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EXPERIMENTAL STUDY ON A NOVEL SHEAR STRENGTHENING TECHNIQUE FOR PRECAST PRESTRESSED HOLLOW-CORE SLABS

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ABSTRACT

Precast, prestressed hollow core (PHC) slabs are widely used in civil construction, typically as floor or roof in office and residential buildings as well as parking structures. Since the manufacturing process does not allow the installation of shear stirrups, shear resistance of PHC slabs relies solely on the shear strength of concrete itself. In some cases, the slab could possibly be subjected to concentrated load or line load caused by moving vehicles and cargos. Thus, shear failure is likely to occur at the region close to supports. Traditional remedies include choosing thicker slabs and filling the voids of PHC slabs, which would inevitably increase self-weight and cost and thus lose the advantages of PHC slabs. Therefore, it is imperative to develop a new shear strengthening strategy for PHC slabs which would not only effectively improve its shear capacity but also retain the original merits. The objective of the current research is to explore the feasibility and effectiveness of applying Carbon Fiber Reinforced Polymer (CFRP) composite sheets to shear strengthening of PHC slabs. An experimental study has been conducted to investigate the behaviour of PHC slabs when externally bonded by Carbon Fiber Reinforced Polymer (CFRP) composite sheets along the perimeter of slab voids. Preliminary results in this paper show that the proposed shear strengthening technique can effectively improve the shear performance of full-width PHC slabs and greatly enhance its shear capacity.

1. INTRODUCTION

A hollow core slab is a precast prestressed structural member (shown in Figure 1) which has several voids extended through member length to reduce its self-weight and increase economic benefit. In general, this type of slab is widely used as floor deck in office, and residential buildings and parking structures because of its thermal and sound isolation characteristics. In addition, due to its light self-weight and high load bearing capacity, hollow core slabs is favorable choice for long spans and heavy live loads. During construction, hollow core slab units are placed side-by-side to each other to form a continuous floor system. A hollow core slab only has bottom reinforcements, which can reduce around 40% usage of steel (Mahmut, 2011). Furthermore, the voids in the slabs can save approximate 30% of concrete.

PHC slabs are generally designed for resisting bending moment under uniformly distributed load. In some cases, the slab could possibly be subjected to concentrated load or line load, which can cause shear failure in the region close to the support. However, the manufacturing technique of PHC slab does not allow the arrangement of shear reinforcement during fabrication. Without shear reinforcement, PHC slabs can only rely on tensile strength of concrete to resist shear force. Traditional methods of improving shear capacity of PHC slabs include increasing slab thickness and filling the voids. According to ACI 318-08 (ACI Committee 318, 2011), increasing thickness of slabs beyond 317.5mm would have negative effect on shear capacity. On the other hand, filling voids would affect the advantages of light self-weight and low cost.

Recently, many experimental studies have been conducted to investigate the effectiveness of using externally bonded fiber reinforced polymers (FRP) composite to rehabilitate and strengthen the flexural and shear capacity of reinforced concrete (RC) members. Islam et al (2002) tested the shear capacity of RC deep beams strengthened by different types of FRP systems. He found that the specimen strengthened by grid type of FRP sheets with groove achieved 40% enhancement in the shear capacity. Abdel-Jaber at el (2007) applied CFRP with different fibre orientations (horizontal, vertical and 45°) to RC beams. All strengthened specimens showed similar shear capacity increment of about 115%. Another experimental study by Li et al. (2014) reported that the average improvement in the flexural capacity of the FRP strengthened PHC slabs was 67% and the average deflection of the strengthened specimens at mid-span increased about 100%. It can be seen from the above review that a considerable improvement in shear or flexural capacity of RC members strengthened by FRP composite sheets was reported in literature. In addition, several parameters could affect the performance of FRP strengthened concrete members were identified. They include: the orientation of FRP fibre, the installation type of FRP sheets (i.e. full-wrap bonding or U-wrap bonding), thickness of FRP sheet (i.e. number of layers), the bonding surface and bonding agent, (Liu et al. 2008; Florutr et al. 2010; Yu, 2002; Monti and Liotta, 2007; Qu, 2008 and Bukhari et al., 2010).

An experimental study is carried out to evaluate the feasibility and effectiveness of a novel shear strengthening technique for PHC slabs, i.e. to use externally bonded CFRP composite sheets and install them along the internal perimeter of slab voids to strengthen the shear capacity of PHC slabs. The entire project consists of two phases. The work in Phases I focused on applying the proposed shear strengthening technique to I-shaped single-web PHC slabs cut out longitudinally from full-width slabs to assess the feasibility and effectiveness of this shear strengthening technique. It was conducted by a former master student (Wu, 2015). It was found that the single-web PHC slab specimens strengthened by 2 layers of CFRP sheets on each side of the slab void surface can not only improve the shear capacity but also enhance the ductility before failure. The average increment on the shear capacity of all specimens was about 20%. The current paper will present the experimental work conducted in the second phase of the project, of which the proposed shear strengthening technique is applied to full-width PHC slabs (Figure 1). A total of three specimens have been tested so far. The ultimate load, the observed failure mode, the crack pattern, the load-deflection relation and the strain in the concrete and CFRP will be reported. This set of preliminary results clearly shows the effectiveness of the proposed shear strengthening technique for PHC slabs.

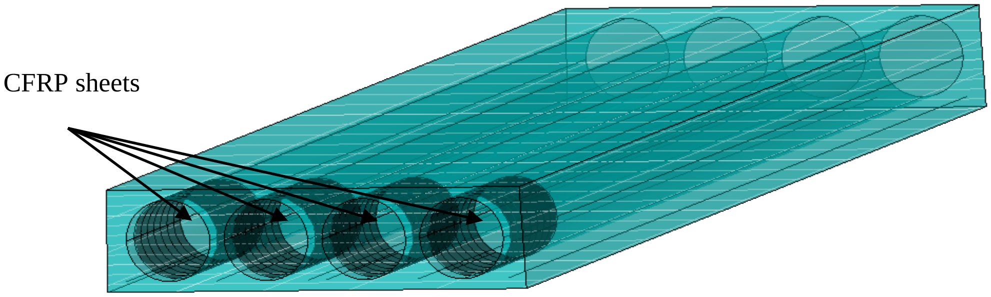


Figure 1: Proposed shear strengthening techniques for hollow core slabs

2. EXPERIMENTAL PROGROM

3.1 Specimen Design

A total of twelve full size PHC slabs are used in the experimental study of phase Ⅱ. So far, three specimens have been tested. All specimens had a length of 4575mm, a depth of 305mm and a width of 1219mm. Each specimen had 8 longitudinal prestressed streel strands at the bottom, with a diameter of 13 mm each. The overall experimental setup is shown in Figure 2.

Figure 2: Overall of experimental setup

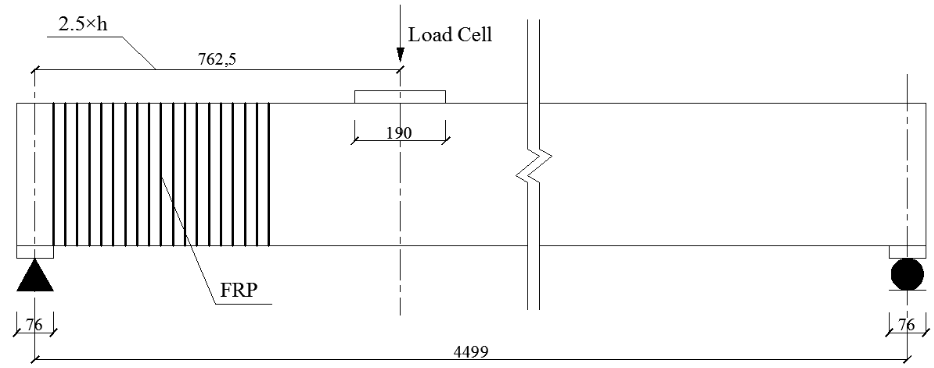
Among the three tested specimens, one of them was used as the control specimen, S2-C, with no CFRP sheets applied. "S" represents slab specimen, "2" represents medium prestressing level (2 strands per web – total of 8 prestressed strands) and "C" represents control slab. Two different thicknesses of applied CFRP sheets, i.e. 1 layer and 2 layers bonded on each slab void surface respectively, were investigated during the experimental study. The ID of the strengthened specimens was defined to include the thickness and the length of the strengthened zone. For example, "S2-2-450" represents two layers of CFRP sheets with 450 mm length were installed for a PHC slab with medium prestressing level. The specifications of each specimen are listed in Table 1.

Table 1: Parameters of PHC slab specimens used in the experimental study

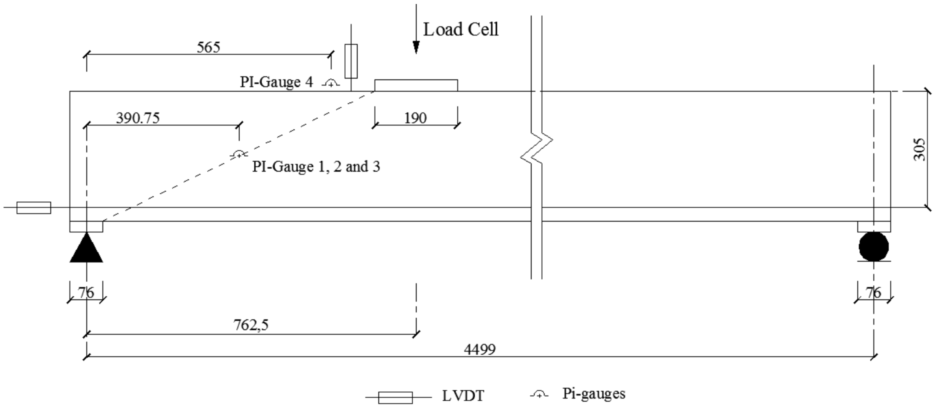
No.	Specimen-ID	No. of CFRP Sheet Layers	Strengthened zone length (mm)
1	S2-C	0	0
2	S2-1-450	1	450
3	S2-2-450	2	450

3.2 Test Set-Up and Instrumentation

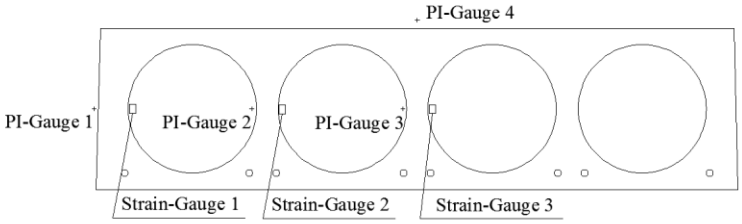
The experimental setup is shown schematically in Figure 3(a). All specimens were tested over a simply supported clear span of 4499mm with the bearing plate width of each support being 76mm. The support near the loading point was a hinge and at the other side was a roller. This would ensure that no axial force would be generated during test. The shear span to depth ratio (a/d) of all slab specimens was 2.5, i.e. the concentrated load was located at a distance of 762.5 mm from the hinged support. All specimens were instrumented at the loaded end. As shown in Figure 3(b), two linear variable displacement transducers (LVDT) were used, one was for measuring the end slippage of the prestressed steel in the second web, and the other was used to measure the vertical displacement at the loading point. Additionally, four displacement transducers, Pi-gauges, were installed to measure the strain in the longitudinal direction of the PHC slabs at mid-height of the web. One was placed on the slab top surface in the longitudinal direction to measure the concrete compressive strain near the loading point and the other three were arranged in the longitudinal direction along the center line of the first, the second and the middle web in the shear-tension region to measure the tensile strain of concrete or CFRP sheets (shown in Figure 3(c)). According to the results from Phase Ⅰ (Wu, 2015), the location of each Pi-gauge was set at the intersection between the specimen horizontal center line and the line connecting the inner edge of the support bearing plate and the inner edge of the loading plate (Figure 3(b)). Besides, three electrical foil strain gauges were glued on the surface of the CFRP sheets on the opposite side of the Pi-gauge to measure the tensile strain in the CFRP sheets.



(a) Schematics of experimental setup



(b) Instrumentations installed on the entire specimen



(c) Arrangement of Pi-gauges and strain gauges

Figure 3: Instrumentation setup of S2- series specimens (unit: mm)

3.3 Material properties

The test specimens were constructed using the same batch of normal-weight concrete with an average 28-day compressive strength of 60 MPa. A total of thirty 100 × 200 mm and fifteen 150 × 300 mm cylinders were prepared under the same condition to evaluate the compressive and tensile strength of concrete at the test time. SikaWrap-900C CFRP sheets and Sikadur300 Epoxy were used in strengthening the PHC slab specimens. The SikaWrap-900C is a uni-directional, fleece stabilized, stitched and heavy carbon fiber fabric for the wet application process of structural strengthening (SIKA Canada). The mechanical properties of the CFRP sheets with epoxy resin are either provided by the supplier or determined by tensile tests on representative samples in accordance with ASTM D3039 (ASTM D3039/D3039M, 2014). The results showed a linear-elastic stress-strain relationship with average values of elastic modulus and tensile strength being 100 GPa and 1120 MPa, respectively (SIKA Canada). The prestressing strands are 7-wire, low-relaxation strands which has a diameter of 13 mm and an ultimate tensile strength of 1860 MPa.

3.4 Preparation of test specimens and testing procedures

All specimens were fabricated at the supplier site, the Prestressed System Inc., and shipped to the Structurers Lab at the University of Windsor for testing. The surface of each slab void where CFRP sheets would be attached to was first cleaned and polished by steel brush. The uni-directional CFRP sheets were then bonded to the void surface in the circumferential direction by applying a wet layup process. The surface of the slab voids and the CFRP sheets should be saturated by epoxy resin before directly bonding the sheets to the void surface. The direction of CFRP fibre was perpendicular to the longitudinal axis of the slab specimen. After attaching the CFRP sheets, the specimen would be tested after two days.

Based on Deutsch Norm (2008), the loading process consists of two steps. During the test, the specimen was first loaded to 70% of the predicted failure load and then unloaded. In the second step, the slab was re-loaded until failure by displacement control.

3. TEST RESULTS

3.1 Crack pattern and failure mode

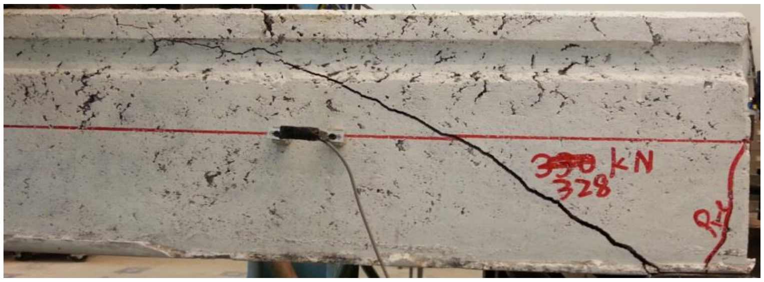
The control specimen, S2-C, showed typical brittle shear failure. When the load reached 280.5 kN, shear failure occurred suddenly along with a big noise. An inclined crack initiated from the support, propagated through the slab and ended near the loading plate at the top. The crack covered the entire shear-tension region with a horizontal distance of 731mm from the support end. The maximum width of this critical shear crack was 2 mm. Thus, 280.5 kN was considered as the ultimate shear capacity of the S2-series control slab. Figure 4(a) shows the crack pattern of the control specimen.

The crack pattern of the S2-1-450 specimen shown in Figure 4(b), is similar to that of the control slab. The shear failure occurred suddenly at 328 kN. A critical shear crack initiated from the inner edge of the support bearing plate and extended to the location near the loading plate. The horizontal length of the crack was 567 mm and the maximum crack width was 2 mm.

Shear failure of S2-2-450 occurred when the load increased to 387kN. Though a critical shear crack also initiated at the slab bottom and propagated through the slab height with an inclination angle of 44° with respect to the horizontal, it is interesting to note that the crack started from a distance of 224 mm away from the inner edge of the bearing plate and then extended to the inner end of the loading plate. It covered a longitudinal region of 530 mm with the maximum crack width of 3 mm.

In the S2-1-450 specimen and the S2-2-450 specimen, the critical shear cracks grew through the slab and no debonding was observed between the CFRP sheets and the concrete surface before failure.

(a) S2-C specimen



(b) S2-1-450 specimen

(c) S2-2-450 specimen

Figure 4: S2-series PHC slab crack pattern

3.2 Ultimate shear capacity

The test results of the three specimens are summarized in Table 2. Failure of the control slab, the S2-1-450 specimen and the S2-2-450 specimen occurred at 280.5 kN, 328 kN and 387 kN, respectively. All specimens failed in a brittle shear failure mode. This set of results indicated that the specimen strengthened by 1 layer CFRP sheet with a length of 450 mm (S2-1-450) had a 17% increment in the ultimate shear capacity, whereas the specimen strengthened by 2 layers CFRP sheets with a length of 450 mm (S2-2-450) gained 38% increment in its ultimate shear capacity. These preliminary results not only demonstrate the effectiveness of the proposed shear strengthening technique for full-width PHC slabs, but also suggest that increasing thickness of CFRP sheets would have a significant impact on improving the shear performance of PHC slabs.

Table 2: Test results of S2-Series slab specimens

Specimen-ID	Failure load (kN)	Percentage of Improvement (%)	Failure mode
S2-C	280.5	-	Brittle
S2-1-450	328	17%	
S2-2-450	387	38%	

3.3 Load-deflection relation

Figure 5 shows the load-deflection relation curves of all three tested specimens. All specimens exhibited a similar behavior in the elastic range. However, the ultimate loads of the strengthened specimens were higher than that of the slab without any strengthening. The maximum displacement of the S2-1-450 and the S2-C specimens at the loading point corresponding to the ultimate load were roughly the same (about 2.4 mm), whereas S2-2-450 specimen had the largest vertical deflection of 4.3 mm at the same loading position. It is worth noting that, when the load in the S2-2-450 specimen reached approximately the ultimate load of the S2-1-450 specimen, the slope of its load-deflection curve decreased slightly. This could be due to the first layer of CFRP in S2-2-450 reached its limit at 328kN and the second layer of CFRP sheet started to contribute which not only increased the ultimate load of the slab, but also furthered its deflection. There was no crack formed during the entire loading process for all specimens. In addition, although the sudden drop in the load-deflection curves of all specimens after reaching the ultimate load indicated that the failure mode of all specimens belong to brittle shear-tension failure, with the installation of two layers of CFRP sheets, the ductility of the strengthened specimen S2-2-450 was considerably enhanced.

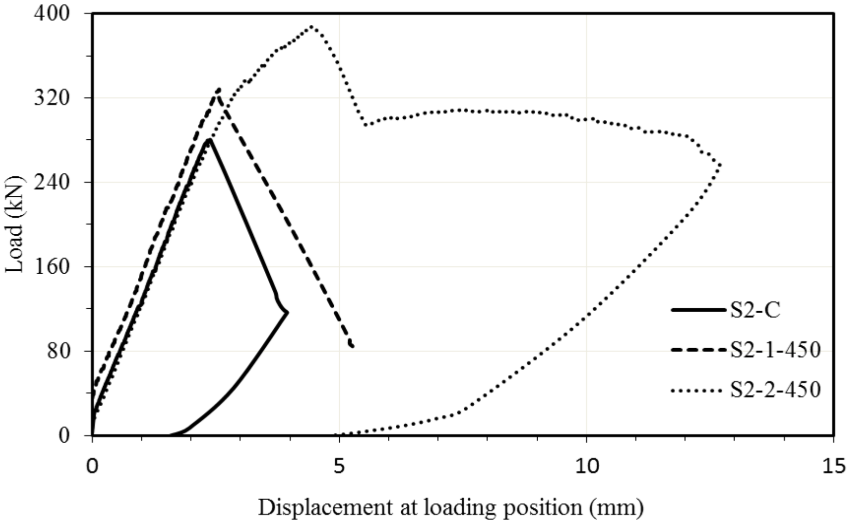


Figure 5: Load-deflection relation

3.4 Strain behaviour

Figure 6 shows the relationship between the load and the longitudinal compressive strain in concrete at the top surface of the slab 565-mm from the loading end measured by Pi-gauge 4 (Figure 3(c)). S2-2-450 showed the same trend but higher compressive strain compared to the control slab. Furthermore, all concrete compressive strains were far below the ultimate compressive strain corresponding to concrete crushing, i.e. 3500 microstrain, which implies the failure was mainly caused by inadequate shear strength.

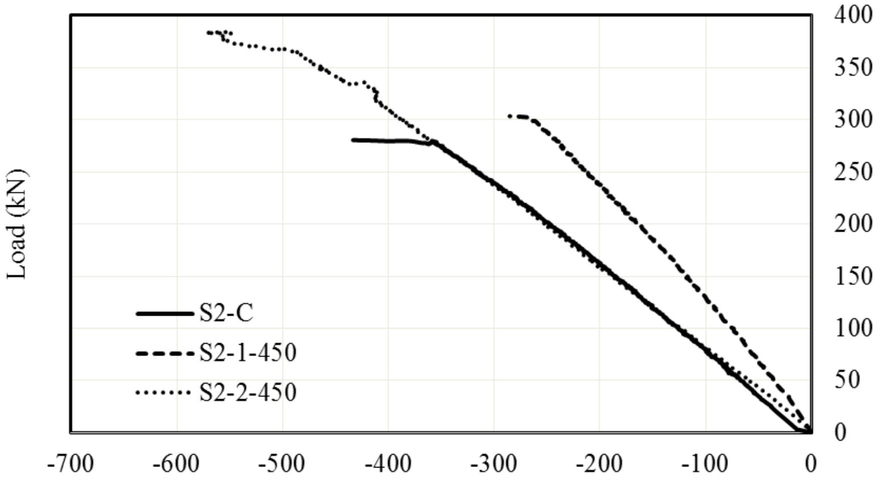


Figure 6: Load vs top longitudinal concrete compressive strain relationships of S2-series specimens

Figure 7 shows the relationship between the load and the longitudinal tensile strain of CFRP sheets (along the circumferential direction of the slab voids) measured by strain gauge 3 at the middle web of the PHC slab (Figure

3(b)). Both of the S2-1-450 and the S2-2-450 specimens showed a linear trend. When the load was less than 320 kN, the measured strain of the CFRP was very small and no crack could be observed on the slabs. However, when the load exceeded 328 kN, shear-tension failure occurred in S2-1-450, whereas the S2-2-450 specimen could resist more shear load and finally failed at 387kN. These results imply that the role of CFRP sheets can be considered as similar to that of the shear reinforcement. Therefore, bonding 2 layers of CFRP sheets on each side of the slab void is as if more stirrups are arranged in the strengthening zone, which would provide more enhancement to the shear capacity of the S2-2-450 specimen.

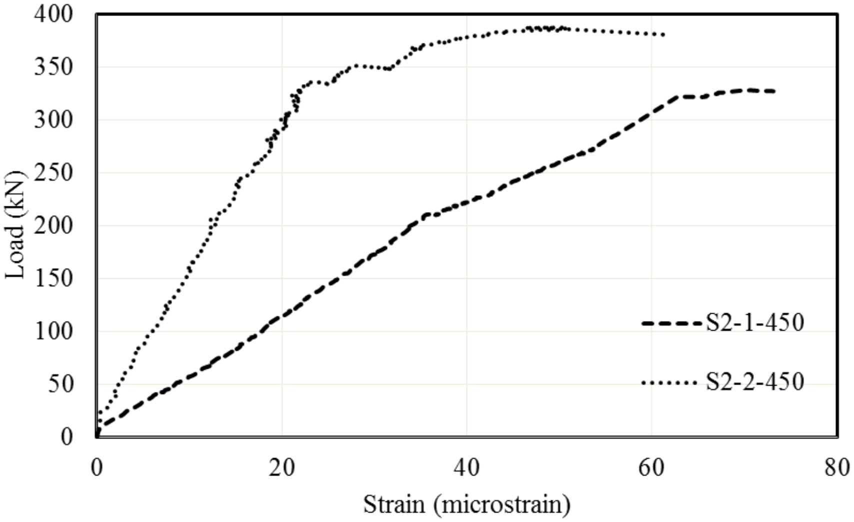


Figure 7: CFRP tensile strain relationships of S2-series specimens

4. CONCLUSION

An experimental study has been conducted to assess the feasibility and effectiveness of externally bonding CFRP sheets along the internal perimeter of PHC slab voids in enhancing the shear capacity of PHC slab. A set of preliminary results of three full-width PHC slab specimens are reported in this paper. The main findings based on the available results are:

1. Using externally bonded CFRP sheets and install them along the internal perimeter of the slab voids can considerably improve the shear performance of full-width PHC slabs. When two layers of 450 mm long CFRP sheets were bonded to surface of each slab void, an increment of 38% in the shear capacity of PHC slabs was found.
2. In the proposed shear strengthening technique, the CFRP sheets play similar role as stirrups. Thus increasing layers of CFRP sheets would considerably enhance the shear performance of PHC slabs.
3. All strengthened specimens failed in brittle shear failure mode and no crack was observed before failure. Furthermore, no debonding failure occurred between the CFRP sheets and the concrete surface.
4. In the remaining tests, the impact of the strengthened zone length, the thickness (the number of layers) of CFRP sheets and the prestressing level of the PHC slab on the effectiveness of this novel shear strengthening technique will be further explored. The results will soon be reported in future publications.

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