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EXPERIMENTAL STUDY OF SPUN PILE TO PILE CAP CONNECTION CONFINED BY STEEL JACKET

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ABSTRACT: The high confinement ratio requirement for precast piles, according to ACI 318-19 with tight-spaced spiral reinforcement, is difficult to implement. A certain amount of reinforcement is necessary from the pile adjacent to the pile cap to ensure the occurrence of a plastic hinge during a severe earthquake. To address the deficiency of the confinement ratio, an economical solution, such as the customization of steel jackets, is suggested instead of increasing the amount of spiral reinforcement in the spun pile. An experimental study was conducted to investigate the performance of the spun pile and pile cap connection with the steel jacket. The jacket was fabricated from a steel plate aligned to the diameter of the spun pile, with rivets to connect it's end. Three specimens with different connection details were tested through cyclic loading. The connection of the steel jacket and the bonding between the pile and the jacket were found to be two crucial factors influencing the pile connection behavior. Although the jacket was not specifically designed to enhance the bending capacity of the connection, the embedment into the pile cap influenced the overall strength of the connection. The presence of the steel jacket increases the bending strength by 18%. Additionally, the jacket improves the connection's deformability and boosts the energy dissipation capacity by 1.8 times compared to a connection without the steel jacket. The study revealed that the steel jacket can be used as a promising alternative solution to fulfill the confinement of the spun pile on the connection area.

Keywords: Spun pile connection, Confinement, Steel jacket, Ductility, Dissipation energy

1. INTRODUCTION

Indonesia is located on two tectonic plates, and earthquakes are highly frequent. However, the design code for substructures employs the elastic method to prevent damage to the foundation during seismic. In practice, spun piles, the most common type of piles in Indonesia, are fabricated with limited spiral reinforcement. The amount is less than the minimum requirement defined by ASCE 7-16 and ACI 318-19, respectively [1,2]. In fact, the conventional elastic method does not address this issue. On the other hand, the recent earthquake risk map indicates an increase in seismic acceleration in almost all regions of Indonesia. Therefore, transitioning to performance-based design for substructures is essential and necessary for Indonesia to achieve economical designs. Furthermore, fulfilling the adequacy of confinement in spun piles is necessary.

The spun piles have tightly spaced spiral reinforcements only at both ends and in smaller amounts in the middle section. In the construction process, spun piles are cut accordingly to the cut-off level following the location of hard soil. Occasionally, the cutting position is located in the middle of the pile, where the number of spiral reinforcements is minimal. Insufficient information related to the cut-off level has led to the production of piles with tightly spaced spiral reinforcements along the entire length of the pile to meet the confinement requirements. However, the installation of sufficient reinforcements along the entire length of the pile is considered uneconomical.

Previous studies explained the need for transverse reinforcements of the precast pile requirement to sustain severe earthquakes with economic values [3-5]. The research criticized the equation in ACI 318-05 related to the irrational design requirement amounts to be fulfilled. For instance, a precast pile diameter of 610 mm and 76 mm concrete cover with concrete strength of 41.3 MPa followed by 413 MPa spiral reinforcement need a requirement of 3.5% spiral reinforcement ratio. The designed spacing resulted in 10 M-long spirals pitched at a diameter of 18 mm. Aside from being uneconomical to build, the spacing would violate the ACI 318-05 minimum pitch [3].

The connection between pile and pile cap is a critical part since the change of area, stress, and stiffness occurs suddenly. It is critical to transfer the load from the upper to the bottom structure and vice versa. Furthermore, a rigid connection leads to maximum curvature, and the plastic hinge or damage might occur at this section. The piles adjacent to the pile cap connection require sufficient confinement to ensure the occurrence of plastic hinges. A post-severe-earthquake observation reported several damages to occur on the pile next to the pile cap [6].

Numerous studies on spun pile connections have been extensively conducted in decades in other countries such as China. Spun pile was performed with different connection details commonly applied in China [7]. The experiment consisted of six specimens and were tested with lateral cyclic loading and a constant axial load. The study reported flexural damage on all specimens, and the ductility was in the range of 2.5 to 3.0. The hysteretic curves revealed a pinching condition and indicated a lack of energy dissipation.

In order to improve the connection behavior of the spun pile, two different types of connection strengthening were employed [8]. The first method conducted by jacketing the pile on the connection region with concrete. The second method is by adding internal T-shaped steel inside the spun pile through the pile cap. The test experiment showed a better hysteretic curve, resulting in the increased flexural strength and ductility of both connections. The ductility of the connection without strengthening was 3.07 and increased to 4.31 and 5.48 with concrete jacketing and T-shaped steel, respectively. Another research was performed by utilizing three layers of Carbon Fiber Reinforced Polymer (CFRP) to confine the spun pile next to the pile cap [9]. However, the presence of CFRP had minimal effect on the behavior and ductility of the connections.

Numerical study on spun pile-to-pile cap connections based on the conditions in Indonesia, has begun in recent years [10-12]. The study found that by filling the hollow with the concrete increases the connection strength. Adequate confinement improves the performance of the connection at peak post-stage that affects the ductility of the connection.

All previous types of strengthening, concrete jacketing, internal T-shaped steel, and CFRP, were not cost-efficient. To overcome these issues, this study proposes utilizing a low-cost steel jacket made of cold-formed steel plate as an addition of confinement to the spun pile adjacent to the pile cap. The jacket can be customized by bending the plate to match the diameter of the spun pile. Research on steel jackets as strengthening has been widely conducted on column structures [13-16]. The study found that steel jacket significantly improves the initial stiffness, strength, ductility and dissipation energy of column. The use of steel jacket to strengthen the spun pile connection based on numerical study found a similar results [17]. However, the jacket was a hot-formed steel which has limited diameter and thickness.

The high confinement ratio required for precast piles by ACI standards necessitates closely spaced spiral reinforcement, which can be difficult to implement. To overcome this, this research proposes steel jackets in the connection area to increase the confinement ratio. The innovation of steel jackets and the associated construction methods have been registered with the Indonesian Patent [registration number P00202109462]. This paper reports two experimental series that have been conducted. The first series was the basic connection type that is commonly used in Indonesia, where the spun pile has limited confinement. The second series was performed by strengthening the spun pile on the region of the connection by using the steel jacket. The effectiveness of the steel jacket was measured by comparing the second series to the first one.

2. RESEARCH SIGNIFICANCE

The research is significant in improving the confinement of spun piles at the connection area. Sufficient confinement is only necessary in the area extending 1.5D around the connection. Since the location of hard soil is uncertain and the pile could be cut at any point, strengthening the connection area is the most cost-effective solution. The significant impact of this study raises questions about the sufficient amount of transverse reinforcement on a spun pile and generates further research on spun pile-to-pile cap connection.

3. THE EXPERIMENTS

3.1 The Specimens

Three full-scale spun pile connections strengthened with a steel jacket were prepared to evaluate their seismic performance. Earlier experimental studies on the connection between spun piles and pile caps were conducted on two specimens without steel jackets. The comprehensive discussion and results were reported on [11]. The results were used as a reference when designing the second series.

Table 1. The Specimens

Specimens		Inside the Spun pile	Steel Jacket
First Series	SPPC01	Empty	No
	SPPC02	Concrete infill & 6D19	No
Second Series	SPPC05	Empty	Yes
	SPPC06	Concrete infill	Yes
	SPPC07	Concrete infill & 6D19	Yes

Table 1 presents a comparison of the first and second series of experiments. The difference between the three specimens was the hollow of the spun pile. The specimens were manufactured with empty spun piles, with concrete infill, and with reinforced concrete infill where their code was SPPC05, SPPC06, and SPPC07, respectively. Compared to earlier studies, SPPC05 and SPPC07 are similar to SPPC01 and SPPC02 in terms of strengthening steel jackets.

Fig. 1 shows the details of the spun pile and the pile cap connection, which were similar to the first series. The pile cap dimension was 1700 x 1200 x 700 mm. It consisted of concrete with the strength of fc' 30 MPa and reinforced with D19-150 bars, which was equal to 1% of the concrete volume. A 450 mm diameter spun pile with an 80 mm wall thickness was employed. It was made of *fc'* 50 MPa concrete strength and reinforced with ten strands of 7.1 mm prestressed wire. It was confined by a 4 mm diameter spiral with a pitch of 120 mm. Fig.1 only shows SPPC05 and SPPC07. Meanwhile, SPPC06 is similar to SPPC07 without the presence of 6D19.

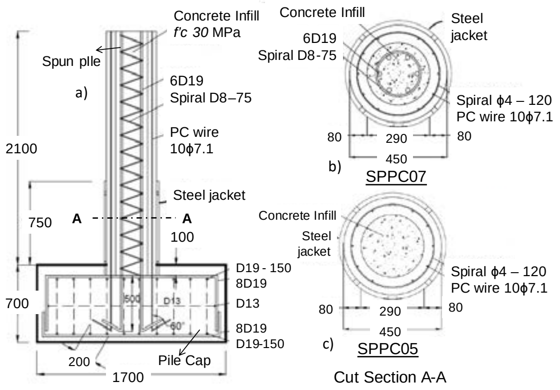

Fig. 1 DED of the specimens
(a) Connection detail, (b) Cut Section A-A: SPPC07; and (c) SPPC05

For the calculation, there are two equations to determine the needs for transverse reinforcement adopted in the Indonesia design code, which is article 10.9.3 of ACI 318-19 and article 14.2.3.2.6 of ASCE 7-16. ACI covers the detailing of the concrete structural design in the building. Meanwhile, ASCE 7-16 is aimed at prestressed precast piles at higher seismic risk. The difference between the two codes is the axial forces. ACI does not consider the axial forces in determining the need for reinforcement, while the ASCE does. The equation was mentioned in ASCE 4 – 17 as follows:

$$\rho_s \min = 0{,}12\left(\frac{f_c^{'}}{f_{yh}}\right)\left(0{,}5+\frac{1{,}4P}{f_c^{'}A_g}\right) \tag{1}$$

$f_c^{'}$ = concrete compressive strength (MPa)

f_{yh} = yield strength of spiral (MPa)

A_g = area of the pile (mm²)

P = axial load (kN)

The steel jacket to enhance the confinement of the spun pile was constructed using a 0.7 mm thick cold-formed steel plate which was bent to match the diameter of the spun pile. The ends of the jacket was connected using rivets to form a circular shape. The steel jacket was 850 mm height. The selection of height is based on the need to ensure that the plastic hinge zone from the previous test is confined. The preceding test found that the zone extended approximately 1.5D from the surface of the pile cap.

The minimum confinement ratio according to ASCE 7-16 for a 450 mm diameter spun pile loaded with *0.1f'c Ag* axial load is 0.768%. Meanwhile, the ratio of spirals with 4 mm diameter and 120 mm spacing is 0.113%, which is only 13% of the minimum requirement. The steel jacket increases the confinement ratio of the spun pile on the connection zone to 0.56%. The amount is 27% lower than the minimum requirement. Moreover, to transfer the force from the pile to the jacket, a 25 mm thick layer of concrete grout with a concrete strength of *fc'* 61 MPa was attached to the pile. Fig. 2 presents the construction stage and the detailed connection of the steel jacket.

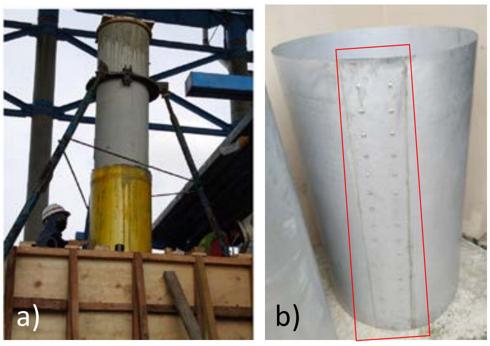

Fig. 2 a) The construction stage; b) The rivet connection of the steel jacket

Furthermore, the spun pile was embedded into the pile cap to a depth of 100 mm. The embedment length of the prestressed concrete (PC) wire was determined according to ACI 318-14M. The required length was 540 mm. To reduce the depth of the pile cap, the length was made of 500 mm straight with an additional of 200 mm bended at 30 degrees. The details are shown in Fig. 1. Moreover, the strength of the steel reinforcement is presented in Table 2.

Table 2. The Steel Strength

Location	*fy* (Mpa)	*fu* (Mpa)	Es (Mpa)
Prestress Bar	1275	1562	$2.0x10^5$
Spiral of Pile	570	703	$2.0x10^5$
D19 Rebar	400	570	$2.0x10^5$
Spiral of Conc. infill	240	370	$2.0x10^5$
Steel jacket	519	529	$2.0x10^5$

3.2 The Test Set-up

The test setup for both series is similar and shown in Fig. 3. The test was conducted after the concrete of the pile cap, and the infill reached more than 28 days. The specimen was attached to a strong floor and secured with ten anchoring bolts. To prevent horizontal movement of the pile cap, two hydraulic jacks were placed at the bottom of the pile caps and equal horizontal forces were applied at both sides. Seven transducers (Tr-2, Tr-3, Tr-5, Tr-7, Tr-9, Tr-21, and Tr-22) were installed to measure the horizontal displacement of the spun pile, and two of the transducers (Tr-13, Tr-14) were placed to measure vertical displacement. Moreover, two transducers (Tr-19, Tr-20) monitored the movement of the pile cap. Concrete strain gauges were placed on the pile cap and positioned 100 mm from the connection. The strain of the reinforcement bar was measured using six strain gauges and located next to the connection in the loading plane, while four strain gauges were attached to the PC wires in the same location.

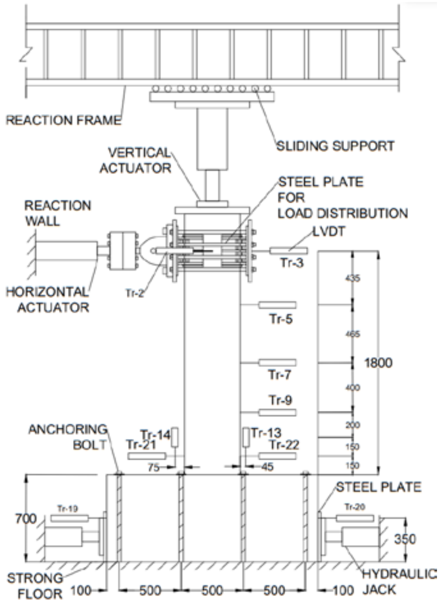

Fig. 3. The Experimental Set-up

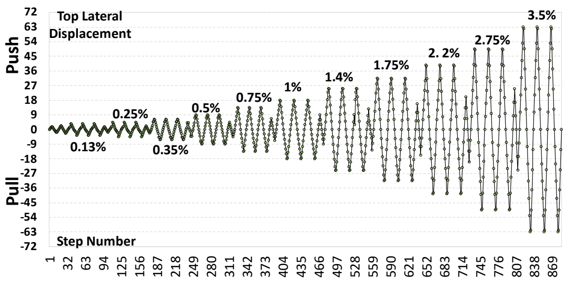

Fig 4. The Loading Protocol

Both experimental series were tested until failure with a cyclic horizontal loading protocol specified by ACI 437-07, as shown in Fig. 4. A constant vertical load of 500 kN, which was equal to 0.1f'cAg, was applied. A steel plate of 500 x 500 mm with a 12 mm thick was set on top of the pile to transfer the force from the actuator to the pile. Additionally, the jack was attached to a sliding frame to ensure that the load was applied in the vertical direction. The test was conducted until a targeted drift of 3.5% was achieved or until the strength of the specimen was dropped more than 50%.

4. RESULTS AND DISCUSSION

To see the effect of steel jacket, the result is presented as a comparison to the first series which was without steel jacket. Hence, SPPC05 was compared to SPPC01 and SPPC07 was compared to SPPC02.

4.1 The Failure Modes

The failure mode of three specimens is presented in Fig. 5-7. The failure of the steel jacket connection was found on specimens SPPC05 and SPPC06 at a drift of 1.75%. The placement of the steel jacket connection on the spun pile was not purposely arranged during the construction. For SPPC05 and SPPC06, the connections are located approximately 30 degrees from the horizontal load path. Hence, the failure of the steel jacket connection was observed in both specimens at a drift of 1.75%. In the case of SPPC07, the connection was found almost perpendicular to the horizontal loading and avoiding failure at the steel jacket connection.

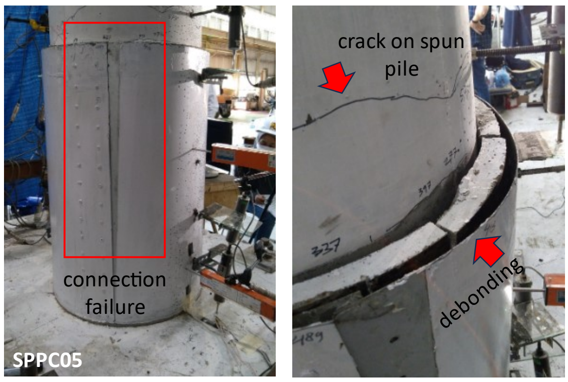

Fig. 5 The Failure Mode of specimen SPPC05

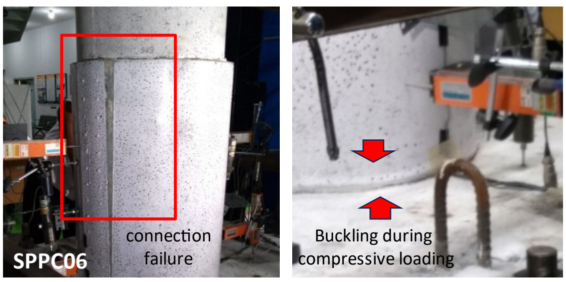

Fig. 6 The Failure Mode of Specimen SPPC06

Once the connection failed, debonding occurred between the steel jacket and the concrete grout as well as between the grout and the spun pile, as shown in

Fig. 5. The debonding breaks forth from the farthest part of the pile cap surface and spread downward. When the connection began to fail, the confinement from the steel jacket was revealed to be still effective on the lower side. Therefore, the failure of the steel jacket did not result in a sudden loss of strength in the connection, as can be seen on the hysteretic curves presented in Fig. 8b and 8d. Another failure mode observed on SPPC06 was the buckling of the steel jacket next to the pile cap. The buckling indicated that the steel jacket lost the lateral support due to debonding from the grout. Interestingly, a fracture of the PC wire was also detected during the testing, indicated by the sound of the bar breaking in all three specimens.

SPPC07 was the only specimen in which the steel jacket performed perfectly according to the design. Hence, the spun pile in the connection zone has sufficient confinement throughout the testing. Cracks occurred on the spun pile outside the steel jacket and also on the surface of the pile cap. At the end of the test, fractures in the steel jacket occurred. Furthermore, the failure mode of SPPC07 is shown in Fig. 7.

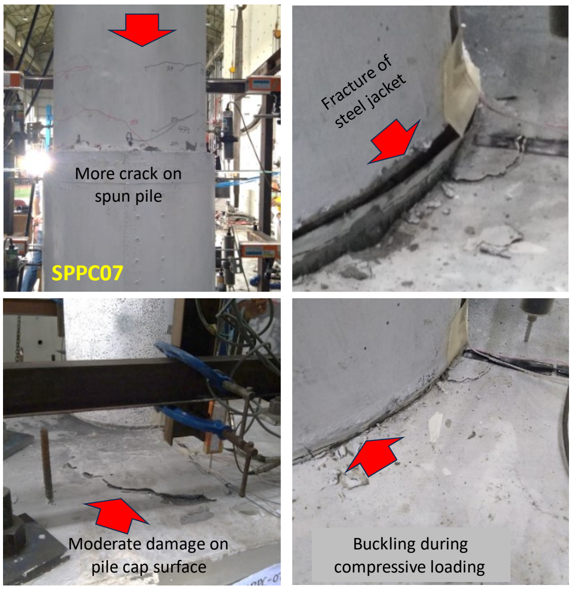

Fig. 7 The Failure Mode of Specimen SPPC07

4.2 The Hysteretic Curve

The results of the cyclic loading test are presented as the hysteretic curves shown in Fig. 8b, 8d, and 8e. The hysteretic curves of SPPC01 and SPPC02 are included for comparison. As shown, the spun pile with steel jackets exceeds the target drift of 3.5%, with SPPC07 even reaching a drift of 5%. The comparison of three specimens, SPPC05, SPPC06, and SPPC07, is displayed in the envelope curves shown in Fig. 8f.

The comparison of SPPC02 and SPPC05, shown in Fig. 8a and Fig. 8b, demonstrates the effectiveness of the steel jacket on an empty spun pile, while Fig. 8c and 8d illustrate steel jacket impact on a spun pile with additional reinforced infill concrete. The steel jacket not only increased the strength of the connection but also improved its deformation capability despite the failure of the steel jacket connection. A similar effect was observed in the spun pile with reinforced infill concrete, although the increase in strength was not as significant as related to the empty spun pile. However, based on the area under the hysteretic curve indicates a significant influence of the steel jacket on the connection's behavior.

The above findings explained that the steel jacket not only provided additional confinement, allowing the connection to deform further but also contributed to an increase in strength. As the steel jacket was embedded into the pile cap, the tensile strength was developed. Moreover, the adequate bonding between the steel jacket and the grout resulted in effectively increasing the area of concrete in the connection region from 450 mm to 500 mm in diameter. Furthermore, the additional moment arm provided by the steel jacket on the outer side of the spun pile also contributed to the increase in the overall strength of the connection.

On the other hand, the hysteretic curve of SPPC06 exhibited asymmetry during the push and pull cycles. This was caused by the failure of the steel jacket connection and the different failure modes on each side. Buckling was observed only on one side of the steel jacket. This behavior is reflected in the hysteretic curve and the maximum capacity, resulting in a strength variation of up to 15%.

The comparison between the three specimens, SPPC05, SPPC06, and SPPC07, is shown in Fig. 8f. This figure does not fully reflect the impact of the steel jacket on the three different spun pile conditions due to the failure of the steel jacket connections in SPPC05 and SPPC06. However, by comparing the behavior before the steel jackets detached (at a drift of 1.75%), it was revealed all three specimens behaved similarly. The differences were apparent at larger drifts, highlighting the effectiveness of the steel jacket as confinement, which is crucial for the concrete to develop its confined compressive strength (*fcc'*) and to achieve greater deformation capacity.

4.3 The Connection Strength

The steel jacket was intended to improve the confinement of the spun pile, but the experimental results found that it also contributed to the overall connection strength. Table 3 presents the comparison of the maximum lateral load of five specimens. The connection strength increased up to 34% in spun piles without concrete infill and by 18% in spun piles with concrete infill. The impact of reinforced concrete infill on connection behavior was consistent between the first series (SPPC02, SPPC01) and those with steel jackets (SPPC07, SPPC05), showing that the connection strength significantly increased with the addition of reinforced concrete infill, both with and without the steel jacket. The effect of steel jacket on the empty spun pile (SPPC05) and one with concrete infill (SPPC06) was found to be similar.

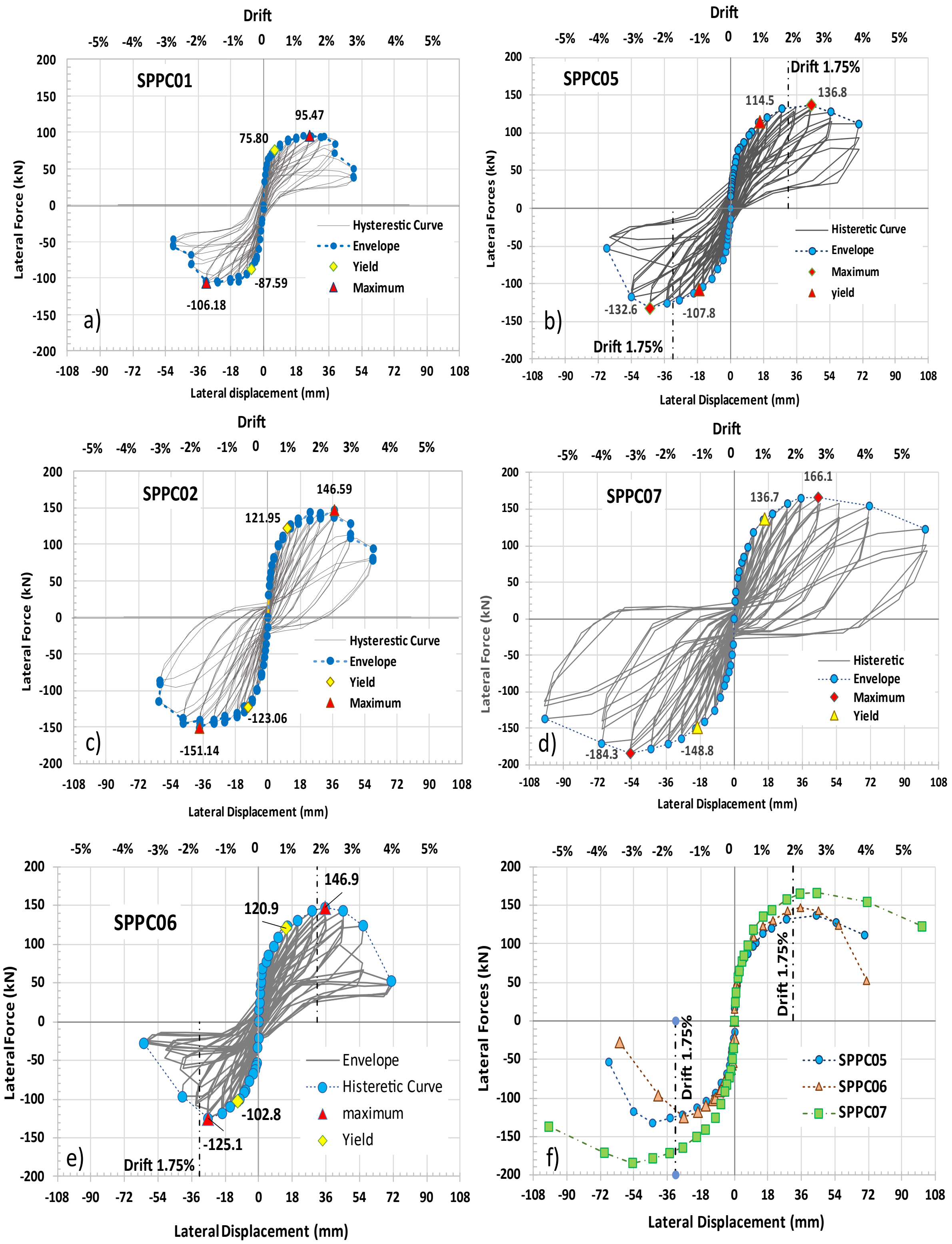

Fig. 8. The hysteretic curves: a), c) from the first series test, b), d), e) from the steel jacket series test, f) the comparison of envelope curves of steel jacket series test

Table 3. The Strength of the Specimens

Specimen	Average Strength (kN)	Ratio	Ratio to SPPC05 (OSR)
SPPC01	100.8	1.34	1
SPPC05	134.7		1
SPPC06	136.0	-	1.01
SPPC02	148.9	1.18	1.48
SPPC07	175.2		1.30

The moment resistance (Mu) of the specimen was determind by multiplying the maximum lateral force by the height of the pile measured from the surface of the pile cap, which was 1.8 meters. Additional moment from P-delta effect was considered which was derived from the axial load (0.1*fc'Ag*) multiplied by the horizontal displacement of the pile.

A comparison between the average Mu and the section capacity (*Mn*), calculated using the P-M interaction and assumption the steel jacket contributes to the overall strength, is shown in Table 4. The ratio of the ultimate bending moment to its capacity is about 1.11 to 1.28.

The results revealed that the capacity of the spun pile-to-pile cap connection exceeds the bending capacity of the section. Friction between the tip and the sides of the spun pile embedded in the pile cap plays a role in enhancing the connection strength. As a result, the overstrength ratio for the connection without a steel jacket is higher due to friction between the concrete surfaces. Meanwhile, for the spun pile with a steel jacket, the overstrength ratio is lower because the friction is between the concrete and steel surfaces. However, the results also indicate that the bending capacity of the specimen (*Mu*) could be approximated based on the sectional capacity, *Mn*. Despite the connection failure of the steel jacket at SPPC05 and SPPC06, the resulting moment (*Mu*) was still able to achieve the sectional moment capacity *Mn*.

Table 4. Bending Capacity of the Specimens

Speci-men	Maximum Momen, *Mu* (kNm) Push	Pull	Ave	*Mn* PM-Diag kNm	OS Ratio c/d
	(a)	(b)	(c)	(d)	
SPPC01	185.98	207.14	196.56	153.92	1.28
SPPC05	260.84	255.62	258.23	220.6	1.17
SPPC06	264.45	225.25	244.85	220.6	1.11
SPPC02	283.13	293.19	288.16	228.71	1.26
SPPC07	309.91	348.05	328.98	289.58	1.14

4.4 The Ductility and The Energy Dissipation

Displacement ductility is determined as a ratio of ultimate displacement (*du*) to yield displacement (*dy*). For reinforced concrete structures, *dy* is not well defined due to the nonlinearity of two materials, i.e., concrete and steel. There are at least two common methods previously used by researchers to determine *dy* and *du*. The first method, *dy* is defined based on the secant stiffness and the second is based on equivalent elastoplastic curve. Meanwhile, *du* represents the deformation at which the structure experiences a 15% reduction in strength.

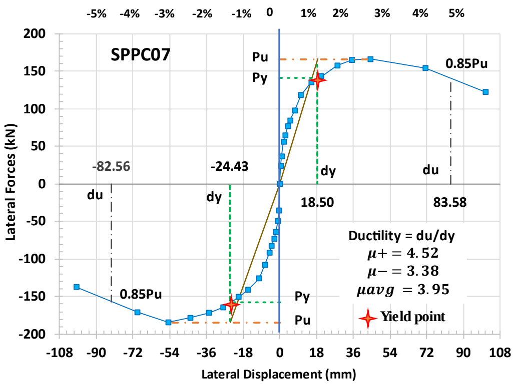

Fig. 9. Yield point based on equivalent elastoplastic curve

Fig. 9 and Fig. 10 illustrate the ductility calculations for SPPC07 based on different definitions of yield point. Since SPPC05 and SPPC06 cannot be considered as specimens that utilize the steel jacket throughout the testing, hence Table 5 only presents the comparison of SPPC07 to SPPC02. The table shows ductility of both specimens' base on the second definition of dy. As can be seen, the steel jacket had only a minor impact on ductility, with SPPC07 achieving a ductility value of 3.95, slightly lower than SPPC02's 4.08. Based on secant stiffness, SPPC07 has ductility 4.72 which is slightly higher than SPPC02 that has ductility 4.69.

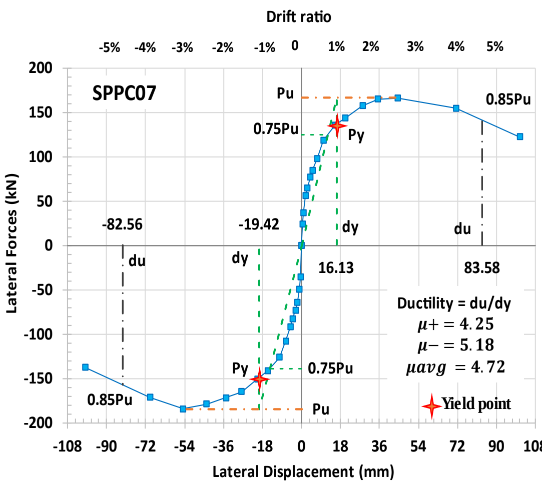

Fig. 10 Yield point based on secant stiffness

The hysteretic curves in Fig. 8 indicate that the connections with steel jackets exhibit better deformation capacity, resulting in greater energy dissipation compared to specimens without steel jackets. Table 5 presents the comparison of the cumulative energy dissipation of SPPC07 and SPPC02, with values measured at a 3.5% drift. The results show that the energy dissipation capability increased by a factor of 1.8 with the addition of the steel jacket. Notably, SPPC07 was able to deform up to a 5% drift, leading to even higher energy dissipation.

Table 5. Ductility and Dissipation Energy

Specimen	*dy* (mm)	*du* (mm)	Ductility	Cumulative Energy Dissipation (kNm)	Ratio
	(1)	(2)	(1)/(2)		
SPPC02	12.53	51.05	4.08	48.63	1.80
SPPC07	21.46	83.07	3.95	87.31	

5. CONCLUSION

The steel jacket offers a cost-effective solution to address the lack of confinement in spun piles without requiring additional spiral reinforcement along the entire length of the pile, particularly given the uncertainty of hard ground locations in the field. Adequate confinement is only necessary at the pile end connected to the pile cap, extending approximately 1.5D. Experimental studies have demonstrated that embedding the steel jacket with the spun pile into the pile cap develops tensile strength in the jacket, which contributes to the moment capacity of the connection.

The connection strength increased by 34% in the spun pile without concrete infill and by 17% in the spun pile with reinforced concrete infill. Although the increase in ductility was modest, the steel jacket reinforcement significantly improved the deformation capacity of the spun pile–pile cap connection, resulting in an increase in energy dissipation by 1.93 times for the spun pile without infill and 1.80 times for the pile with reinforced concrete infill.

Further studies are needed to evaluate the effectiveness of the steel jacket when used solely for confinement without embedding it into the pile cap. This would allow the steel jacket to function only in the radial direction of the spun pile.

6. ACKNOWLEDGMENTS

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