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STRENGTH BEHAVIORS OF PRESTRESSED CONCRETE SLEEPERS WITH CRACK RESISTING STIRRUPS

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ABSTRACT:

This research investigates the effects of stirrups on shear strength and cracking behaviors in Prestressed Concrete Sleepers (PCSs). A total of five PCSs with a cross-section of 258 × 205 mm with varied stirrup's ratio of 0.4 to 1.0 % (a stirrup's spacing of 30, 60 and 90 mm) were subjected to statically three-pointed bending load. Shear strength of PCSs with stirrups can be enhanced from 5.5 to be more than 15.7 %, whereas ductility of PCSs with stirrups can be enhanced from to 32.7 to 70.7%, compared to PCS without any stirrup. When increasing stirrup's ratio to 1.0 % in PCSs, failure modes of PCSs was shifted from shear or shear-flexural to flexural failures. PCSs with rounded-bar stirrups also showed more severe shear cracks than that in PCSs with deformed-bar stirrups, proving higher bonding interface between concrete and stirrups due to ribs of the deformed bars. These significantly indicate the optimized stirrup's ratio and proper type of steel stirrups for PCS's design in the future.

KEYWORDS: Railway sleeper, Prestressed concrete, Stirrup, Crack resistance

1. Introduction

In rail systems, railway sleepers are one of the most important key elements since they transfer and distribute the axle loads from rails to substructures. To ensure both track performance and safety for people, these sleepers functionally sustain the track gauge, while withstanding the multi-directional movement of rails [1]. Currently, Prestressed Concrete Sleepers (PCSs) are widely used owing to their high load-carrying capacity and durability [2]. However, PCSs usually suffer from severe cracks due to both static and dynamic rail loads, causing unsafety for railway [3, 4]. Therefore, sleepers are usually required to be in high strength with appropriate dimension and under qualifications conformed to the railway throughout their lifetimes. In addition, for heavy duty of railway track such as track of high speed train or bullet train, application of high performance concrete may be necessary [5].

This research, therefore, focuses on the investigation of shear strength and cracking behaviors in PCSs with varied stirrup's ratio of 0.4 to 1.0%, namely varied stirrup's spacing of 30, 60 and 90 mm as well as stirrup's types of rounded bar (RB) and deformed bar (DB). To study the enhanced shear strength due to stirrups, a total of five PCSs with cross-section of 258 × 205 mm prestressed with 10 PC-strands of diameter 9.5 mm were subjected to statically three-point bending test following the previous research by Yang et al. [6] and American Railway Engineering and Maintenance of Way Association (AREMA 2010) [7]. With larger size of stirrups from RB6 (diameter of 6 mm) to DB10 (diameter of 10 mm) as well as smaller spacing of stirrups, the shear crack widening may decrease, resulting in higher shear strength and greater ductility. It is also found that failure modes shifted from brittle shear to more ductile flexural failures. Eventually, this research can lead to a development of optimized stirrup's ratio and proper type of steel stirrups for PCS's design in the future.

2. Experimental Program

2.1 Material Properties

Concrete

Concrete used in the experiment was based on the mix design as shown in Table 1. The cement Type 1 with admixture Type F was used in accordance to ASTM Specification C150 standard [8]. The designed concrete strength is 43 and 55 MPa at 24 hours and 28 days, respectively. From the compression test, the actual concrete strength is 43 and 58 MPa at 24 hours and 28 days, respectively (see Table 2).

Table 1 Mix design of concrete

Mix	Mix design				
	Cement (kg/m^3)	**Water (kg/m^3)**	**Limestone (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**Admixture Type F (Lt/m^3)**
C150	465	140	729	1,119	6

Table 2 Concrete's Properties

Mix	Concrete Properties		
	Slump (mm)	**f'_{ci} at 24 hours (MPa)**	**f'_c at 28 days (MPa)**
C150	175	43	58

* f'_{ci} = compressive strength of concrete at 24 hours and f'_c = compressive strength of concrete at 28 days

Prestressing Tendon

PC strands used in this experiment are seven-wire strands qualified by the ASTM A416 [9]. The seven-wire strands had a diameter (d_w) of 9.5 mm with a cross sectional area (A_p) of 54.9 mm^2. Their designed yielding and ultimate strengths are 1,712 MPa and 1,902 MPa, respectively. From the tensile test, the actual yielding and ultimate strengths are 1,740 MPa and 1,871 MPa, respectively.

Steel Reinforcement

The steel reinforcement used for stirrups is rounded bar with a diameter (d_b) of 6 mm (RB6) and deformed bar with a diameter (d_b) of 10 mm (DB10), following ASTM A615 [10]. RB6 had a cross sectional area (A_s) of 28.3 mm^2 with designed yielding and ultimate strengths are 235 and 385 MPa, respectively. DB10 had a cross sectional area (A_s) of 87.5 mm^2 with designed yielding and ultimate strengths of 390 and 560 MPa, respectively. From tensile test of steel reinforcement of RB6, the actual yielding and ultimate strengths are 410 and 509 MPa, respectively. From tensile test of steel reinforcement of DB10, the actual yielding and ultimate strengths are 576 and 653 MPa, respectively.

2.2 Details of PCS Specimens

A total of five PCS specimens were prepared in order to investigate the effect of stirrups' ratio on shear strength. Using an allowable stress design based on AREMA-2010 [7], the PCSs were designed to have a cross section of 258 × 205 mm with a total cross sectional area (A_c) of 49,800 mm^2. All PCSs were prestressed by 10 PC - strands with a diameter of 9.5 mm under a jacking force of 8,000 kg per strand. An effective distance of the PC strands is 104 mm from top of the cross section. The details of PCS's cross section are as shown in Figure 1.

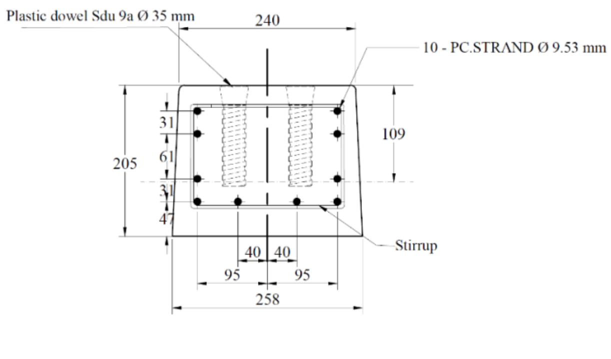


Figure 1 Cross section of PCS, unit : mm

Specimen S1-C (control) represents a PCS without any stirrup which its failure was controlled to occur only one side by placing DB10-stirrup at a spacing of 30 mm on the non-failure side (see Figure 2a). Four other PCSs represent PCSs with RB6- and DB10- stirrups at a spacing of 30, 60, and 90 mm to resist shear cracks (Figures 2 (b) -2 (e)). Specimens S1R6-30 and S1R6-60 had RB6-stirrups with a spacing of 30 and 60 mm, whereas specimen S1D10-60 and S1D10-90 had DB10-stirrups with a spacing of 60 and 90 mm. In all specimens, cracks were expected to occur only on the left side since amount of stirrups is less than that on the right side. Strain gauges were attached on PC strands and stirrups in order to measure strain's development. The locations of strain gauges from top of the PCSs are shown in Figure 2. Development of targeted strain where major cracks passed is observed to investigate the effect of stirrups on shear cracking resistance.

Table 3 Details of PCS specimens

No.	Label	Stirrup type	*b* (mm)	*h* (mm)	*a* (mm)	*s* (mm)	A_s (mm^2)	ρ_w (%)
1	S1-C (Control)	-	258	205	330	-	-	-
2	S1R6-30	RB6	258	205	330	30	56.6	0.7
3	S1R6-60	RB6	258	205	330	60	56.6	0.4
4	S1D10-60	DB10	258	205	330	60	157.0	1.0
5	S1D10-90	DB10	258	205	330	90	157.0	0.7

* b = width at a bottom of cross section,
h = height of cross section,
a = shear span length,
s = spacing of stirrup,
A_s = area of stirrups, and
ρ_w = stirrup's ratio (=A_s/bs)

Table 3 shows details of five PCS specimens in which a spacing of stirrups is varied from 30 to 90 mm, indicating different stirrups' areas of 56.6 to 157 mm^2 as well as stirrup's ration of 0.4 to 1.0 %. Shear span of all specimens is 330 mm.

2.3 Instrumentation and Test setup

To investigation the strength behavior of PCSs with stirrups, PCSs with a total length of 2,200 mm and a shear span length of 330 mm were subjected to three-point bending test based on AREMA-2010 standard [7], as shown in Figure 3. The load applied onto the rail seat with expected failure side (see Figure 3) was increased with a rate of 22 kN/min according to AREMA-2010 standard [7]. The deformation at center and support was measured using Linear Variable Displacement

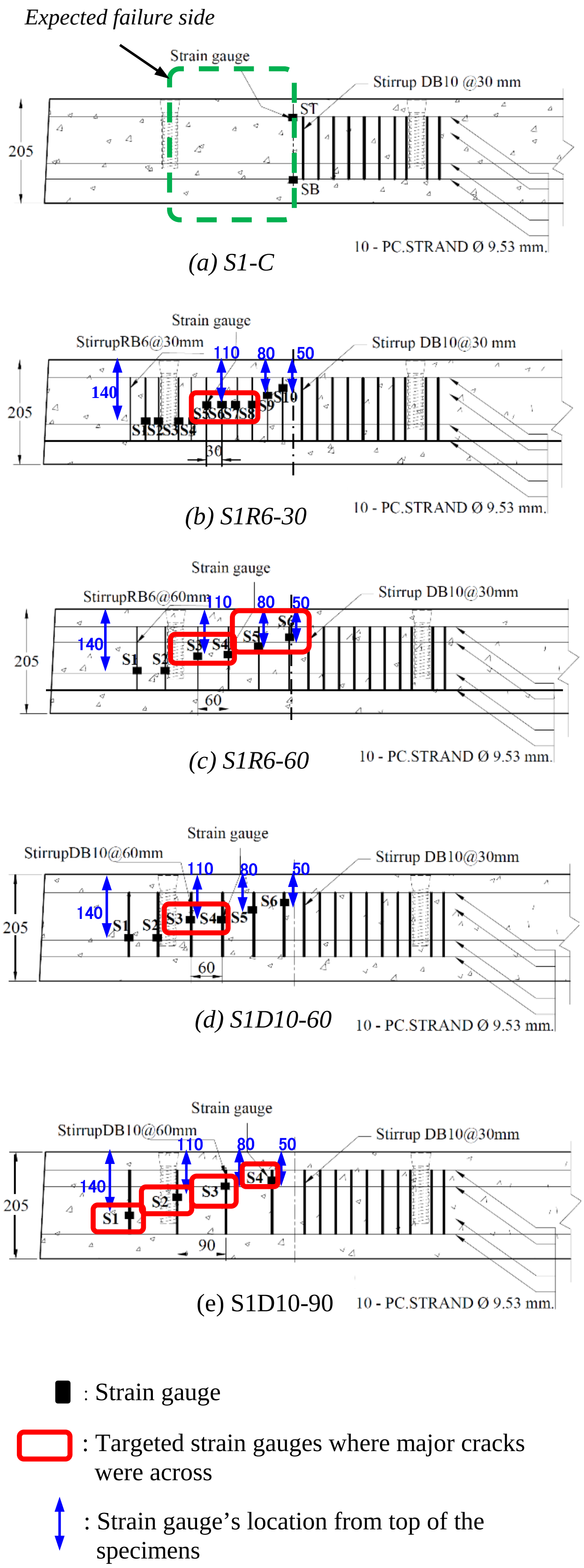


Figure 2 PCS specimens

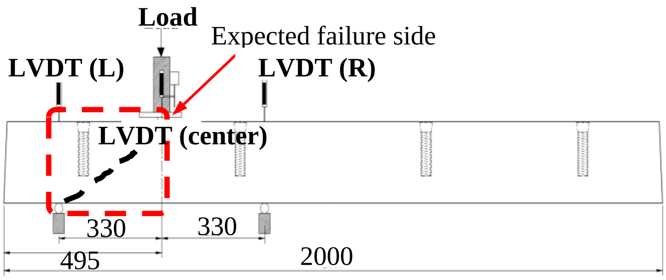


Figure 3 Three-point bending test, unit : mm

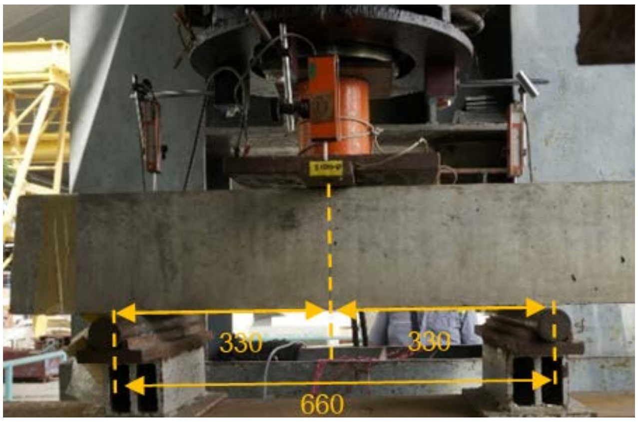


Figure 4 Actual instrumentation and test setup at the expected failure side, unit : mm

Transducer (LVDT). Specimens were loaded until failure to observe the relationship between shear force and deformation. The actual instrumentation and test setup are shown in Figure 4.

3. Experimental results

3.1 Failure Modes and Crack Patterns

Without any stirrup, specimen SC-1 catastrophically failed in shear since only concrete component could carry the applied shear force. Extensive shear cracks propagated from the support to loading point. Eventually, crushing of concrete occurred at top, leading to the failure of the specimen (see Figure 5).

Figure 5 Crack patterns of specimen S1-C (control)

(a) S1R6-30

(b) S1R6-60

(c) S1D10-60

(d) S1D10-90

Figure 6 Failure modes of PCSs with stirrups

In all specimens, the initial cracks observed were flexural crack at the specimens' mid-span. In specimens S1R6-30, S1R6-60 and S1D10-90 with a stirrup's ratio of 0.4 to 0.7 %, failure modes were shear-flexural failure with crushing of concrete at the compression region (see Figures 6 (a), (b) and (d)). When increasing stirrup's ratio to 1.0 % in specimen S1D10-60, the failure mode was shifted from shear to flexural failure, as shown in Figure 6 (c). In addition, specimens S1R6-30 and S1R6-60 with RB6 (with rounded bars) show more severe shear cracks than that in specimens S1D10-60 and S1D10-90 (with deformed bars). This may be caused by higher bonding interface between concrete and stirrups due to ribs of the deformed bars, leading to adequate stress transfer. As a result, these indicate that sufficient stirrup's ratio and proper type of stirrups significantly changes failure modes and crack patterns of PCSs.

Table 4 Summary of experimental results

Specimen	V_{peak} (kN)	Δ_{ult} (mm)	% Increase of shear strength	% Increase of ultimate deformation	Failure mode
S1-C	236	11.1	0	0	Shear
S1R6-30	271	16.4	14.8	48.1	Flexure - shear
S1R6-60	249	14.7	5.5	32.7	Flexure - shear
S1D10-60	273	18.9	>15.7	70.7	Flexure
S1D10-90	265	16.4	12.3	48.1	Flexure - shear

3.2 Relationship between Shear Force & Deformation

The relationship between shear force and deformation is shown in Figure 7. For specimen S1-C without any stirrup, its stiffness and strength are smaller than that in PCSs with stirrups since only concrete resists applied force as well as opening of cracks. When the loads reached to peak, the control specimen failed in shear, resulting in a sudden drop of load and small ductility. The experimental results are also summarized in Table 4. The maximum shear strength of specimen S1-C without stirrup (see Table 4) developed only 236 kN owing to shear failure, whereas other specimens with stirrups developed higher shear strength due to shear-flexural and flexural failures.

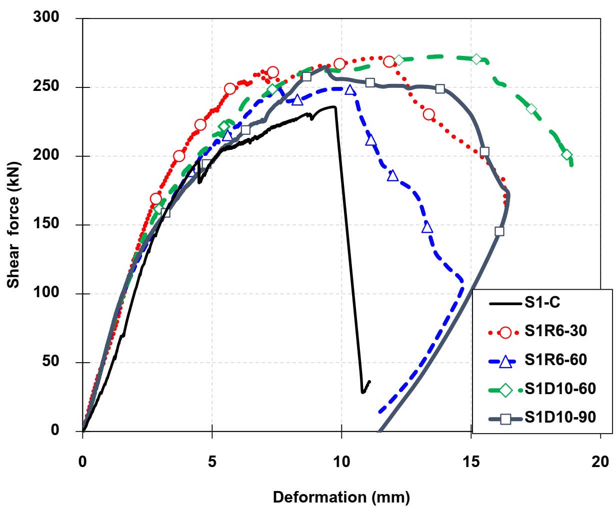


Figure 7 Relationship between shear and deformation of PCSs

The PCSs with RB6- and DB10- stirrups show higher shear strength than that in specimen S1-C (control), as shown in Figure 7 and Table 4. In Table 4, V_{peak} denotes shear strength at peak load obtained from experiment, Δ_{ult} is the ultimate deformation from experiment, while % Increase of shear strength and ultimate deformation can be calculated from equation (1) and (2), respectively, as follows:

% Increase of shear strength =

$$\frac{V_{peak,specimen} - V_{peak,S1-C}}{V_{peak,S1-C}} \times 100 \quad \text{......................(1)}$$

% Increase of ultimate deformation =

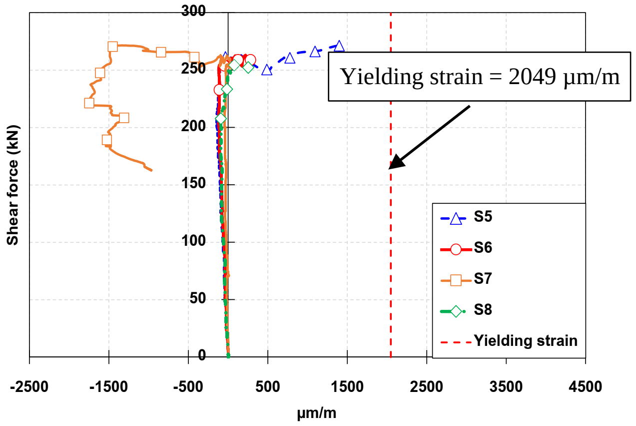
$$\frac{\Delta_{ult,specimen} - \Delta_{ult,S1-C}}{\Delta_{ult,S1-C}} \times 100 \quad \text{........................(2)}$$

When applying higher stirrups' ratio, the PCSs exhibited higher shear strength than that in specimen S1-C (control) approximately 5.5 to more than 15.7 % (Noted that, the failure of specimen S1D10-60 is in flexural mode, therefore, shear strength of this specimen shall be higher than the test result of 15.7% which is obtained when flexural failure occurred). The ultimate deformation of PCSs with stirrups also significantly enhances around 32.7 to 70.7%, resulting in improvement of PCSs' ductility.

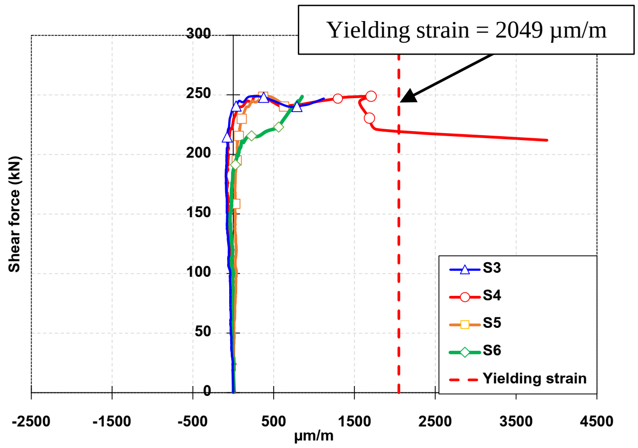
3.3 Development of Strain in Stirrups

For specimens S1R6-30 and S1R6-60, development of strain in stirrups is shown in Figure 8. In specimen S1R6-30, the targeted strains where major shear cracks passed (strains S5-S8 in Figure 2) did not yield owing to small spacing of stirrups (30 mm), as shown in Figure 8 (a). On the contrary, the targeted strains in specimen S1R6-60 (strain S4 in Figure 2) yielded because of its larger spacing of stirrups (see Figure 8 (b)) compared to that in specimen S1R6-30. This yielding of stirrups is also affected by crack opening of concrete since specimen S1R6-30 exhibited smaller crack opening than that in specimen S1R6-60.

For specimens S1D10-60 and S1D10-90, development of strain in stirrups is shown in Figure 9. Similarly to specimens S1R6-30 and S1R6-90, yielding of stirrups occurred in specimen S1D10-90

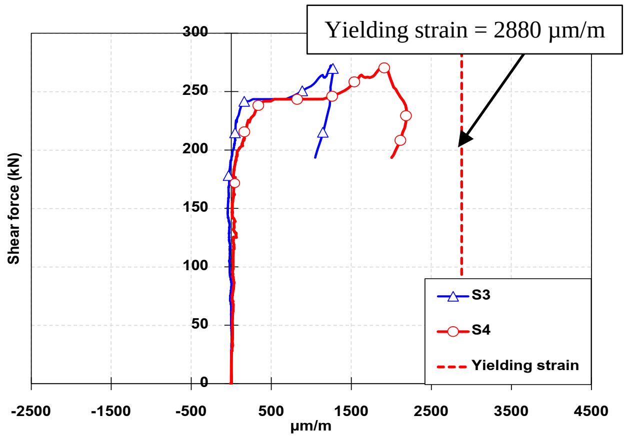


(a) *Specimen S1R6-30*

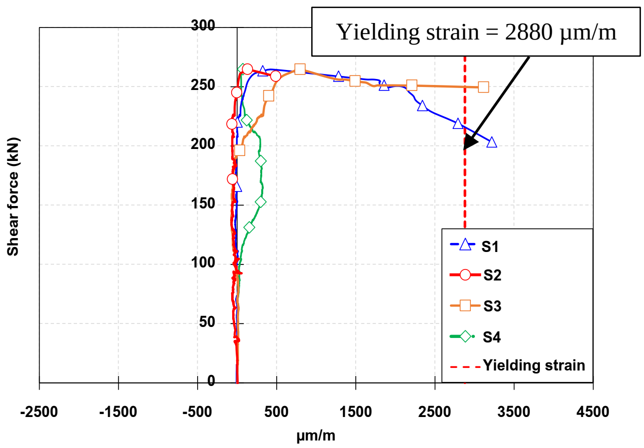


(b) *Specimen S1R6-60*

Figure 8 Relationship between shear force and strain in stirrups



(a) *Specimen S1D10-60*



(b) *Specimen S1D10-90*

Figure 9 Relationship between shear force and yield strain of stirrups of specimens S1D10-60 and S1D10-90

with larger spacing of stirrup compared to that in specimen S1D10-60. This is evident that spacing of stirrup can influence on development of strain and yielding behavior in stirrups.

4. Comparison between Shear Strength from Test and ACI-318 Standard [11]

According to ACI-318 Standard [11], total shear strength (V_t) can be calculated by a summation between shear strength carried by concrete (V_c) and stirrup (V_s) as in equation (3).

$$V_t = V_c + V_s \tag{3}$$

For prestressed concrete members, the shear strength carried by concrete should be the minimum value of shear strength carried by concrete when diagonal cracking results from combined shear and moment (V_{ci}) and shear strength carried by when diagonal cracking results from high principal tensile stress in web (V_{cw}).

$$V_c = \min(V_{ci}, V_{cw}) \tag{4}$$

$$V_{ci} = 0.05\lambda\sqrt{f_c'}b_w d_p + V_d + \frac{V_i M_{cr}}{M_{max}} \geq 0.14\lambda\sqrt{f_c'}b_w d \tag{5}$$

$$V_{cw} = \left(0.29\lambda\sqrt{f_c'} + 0.3 f_{pc}\right)b_w d_p + V_p \tag{6}$$

where λ = modification factor reflecting the reduced mechanical properties of lightweight concrete (λ=1), b_w = web width (mm), d_p = distance from extreme compression fiber to centroid of prestressing steel, (mm), f'_c = compressive strength (MPa), f_{pc} = compressive stress in concrete (after allowance for all prestress losses) at centroid of cross section resisting

Table 5 Summary of shear strength obtained from experiment and ACI-318 Standard [11]

Item		unit	Specimen				
			S1C	S1R6-30	S1R6-60	S1D10-60	S1D10-90
Calculation ACI 318	V_c	kN	99.22	99.22	99.22	99.22	99.22
	V_s	kN	0	72.7	36.4	167.4	111.6
	V_t	kN	99.22	171.92	135.62	266.62	210.82
Test	V_{peak}	kN	236.0	271.0	249.0	273.0	265.0
Failure mode			Shear	Flexural Shear	Flexural Shear	Flexural	Flexural Shear

* V_c = shear strength carried by concrete, V_s = shear strength carried by stirrup,
V_t = total shear strength due to shear strength capacity (V_c+ V_s) and V_{peak} = peak shear from test

externally applied loads or at junction of web and flange when the centroid lies within the flange, V_d = shear force at section due to unfactored dead load (N), V_i = factored shear force at section due to externally applied loads occurring simultaneously with M_{max} (N), V_p = vertical component of effective prestress force at section (N), M_{max} = maximum factored moment at section due to externally applied loads (N·mm), and M_{cr} = cracking moment (N·mm).

Table 5 shows a summary of shear strength obtained from experiment and ACI-318 Standard [11]. In control specimen (S1C), the calculated V_t (=99.22 kN) is smaller than V_{peak} (=236.0 kN) from test. In PCS specimens with stirrups, it also can be seen that all calculated V_t –values are smaller than V_{peak} obtained from test. Therefore, it can be implied that stirrup design by using ACI code is conseravative in the safe side, but not economic. The reason of these difference may be due to higher yield strength of used stirrups in the specimens than the design value. Nevertheless, the optimized stirrup's ratio for PCS's design should be considered in future.

5. Conclusions

The research aims to investigate the shear strength behavior of PCSs with stirrups (RB6 and DB10) at a spacing of 30, 60 and 90 mm (stirrup's ratio of 0.4 to 1.0 %). The conclusions can be summarized as follows:

1) PCS without any stirrup exhibited severe shear failure, whereas PCSs with stirrup's ratio of 0.4 and 0.7 % showed shear-flexural failure. When increasing stirrup's ratio to 1.0 %, failure mode of PCSs was shifted from shear-flexural to flexural failure. This significantly indicates the optimized stirrup's ratio for future PCS's design.

2) PCSs with rounded-bar stirrups showed more severe shear cracks than that in PCSs with deformed-bar stirrups. This may be caused by higher bonding interface between concrete and stirrups due to ribs of the deformed bars, leading to adequate stress transfer.

3) PCSs with varied stirrup's ratio from 0.4 to 1.0 % can enhance shear strength from 5.5 to more than 15.7 %. In addition, ductility of PCSs with stirrups can be enhanced from to 32.7 to 70.7%, compared to PCS without any stirrup.

4) Yielding of stirrups occurred in case of PCSs with larger spacing of stirrups. The yielding of stirrups is also affected by crack opening of concrete as specimens with larger spacing of stirrups exhibited larger crack opening, resulting in yielding of stirrups. This is evident that spacing of stirrup can influence on development of strain and yielding behavior in stirrups.

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