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A Review of Prestressed Concrete Pile with Circular Hollow Section (Spun Pile)

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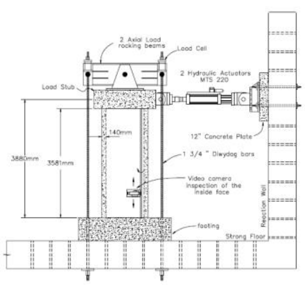
Graphical abstract



Abstract

Spun pile is one of the types of piles are widely used in the world construction, for example in building and bridge. Spun pile is a prestressed concrete pile with circular hollow section. This paper provides an overview of the research development of spun pile, starting from 80's until now. This overview is related to methods of increasing the strength and reliability of spun pile due to earthquake loads, either by modifying the longitudinal reinforcement and confinement. In addition, this paper also discusses about the failure patterns of spun pile due to seismic loads. Finally, this paper can be a reference for understanding the scope of the research topics that have been done by researchers. Thus, by this overview can be obtained new idea for the next research to improve the performance of spun pile carry seismic loads.

Keywords: Spun piles; prestressed concrete; confinement; ductility; seismic load

1.0 INTRODUCTION

Spun piles are hollow, precast and prestressed concrete piles, in sizes generally ranging from 300 to 1200 mm outside diameter, that are fabricated by prestressing methods. The dimension of spun pile that is generally used according to Japan Industrial Standard (JIS) 5335 1987 [1] given in Table 1. For spun piles with large diameter (ranging from 915 to 1676 mm) generally called as cylinder pile. It is introduced in 1950 by the Raymond Concrete Pile Company [2]. Spun pile used in Hong Kong also defined as closed-ended tubular sections of 400 to 600 mm with maximum allowable axial load 3000 kN. Pile sections are usually 12 m long, for specially made until 20 m [3].

The material of spun piles consists of high strength concrete 50 to 75 MPa and prestress steel. The production method of spun pile usually using spinning method [3] which originally developed the Raymond Concrete Pile Company [2].

Advantages of using spun pile are spun piles is less permeable than reinforced concrete pile, thus it has a good performance in a marine environment [3]. Beside advantages, spun piles also have some disadvantages. When driving process they are possible to get spalling, cracking and breaking [3].

Table 1 The dimensions of spun pile

Outside diameter / mm	Thickness / mm
300	60
350	65
400	75
450	80
500	90
600	100
700	110
800	120
1000	140
1200	1500

2.0 RESEARCH RELATED WITH SPUN PILE

Akiyama *et al*., 2011 [4] proposed an innovation of spun pile to improve its ductility. Akiyama *et al*. filled hollow of spun pile 400 mm in diameter and 70 mm thickness with concrete infilling and wrapped using carbon fiber. Pile specimens used prestressing steel bar in the middle of hollow's spun pile. Those specimens were shown at

Figure ***1***. The specimens was tested using two point load monotonic flexural loading as shown at Figure 2.

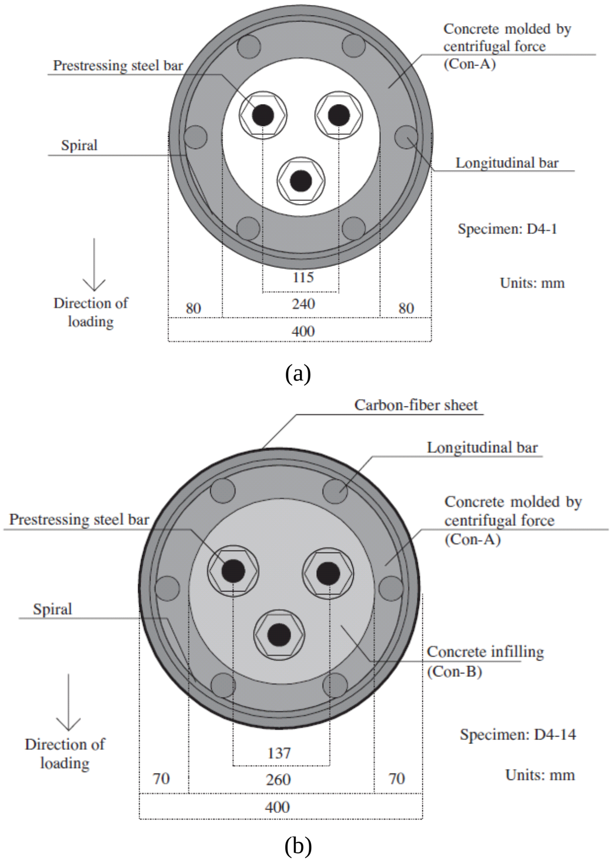


Figure 1 Section of specimens Akiyama *et al.* research [4]

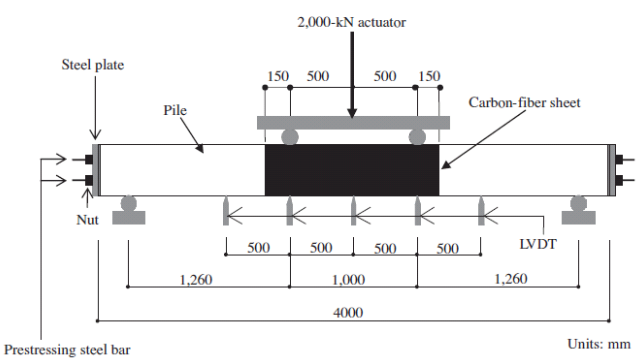


Figure 2 Two point monotonic flexural loading Akiyama *et al.* research [4]

From this research Akiyama *et al*. conclude that spun pile with carbon-fiber sheets and concrete infilling had a much higher flexural capacity than a conventional precast spun pile. Concrete infilling can prevent a sudden decreasing of load after spalling of the concrete cover.

Lignola *et al.* [5] at 2008 published an analyses of spun pile model with external confinement using Fiber Reinforced Polymer (FRP). In this paper Lignola *et al.* proposed a unified theory for confinements of circular hollow section concrete using FRP. Lignola *et al*. make a conclusion that FRP jacketing can increase the ultimate load and ductility of circular hollow section concrete.

Ranzo and Priestly 2000 [6] conducted an experimental study of large reinforced concrete circular hollow columns subjected to constant compressive axial load and cyclically lateral load. The cross section of specimens is shown in Figure 3. The reinforcement of the specimen consist of 34 bundles of 2 non prestressed bars and spiral reinforcement with 6 mm in diameter and 70 mm spacing.

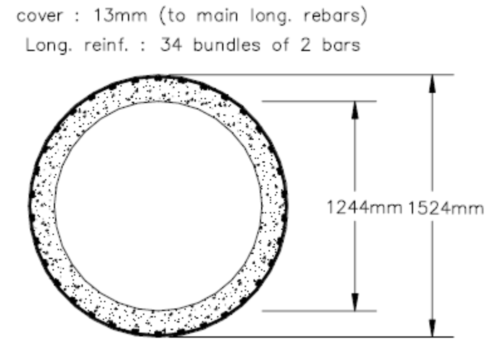


Figure 3 Cross section of Ranzo and Priestly Specimens [6]

Three specimens were tested in this research. The axial load which applied to specimens were combined with lateral cyclic load. The set up of specimens were shown in Figure 4.

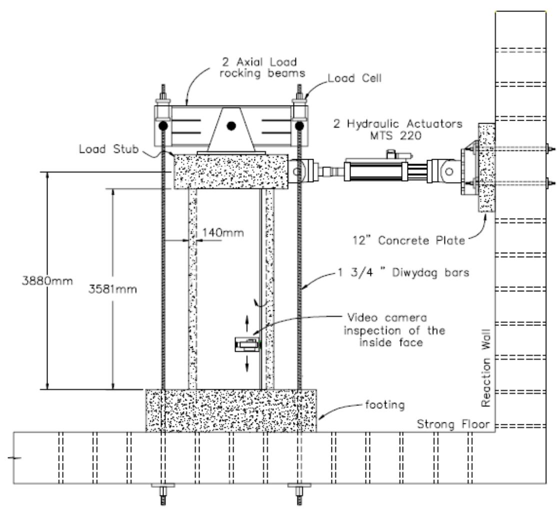


Figure 4 Set up of Ranzo and Priestly Specimens [6]

The ratio of axial load which applied with axial capacity (f'c Ag) is 5%, 5% and 15% for specimens 1, 2, and 3, respectively. The response of specimens is shown in force-displacement chart at Figure 5. The modes of failure for each specimens are flexural for specimen 1 and shear for specimen 2 and 3.

From this research Ranzo and Priestly made conclusions that a circular hollow column with high flexural capacity needed to be designed with quite thickness to prevent spalling in the inside surface of large circular hollow column. Ranzo and Priestly also suggested that the effect of axial load be neglected on shear strength.

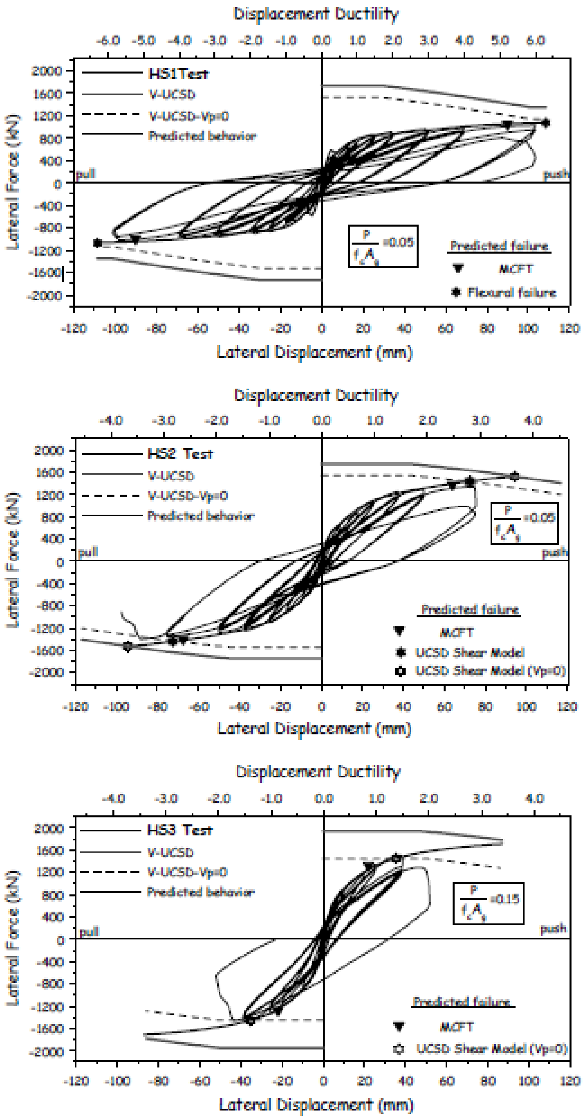
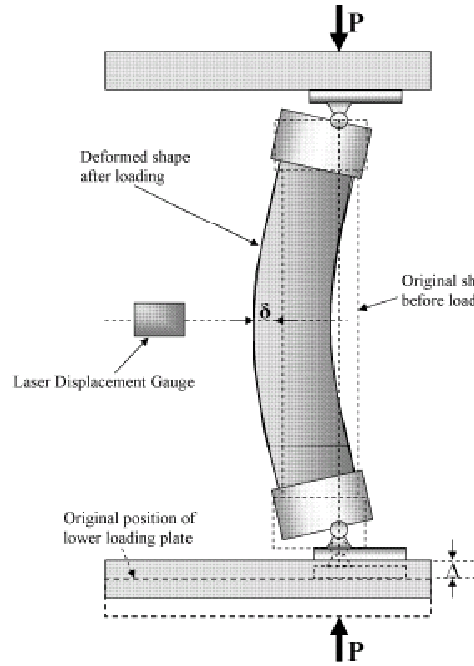
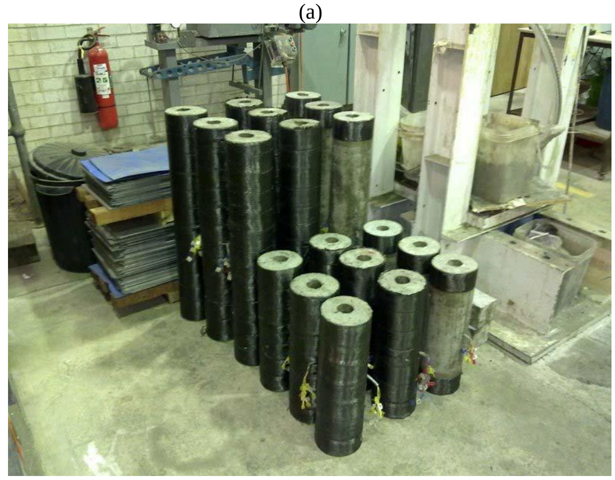


Figure 5 Chart of force-displacement response of Ranzo and Priestly research

Yazici 2012 [7] conducted a research to predict the behavior of circular hollow column confined Fiber Reinforced Polymer (FRP). 18 specimens were tested under axial eccentrically compression loading with pinned support in both end as shown at Figure 6. The eccentricity is 0, 25 and 50 mm with 500 and 885 mm of height.



(a)



(b)

Figure 6 Set up of compression test and specimens of Yazici research, 2012 [7]

From this research Yazici (2012) make conclusion that the vertical FRP strips help to increase the axial load capacity for larger eccentricities by delaying the premature failure. The wrapping of FRP to hollow columns can increase the axial load capacity under axial compression force.

Budek *et al.* 1997 [8] conducted an experimental focus on ductility's investigation of solid and hollow prestressed piles. Ten varied specimens were tested using distributed lateral loads in the center of specimen's length as shown at Figure 7. The variations of specimens are four specimens are solid pile, four specimens are hollow pile and two specimens are solid pile with glass fiber jacket.

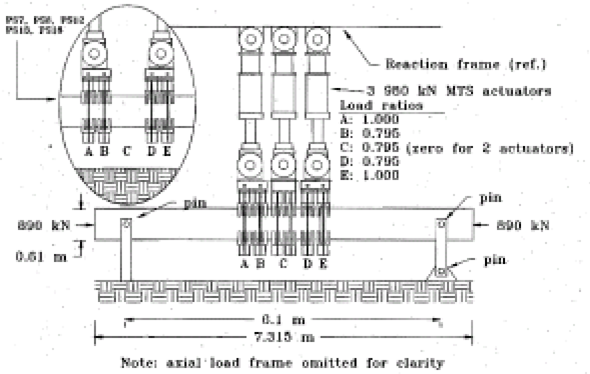


Figure 7 Specimens loading model Budek *et al*. [8]

The mode failure of hollow prestressed pile shown at Figure 8. Under cyclically lateral loading occurred concrete crushing in the center of specimen's length at compression zone both outside and inside face of pile wall (as shown at Figure 8a and Figure 8b). Concrete spalling was occured in this location, thus at the ultimate condition just remained prestressing bars without concrete (Figure 8c). The displacement ductility level for hollow prestressed pile from Budek *et al*. research obtained μΔ 2.5 and 4.

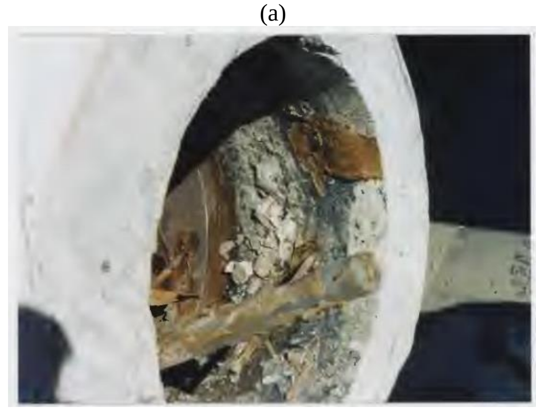
The conclusions that derived by Budek *et al*. related with behavior of hollow prestressed pile under cyclic loading were:

- Initial failure occurred due to implosion at core's inner surface when surface strain reached 0.005.
- The ratio of transversal reinforcement is not influence the ultimate ductility capacity. It is just provide shear capacity.
- The additional non prestressed steel and external confinement i.e. fiber jacketing at plastic hinge region is not improve the ductility of hollow prestressed pile.
- The behavior of hollow pile is low energy-absorbing and suddenly and violently failure.

Kishida *et al.* 2000 [9] conducted an experimental study to investigate the ultimate shear behavior of pretentioned spun high strength concrete pile with large diameter and make a prevention of brittle failure of this pile. The specimens were spun pile with large diameter according to Japanese Industrial Standard (JIS). The novelty specimens of this research to improve shear capacity was filling the concrete into hollow part of pile and increasing spiral reinforcement ratio. The detail of specimens were shown at Figure 9a. diameter of specimens is 300 mm with 900 mm length. The loading setup shown at Figure 9b. The anti-symmetric bending shear experiments was used in this test.

The conclusions of this research were the increasing of spiral reinforcement ratio caused the increasing of shear stress at ultimate shear strength with ductile shear failure. The additional of filling concrete at pile's hollow also increased the ultimate shear strength but the brittle failure was occurred.

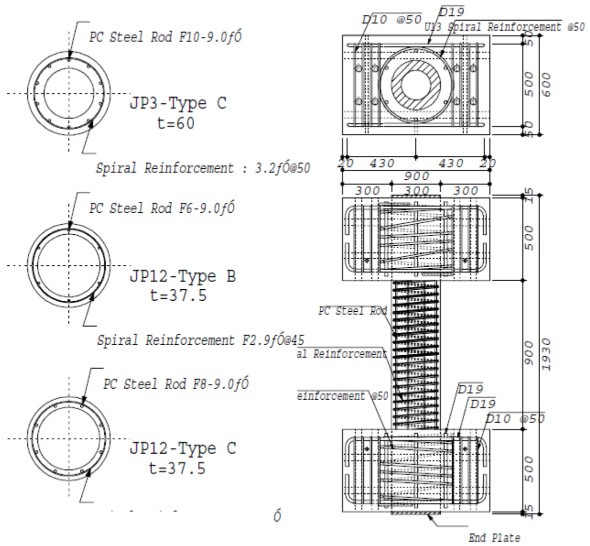
(a)



(b)

(c)

Figure 8 Mode failure of hollow prestressed pile [8]



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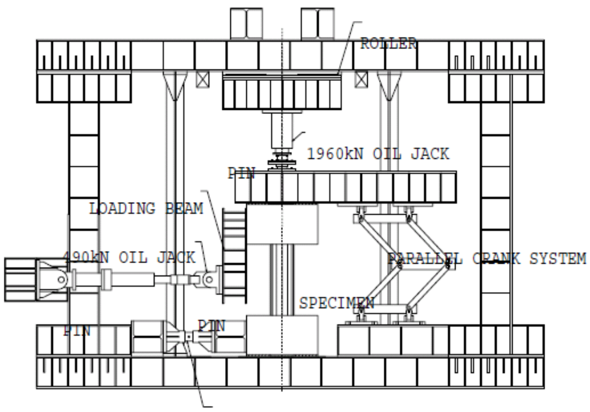
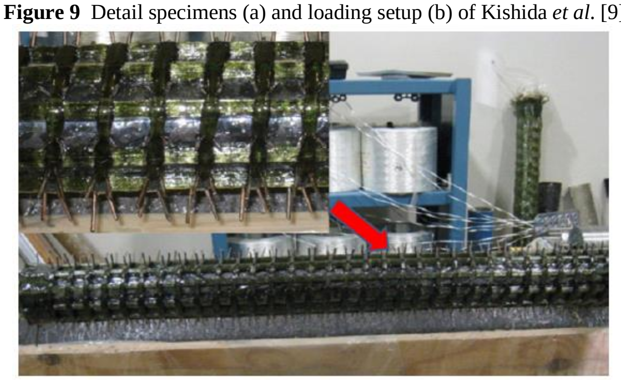


(b)

Figure 9 Detail specimens (a) and loading setup (b) of Kishida *et al*. [9]



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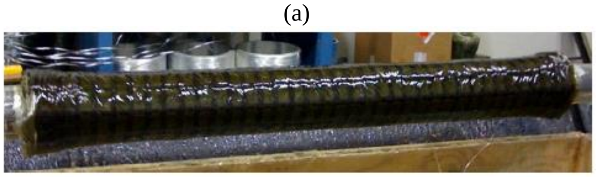


(b)

Figure 10 FRP-AGS model of Gefu *et al*. [10]

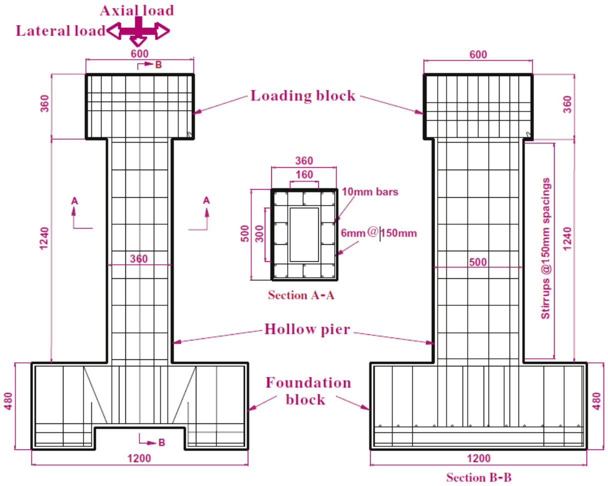
Gefu *et al*. 2009 [10] proposed a new model of external confinement using fiber reinforced polymer (FRP) with modification of advanced grid stiffened (AGS). FRP-AGS was expected to improve ductility and drivability of conventional FRP tube confined concrete cylinders for pile application. Moreover with the roughness of inner surface of FRP-AGS hoped to increase interfacial shear strength between concrete and FRP. FRP-AGS production shown at Figure 10. Figure 10a was fabrication of AGS skeleton and Figure 10b was AGS skeleton wrapped by FRP skin. The specimen is shown at Figure 11 were tested using axially compression loading.

Figure 11 Specimen AGS-FRP Gefu *et al*. 2009 [10]

The conclusions of this study was the interfacial shear strength between concrete and FRP-AGS was higher than conventional FRP wrapping. There are two mechanisms that improve this strength, first due to frictional force provided by confinement and due to mechanical interlocking.

Zhang *et al*. 2013 [11] conducted an experimental and numerical research study concern with seismic behavior of reinforced concrete (RC) and steel fiber reinforced concrete (SFRC) of rectangular hollow bridge piers. The detail of reinforcement of both specimens was shown at Figure 12a and the schematic testing system was shown at Figure 12b. Double layer reinforcement was applied for the specimens.

The behavior's comparison of RC and SFRC pier was shown at Figure 13. Displacement ductility of RC and SFRC pier was 2.98 and 4.11, respectively, thus the ductility of SFRC pier is higher than RC piers. Plastic hinge region was occurred at 360 mm vertically from fixed support (foundation block). It means that length of plastic hinge region is the smallest dimension of rectangular cross section. The model of pier's failure is the spalling and cracking of outside cover and yielding of longitudinal reinforcement. The result of Zhang *et al*. research give an indication that existing of fiber reinforced improved pier's ductility and contributed as transverse reinforcement for seismic design.



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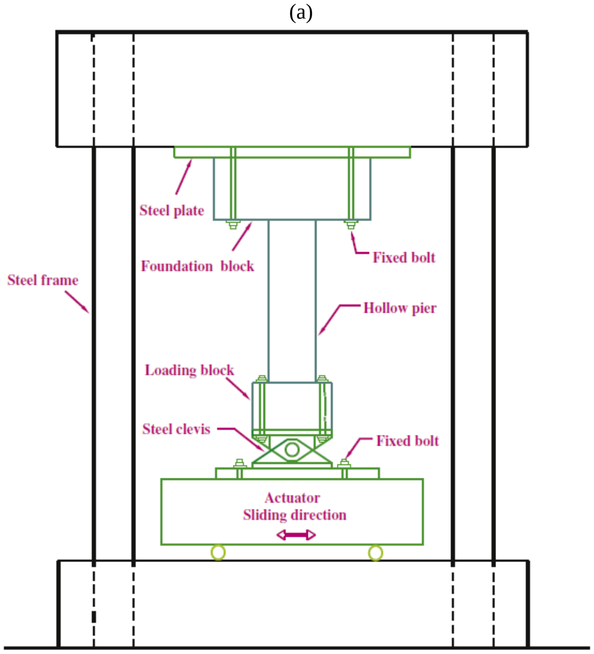
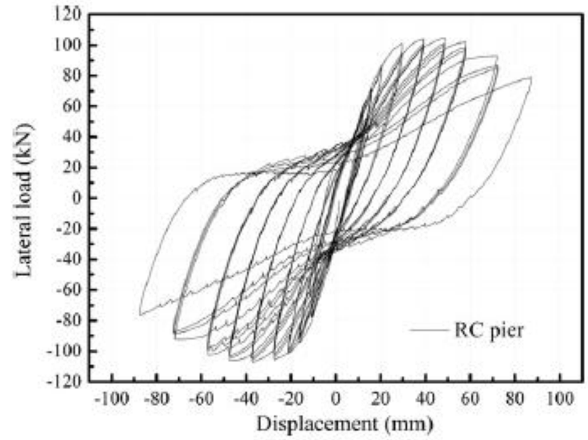
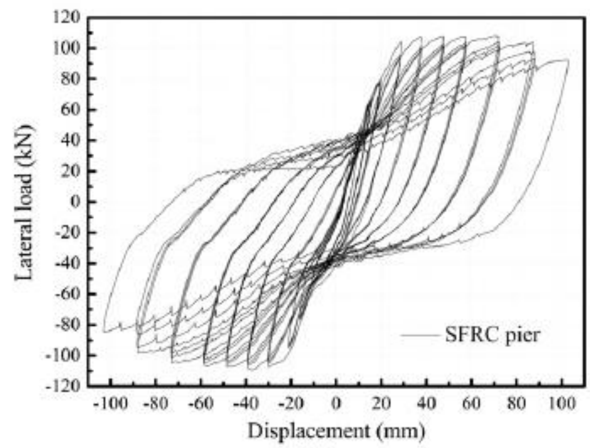


(b)

Figure 12 Specimens details (a) and **s**chematic of testing system (b) Zhang *et al.* 2013 [11]



(a)



(b)

Figure 13 Histeretic curves of specimens (a) RC pier and (b) SFRC pier [11]

Shin *et al*. 2013 [12] conducted a research focused on concrete contribution to the shear strength of rectangular hollow column with single layer longitudinal reinforcement without transverse reinforcement as shown at Figure 14. The specimens was tested using lateral loading with increasing cyclically displacement (Figure 15). The important conclusion of this research was the specimen tested under reversed cyclic loading achieved approximately 83% of the shear strength of the counterpart specimen under monotonic loading. This was mostly because the part of the concrete section that would remain uncracked in monotonic loading was damaged by flexural cracks in cyclic loading.

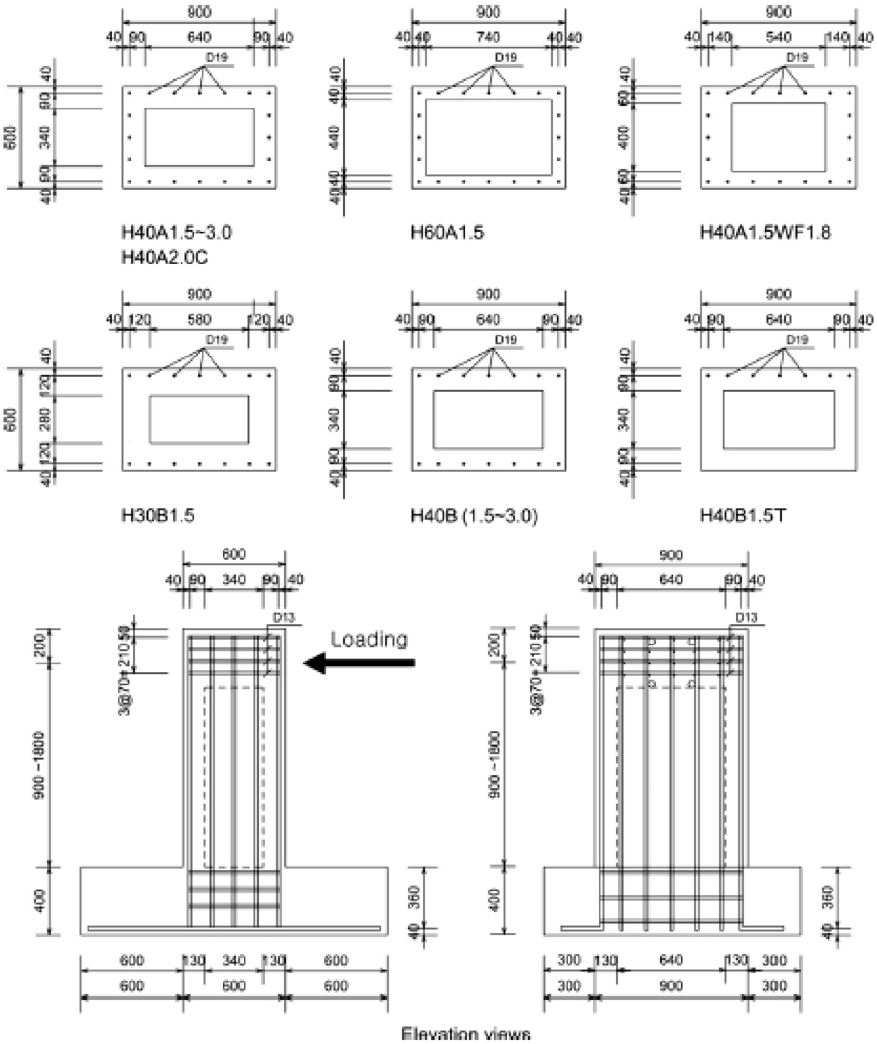


Figure 14 Detail of reinforcement and variation specimens [12]

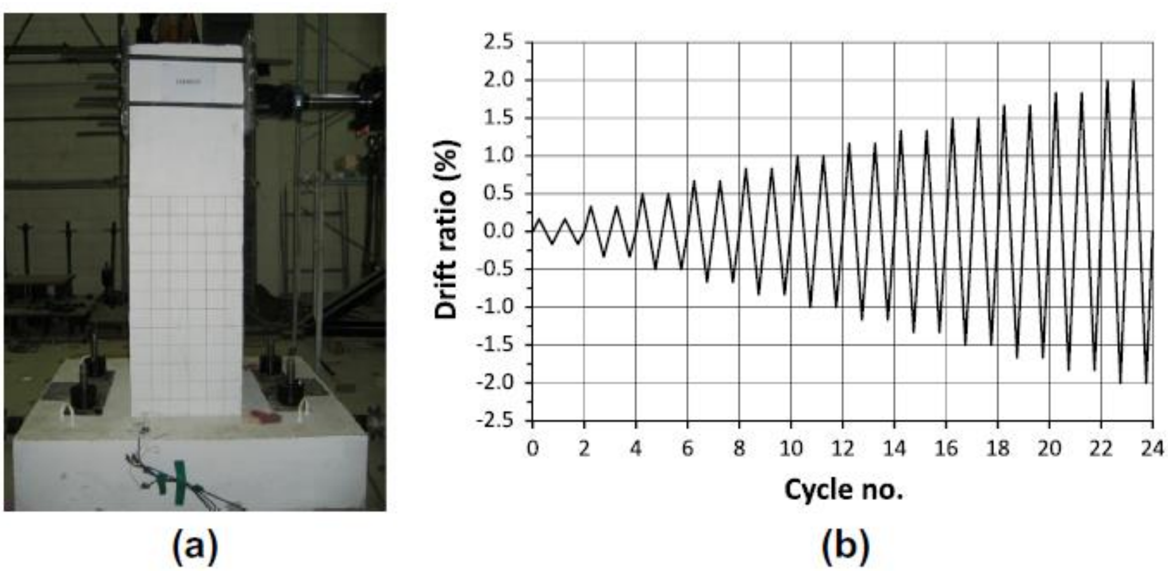


Figure 15 Specimen testing setup and cyclically lateral loading pattern [12]

Hoshikuma and Priestly, 2000 [13] conducted a research about the flexural behavior of circular hollow column with large a single layer of reinforcement due to seismic loading. As support of this research, Hoshikuma and Priestly mentioned some advantages of circular hollow columns were reduce their mass, reduce seismic inertia force, and reduce foundation force. Large diameter pile with single layer reinforcement shown at Figure 16 was tested using lateral cyclically loading as shown at Figure 17.

The result of this study showed that the failure pattern of circular hollow column was suddenly failure. It was occurred due to crushing concrete inside surface of column's wall. The brittle failure was indicated by concrete crushing and transverse reinforcement was not yield. A phenomenon that poor lateral pressure inside surface of hollow pile caused crushing of concrete inside wall as shown at Figure 18.

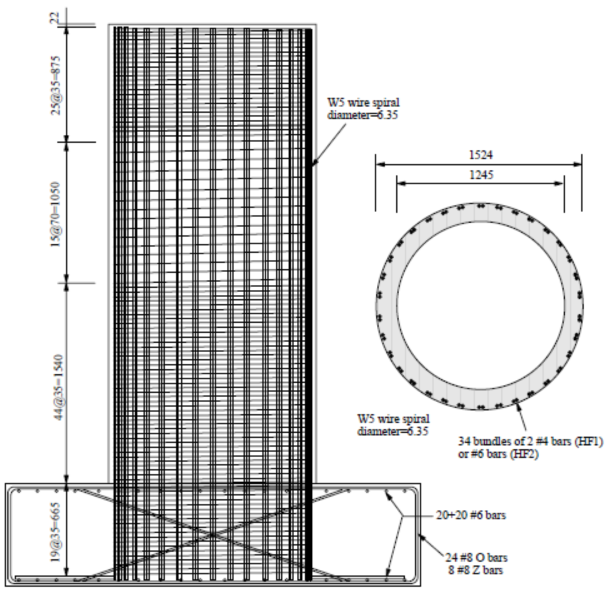


Figure 16 Detail renforcement of specimens [13]

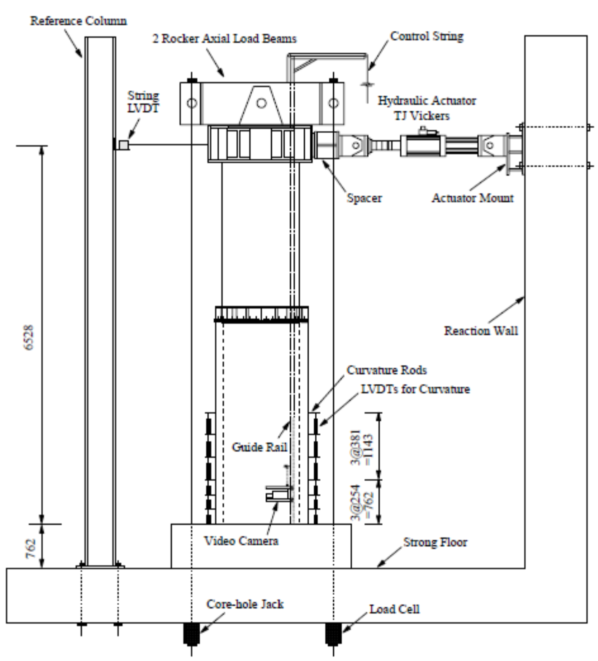


Figure 17 Setup of testing system [13]

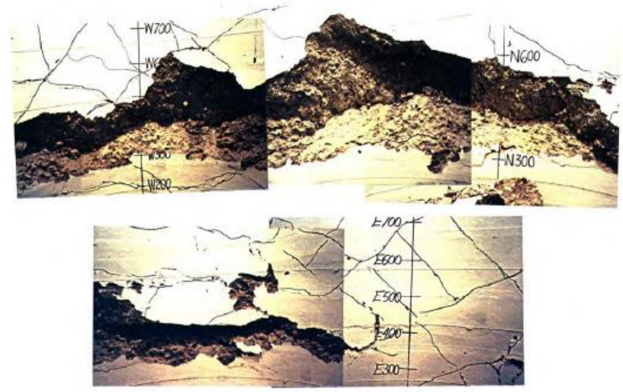


Figure 18 Concrete crushing inside face of circular hollow pile [13]

3.0 RESULTS AND CONCLUSIONS

The results of this literature review is a resume of some research related with prestressed concrete pile with hollow section (spun pile) as shown at Table 1. Although still there are many research that is not recorded in this literature study.

Two important conclusions are obtained from this literature review related with spun pile:

- The method that generally proposed by researchers to increase the strength and ductility of spun pile due to earthquake loads is using external confinement by providing Fiber Reinforced Polymer (FRP) jacketing. Researches also proposed concrete infilling method to prevent a suddenly (brittle) failure due to decreasing of load after spalling of the concrete cover.
- Almost all of researchers make a conclusions that the failure patterns of spun pile due to seismic loads is a brittle failure. Initial failure occurred due to implosion at core's inner surface. The ratio of transversal reinforcement is not influence the ultimate ductility capacity. It is just provide shear capacity.

Acknowledgement

We are grateful for the Indonesia Government scholarship to Author 1.

Table 1 Result of literature review: resume of research related with spun pile

Years	Researchers	Focused on	Important results
2013	Myoungsu Shin, Yoon Young Choi, Chang-Ho Sun, Ick-Hyun Kim	A research focused on concrete contribution to the shear strength of rectangular hollow column with single layer longitudinal reinforcement without transverse reinforcement.	The specimen tested under reversed cyclic loading achieved approximately 83% of the shear strength of the counterpart specimen under monotonic loading. The part of the concrete section that would remain uncracked in monotonic loading was damaged by flexural cracks in cyclic loading.
2013	Yu-ye Zhang, Kent A. Harries, Wan-cheng Yuan	An experimental and numerical research study concern with seismic behavior of reinforced concrete (RC) and steel fiber reinforced concrete (SFRC) of rectangular hollow bridge piers.	The ductility of SFRC pier is higher than RC piers. The length of plastic hinge region is the smallest dimension of rectangular cross section. The model of pier's failure is the spalling and cracking of outside cover and yielding of longitudinal reinforcement. The existing of fiber reinforced improved pier's ductility and contributed as transverse reinforcement for seismic design.
2012	Akiyama, M., Satoshi Abe, Nao Aoki, Motoyuki Suzuki	Innovation of spun pile to improve its ductility by filled hollow of spun thickness with concrete infilling and wrapped using carbon fiber.	Spun pile with carbon-fiber sheets and concrete infilling had a much higher flexural capacity than a conventional precast spun pile. Concrete infilling can prevent a sudden decreasing of load after spalling of the concrete cover.
2012	Veysel Yazici.	The behavior of circular hollow column confined Fiber Reinforced Polymer (FRP)	The vertical FRP strips help to increase the axial load capacity for larger eccentricities by delaying the premature failure. The wrapping of FRP to hollow columns can increase the axial load capacity under axial compression force.
2009	Gefu Ji, Zhenyu Ouyang, Guoqiang Li	A new model of external confinement using fiber reinforced polymer (FRP) with modification of advanced grid stiffened (AGS)	The interfacial shear strength between concrete and FRP-AGS was higher than conventional FRP wrapping. There are two mechanisms that improve this strength, first due to frictional force provided by confinement and due to mechanical interlocking.
2008	G.P. Lignola, A. Prota, G. Manfredi and E. Cosenza	An analyses study of spun pile model with external confinement using Fiber Reinforced Polymer (FRP).	FRP jacketing can increase the ultimate load and ductility of circular hollow section concrete.
2000	Jun-Ichi Hoshikuma and M.J.N. Priestley	A research about the flexural behavior of circular hollow column with large a single layer of reinforcement due to seismic loading.	The failure pattern of circular hollow column was suddenly failure due to crushing concrete inside surface of column's wall. A phenomenon that poor lateral pressure inside surface of hollow pile caused crushing of concrete inside wall.
2000	Giulio Ranzo and M J N Priestley	An experimental study of large reinforced concrete circular hollow columns subjected to constant compressive axial load and cyclically lateral load.	A circular hollow column with high flexural capacity needed to be designed with quite thickness to prevent spalling in the inside surface of large circular hollow column. Ranzo and Priestly also suggested that the effect of axial load be neglected on shear strength.
2000	Shinji Kishida, Masahiro Horii, Fumio Kuwabara and Shizuo Hayashi.	An experimental study to investigate the ultimate shear behavior of pretentioned spun high strength concrete pile with large diameter and make a prevention of brittle failure of this pile.	The increasing of spiral reinforcement ratio caused the increasing of shear stress at ultimate shear strength with ductile shear failure. The additional of filling concrete at pile's hollow also increased the ultimate shear strength but the brittle failure was occurred.
1997	Budek, Gianmario Benzoni M.J. Nigel Priestley	An experimental focus on ductility's investigation of solid and hollow prestressed piles. Ten varied specimens were tested using distributed lateral loads in the center of specimen's length	Initial failure occurred due to implosion at core's inner surface when surface strain reached 0.005. The ratio of transversal reinforcement is not influence the ultimate ductility capacity. It is just provide shear capacity. The additional non prestressed steel and external confinement i.e. fiber jacketing at plastic hinge region is not improve the ductility of hollow prestressed pile. The behavior of hollow pile is low energy-absorbing and suddenly and violently failure.

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