Study of spun pile connection with steel jacket strengthening

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Abstract. The amount of spiral reinforcement in the spun pile manufactured in Indonesia is below the minimum requirement. Additional shear reinforcement is needed, particularly on a pile at the adjacent pile cap. To cope with the deficiency, steel jacket is initiated to strengthen the pile. A numerical study was performed to study the effect of steel jacket addition to spun pile behavior. Two different software, SAP and Abaqus were employed. Pushover analysis was performed with a monotonic loading approach. The parameters studied were the steel jacket’s thickness and the existence of adhesive between the steel and the concrete surface. Brittle behavior was detected with the presence of steel jacket which was indicated by the force displacement curve. The steel improves the strength of the spun pile connection but decreases the ductility. It seems that pile is in over reinforced condition. To get a thorough understanding, a 3D model with Abaqus software was performed. Steel jacket is applied on the spun pile without rebar inside concrete fill and thinner steel was selected to prevent over reinforce. Hence, different results were found where spun pile connections behave in a ductile manner. Steel jacket improves not only the strength of spun pile connection but also the ductility.

1. Introduction
Spun piles are precast prestressed piles that are commonly used for medium-rise building, bridge, and port. It has the advantages of convenience in construction, lower cost, higher bearing capacity, and more reliable quality. The connection between pile to pile cap is a critical part since the change of area, stress, and stiffness occurs in this region suddenly [1]. Assuming the connection as rigid will lead the maximum curvature to takes place here. Hence, it should be designed to possess large ductility which is defined as the ability to undergo large deformation in the post elastic range without a significant reduction in strength [2]. In performance-based design, the connection should be able to transfer force induced by an earthquake from the upper and bottom structure and vice versa.

The earthquake is the process of releasing energy in the soil layer that is forwarded to the building. To survive, the building must be able to receive that energy. During extreme earthquakes, damages are allowed to dissipate the energy which is known as plastic hinges. To prevent structural collapse, the hinges are designed to form on particular places depend on the seismic resistance structural system. It is known as a strong column weak beam concept on the upper structure. To prevent excessive deformation, a plastic hinge is allowed to form on the bottom structure with some limitations [3,4]. However, Indonesia still adopts the elastic design concept for bottom structural design by limiting maximum lateral displacement to 25mm for large earthquake [5].

Seismic resistance of the PHC pile has been a matter of concern following the typical failure modes observed during the earthquake reported by Mizuno [6]. Most of the cases of damage to PHC piles close to the top appear to have initiated in the bending shear mode resulting in the weakened section ultimately. It indicates that damage at the bottom structure is unavoidable due to an extreme earthquake. Hence, Indonesia should convert to performance-based on the bottom structural design since the current design code leads to uneconomic results. Moreover, the new Indonesian Seismic Map 2017 indicates the increase of seismic demand than 2010, especially on Java Island.

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The spun pile is one of the favorable foundations employ for bottom structure in Indonesia due to its advantages. However, a study about spun pile behavior does not attract many researchers in Indonesia [7-10]. Irawan et al conducted an experimental study on bending capacity, failure mode, and ductility of spun pile manufactured in Indonesia. It is found that displacement ductility of the pile in the range of 3.50 – 4.00, and according to NEHRP 2000, the pile should be limited to low to a medium seismic zone. A study conducted in 2018 [9], found that confinement provided by transverse reinforcement is insufficient to resist the explosion of the pile’s concrete at the ultimate state due to compression. Setiawan [11] performed finite element analysis of spun pile using OpenSees software. The spun pile showed low energy absorption detected from FE analysis. The software can simulate the experiment conducted by Irawan [7] very well and the model can be used for further study.

An intensive study of spun pile connection has been conducted in China during the last decade [11-13]. Wang [11] conducted an experimental and numerical study of the connection based on China’s design guide. The spun pile was prestressed high strength concrete (PHC). The ductility of the PHC connection was around 3-4. A similar study was conducted by Zhaosheng [12] with different connection details. The connection was strengthened with two different details to improve strength, ductility, and energy absorption. Higher strength and ductility were achieved. Yang [14] conducted an experimental study of the connection with two different strengthened PHC. Steel fiber and FRP were applied to PHC, however, it did not significantly improve the strength and ductility of the connection. The results were almost similar to a study conducted by Bang [1] in Korea. Improvement of connection behavior was not as high as when the strengthening was applied on connection details rather than on the spun pile.

None of the studies has been conducted on spun pile connection in Indonesia, perhaps because of pile damaged is forbidden. However, due to the increase of seismic demand, seismic performance of the spun pile connection is necessary. One of the concerns is most of the spun pile produced in Indonesia has limited spiral reinforcement, where the amount is below the minimum requirement according to ACI 318-19 [15]. Nevertheless, sufficient confinement is compulsory to prevent shear failure and buckling of the prestressed bar. The spun pile is constructed with different spiral confinement, closer distance at the pile end to protect the pile during the driving process and far distance in the middle. Most of the time, piles should be cut to the proper elevation when the depth does not coincide with the finished elevation of the cap. Hence, confinement of the piles adjacent to connection is auxiliary insufficient. However, section properties of the pile next to the pile cap play an important role in ensuring the form of a plastic hinge. To cope with the deficiency, additional shear reinforcement is needed on the pile next to the pile cap. Steel jacket is initiated to strengthen the pile. A numerical study that uses SAP 2000 was performed to study the effect of steel jacket to pile performance. The connection between spun pile and pile was assumed as rigid. To get an in-depth understanding, 3D modeling with Abaqus was carried out to simulate the connection details.

2. Research Methodology

2.1. Validation model

The study starts with the validation phase to ensure the modelling approach could represent the actual structure. An experimental study conducted by Wang, et al. [11] used as a reference. The study consisted of six prestressed high strength concrete (PHC) pile to pile cap connections with different detailing which were tested to evaluate the seismic performance. A 500 mm diameter PHC pile with 100 mm in thickness, 2000 mm in length was embedded into the cap as 100 mm. The pile consisted of ten 9.0 mm in diameter of 270 ksi grade of prestressed bars with an applied prestresses of 994 MPa (70% gross ultimate tensile strength). The stirrup spacing and diameter was 40 mm and 50 mm respectively. The specimen named CT4 was chosen as a reference for validation. It was filled with concrete and reinforced by six anchor bars. This model also may represent the fixed restraint in the numerical model due to its slope of the anchor bar that could be hooked to the pile cap, produced a fully rigid connection.
Figure 1 shows the experimental setup of Wang’s research. In SAP2000, the pile was modelled as a single frame element, the cross-section of the pile was generated using a section designer feature, and the connection between pile to pile-cap is modelled as fixed restrain. The discrete fiber model in the section designer of SAP was used to describe section properties of the spun pile. To reduce computational work, a concentrated fiber hinge was used where the hinge was assigned at the maximum moment along with the pile which is near the connection region.

**Figure 1.** Wang’s (2016) Experimental Study

Monotonic pushover analysis was performed to represent the experiment where displacement-controlled lateral load which continuously increases through elastic and inelastic behavior until an ultimate condition is reached. Results were plotted together with the experimental results and presented in Figure 2. As shown, the finite analysis results coincided with the experimental data, which can accurately simulate experimental results. The average relative error of the result is only 3.35 %. This means the SAP2000 modelling approach to Wang’s experimental result shows a good agreement. Consequently, the FE model can accurately obtain the elastic stage to post yielding behavior of the pile close to the experiment. Therefore, it can be concluded that the numerical model is valid and can represent the real structure. Hence, further study to investigate the behavior of spun pile can be carried out.

**Figure 2.** Validation Results
2.2 Numerical Study
The purpose of adding steel casing as additional strengthening on the pile is to fulfil the shortage of the minimum confinement required for spiral confinement of prestressed concrete pile according to ACI 318-19 which converted into an equivalent thickness of the casing. The study was conducted on one of the typical spun pile that is usually used in Indonesia. The pile has 500mm in diameter with a wall thickness of 90mm. It is made of 52MPa of concrete strength reinforced by 10 of 9mm in diameter of PC bar. The spiral diameter is 4mm with a spacing of 50mm. The pile is filled by reinforced concrete consisted of 6D19 and the concrete strength is 30Mpa.

According to ACI 318-19 [15], confinement that should be provided for reinforced concrete structures is presented as follow:

\[
\rho_s = 0.45 \left( \frac{f'_c}{f_{yh}} \right) \left( \frac{A_g}{A_{ch}} - 1 \right) \geq 0.12 \left( \frac{f'_c}{f_{yh}} \right)
\]

where \( f'_c \) is the compressive strength of unconfined concrete, \( f_{yh} \) is the yield strength of transverse reinforcement, \( A_g \) is gross area and \( A_{ch} \) is cross-sectional area of confined core concrete section, measured out-to-out of the spiral reinforcement. Meanwhile, the volumetric ratio of spiral transverse reinforcement is determined based on equation 2, as follow:

\[
\rho_s = \frac{4A_{sp}}{D's}
\]

where \( A_{sp} \) is the area of transverse reinforcement bar, \( D' \) is the diameter of confined concrete and \( s \) is spiral spacing. Based on both equations, the minimum spiral confinement spacing ratio for pile with a diameter 500 mm is 0.0115 or round up to 1.2% while the configuration of Indonesia manufacture is only 0.25% for 50 mm spacing and 0.12% for 100 mm spacing which is very far below the minimum requirement.

| Table 1. Properties of steel reinforcement |
|-------------------------------------------|
| Reinforcement (mm) | Fy (MPa) | Fu (MPa) | Es (MPa) |
|---------------------|----------|----------|----------|
| Spun Pile           | Prestressed Bar | 10D9     | 1275     | 1420     | 2.00 x 10^5 |
|                     | Spiral Wire | D4 - 50  | 540      | 712      | 2.00 x 10^5 |
| Concrete infill     | Core Rebar | 6D19     | 390      | 560      | 2.00 x 10^5 |
|                     | Circular Hoop | 8-100     | 235      | 380      | 2.00 x 10^5 |
| Steel Jacket        | Steel Jacket | \( t=5 \) | 240      | 370      | 2.00 x 10^5 |

The shortage then converted into additional steel jacket which is varied to 3, 5, and 6 mm. The addition of 3mm steel jacket lead to confinement with a volumetric ratio reaches 5.7% by assuming transverse reinforcement as 3mm in diameter with a spacing of 1mm. The material used for steel jacket or steel casing is using the most common steel property material that is widely applied in Indonesia which is BJ-37 steel properties. The stress-strain curve of the BJ-37 is similar to the conventional rebar stress-strain curve, where the ultimate strain percentage is 14%. Steel casing then added to the pile outer diameter using a section designer by defining the thickness beforehand. The steel casing is applied along with 1D of the pile length which 500 mm from the pile and pile cap connection. It is conducted by considering the maximum moment location where the plastic hinge would occur. The discrete fiber model in the section designer of SAP was used to describe section properties of the spun pile as shown in Figure 4. Concentrated plastic hinge was assigned on two locations, adjacent to the pile cap and above the steel jacket. Effective prestress force was applied in the FE model. According to the pile specification, the force is 51.78kg/cm².
Similar to the validation stage, the pile was modeled as a single frame element where the section was generated as a fiber cross-section consist of unconfined and confined concrete which is separated by transverse reinforcement, as shown in Figure 4. The constitutive law of confined and unconfined concrete follow the Meander stress-strain curved provided in SAP. The prestressed bar (PC bar) of the spun pile is referring to JIS G 3137-1994 and modeled as a tendon that represents the reinforcement of the spun pile. The prestressed grade is 270 ksi and the strain was limited to 3-5%, which indicates a low ductility phase after the yielding point is reached. The spiral wire used for the spun pile is referring to JIS G 3536-1999 that has SWPD1 (Deformed Wire Type) specification which is uncoated stress-relieved steel wires. The reinforcement bar of concrete infill is BJTP24 and transverse reinforcement is BJTP40. Both refer to SNI 07 – 2052 – 2002. The stress-strain curve of different reinforcement used in the FE study is presented in figure 3.

Figure 3. Stress-strain curve of PC bar; spiral wire and rebar

Figure 4 display the FE model of spun pile with steel jacket with a diameter of 500mm. The jacket was modelled as casing with different adhesive conditions, which were fully bonded, partially bonded and unbonded. The software provides longitudinal factor to specify the fraction of the thickness to the fibre section. The factor value 1 assumes that the casing is completely bonded to the section and hence its thickness contributes to the moment curvatures of fibre section. The factor of 0.5 was chosen to represent partially bonded.

3. Results and Discussion

3.1. Numerical Study based on 2D model on SAP2000
Bonding between the steel jacket and the pile is one of the main issues regarding workability in the construction practice. Figure 6 presents the effect of adhesive between spun pile and 5mm in thickness of steel jacket to the load-displacement curve. The results are compared to the spun pile without steel jacket (SPC). As can be seen, steel jacket changes the behavior of the spun pile connection. The jacket
improves the strength of the connection significantly compared to SPC. It partially bonded steel jacket increase bending capacity by 29.7% from 363.95kNm to 472.11kNm. Meanwhile, fully bonded steel jacket improves bending capacity by 74.2%. The shear capacity of the spun pile is 519 kN which is greater than the bearing force. Hence, the failure mode of all specimens is flexure.

Displacement ductility

\[ \mu = \frac{\Delta_u}{\Delta_y} \]  

(2)

**Figure 5.** Definition of yield and ultimate displacement [16]

Improvement in flexural strength was not followed by displacement ductility. As shown in Figure 3 and 4, the failure mode of the spun pile with steel jacket is more brittle than SPC. The sudden drop of strength was observed after the ultimate capacity is achieved. The method proposed by Pam (1988) was used to determine the displacement ductility of the spun pile and the value is less than 2.00 as shown in Table 3. Ductility of the spun pile with steel jacket decrease 15% to 30% compared to SPC without steel jacket. It seems that steel jacket put the spun pile at over reinforced condition that lead to brittle failure mode since steel jacket act not only as transverse but also as longitudinal reinforcement. Hence the spun pile has double reinforcement, rebar in concrete infill (6D19), and steel jacket. The ductility of the spun

| Specimen                          | Bending Capacity Mu (KNm) | Bearing Capacity V (KN) | Displacement ductility |
|----------------------------------|---------------------------|-------------------------|------------------------|
| SPH : Hollow Spun Pile           | 257.00                    | 152.98                  | 3.10                   |
| SPC : Spun Pile with concrete infilled (6D19) | 324.75                  | 192.26                  | 1.67                   |
| SPC with 5mm jacket (partially bonded) | 397.10                  | 236.37                  | 1.44                   |
| SPC with 5mm steel jacket        | 532.95                    | 317.23                  | 1.17                   |
| SPC with 3mm steel jacket        | 412.48                    | 245.52                  | 1.35                   |
| SPC with 6mm steel jacket        | 576.93                    | 343.41                  | 1.41                   |

**Figure 6.** Effect of Different Adhesive Condition

**Figure 7.** Effect of thickness variation

**Figure 8.** Definition of yield and ultimate displacement [16]
pile with and without steel jacket is less than 2.00 as presented in Table 2. The study conducted by Irawan [7] found the ductility was around 3.0. Further study was conducted to investigate the behavior of spun pile connection by using a 3D model with Abaqus software.

3.2. Numerical Study with Abaqus

A spun pile of 450mm with 80mm wall thickness was chosen for numerical study. It is reinforced by 10 PC bars with 7.1mm in diameter. The concrete strength of the spun pile was similar to the previous study, 52MPa. A rebar of 4mm-diameter with a spacing of 100mm was used as transverse reinforcement which is equivalent to volumetric ratio of 0.136%. This value is far below the minimum ratio as specified by ACI 318-19, which is 1.16%. To avoid an over-reinforcement condition, the spun pile with steel jacket was filled with plain concrete of 30Mpa. Thinner steel jacket as 2.3mm and 3.2mm were selected with an equivalent volumetric ratio of 3.7% and 7.1%, respectively. Similar steel strength presented in Table 1 were employed.

A validation model was conducted to ensure that the FE model with Abaqus can represent the actual condition. Wang’s experimental study, CT5, was chosen as a reference. Predefined field menu was chosen to include the initial prestressed as mentioned in paper Wang [11] as 994Mpa. The 3D FE model can represent the connection between the spun pile and pile cap. Since the spun pile is not reinforced by rebar, the connection between spun pile and pile cap was based on 10 PC bars which are embedded to pile cap with a depth of 500mm. Figure 8b shows the FE model and the results, where the error is 4.62%.

Figure 8. Summary of FE Model with Abaqus

Figure 9. Effect of Adhesive and thickness Variation based on Abaqus
The study results were presented in Figure 9. Similar to 2D model, steel jacket acts as casing. Contact between steel jacket and spun pile were modelled as fully and partially bonded. A gap as 1 mm was assumed between steel and spun pile to represent partially bonded. The interaction is modelled as surface-to-surface contact with a coulomb friction as 0.3. As can be seen, the behavior of the spun pile connection from the 3D model is totally different from the 2D model built by SAP. The bonding effect which represents as a gap as 1mm in the FE model only slightly decreases the connection strength. The force-displacement curve increases gradually until the ultimate capacity is reached and the strength drops smoothly.

**Spun Pile with Steel Jacket 3.2mm, fully bonded**

![Stress Distribution](image1)

**Spun Pile with Steel Jacket 3.2mm, partially bonded**

![Stress Distribution](image2)

**Figure 10.** Stress distribution (in MPa) of spun pile connection at Spun Pile, PC bar, Pile Cap and steel jacket

Figure 10 presents stress distribution of two specimen that represent the failure mode of spun pile connection with steel jacket. Von Misses yield criteria was used to determine stress on PC bar and steel jacket. As can be seen, the failure mode of the specimens are crushing of concrete on spun pile and pile cap next to the connection and also yielding of the PC bar and the steel jacket. Similar failure mode was detected on specimens with steel jacket of 2.3mm. The summary of this study is presented in Table 3. As shown, steel jacket can improve the strength and ductility of the spun pile connection.

**Table 3.** Summary of parametric study using Abaqus

| Specimen                                             | Bending Capacity Mu (KNm) | Bearing Capacity V (KN) | Displacement ductility |
|-------------------------------------------------------|---------------------------|-------------------------|------------------------|
| SPPC : Spun Pile with plain concrete infilled         | 243.50                    | 144.95                  | 3.40                   |
| SPC : Spun Pile with concrete infilled (6D19)         | 279.80                    | 166.56                  | 2.49                   |
| SPPC with 2.3mm jacket (gap)                          | 278.90                    | 166.04                  | 3.74                   |
| SPPC with 2.3mm steel jacket                          | 295.48                    | 175.88                  | 3.82                   |
| SPPC with 3.2 mm steel jacket (gap)                   | 279.05                    | 166.10                  | 4.01                   |
| SPPC with 3.2 mm steel jacket                         | 292.78                    | 174.27                  | 3.83                   |
4. Conclusion
The numerical result in this research shows a good agreement with the experimental result conducted by Wang (2016). Fibre element with concentrated plastic hinge can be employed to present the spun pile connection. SAP2000 provided constitutive law of steel and concrete in confined and unconfined conditions. Pushover analysis with large deformation can be used to represent the experiment. The addition of steel jacket to strengthen the spun pile connection should be designed properly to ensure under reinforced or balance conditions to prevent brittle failure. It is suggested to remove the reinforcement bar in concrete infill when steel jacket was applied. The proper amount of steel jacket improves not only the strength of connection but also the ductility. The gap between steel and spun pile concrete slightly decreases the connection strength as 4.6 to 5.2%.

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