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Study of Spun Pile to Pile Cap Connection with Steel Jacket Strengthening

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ABSTRACT

Spun piles in Indonesia are designed to behave as an elastic structure according to SNI8460:2017. The piles are designed with low confinement where the amount does not meet ASCE 7-16 requirements. Indonesia should apply a performance-based design for the bottom structure someday since the seismic demand tends to increase based on the current seismic risk map. Steel jackets are proposed to fulfill the need for transverse reinforcement, particularly at the connection region where the curvature demand is higher. The steel jacket was made from high-quality zincalume steel, a high-quality rolled steel that is customizable following the size of the spun pile and has a low cost. Experimental and numerical studies were conducted. A 500mm diameter spun pile was retrofitted with a steel jacket loaded vertically and horizontally. The experimental study applied the cyclic loading according to ACI374.2r, and 0.1fc'Ag vertical load was applied. The experimental study applied the cyclic loading according to ACI374.2r, and 0.1fc'Ag vertical load was applied. The experimental study found that the spun pile and grouted concrete interaction was not perfectly bonded. A further finite element study was conducted to understand the connection's performance thoroughly. Two parameters were investigated, the steel jacket's height and thickness. A numerical study performed pushover analysis on the 3D model using the ABAQUS software to see the effect of the height and moment-curvature analysis obtained from fiber section element from SAP software to study the impact of the thickness. The results were presented in terms of its strength and ductility.

Key word: spun pile-pile cap connection; steel jacket; ductility; moment-curvature; strength.

INTRODUCTION

Indonesia is an earthquake-prone area because it is on the path of the most active earthquakes in the world. The increase in earthquake acceleration in Indonesia, as shown by a map from Pusat Studi Gempa Nasional in 2017, also increases the risk of foundation failure, especially flor spun piles that are often used in Indonesia. The map can carry out preparation and prevention in planning, implementing and supervising infrastructure development. Ductility in seismic design is the ability of a structure to endure large deformations in the plastic range without a substantial reduction in strength (Park, 1988). Bending and collapse can occur in the spun pile to pile cap connection if the pile doesn't have adequate ductility after the earthquake occurs. A spun pile with a diameter of 400mm made in Indonesia is not suitable for use in moderate to high earthquake risk areas (Irawan, 2017).

The lack of research on spun pile connections in Indonesia may be caused by the fact that the spun pile design is not allowed to suffer damage. The allowable lateral deformation capacity of pile foundations is only 12mm for design earthquakes and 25mm for strong earthquakes based on SNI 8460:2017. The plastic hinge area of the pile is identified as a weak point and is easily damaged under earthquake loading. Increasing the amount of stirrup reinforcement and modifying the shape of stirrups in the plastic hinge area is a possible approach but has limited performance (Zhang, 2013). Additional confinement in the plastic hinge area is an effective way to strengthen piles. Spiral reinforcement or confinement in Indonesia is not strong enough to withstand the explosion of concrete piles at the ultimate compressive force (Irawan, 2018). Confinement in spun piles in Indonesia is still under the minimum requirements of ASCE 7-16, so additional confinement is needed. However, this is considered less economical. The solution used is with a steel jacket in the connection of spun pile to the pile cap. An experimental study of spun pile has been studied by Callista (2021) in Indonesia, so that the effect of additional steel jacket on spun pile to pile cap connection can be carried out.

The use of steel jackets as a retrofit has been widely studied for the retrofit of reinforced concrete columns. The use of steel jackets has been shown to; increase strength and ductility (Choi, 2009). A numerical study on strengthening steel jacket with ordinary quality steel materials for the spun pile to pile cap connection has been carried out by Orientilize (2021) in Indonesia and have increased strength and ductility. The use of steel jacket material made from zincalume with grade 550 was carried out in experimental tests and parametric studies. Zincalume, which contains 55% aluminium, 43.5% zincalume and 1.5% silicon, is a high-quality rolled steel that is customizable following the size of the spun pile and has a low cost. The use of steel jacket to retrofit the spun pile connection has been registered as patent No. P00202109462 in Indonesia. Zincalume obtained improvements in strength, stiffness, energy dissipation and over-strength ratio. However, there needed to be better modeling of a perfectly adherent specimen. The failure that occurs is the failure of the steel jacket connection so that the grouted concrete breaks when the steel jacket slips. Another area for improvement is the need for special treatment to create friction between precast spun pile and cast in situ grouted concrete. This failure can be seen at the end of the test; when the steel jacket is removed, the grouted concrete falls or said that it is not perfectly bonded to the spun pile. Therefore, a finite element study was carried out to validate the test object modeled by ABAQUS software under experimental conditions. It is also necessary to conduct further finite element studies on specimen objects that do not have interaction failure. The parametric study that will be carried out using finite elements with ABAQUS and SAP2000 software is to vary the thickness and height of the steel jacket of specimen objects which perfectly bonded to determine the effectiveness of the steel jacket on the behaviour of the spun pile connection to the pile cap.

Figure 1. Failure on experimental study of SPPC05

RESEARCH METHODS

Experimental Study

An experimental study was carried out on a spun pile with steel jacket (SPPC 05) with a diameter of 450mm, a thickness of 80mm and a height of 2100mm, which was embedded into the pile cap as far as 100mm and a spun pile without steel jacket (SPPC01). SPPC 05 is reinforced with a steel jacket made of zincalume grade 550, 0.7mm thick and 850mm in length, embedded into the pile cap as far as 100mm. SPPC 05 and SPPC 01 are made of 52 Mpa concrete, ten pieces of PC Bar reinforcement with a diameter of 7.1mm and confined with spiral reinforcement with a diameter of 4mm and a distance of 120mm. Axial loading of 0.1fc'Ag and cyclic lateral loading according to ACI 374.2r-13 standards are given in SPPC 05. Cyclic loading is stopped at 3.5% drift or when the lateral force capacity has decreased by 75% from the ultimate capacity. Horizontal displacement was captured by using transducers.

Figure 2. Set-up testing of SPPC05

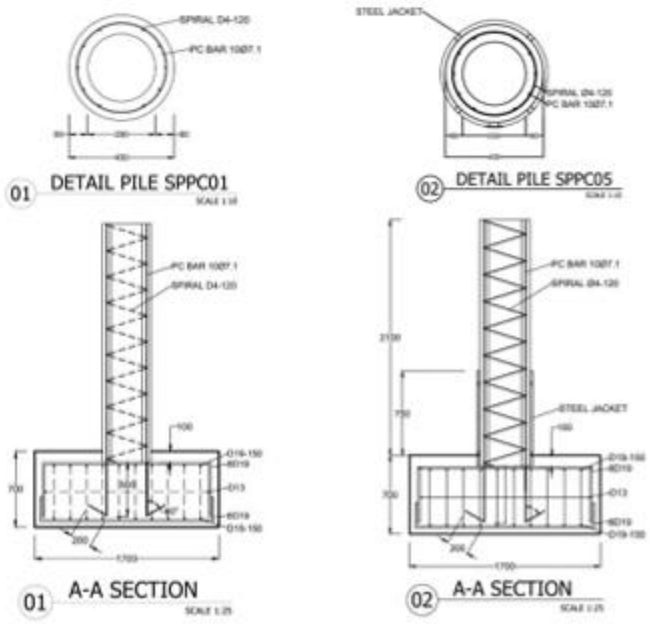


Figure 3. Details of SPPC01 and SPPC05

Table 1. Properties of Steel Materials

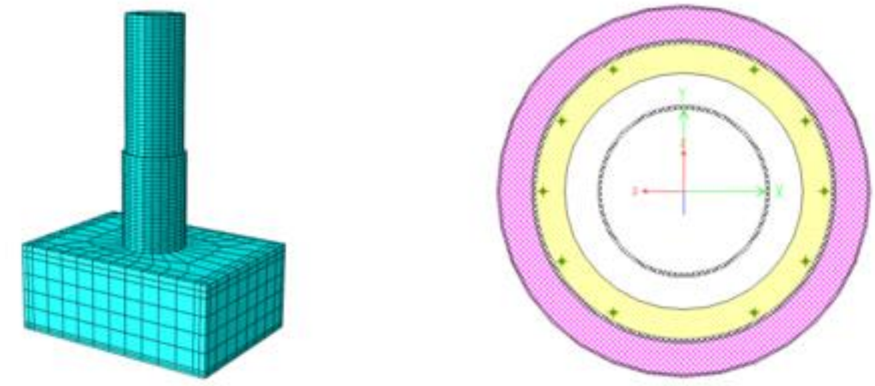
	Reinforcement (mm)		**Fy**	**Fu**
Spun Pile	Prestressed Bar	10Φ7.1	1240	1440
	Confinement	D4-120	390	703
Pile Cap	Longitudinal Reinforced	8D19	400	570
	Confinement	D19-150	390	703
Steel Jacket	Zincalume	t = 0.7	519	529

Finite Element Study

Finite element study uses ABAQUS software to model experiments in 3D. SPPC 05 is divided into several parts. The solid is used for spun piles, grouted concrete, and pile cap. In comparison, the shell part is used for the steel jacket. The Truss part is used for PC Bar, spiral reinforcement, and pile cap reinforcement. Reddiar's constitutive law for high-strength concrete is used for concrete materials. At the same time, steel materials use the constitutive law of Thompson and Park. The input damage parameter in ABAQUS software must not produce negative plastic strain values or show degradation. The mesh feature in the ABAQUS software divides parts into smaller parts to get convergent results. Parts that have been meshed are then arranged into a group with assembly features. Interaction is used to define the parts that touch each other. The spun pile and pile cap interaction is a hard contact with a friction coefficient value.

In contrast, the interaction between reinforcement and concrete is defined as a constraint with embedded region type, which embeds a region in a particular model part. The loading step is divided into initial, axial, and lateral sequentially. In the experimental study, the pile cap is anchored on the solid floor and modelled as a fixed condition at the base of the pile cap with boundary conditions. Displacement control is given at the midpoint of the upper spun pile with the amplitude according to the experimental study. The axial loading of the experimental study 0.1fc'Ag is given as a uniform load on the top of a spun pile.

The minimum steel jacket thickness based on the requirement of the Seismic Retrofit Manual for Highway Structures is 1mm. The variation in the steel jacket height is between 350mm to 950mm, and the steel jacket thickness is between 1mm to 3mm. The steel jacket's height is determined by the length of the plastic hinges, which is then added by 100mm (Olmos, 2019). The length of plastic hinges, according to the California Building Code for prestressed concrete piles with embedded pile type, is 0.5 times the pile diameter. These parameter variations will be used for the perfectly bonded specimen objects. This is done to see how the addition of thickness and height of a steel jacket increases strength and ductility.



a. using ABAQUS software

b. using SAP2000 software

Figure 4. Finite element model

RESULT AND DISCUSSION

Experimental Result

With the material specification used, it is known that the spun pile confinement ratio is only 0.113. in other words, Indonesia's spun pile confinement ratio is only fulfilled at 11%, while the required confinement ratio is 102.2%, according to ASCE7-16. The lack of this confinement ratio is the background of the spun pile research using steel jacket. In this study, the steel jacket used has a thickness of 0.7mm which is installed around a 850mm high spun pile. The analogy is that steel jacket is stirrups with a distance between steel jacket of 1mm. Then the equivalent diameter value of the steel jacket is sought to meet the ratio of confinement requirements. The confinement ratio of spun pile that have been given steel jacket reinforcement increases to 0.56 or 5 times that of spun piles without steel jacket reinforcement.

Table 2. Confinement Ratio

ASCE 7-16			Without Steel Jacket	With Steel Jacket
A_g (mm^2)	159043	d spunpile (mm)	370	500
fc' (MPa)	52	A_{spiral} (mm2)	12.5644	0.6999
f_{yt} (MPa)	390	s (mm)	120	1
A_{ch} (mm^2)	107521	d_{spiral}	4	0.944
P (N)	827024	**ρ_s**	**0.113**	**0.56**
ρ	1.022	Ratio	11.07%	54.77%

The experimental test results obtained from cyclic loading are ductility and hysteretic curves. Ductility is the ratio between the ultimate and yield displacement; the calculation used is Park 1988. The ultimate displacement is the displacement when the maximum lateral load is reached, and the yield displacement is calculated using the secant method. The monotonic pushover analysis curve Is used to get the ductility value when the direction is pushed. As seen in Figure 4, the ductility of SPPC01 without steel jacket is bigger than SPPC05 with steel jacket because its yield displacement is smaller and also the interaction failure of steel jacket on SPPC05 model. SPPC05 got ductility of 2.895 and a strength of 247.317kNm at 37.680mm displacement, while SPPC01 got ductility of 3.336 and a strength of 171.78kNm at 25.440mm displacement. The addition of steel jacket retrofitting increases the strength but decrease the ductility.

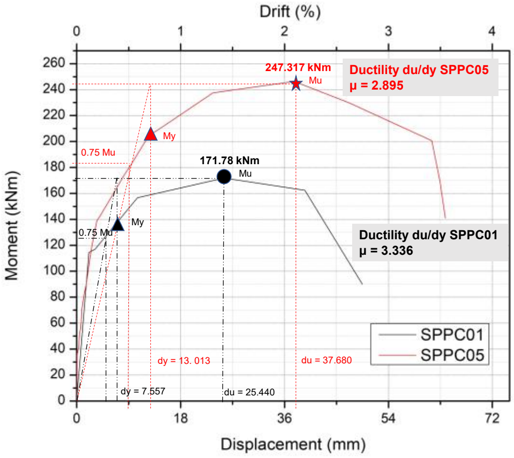
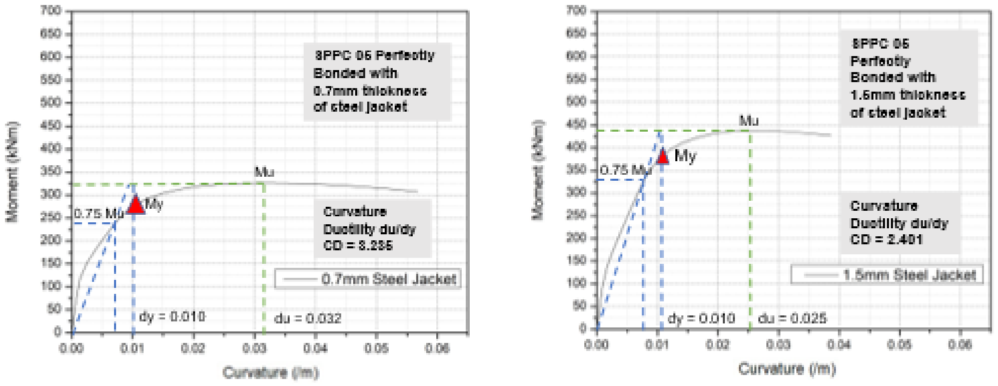


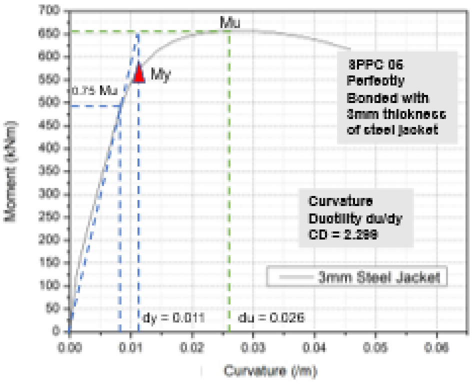
Figure 5. Ductility of SPPC01 and SPPC05

Finite Element Result

From the experimental test results, the pc bar reinforcement was fractured, which meant that the anchorage length was sufficient (the pc bar reached its ultimate stress and then fractured). It is known the pc bar connection was rigid so that the cross-section of the spun pile dominated the behavior of the spun pile connection to the pile cap. The cross-section of the spun pile includes spun pile to grouted concrete and steel jacket to grouted concrete. To vary the thickness of the steel jacket on the spun pile cross-section takes a long time in the ABAQUS software. So SAP2000 software facilitates parametric study with a perfectly bonded model. The addition of steel jacket thickness affects the cross-section of the test object. This parametric study was conducted to obtain the curvature ductility obtained from calculating the curvature moment of the cross-section. The ratio between ultimate curvature and yield curvature defines curvature ductility. The addition of steel jacket thickness affects the curvature ductility value of the test object. The greater the curvature ductility value, the more ductile the spun pile connection to the pile cap. The thicker the steel jacket used, increases the more strength but decreases the curvature ductility.



a. 0.7mm thickness of steel jacket   b. 1.5mm thickness of steel jacket



c. 3.0mm thickness of steel jacket

Figure 6. Curvature ductility of perfectly bonded model with 0.7mm (a) 1.5mm (b) and 3.0mm (c) of steel jacket thickness

The results of modelling the SPPC 05 test object in the ABAQUS software were validated against experimental conditions and expressed in a monotonic loading curve. As previously mentioned, there is a failure of the steel jacket connection and a lack of special treatment on the grouted concrete surface in contact with the steel jacket, as well as the spun pile surface in contact with the grouted concrete, which destroys the grouted concrete when the steel jacket slips. Friction coefficients are assigned to these interactions to validate experimental conditions.

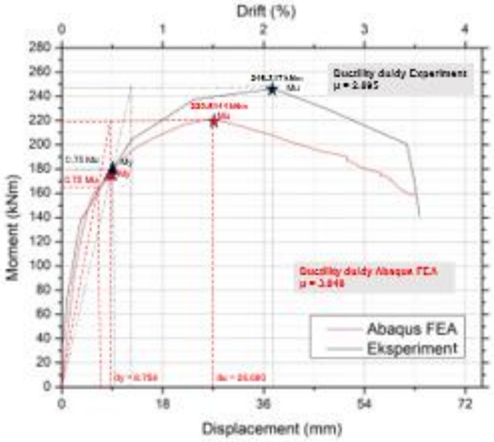
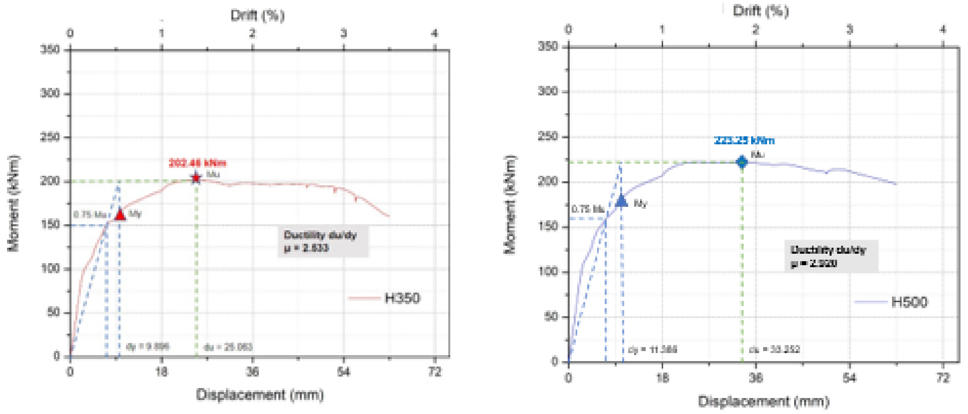


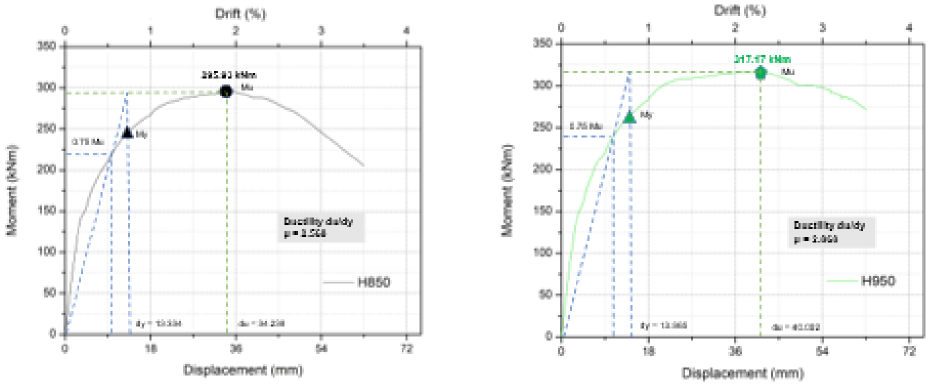
Figure 7. Validation Results of Finite Element Study

Due to the interaction failure on the experimental test object, it is necessary to conduct further studies on perfectly bonded test objects called ideal conditions. It is essential to model a perfectly bonded test object to find the differences between the experimental and excellent conditions of the test object. Parametric studies were also carried out on the height of the steel jacket and grouted concrete in ABAQUS software on perfectly bonded specimens. The monotonic pushover curve can determine the ductility and strength of each model. The addition of steel jacket height has a significant effect on ductility and strength. However, when using a steel jacket with a height of 850mm, the test object yields longer so that the ductility value Is small. Figure 8 explains that the higher the steel jacket and concrete grouting, the greater the strength and ductility.



a. 350mm height of steel jacket

b. 500mm height of steel jacket



c. 850mm height of steel jacket

d. 950mm height of steel jacket

Figure 8. Ductility and strength of perfectly bonded model with 350mm (a) 500mm (b) 850mm (c) and 950mm (d) of steel jacket height

CONCLUSION

The confinement ratio of the spun pile that has been given steel jacket reinforcement increases to 0.56 or 5 times that of spun piles without steel jacket reinforcement, according to ASCE 7-16 calculations. The experimental test between spun pile with steel jacket (SPPC05) has a greater strength of about 43.79% than spun pile without steel jacket (SPPC01). The experimental test also showed the steel jacket made from Zincalume increases the strength of the spun pile. Still, there was an interaction failure between the steel jacket and grouted concrete, and also spun pile and grouted concrete, which caused the ductility more decrease than SPPC01. The finite element analysis closely represents the condition of the experimental result. The finite element analysis gave a friction coefficient to illustrate the interaction failure. The finite element analysis in this research is also used to model SPPC05 with a perfectly bonded condition, which means steel jacket, which is perfectly bonded with grouted concrete and grouted concrete that perfectly bonded with the spun pile or no interaction failure. The cross-section of the spun pile dominated the behavior of the spun pile connection to the pile cap due to the rigid connection of the PC Bar. The perfectly bonded specimen is modeled on SAP2000 software in addition to varying the thickness of the steel jacket because the thickness affects the cross-section. The minimum steel jacket thickness based on the Seismic Retrofit Manual for Highway Structures is 1mm. The variation in the steel jacket height is between 350mm to 950mm, and the steel jacket thickness is between 1mm to 3mm. The specimen with the thicker steel jacket increases the strength but decreases the curvature ductility. The greater the curvature ductility value, the more ductility the spun pile connection to the pile cap. The perfectly bonded specimen is also modeled on ABAQUS software in addition to varying the height of the steel jacket. The height of the steel jacket is determined by the length of the plastic hinges, which is then added by 100mm (Olmos, 2019). The addition of steel jacket height increases the strength but slightly decreases the ductility.

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