- Technical Paper -

BEHAVIORS OF PRETENSIONED PC BEAMS STRENGTHENED IN SHEAR USING EXTERNALLY BONDED CFRP SHEETS

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ABSTRACT

This paper discusses the performance of pretensioned prestressed concrete beams strengthened in shear using externally bonded CFRP sheets. The shear capacity and stiffness in the post-cracking region were increased with smaller spacing between the strips of CFRP sheets. Furthermore, the strip spacing, wrapping types and thickness of CFRP sheets influenced failure behaviors of the strengthened PC beams. Besides, the equations in the design guidelines of ACI and JSCE overestimated the shear capacity carried by bonded CFRP sheets for strengthening PC beams.

Keywords: CFRP sheet, shear strengthening, prestressed concrete beam, debonding

1. INTRODUCTION

Owing to the advantages as high strength to weight ratio and high durability, prestressed concrete (PC) has been used widely in civil engineering, especially for long span girders. After PC was invented in 1940s, there have been an increasing number of PC bridges constructed in Japan and worldwide, especially in the period from 1960s to 1990s. Recently, the deterioration of aging structures that leads to the decrease of strength and durability has been reported. The requirement for sustainability and safety of the structures has been of a concern in many countries. Moreover, the expansion in transportation demands results in the requirements for upgrading the capacity of existing PC girders, whereas, the enhancement in shear capacity is one of the important features.

Recent years have witnessed the growth in the application of fiber reinforced polymers (FRPs) in construction industry. Among various types of FRPs such as bars, grids, meshes and sheets, carbon fiber reinforced polymer (CFRP) sheets have been commonly used for external strengthening of existing structures. The well-known advantages of CFRP sheets include high strength, corrosion resistance, easy construction, and less impact to the original geometry of structures. This method may overcome the drawbacks of traditional strengthening methods because it can be implemented in a short time and does not require heavy equipment or large space.

Up to now, there have been numerous studies on the effects of externally bonded CFRP sheets on shear strengthening of reinforced concrete (RC) beams. Nevertheless, little attention has been paid to the effects of this strengthening method on pretensioned PC beams. In their study on shear strengthening of two PC beams using externally bonded CFRP sheets, Kang and Ary [1] reported that not only the shear capacity of PC beams was increased but also the ductility of the strengthened beam was significantly improved. However, since the shear resistance of PC beams is influenced by the prestressing level in prestressing strands, the behaviors of pretensioned PC beams strengthened with CFRP sheets have not been well understood. So far, the prediction on shear capacity of RC beams strengthened by externally bonded FRP sheets has been developed in the design guidelines of many organizations such as ACI [2] and JSCE [3]. The adoption of the equations in the guidelines to PC beams strengthened by externally bonded FRP systems has been found conservative.

In this regards, this study aims to investigate the performance of pretensioned PC beams strengthened in shear with externally bonded CFRP sheets. One control beam and six strengthened beams have been tested. This paper discusses the effects of different parameters (CFRP strip spacing, CFRP sheet thickness and wrapping types) based on the experimental outcomes.

2. EXPERIMENTAL PROGRAM

2.1 Test specimens

(1) Details of pretensioned PC beams

Fig. 1 shows details of pretensioned PC beams. The specimens have rectangular cross section of 150 mm width by 300 mm height. The shear span was set to obtain shear span to effective depth ratio equaled to 3. Two high strength bars with 22 mm diameter (nominal area of 380.1 mm^2) and two prestressing strands (seven-wire type) with 12.7 mm diameter (nominal area of 98.71 mm^2) were used as tensile reinforcement. The initial stress of 950 N/mm^2 was introduced in the prestressing strands. Two deformed bars with 16 mm diameter were arranged in the compression zone. Within development length of prestressing strands, the stirrups with diameter of 13 mm were set with a spacing of 100

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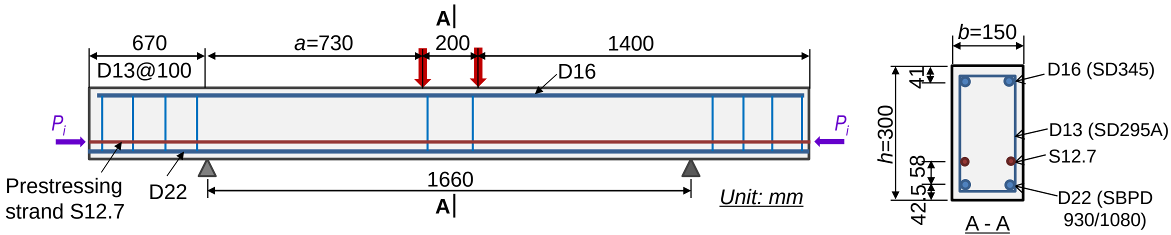


Fig. 1 Details of pretensioned PC beams

Table 1 List of experimental cases

No.	Name	CFRP			
		t_f	w_f	s_f	ρ_f
1	B0	-	-	-	-
2	B0-0.9SF	0.333	50	250	0.09
3	B0-1.1SF	0.333	50	200	0.11
4	B0-1.9SF	0.333	50	120	0.19
5	B0-0.6SFa	0.111	50	120	0.06
6	B0-1.1SU	0.333	50	200	0.11
7	B0-4.4CF	0.333	680	0	0.44

t_f: thickness of CFRP sheet (mm); w_f: width of CFRP sheet (mm); s_f: spacing of strips; ρ_f: CFRP ratio (%)

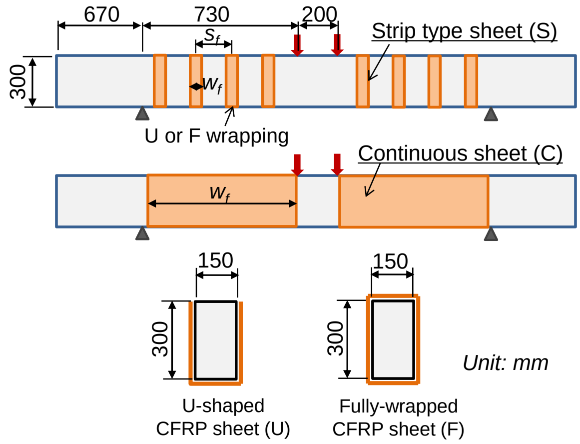


Fig. 2 Attaching layout of CFRP sheets

mm. Stirrups were not provided in the shear span.

Concrete with a design compressive strength of 50 N/mm^2 was used. The tensile strength and yield strength of prestressing strands were 1,945 N/mm^2 and 1,854 N/mm^2, respectively. The deformed bar D22 had yield strength of 947 N/mm^2 and ultimate strength of 1157 N/mm^2. The yield strengths of compression steel and stirrups were 386 N/mm^2 and 373 N/mm^2, respectively.

Two types of unidirectional CFRP sheets whose thickness were 0.111 mm (type a) and 0.333 mm (type b), were used in the experiment. The nominal tensile strength of 3,400 N/mm^2 and modulus of elasticity of 2.3x10^5 N/mm^2 of CFRP sheets were the same for both sheet types.

(2) Strengthening schemes

The experimental cases are listed in Table 1. Fig. 2 illustrates the attaching layout of externally bonded CFRP sheets. B0 denotes control beam, which was not strengthened by CFRP sheets. For the strengthened beams, CFRP sheets were used in two types: strip or continuous sheet configurations. For the specimens strengthened with strip types (cases 2 to 6), the width of strips was constant of 50 mm. The spacing between the strips was decreased from 250 to 200 and 120 mm in cases 2 to 4. From cases 2 to 5, CFRP strips were fully wrapped around the beam section. Although the cases 4 and 5 had the same strengthening scheme, the only difference was the thickness of CFRP sheets. In case 6, the attaching layout of CFRP strips was similar to that of case 3, however, the U-shaped strips were used. For case 7, the continuous sheets were fully wrapped in the whole shear span. The names of strengthened specimens indicate control beam (B0), ratio of CFRP sheets, strip (S) or continuous (C) type, U-shaped or fully wrap, type of CFRP sheets (type b was omitted in specimen names).

The CFRP sheets were bonded to the PC beams by the wet layup method using epoxy resin. After the sheets were bonded, the specimens were cured in room temperature for at least seven days before the loading tests.

2.2 Instrumentations and loading method

Four linear variable differential transducers were set at the midspan and two supports to measure the beam deflection. Strain gauges were attached to top fiber of concrete at mid span to measure the compressive strain in concrete. In addition, strain gauges were bonded on the surface of CFRP sheets in order to measure tensile strains. The specimens were subjected to a static four-point bending using 1000 kN loading machine until failure. All of the measurements were recorded through a data logger. Two cameras were set to capture the status of each shear span with the interval of 10 kN of the applied load. Besides, the propagation of cracks was marked with the value of applied load during the loading process.

3. RESULTS AND DISCUSSIONS

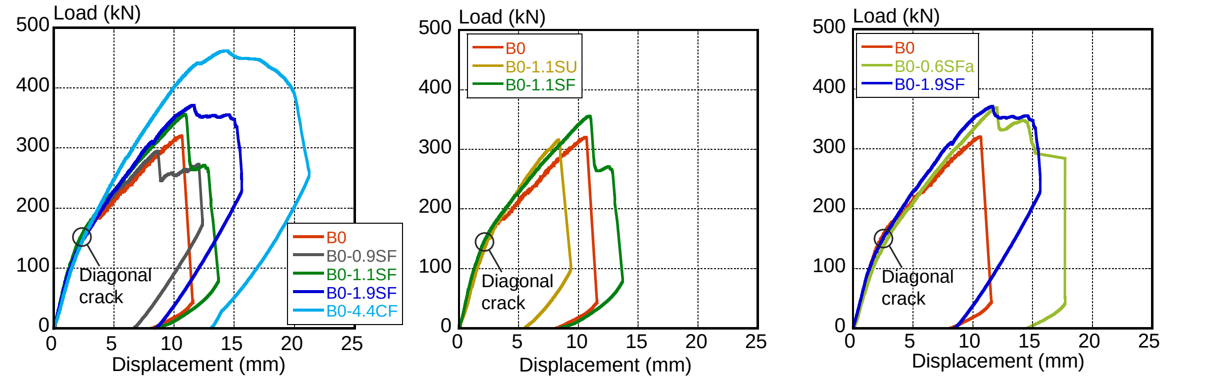
3.1 Shear strength and stiffness

The experimental results are summarized in Table 2 in terms of the average effective stress in prestressing strands, compressive strength of concrete, ultimate shear capacity, shear capacity carried by bonded CFRP sheets and failure modes. Fig. 3 (a) represents the relationships between the applied load and displacement of the specimens strengthened with different spacing between strips. The specimen strengthened with smaller spacing of strips obtained higher ultimate load. The ultimate load increased from 356.0 kN in B0-1.1SF to 371.2 kN in B0-

Table 2 Summary of experimental results

No.	Name	f_{pe} (N/mm^2)	f'_c (N/mm^2)	P_u (kN)	V_u (kN)	V_u/V_u^{B0}	$V_f^{(exp)}$ (kN)	Failures
1	B0	785	66.8	320.6	160.3	-	-	Shear
2	B0-0.9SF	769	66.8	295.2	147.6	0.92	-	Debonding
3	B0-1.1SF	756	66.8	356.0	178.0	1.11	17.7	Debonding
4	B0-1.9SF	821	64.1	371.2	185.6	1.16	25.3	Shear
5	B0-0.6SFa	809	64.1	369.0	184.5	1.15	23.7	Shear
6	B0-1.1SU	776	66.8	316.6	158.3	0.99	-	Debonding
7	B0-4.4CF	783	64.1	462.0	231.0	1.44	70.7	Flexure

f_{pe}: average effective stress in prestressing strands; f'_c: compressive strength of concrete; P_u: ultimate load; V_u: ultimate shear capacity; $V_f^{(exp)}$: shear capacity carried by bonded CFRP sheets ($V_f^{(exp)} = V_u - V_u^{B0}$)



(a) Effects of spacing (b) Effects of wrapping (c) Effects of thickness

Fig. 3 Load-displacement relationships

1.9SF. The highest ultimate load was achieved in the beam where CFRP sheets were bonded continuously on the whole shear span (B0-4.4CF). The increment in the ultimate load was nearly proportional to the increase in the amount of CFRP. However, in case of B0-0.9SF, even though the CFRP strips were bonded for strengthening, but in a large spacing of strips (s_f = 250 mm), the ultimate load was smaller than that of B0.

Before the formation of a diagonal crack, the strengthened beams showed a similar behavior to that of B0. After the cracking point, the stiffness of the strengthened PC beam was improved in comparison to the control beam, particularly, in the beam strengthened with continuous sheets. The results implied that pretensioned PC beams strengthened with bonded CFRP sheets provided higher shear strength and better post-cracking stiffness with smaller spacing of similar thickness strips.

Fig. 3 (b) shows the effect of wrapping types on the load-displacement relationship. Since the difference in the slope of the curves between two strengthened beams was small, the effect of wrapping types on the stiffness can be negligible. However, it is clear that the ultimate load in the beam strengthened by U-shaped strips (316.6 kN) was approximately close to that of B0 (320.6 kN), whereas the beam strengthened with fully wrapped strips experienced 11% increase in the ultimate load compared to B0.

The effect of the CFRP sheet thickness on the load-displacement relationship is shown in Fig. 3 (c). The curve became steeper in the post-cracking region for

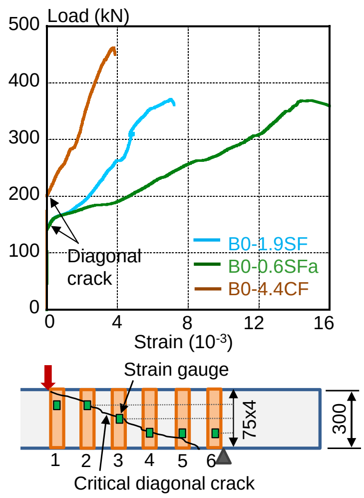


Fig. 4 Development of strain gauge 3

PC beam strengthened with thicker strips (B0-1.9SF). Nevertheless, because the debonding of the strip occurred and accelerated the failure, the ultimate load of this specimen did not improve from that of the beam strengthened with the thinner strip.

3.2 Utilization of bonded CFRP sheets

The location of strain gauges attached on the surface of CFRP sheets and the measured values of strain gauge number 3 corresponding to the applied loads are shown in Fig. 4. Before the presence of diagonal cracks, the values of strain gauges were almost zero. After the diagonal cracks were formed, the bonded sheets

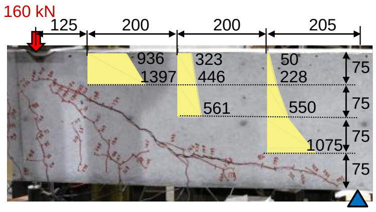


Fig. 5 Distribution of compressive strain (B0)

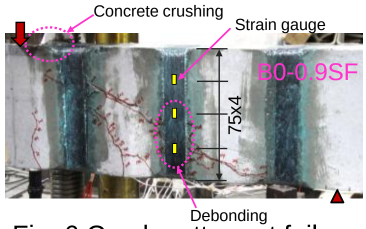


Fig. 6 Crack pattern at failure (B0-0.9SF)

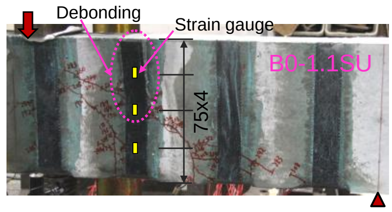


Fig. 8 Crack pattern at failure (B0-1.1SU)

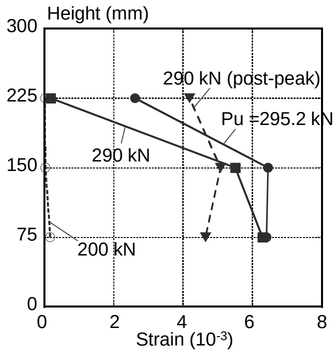


Fig. 7 Strain development in strip (B0-0.9SF)

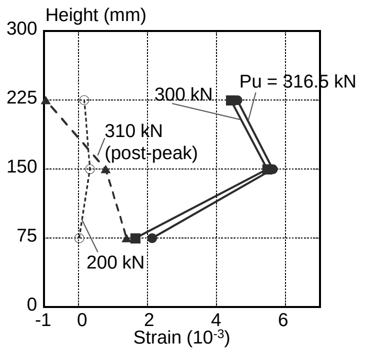


Fig. 9 Strain development in strip (B0-1.1SU)

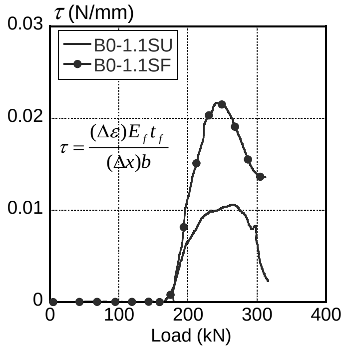


Fig. 10 Bond stress in strips

participated to resist the stresses. In the beams strengthened with strip types, the bonded strips started to carry the tensile stress at almost similar load level of 150 kN, whereas in the PC beam strengthened with continuous sheets for the whole shear span, the bonded sheets participated effectively from the load of about 200 kN. It is probable that the sheets bonded on the whole shear span provided a confinement effect which enhanced the concrete strength, hence, the formation of flexure-shear crack was delayed. Moreover, by comparing the strain development at a given load level, the graph demonstrates that the strain in the continuous sheets was much smaller than that of the other specimens. In addition, with the same bonding layout, the strain became smaller in the thicker strips.

3.3 Effects of bonded CFRP sheets on failure behaviors

Typically, several flexural cracks were formed in the constant moment region at the beginning, then spread into the shear span as increasing of the applied load. As the shear force increased, a diagonal crack was formed from the flexural crack in the shear span and propagated towards the loading point and the supporting point simultaneously (flexural-shear crack). In case of B0, the shear force was resisted by beam action (concrete in compression zone, vertical component of aggregate interlock and dowel action). Fig. 5 illustrates the distribution of horizontal compressive strain in concrete just before the ultimate load. It was apparent that a compression arch formed above the diagonal crack that participated in transferring the shear force to the supports. Thus, the increase in the load after the formation of flexure-shear crack was due to the effectiveness of the beam and arch action. The beam failed when the concrete in the compression zone crushed and splitting occurred. This failure was brittle and led to a sudden drop of the load carrying capacity in the load-displacement curve in Fig. 3 (a).

Fig. 6 shows the crack pattern at failure of the specimen bonded with the strip spacing of 250 mm (B0-0.9SF). The failure in this specimen was initiated by a localized debonding of the middle CFRP strip. Fig. 7 presents the behaviors of strain along the height of strip. The locations of strain gauges were detailed in Fig. 6. The strains rapidly developed in the portion where the strip intersected the flexural-shear crack. At the ultimate load, the strain values were almost equal in two locations at bottom portion indicating the occurrence of debonding of the CFRP strip. Because the strip was disaffected in resisting shear force, the load sharply decreased from 295.2 kN to around 246.5 kN as can be seen in the load-displacement curve (Fig. 3 (a)). The progressive debonding of the strip resulted in a gradual loss of the aggregate interlock. Thus, the shear carrying capacity of this specimen was smaller than that of B0 because the combination of shear resisting components were not maintained.

Unlike, in the specimen strengthened with U-shaped strips, the debonding of bonded strips occurred in a different manner. Fig. 8 shows the crack pattern at failure and Fig. 9 illustrates the behaviors of strains in specimen B0-1.1SU. Since the diagonal crack crossed the strip near the middle height of the beam, the strains in bonded sheets increased dramatically in this portion. Nevertheless, the increment of the strains became slight after the load of 300 kN. Fig. 10 compares the bond stress in the strips located at the same location in two specimens, which were strengthened with U-shaped and fully wrapped strips. As longer anchorage length was provided, the higher bond stress was obtained in the fully wrapped strip. Even though the progressive debonding occurred leading to the decrease in bond stress in two specimens, the remaining bond stress was higher in fully

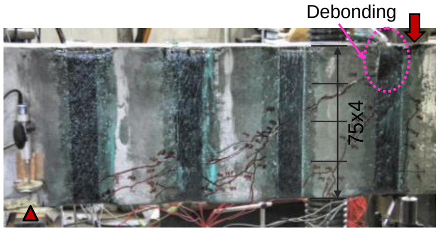


Fig. 11 Crack pattern at failure (B0-1.1SF)

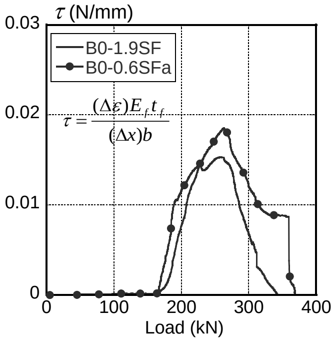


Fig. 12 Bond stress in strips

wrapped strip. Because the spread of interfacial micro cracks led to a reduction of effective bond length, the length required for developing the strength in the bonded sheets. Thus, the stresses were not well-transferred. For B0-1.1SU, when the micro cracks propagated near to the free end of U-shaped strip, the development bond length became insufficient for the effective stress in the bonded strip. Consequently, the strip was peeled off from the top of the U-shaped strip without a forewarning. Accordingly, in Fig. 9, the strains in CFRP strip was abruptly released in the top portion right after the peak load. Because the strip was peeled off and bended, the negative strain was induced in the strip. In B0-1.1SF, the peeling-off of the strips was prevented. The failure occurred with debonding of the strip near loading point, which was followed by crushing of concrete at the tip of the diagonal crack (Fig. 11). Therefore, a higher strengthening effect can be expected with the fully wrapped strips.

Fig. 12 compared the bond stress in the strips located at the same location in two specimens, which were strengthened using the same layout of strips with different sheet thicknesses. The debonding was initiated at almost the same load level in both specimens. Nevertheless, the strip in B0-1.9SF was completely disaffected at a smaller load. After a strip was debonded, the shear force resisted by the remaining bonded strips and the other mechanisms (concrete in compression zone, aggregate interlock, dowel action and compression arch). As can be seen in Fig. 13, the compressive strain of concrete in B0-1.9SF gradually increased as the debonding of strip progressed indicating the increase in the shear portion transmitted by compression arch. The specimen failed when concrete above the flexure-shear crack became insufficient to resist the force and crushed (Fig. 14). For B0-0.6SFa, because the sheet was thinner, the remaining amount of the strips and the other mechanisms became insufficient to carry the existing shear force, the failure took place when the strip was

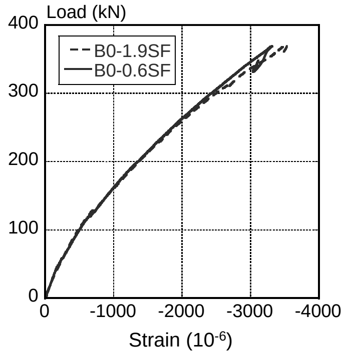


Fig. 13 Strain in concrete at midspan

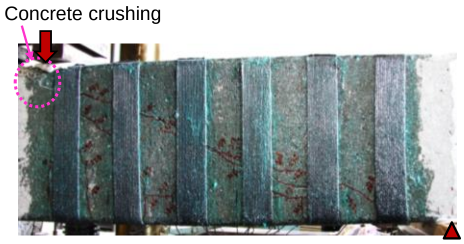


Fig. 14 Strain development in strip (B0-1.9SF)

disaffected.

Apart from the previous cases, the performance of the beam bonded with continuous CFRP sheets on the whole shear span (B0-4.4CF) was more ductile (Fig. 3 (a)). The failure of this specimen changed to flexure when concrete crushed at top fiber of the midspan section.

3.4 Evaluation of shear carried by bonded sheets calculated by equations in design guidelines

In the recent design guidelines of ACI [2] and the recommendations of JSCE [3] for shear capacity of RC beams strengthened by externally bonded FRP system, the shear capacity of the strengthened beam is computed by adding a shear capacity carried by the bonded FRP to the shear capacity of the original beam. A simple method for calculating the shear capacity carried by bonded FRP is introduced in the guidelines. In which, the shear resisted by bonded FRP system can be calculated based on the truss analogy model with the assumptions: (i) angle of diagonal crack is equal to 45 degree and (ii) all the strips intersected by the diagonal crack contribute uniformly with an average stress level.

The equation for shear carried by FRP is given by ACI guidelines as follows:

$$V_f = \psi_f A_f f_{fe}(\sin\alpha + \cos\alpha) d_f / s_f \qquad (1)$$

The effective stress (f_{fe}) is proportional to the strain developed in bonded FRP at nominal strength.

$$f_{fe} = \varepsilon_{fe} E_f \qquad (2)$$

In order to compute the effective stress in the bonded sheets, the limitation of effective strain in bonded FRP sheets at failure (ε_{fe}) for different types of wrapping is provided.

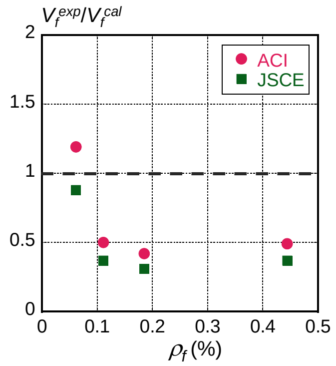


Fig. 13 Evaluation of equations in ACI and JSCE guidelines

For fully wrapped CFRP sheets:

$$\varepsilon_{fe} = 0.004 \leq 0.75\varepsilon_{fu} \tag{3}$$

where,

A_f: cross section area of FRP with spacing s_f (mm^2)
ψ_f: reduction factor (0.95 for fully wrapped sections; 0.85 for U-shaped wrapped sections)
α: angle formed by FRP sheet and member axis (degree)
d_f: effective depth of FRP shear reinforcement (mm)
E_f: modulus of elasticity of FRP (N/mm^2)
ε_{fu}: rupture strain of FRP (mm/mm)

On the other hand, JSCE introduces a coefficient expressing the shear reinforcing efficiency of continuous fiber sheets (K) in its equation:

$$V_f = K\left[A_f f_{fu}(\sin\alpha + \cos\alpha)\right]z/s_f \tag{4}$$

$$K = 1.68\text{-}0.67R;\ 0.4 \leq K \leq 0.8 \tag{5}$$

$$R = (\rho_f E_f)^{1/4}(f_{fu}/E_f)^{2/3}(1/f_c')^{1/3} \tag{6}$$

with $0.5 \leq R \leq 2.0$
where,
f_{fu}: tensile strength of FRP (N/mm^2)
f_c': compressive strength of concrete (N/mm^2)
E_f: modulus of elasticity of FRP (kN/mm^2)
ρ_f: FRP reinforcement ratio
z: lever arm length (mm)

Fig. 13 illustrates the ratio of shear carried by bonded CFRP in experiment to calculated shear strength related to the ratio of CFRP sheets. The experimental values were determined by subtracting the shear strength of B0 from the shear strength of strengthened PC beams. In most of the cases, the equations in the recent design guidelines overestimated the increase in shear carrying capacity in pretensioned PC beams strengthened with externally bonded CFRP sheets.

The discrepancy can be explained by several reasons. First, the equations in the design guidelines were developed based on the experimental data of strengthening of RC beams. In PC beams, due to the effect of prestressing, the distribution of compression stress in concrete along member axis under loading creates an arching action, which can resist a portion of shear force. Thus, the shear strength gained by the bonded sheets in PC beams was not high as in the calculation. Moreover, based on only few test data of the failure of concrete in compression zone for evaluating Eqs. 5 and 6 [3] may lead to an inaccuracy when this failure governs the specimens. It can be seen that further experimental data are necessary and a modification factor is needed when adopting the equations of existing design guidelines for shear strengthening of pretensioned PC beams with externally bonded FRP.

4. CONCLUSIONS

The shear capacity and post-cracking stiffness of pretensioned PC beams can be enhanced with smaller spacing between externally bonded CFRP strips. The effects are more significant when continuous sheets are bonded for the whole shear span of PC beams. Furthermore, the use of thicker sheet results in smaller utilization of its strength (smaller strain in the strip at the ultimate load). A large spacing of strips or U-shaped wrapping should be avoided because they may lead to a premature debonding failure. In addition, the spacing between the strips and the sheet thickness greatly influence failure behaviors, consequently, affect the capacity of the strengthened PC beams.

The equations in the guidelines of ACI and JSCE overestimated the shear capacity carried by bonded CFRP sheets in strengthening pretensioned PC beams. Because the equations were developed based on the data of strengthened RC beams, a reasonable prediction for strengthening of PC beams needs to be addressed.

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