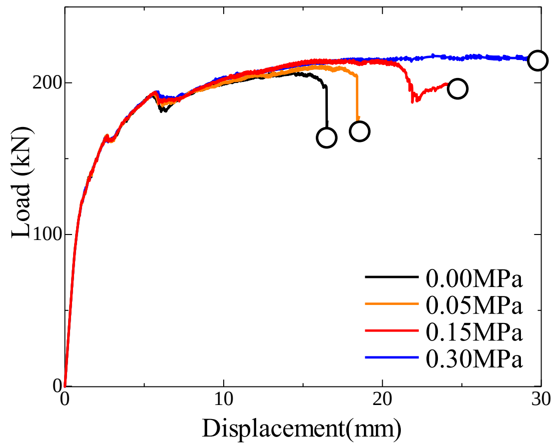


Fig.15 Load-Displacement Curve in Different Active External Confinement under Monotonic Loading

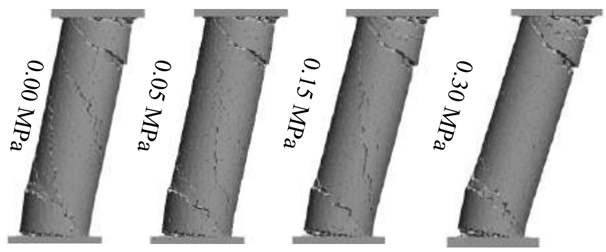


Fig.16 Deformation of External Confinement Effect under Monotonic Loading

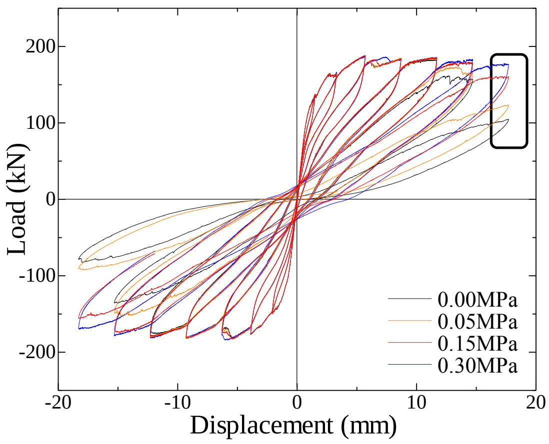


Fig.17 Load-Displacement Curve in Different External Confinement under Cyclic Loading

The result under cyclic loading is shown in Fig.17. The behaviors are almost same with stirrup section area cases. The effect of external low active confinement can be observed at Fig.18, which shows that not only under monotonic condition, low external active confinement also can work well to prevent shear crack through whole part under cyclic loading.

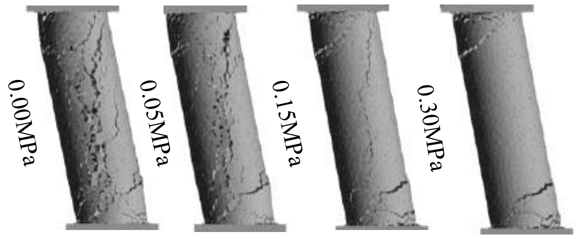


Fig.18 Deformation Comparison of External Confinement Effect under Cyclic Loading

These phenomenon suggest that, PHC-Pile will perform excellent seismic performance over designer's expectation if external low confinement such as soil pressure. It is noted that the value of pressure is set as uniformed active external confinement during whole loading history.

5. ROLE OF CONFINEMENT PRESSURE

The effects of both internal and external confinement pressure were confirmed by 3D-RBSM. Simulating accurate cracking behaviors is the merit of 3D-RBSM. In this chapter, cracking behavior in cross section of middle of pile body as shown in Fig.19 is observed, at which shear crack through whole part propagate, to discuss the role of confinement pressure.

The crack propagation for the cases of standard specimen, 4 times of stirrup cross section area specimen and 0.30MPa active external confinement pressure specimen are shown in Fig.20. The crack corresponding to the displacement of 11mm ~ 27mm as shown in Fig.21. The process of shear crack propagation through whole part is understood from results of standard specimen. The crack from inner side along loading direction occur first, which is hard to be observed in test (11mm). Once the inner crack occur, the shape of cross section deform from original shape (15mm). The deformation make tensile stress at outside of cross section which is perpendicular to loading direction. As the results, main shear crack which follows sudden load drop occur with combination of the tensile stress from cross section deformation and shear force (17mm).

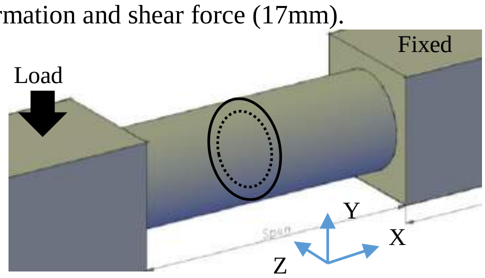


Fig.19 Cross-Section Position Image

On the other hand, with the reinforcement of stirrups, the occurrence of inner crack along load direction is delayed, which mean the main shear crack is also delayed. The role to prevent the occurrence of inner crack is more effective for the case of external confinement pressure. It produce compression stress due to active pressure and keep the initial shape of cross section.

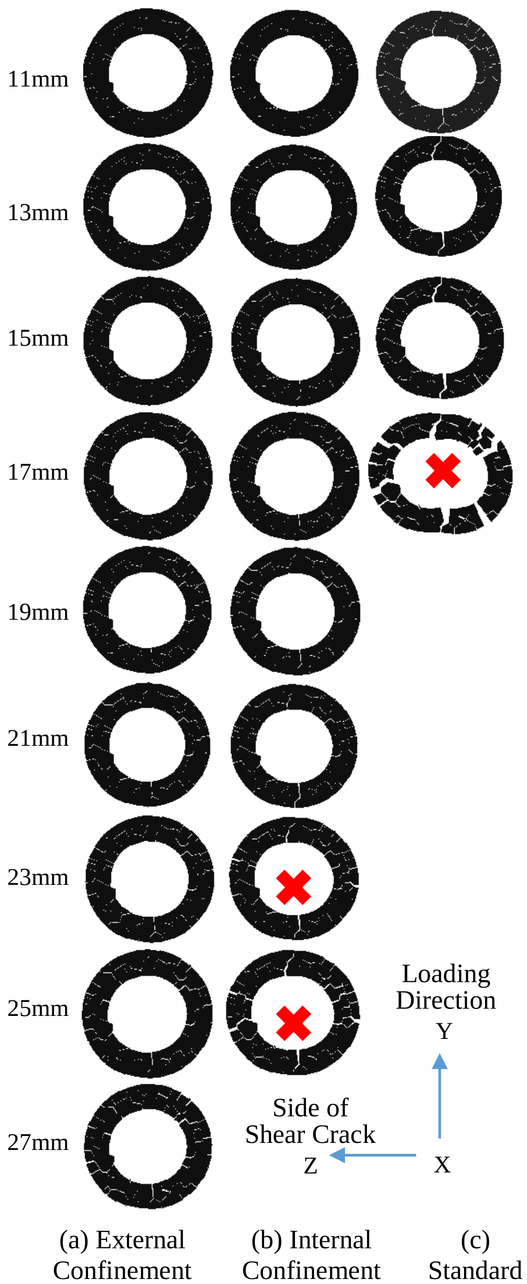


Fig.20 Deformation of Cross Section

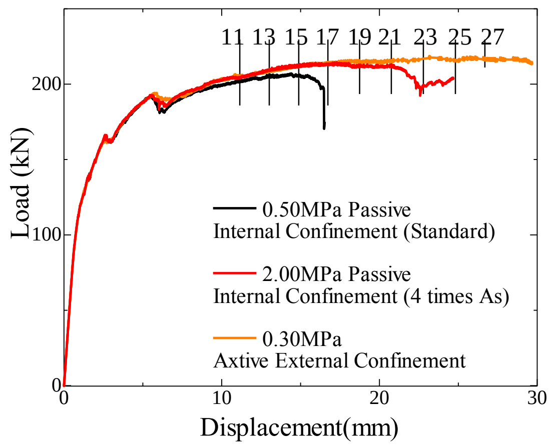


Fig.21 Load Displacement Curve

6. CONCLUSIONS

(1) Monotonic and cyclic simulation by using 3D-RBSM were carried out in order to investigate the applicability to PHC-Pile structure. 3D-RBSM can correctly predict their load capacity and deformation performance till post-peak, and demonstrate crack propagation realistically.

(2) The space of stirrup for internal confinement is more effective than the cross section area when stirrup ratio is same.

(3) Regardless monotonic or cyclic load, low active external confinement is more effective than internal passive one's. Even low pressure around pile body is very effective to prevent sudden shear failure and leads the considerable ductile performance.

(4) The role of confinement effect is revealed by 3D-RBSM. Inner crack along loading direction at middle part of pile can lead the cross section deformation which led the occurrence of main shear crack through whole part. And active external confinement pressure can prevent it effectively.

REFERENCES

[1] Kisida. S., et. al.,"Experimental study on shear strength of the PHC pile with large diameter," Proceedings of AIJ. Vol. 510, Aug. 1998, pp. 123-130.

[2] Yamamoto. N., et. al.,"Analytical study on shear failure of the PHC Pile with Large Diameter," Proceedings of JCI. Vol.20, No.3, 1998, pp. 379-384.

[3] Kisida. S., et. al.,"Experimental study on improving the ultimate deformation behavior and the shear strength of large diameter PHC piles," Proceedings of AIJ. Vol. 521, July. 1999, pp. 81-88.

[4] Abe. R., et. al.,"Cyclic test of high strength RC-pile reinforced by CFRP sheet," Proceedings of JCI. Vol.32, No.2, 2010, pp.877-882.

[5] Miyagawa. Y., et. al.,"Flexural Confinement PHC Pile" Proceedings of JCI. Vol.34, No.2, 2012, pp. 595-600.

[6] Imamura. T., et. al.,"Evaluation of ductility for RC piles subjected to confining pressure in the ground," Structural Engineering / Earthquake Engineering. Vol.24, No.1, 2006, pp.23-30

[7] Ju. C,. et. al.,"Analysis on failure behavior of PHC-pile by using 3D-RBSM," Proceedings of the Symposium on Developments in Prestressed Concrete. Vol.22, 2013, pp.33-38

[8] Yamamoto. Y., et. al.,"Analysis of compression failure of concrete by three-dimension Rigid Body Spring Model." Doboku Gakkai Ronbunsyuu, Vol.64, No.4, 2008, pp.612-630.