Shear strengthening of prestressed concrete hollow-core slabs using externally bonded carbon-fiber-reinforced polymer sheets

Xianzhe Meng, Shaohong Cheng, and Amr El Ragaby

- Manufacturing processes limit the ability to add shear reinforcement in the fabrication of prestressed concrete hollow-core slabs. As a result, the web shear resistance of the slab is provided by the concrete.
- This paper explores the effectiveness of applying carbon-fiber-reinforced polymer (CFRP) sheets within the voids of prestressed concrete hollow-core slabs to increase the shear strength of the system.
- Both experimental and numerical simulations were reviewed for 10 full-sized hollow-core slab specimens. Parameter variations included prestressing level for the longitudinal prestressing strands and length, thickness, and applied width of the CFRP sheets.

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A precast, prestressed concrete hollow-core slab is a structural member that has several voids extended through the member length to reduce its self-weight and increase economic benefit. Compared with an ordinary reinforced concrete slab with the same capacity, a prestressed concrete hollow-core slab could save 40% to 50% of steel and 20% to 40% of concrete. It is generally designed to resist bending moments under uniformly distributed loads and is widely used for floor decks in office buildings, residential buildings, and parking structures. Nevertheless, it could be subjected to a large concentrated or line load and result in web-shear failure in the region close to the support. Because the manufacturing process of prestressed concrete hollow-core slabs does not allow the arrangement of shear reinforcement during fabrication, the shear stress in prestressed concrete hollow-core slabs is typically resisted by the shear strength of the concrete. Traditional remedies are either to choose a deeper profile or to fill the slab cores with concrete. However, the former reduces the shear strength of the prestressed concrete hollow-core slab because of size effect,[1,2] whereas the latter involves extra labor and material costs. Furthermore, both solutions inevitably increase the self-weight of the prestressed concrete hollow-core slab and thus have a negative economic impact. Therefore, the best option to retain the advantages of prestressed concrete hollow-core slabs while avoiding the occurrence of shear failure is to enhance their shear capacity.

Fiber-reinforced-polymer (FRP) composites have been extensively used in strengthening and rehabilitating existing civil structures. Although FRP composites are mostly used to strengthen the flexural capacity of concrete slabs, many studies have been conducted to investigate the effectiveness of using externally bonded FRP composites to enhance the shear capacity of reinforced concrete members.[3–6] Yu[7] found that applying a continuous full carbon-fiber-reinforced polymer (CFRP) wrap is more effective in improving the shear capacity of reinforced concrete beams than applying the interval CFRP wrap. After evaluating the effect of the width-to-spacing ratio of CFRP strips, Mofidi et al.[8] reported that reinforced concrete beams strengthened by wider CFRP strips had higher shear resistance than those strengthened by narrower strips. Islam et al.[9] attached CFRP sheets to the side of the reinforced concrete beams in two different fiber orientations. Results showed that when the FRP fibers are oriented perpendicularly to the beam axis, the shear capacity of the reinforced concrete beams can be improved by about 20% compared with FRP sheets arranged at 45 degrees. Alzate[10] found that applying thicker FRP sheets better enhances the shear capacity of the strengthened reinforced concrete beams.

This review shows that externally bonded FRP sheets considerably improve the shear capacity for strengthened reinforced concrete members. Inspired by the experience of using externally bonded FRP sheets to enhance the shear capacity of reinforced concrete members, a novel shear-strengthening technique for prestressed concrete hollow-core slabs was proposed by the current research group, in which the prestressed concrete hollow-core slabs were strengthened using CFRP composite sheets externally bonded along the perimeter of slab voids.[11] The feasibility and effectiveness of this idea were first evaluated using 16 concrete I-shaped single-web beams cut out longitudinally from the full-width prestressed concrete hollow-core slabs. The preliminary results showed an average shear capacity increase of 14.5% and 27.3% for low-prestress and medium-prestress specimens, respectively. Attaching two layers of CFRP sheets on each side of the specimen web can improve the shear capacity and also enhance the ductility before failure. Furthermore, it was found that increasing the thickness and the length of the strengthened zone can further promote the shear-strengthening effect. Therefore, it is expected that the proposed shear-strengthening technique should also be applicable to full-width prestressed concrete hollow-core slabs.

In the current study, the application of this new shear-strengthening technique was extended to full-width prestressed concrete hollow-core slabs. Experimental tests and finite element simulations were conducted to investigate the behavior of full-sized prestressed concrete hollow-core slabs when externally strengthened by CFRP composite sheets along the perimeter of slab voids. The influence of several parameters on the shear-strengthening effect of prestressed concrete hollow-core slabs, including the length, width, and thickness of the applied CFRP sheets, as well as the prestressing level of the prestressed concrete hollow-core slabs, were examined.

Experimental study

Test specimens

A total of ten full-sized prestressed concrete hollow-core slab specimens were tested in the current study. All specimens had a length of 4575 mm (180 in.), a depth of 305 mm (12 in.), and a width of 1216 mm (48 in.). They were divided into two series, S1 and S2, based on the prestressing level. There were four S1 series specimens and six S2 series specimens. Each S1 series (low prestressing) specimen had six 13 mm (0.5 in.)

Table 1. Parameters of prestressed concrete hollow-core slabs used in experimental study

Specimen series	Specimen ID	Prestressing level, MPa	Number of carbon-fiber-reinforced-polymer sheet layers	Strengthened zone length, mm
S1	S1-C	2.7 (low)	0	0
	S1-1-450		1	450
	S1-2-450		2	450
	S1-2-450-2nd		2	450
S2	S2-C	5.4 (medium)	0	0
	S2-1-450		1	450
	S2-2-300*		2	300
	S2-2-450		2	450
	S2-2-450-2nd (untested)		2	450
	S2-2-450-3rd		2	450

Note: 1 mm = 0.0394 in.; 1 MPa = 0.145 ksi.

* The shorter length of strengthened zone was only tested in the S2 series due to limits of the experiment.

diameter longitudinal prestressing strands arranged at the bottom of the slab with one strand per web, which resulted in an average prestress of 2.7 MPa (392 psi). Each S2 series specimen (medium prestressing) had eight 13 mm diameter longitudinal strands at the slab bottom with two strands per each of the three middle webs and was prestressed to an average stress of 5.4 MPa (783 psi). **Figure A.1** shows the cross sections of the S1 and S2 series specimens (for appendix figures, go to https://www.pci.org/2019Sept-Appx).

Table 1 gives the specifications of each specimen, where S1-C and S2-C represent the control (unstrengthened) specimen in the S1 and S2 series, respectively. Two different CFRP sheet thicknesses were investigated: one layer and two layers on each slab void surface. Furthermore, the effect of increasing the strengthened zone (CFRP sheet) length from 300 to 450 mm (11.8 to 17.7 in.) was also investigated. The ID of the strengthened specimens is given according to the convention [prestressing level]-[number of layers of CFRP sheets]-[length of CFRP sheets]-[number of specimen (if repeated)]. For example, S1-2-450 indicates a low-prestressing-level prestressed concrete hollow-core slab strengthened with two layers of 450 mm long CFRP sheets and S1-2-450-2nd indicates a second test of a low-prestressing-level prestressed concrete hollow-core slab strengthened with two layers of 450 mm long CFRP sheets.

The ten hollow-core slab specimens were fabricated using the same batch of normalweight concrete with an average 28-day compressive strength of 60 MPa (8.7 ksi). To test the batch strength, a total of thirty 100 × 200 mm (3.9 × 7.8 in.) and fifteen 150 × 300 mm (5.9 × 11.8 in.) test cylinders were prepared under the same conditions to evaluate the compressive and tensile strengths of concrete at the time of the experimental slab testing.

CFRP sheets and epoxy were used to strengthen the prestressed concrete hollow-core slab specimens. The CFRP sheets were unidirectional, fleece-stabilized, stitched heavy carbon-fiber fabric for the wet application process of structural strengthening. The mechanical properties of the cured CFRP sheets were verified in the Wu et al.[11] study, and the average elastic modulus and tensile strength were 100 and 1120 MPa (14.5 and 162 ksi), respectively.

The prestressing strands used in the hollow-core slab specimens were seven-wire low-relaxation strands with a diameter of 13 mm (0.5 in.) and an ultimate tensile strength of 1860 MPa (270 ksi).

All specimens were fabricated and cured at the supplier's site and then shipped to the laboratory for testing. The surface of each slab void was cleaned using a steel brush before the CFRP sheets were attached. The unidirectional CFRP sheets were then bonded to the void surface in the circumferential direction following a wet layup process (**Fig. 1**). Both the CFRP sheets and the surface of the slab voids were saturated with the epoxy before directly bonding the sheets

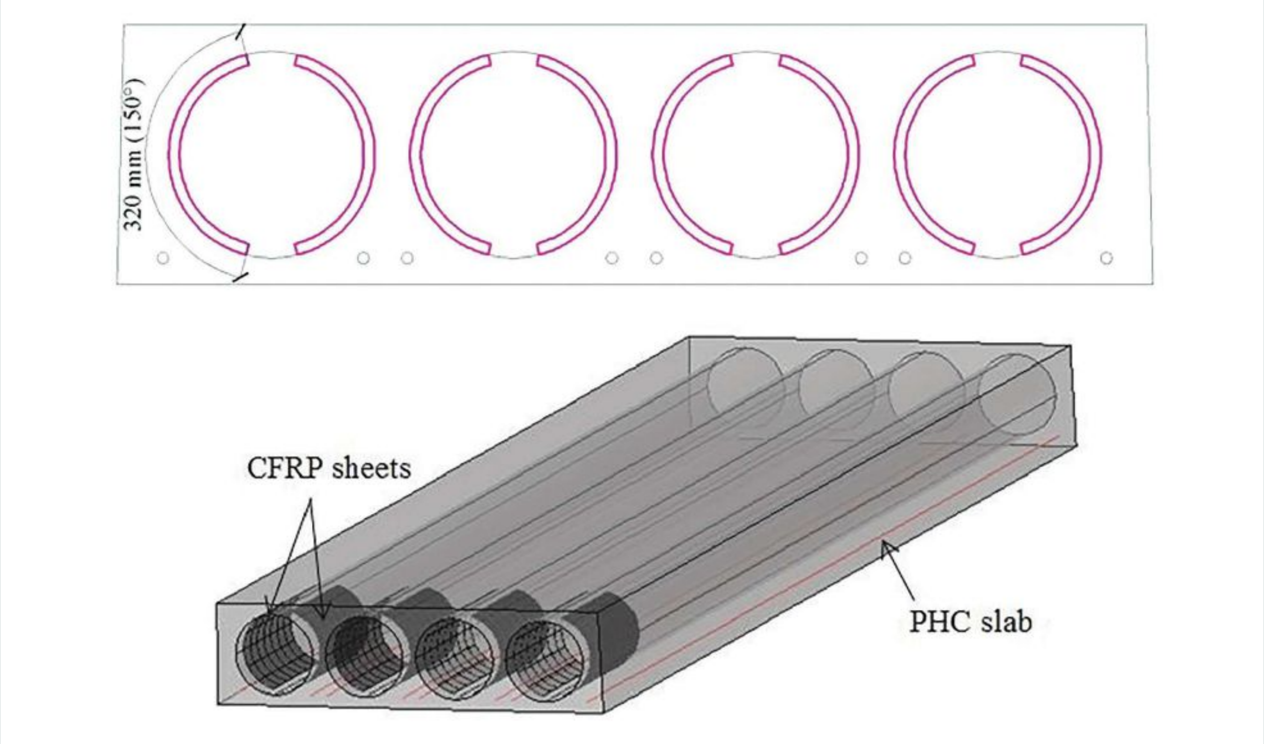
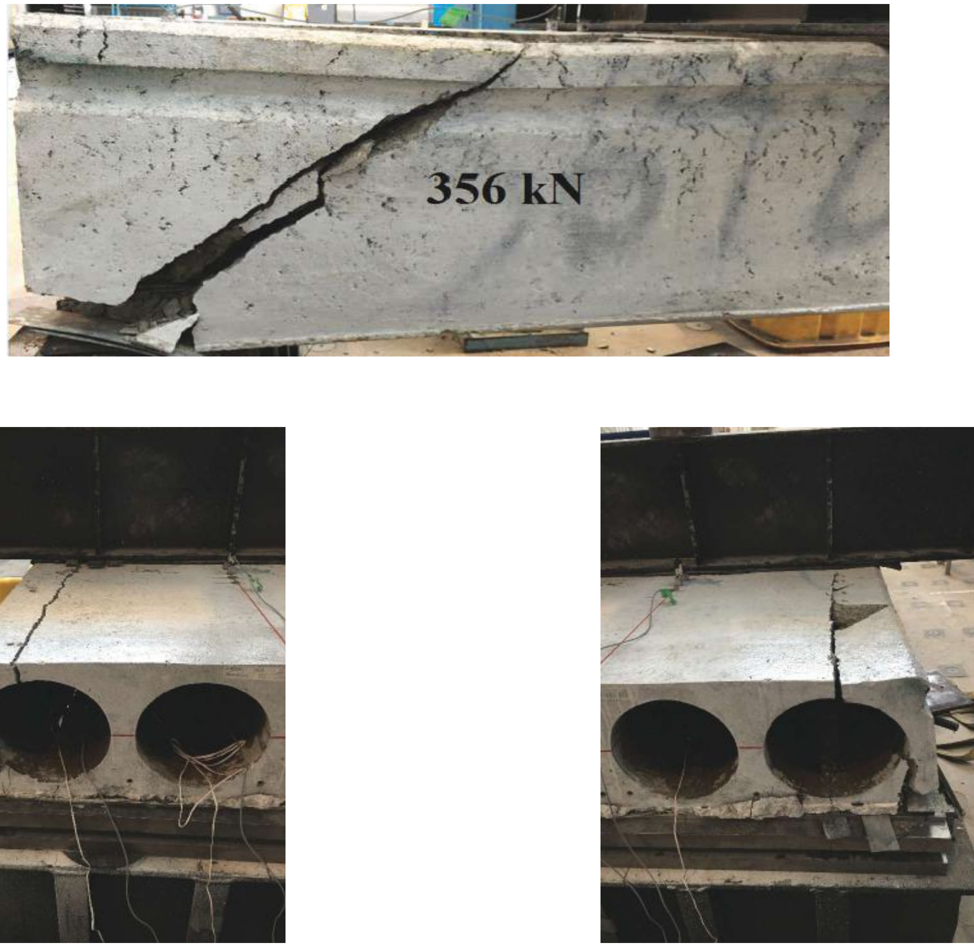


Figure 1. PHC slab strengthened in shear by CFRP sheets. Note: CFRP = carbon-fiber-reinforced polymer; PHC = prestressed concrete hollow-core. 1 mm = 0.0394 in.



Side view

At loading ends

Figure 2. S1-1-450 (specimen with one layer of CFRP at 450 mm length for low prestressing series) prestressed concrete hollow-core slabs at failure. Note: CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

to the void surface. If a second layer of CFRP was used, the CFRP sheet was saturated with epoxy and then directly bonded to the first layer of CFRP. The CFRP fiber was oriented perpendicular to the longitudinal axis of the slab specimen. The CFRP sheets were applied over an arc width corresponding to a 150-degree angle on each side of the web. The detailed procedure for attaching the CFRP sheets to the prestressed concrete hollow-core slabs is described in Wu et al.[11] The specimens were tested at least three days after attaching the CFRP sheets.

Experimental setup

Figure A.2 shows the experimental setup. All specimens were tested over a simply supported clear span of 4499 mm (177 in.) and were supported on 76 mm (3 in.) wide bearing plates on each side. The support near the loading point was a hinge and on the other side was a roller. This ensured that no axial force would be generated during the test. The shear span–to–depth ratio *a*/*d* of all slab specimens was 2.5; that is, the concentrated load was located at a distance of 762.5 mm (30 in.) from the hinged support. All specimens were instrumented at the loaded end. One linear variable displacement transducer (LVDT) was used to measure the end slippage of the prestressed steel in the second web. Another LVDT was used to measure the vertical displacement at the loading point. In addition, one displacement transducer, a pi gauge or digital pressure test gauge, was placed on the top surface of the slab in the longitudinal direction to measure the concrete compressive strain near the loading point. In addition, three electrical foil strain gauges were glued on the surface of the CFRP sheets at midheight of the web in the direction of the fibers to measure the tensile strain in the CFRP sheets. Based on the experience gained from the strengthened I-shaped single-web prestressed concrete hollow-core slabs in Wu et al.,[11] the location of each strain gauge was set at the intersection of the specimen's horizontal centerline and the line connecting the inner edge of the support bearing

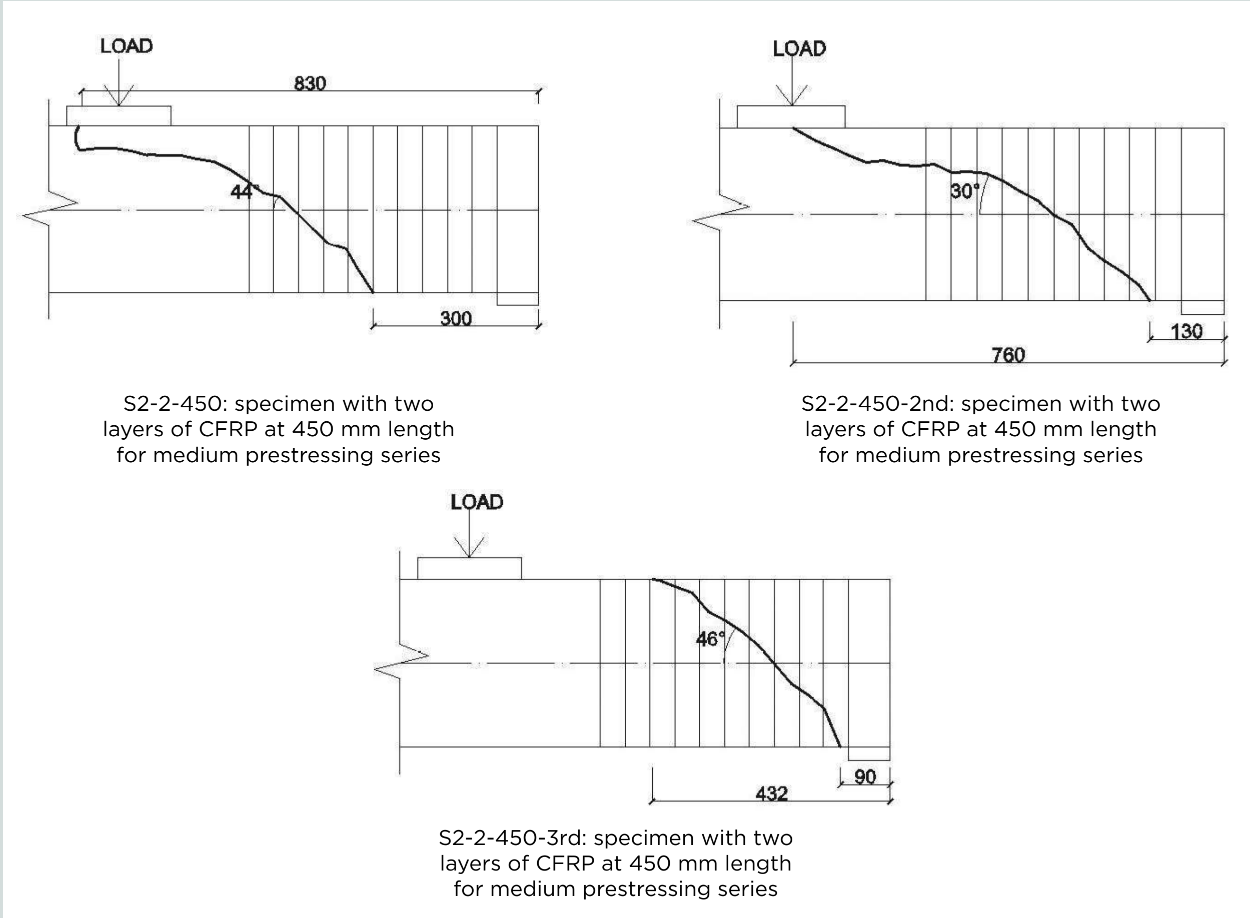


Figure 3. Crack profiles of S2-2-450-series specimens (shaded region represents the strengthened zone). Note: All dimensions are in millimeters. CFRP = carbon-fiber-reinforced polymer. 1 mm = 0.0394 in.

plate and the inner edge of the loading plate. In addition, rubber pads were used between the slab and loading plates as well as between the slab and loading beam to secure the flat touching surface.

Based on DIN EN 1168-08,[12] the loading process consisted 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 reloaded until failure by displacement control.

Experimental results

Ultimate load and failure mode

The two control specimens, S1-C and S2-C, manifested similar behavior in crack development, ultimate load, and failure mode. For example, in S1-C, a typical shear-tension failure occurred suddenly when the load reached 291 kN (65.4 kip). **Figures 2**, **A.3**, and **A.4** show ultimate failure loads and cracks that developed for three specimens. For S1-C, a crack developed suddenly at midheight and extended toward the inner edge of the hinge support and the middle of the loading plate, forming a 27-degree angle and ending at about 161 mm (6.3 in.) from the face of the support. For S1-1-450, the crack at failure was at an angle of 44 degrees with respect to horizontal; whereas in the case of S1-2-450, the average angle between the crack and horizontal was 36.5 degrees for the two repeated tests. Some vertical and radial cracks around the prestressing strand developed at the face of the loading end in all specimens only during loading due to the interaction between the prestressing strands and the high tensile force in the strand at the slab end. Similar cracking behavior was observed in all strengthened S2 series specimens. The crack angle was 39 degrees in S2-C, 30 degrees in S2-1-450, 37 degrees in S2-2-300, and an average of 40 degrees for three S2-2-450. No debonding between the CFRP sheets and the concrete was observed before failure of all strengthened specimens. **Figures 3** and **A.5** show the crack profiles for each specimen of the S1 and S2 series.

Table 2 summarizes the testing results of both S1 and S2 series prestressed concrete hollow-core slab specimens in terms of the ultimate load, ductility index, and failure mode. The ductility index is the ratio between the total deformation at the maximum load and the elastic limit deformation.

Table 2. Summary of experimental results

Specimen series	Specimen ID	Shear capacity		Ductility		Failure mode
		Failure load, kN	Improvement, %	Index	Improvement, %	
S1	S1-C	291	n/a	1.18	n/a	Brittle
	S1-1-450	356	22	3.36	184	
	S1-2-450	332	14	1.89	60	
	S1-2-450-2nd	338	16	2.31	95	
S2	S2-C	281	n/a	1.05	n/a	Brittle
	S2-1-450	328	17	1.21	15	
	S2-2-300	310	11	1.05	n.d.	
	S2-2-450	387	38	1.54	46	
	S2-2-450-2nd	368	31	1.23	17	
	S2-2-450-3rd	378	35	1.47	40	

Note: n/a = not applicable; n.d. = no data available. 1 kN = 0.225 kip.

The table shows that due to the proposed shear-strengthening technique of externally bonding the CFRP sheets along the perimeter of the slab voids, the ultimate load of the strengthened prestressed concrete hollow-core slabs increased considerably. In particular, S2-2-450, which was strengthened by two layers of 450 mm (17.7 in.) long CFRP sheets, obtained an ultimate load of 387 kN (87 kip), compared with only 281 kN (63 kip) for the control specimen S2-C. To confirm the strengthening effect of this pattern, the test was repeated twice, S2-2-450-2nd and S2-2-450-3rd, with exactly the same configuration and properties as S2-2-450. These two repeated specimens failed at 368 and 378 kN (82.7 and 85 kip), respectively. It can be concluded based on this set of results that applying two layers of CFRP sheets with a length of 450 mm from the end could result in an average increase of 35% in the shear capacity

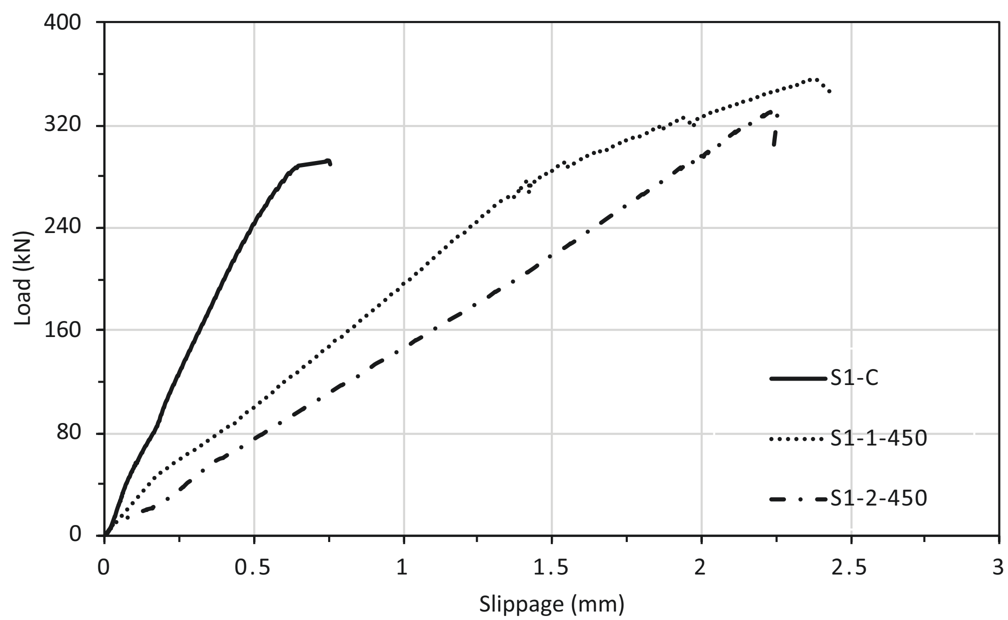


Figure 4. Strand slippage in the middle web of the S1 series (low prestressing) specimens. Note: CFRP = carbon-fiber-reinforced polymer; S1-1-450 = specimen with one layer of CFRP at 450 mm length; S1-2-450 = specimen with two layers of CFRP at 450 mm length; S1-C = control specimen. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

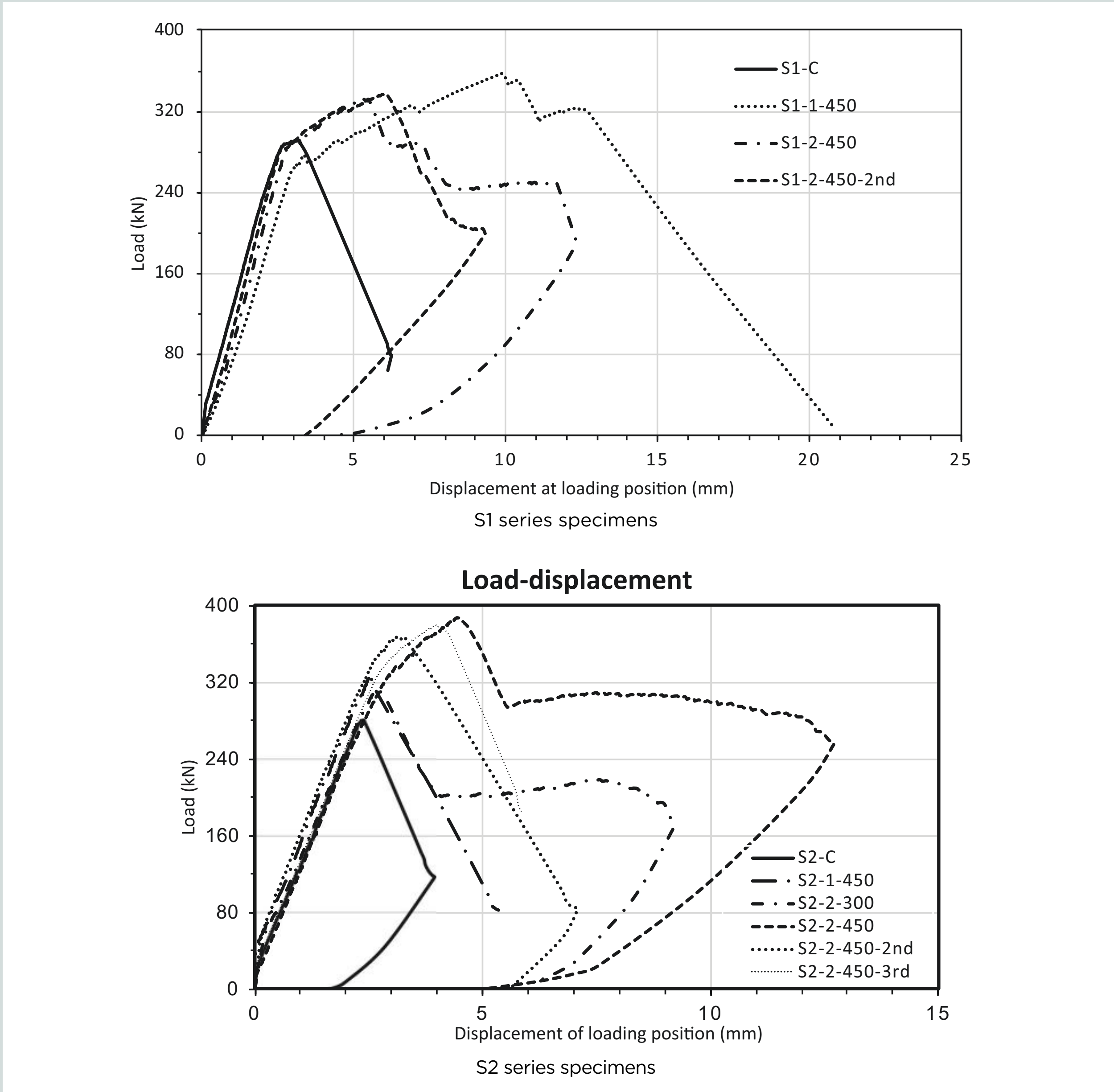


Figure 5. Load-deflection curves of prestressed concrete hollow-core slab specimens for S1 (low prestressing) and S2 (medium prestressing) series. Note: CFRP = carbon-fiber-reinforced polymer; S1-1-450 = specimen with one layer of CFRP at 450 mm length; S1-2-450 = specimen with two layers of CFRP at 450 mm length; S1-C = control specimen; S2-1-450 = specimen with one layer of CFRP at 450 mm length; S2-2-300 = specimen with two layers of CFRP at 300 mm length; S2-2-450 = specimen with two layers of CFRP at 450 mm length; S2-C = control specimen. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

of hollow-core slabs with a medium prestressing level. The relatively lower shear capacity of S2-2-450-2nd is believed to be due to the partial detachment of one CFRP sheet from one web before the test, whereas that of S2-2-450-3rd was found to be more consistent with the first specimen. The test results of the S2 series showed that using only one layer of 450 mm long CFRP in strengthening, S2-1-450, resulted in a 17% increase in the ultimate shear capacity, while using two layers of 300 mm (11.8 in.) long CFRP sheets to strengthen, S2-2-300, resulted in only an 11% increase in the ultimate shear capacity.

For the S1 series, the two S1-2-450 specimens developed an average 15% increase in the ultimate shear capacity compared with a 22% increase in S1-1-450. Further investigation showed that the poor performance of both S1-2-450 specimens was mainly due to considerably more slippage of prestressing strands than those in S1-1-450 during the loading process (**Fig. 4**). This resulted in more loss in the prestress of the specimens and thus reduced their ultimate loading capacity. Strand slippage was measured using an LVDT at the strand end in the second web of both the S1 and S2 series of specimens.

Furthermore, when the load reached about 300 kN (67.4 kip), a fine vertical flexural crack near the loading point was observed on all strengthened S1 series specimens. According to the *PCI Manual for the Design of Hollow Core Slabs*,[13] the flexure cracking load of the S1 series specimens was calculated to be 290 kN (65.2 kip). This explains the appearance of the vertical flexural cracks in the strengthened S1 series specimens.

Concrete compressive strain curves

The pi gauge installed on the slab top near the loading zone was used to measure the longitudinal concrete compressive strain during the loading process. **Figure A.6** shows the relationship between the load and the longitudinal compressive strain in concrete at the top surface of the slab 565 mm (22.2 in.) from the loading end. All S1 series and S2 series specimens showed similar behaviors up to about 290 kN (65.2 kip), which is the capacity of the control specimen. When the applied load increased beyond 290 kN, the strengthened specimens showed larger compressive strain compared with that of the control slab up to the failure load. Furthermore, all concrete compressive strains were far below the concrete crushing strain of 3500 $\mu\varepsilon$. Therefore, the failure of the specimens was mainly caused by web shear-tension failure.

Load-deflection curves

Figure 5 shows the load-deflection curves of the S1 and S2 series specimens. All control and strengthened specimens manifested similar behavior in the elastic range, and the strengthened specimens showed higher shear capacity and much larger deformation than the control ones. The results of the S1 series specimens indicated that when the load reached the ultimate capacity of the control slab around 290 kN (65.2 kip), the slope of the load-deflection curve of all strengthened slabs decreased. This could be because at this load, the slab reached the shear capacity provided by concrete and more cracks developed, which caused loss of stiffness. However, the presence of CFRP sheets helped carry more shear force, which increased the specimen capacity beyond 290 kN. Compared with S1-C, the shear capacity for S1-1-450 was increased by 22% and the maximum deflection was tripled, which reached about 10 mm (0.4 in.). The load-deflection curve for the S2 series shows a similar stiffness loss phenomenon, in which the slope of the load-deflection curves decreased slightly when the load in all three S2-2-450 specimens reached approximately the ultimate load of S2-1-450. Figure 5 also suggests that with the installation of two layers of CFRP sheets, the slab not only carried more shear load before failure but also underwent larger deformation. The two repeated tests of S2-2-450 showed behaviors similar to the first one except that there was no sizable improvement in their ductility.

Finite element simulation

Although experimental testing is the most reliable way to study the behavior of structures, it does limit the parameters that can be rapidly changed and investigated. To address these issues, finite element simulation is commonly adopted. A robust finite element model is not only capable of accurately simulating the behavior of the studied structure but is also a cost-effective way to conduct an extensive parametric study. In the current work, finite element models of the control and the strengthened full-sized prestressed concrete hollow-core slabs were developed using commercial finite element software. The validity of the finite element model was verified by the experimental results and then used to supplement the parametric study to understand the effects of various strengthening parameters on the shear performance of the CFRP-strengthened prestressed concrete hollow-core slabs.

In the developed finite element model, concrete was simulated using a three-dimensional, eight-node, reduced-integration solid element. The concrete damage plasticity model was used as the constitutive model to simulate the concrete behavior in prestressed concrete hollow-core slabs. **Table 3** gives the required material properties for the concrete element.

A two-node, three-dimensional truss element was used to simulate the seven-wire, low-relaxation 13 mm (0.5 in.) prestressing strands of prestressed concrete hollow-core slabs that had an ultimate tensile strength of 1860 MPa (270 ksi), a modulus of elasticity of 196,500 MPa (28,500 ksi), and a Poisson's ratio of 0.3, as provided by the supplier. The constitutive model of the prestressing strand in this study was based on the dual slash-curve model reported by Yu.[7]

The element type used to model the CFRP sheets was the four-node quadrilateral in-plane stress/displacement shell element with reduced integration and a large-strain formulation. The direction of the simulated CFRP sheets was perpendicular to the longitudinal axis of the slab. As previously mentioned, the tensile strength and the elastic modulus of the CFRP

Table 3. Material properties of the three-dimensional, eight-node, reduced-integration solid element for simulating concrete

Specimen series	Ultimate compressive strength f'_c, MPa	Young's modulus E_c, MPa	Poisson's ratio	Average tensile strength f'_t, MPa
S1	59.3	22,167	0.26	3.35
S2	52.2	23,946	0.26	3.35

Note: 1 MPa = 0.145 ksi.

sheets with epoxy resin were 1012 and 94,000 MPa (147 and 13,633 ksi), respectively. A linear elastic behavior was assumed in the simulation.[14–17] The bearing plates at the supports were modeled by the same element as for the concrete. Their material properties were assumed to be linear elastic with a modulus of elasticity of 200 GPa (29,000 ksi) and a Poisson's ratio of 0.3.

The interface between the reinforcement and the concrete was simulated by the embedded element. This technique can be used to simulate a reinforcement, shell, or surface element that lies embedded in a set of solid elements and will not restrict the rotational degree of freedom of the embedded elements. In the current study, the steel strands were embedded into the host element for concrete. The translational degree of freedom at the nodes of the embedded elements was constrained by the corresponding degree of freedom of the host elements.

Based on the reviewed literature and experimental observations, the interface between the concrete and the CFRP sheets was simulated by the tie constraint, whereas the interface between the concrete slab and the steel bearing plate was simulated as perfect bonding.[14,15] This interaction was also proved through experimental study as part of this program. Even after failure during the experimental testing, the CFRP sheets could hardly be removed from the strengthening area.

Figure A.7 shows a three-dimensional view of the geometry of the finite element model developed for the control slab and the strengthened slab. The x axis was along the longitudinal direction of the slab. The y-z plane coincided with the slab cross section, with the y and z axes in the horizontal and the vertical directions, respectively. In the experimental study, all slabs were tested under simply supported conditions. The support near the loading point was a pin, and the other was a roller. To simulate the pin support, all nodes at the bottom surface of the bearing plate were constrained in the x, y, and z directions; whereas for the roller support, the nodes at the bearing plate bottom surface were constrained only in the y and z directions. The displacements of the constrained nodes were set as zero to satisfy the actual testing conditions.

The finite element analysis was divided into two steps. In the first step, prestress was applied to the prestressing strands. This was simulated by decreasing the temperature of the strands to let the concrete shrink. The tie constraints between the steel bearing plates and the concrete as well as the bonding between the CFRP sheets and the concrete were removed in this step. In the second step, the line load was gradually applied to the prestressed concrete hollow-core slab, as in the physical tests, and the tie constraints were added back. The load increased with an increment of 1.0 kN (0.225 kip) until the slab failed. The full Newton-Raphson method was used in solving the nonlinear equilibrium equations. The convergence criterion was based on load, with the tolerance limits of the first and the second steps being 0.05 and 0.005, respectively. The numerical simulation process ended when the solution was difficult to converge.

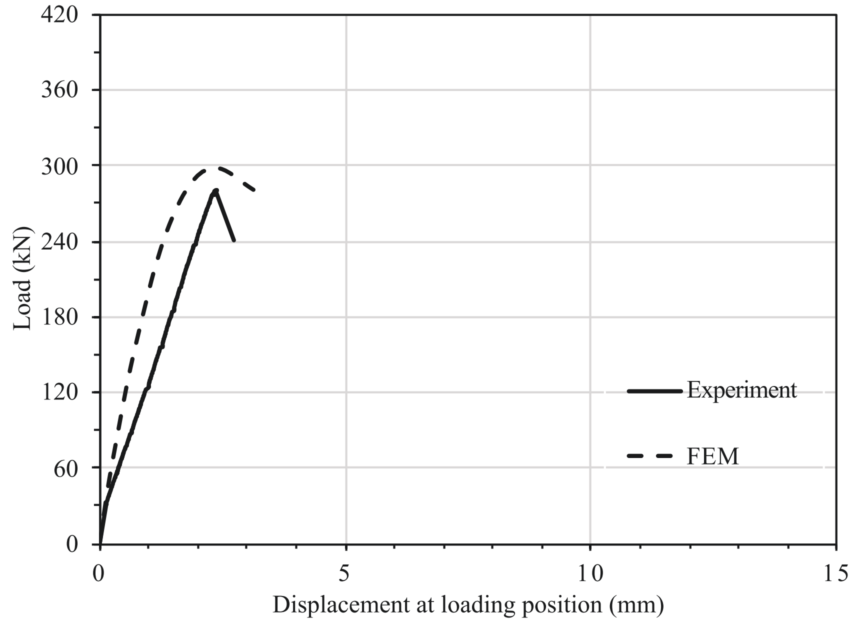
Model validation

Table 4 gives a comparison of the ultimate loading capacity of all studied specimens obtained from the experimental tests and the finite element simulation. The two sets of results agree well with each other, with an average difference of about 7%. In majority of the cases, the difference is less than 10%, except those for the two S1-2-450 specimens, which are relatively large: 18% and 16%, respectively. This is believed to be mainly caused by the previously mentioned excessive slippage of strands in those two specimens (Fig. 4), which is also reflected

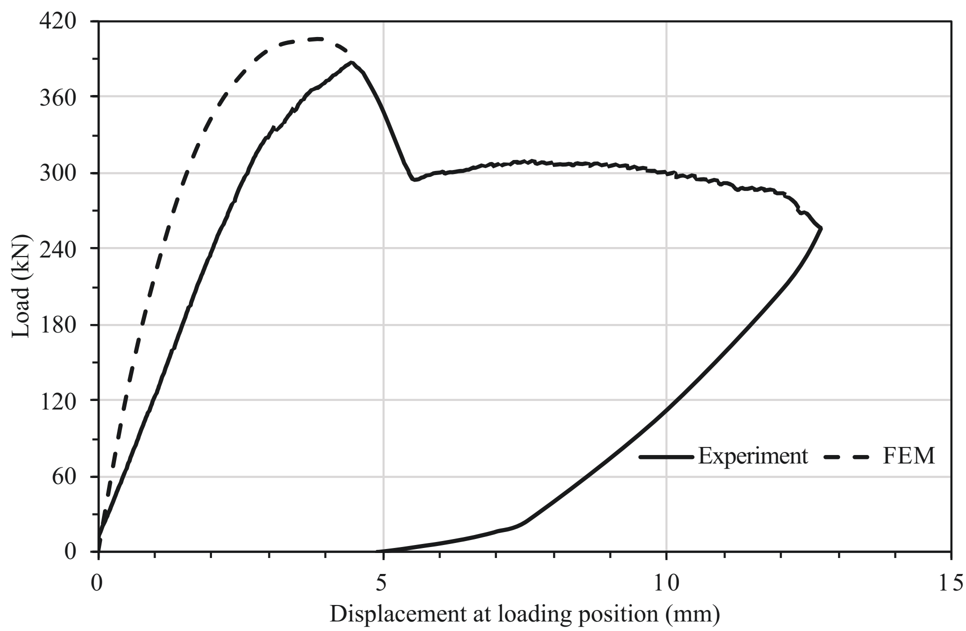
Table 4. Comparison of ultimate load between experimental and numerical simulation results

Specimen series	Specimen ID	Failure load, kN		
		Experiment	Finite element model	Difference, %
S1	S1-C	291	304	5
	S1-1-450	356	374	5
	S1-2-450	332	393	18
	S1-2-450-2nd	338	393	16
S2	S2-C	281	298	6.2
	S2-1-450	328	342	4.3
	S2-2-450	387	405	4.7
	S2-2-450-2nd	368	405	10.5
	S2-2-450-3rd	378	405	7.1
	S2-3-450	n.d.	457	n/a

Note: n/a = not applicable; n.d. = no data available. 1 kN = 0.225 kip.



S2-C: control specimen for medium prestressing series

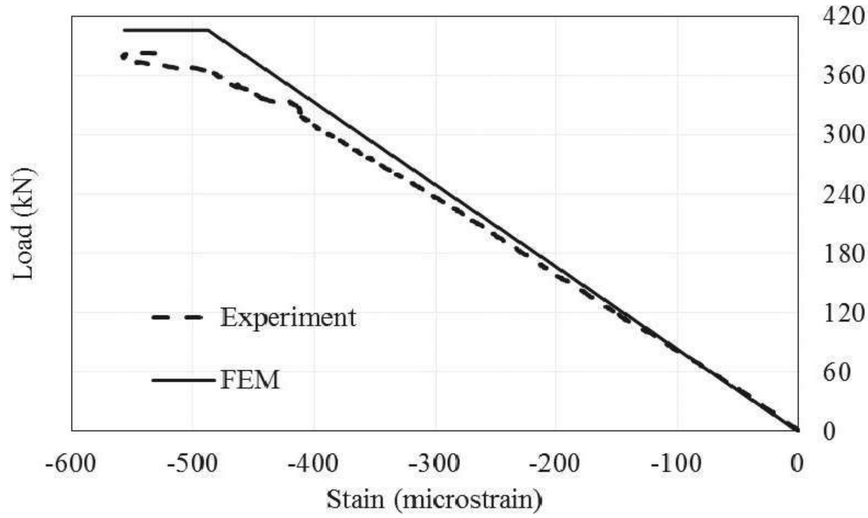


S2-2-450: specimen with two layers of CFRP
at 450 mm length for medium prestressing series

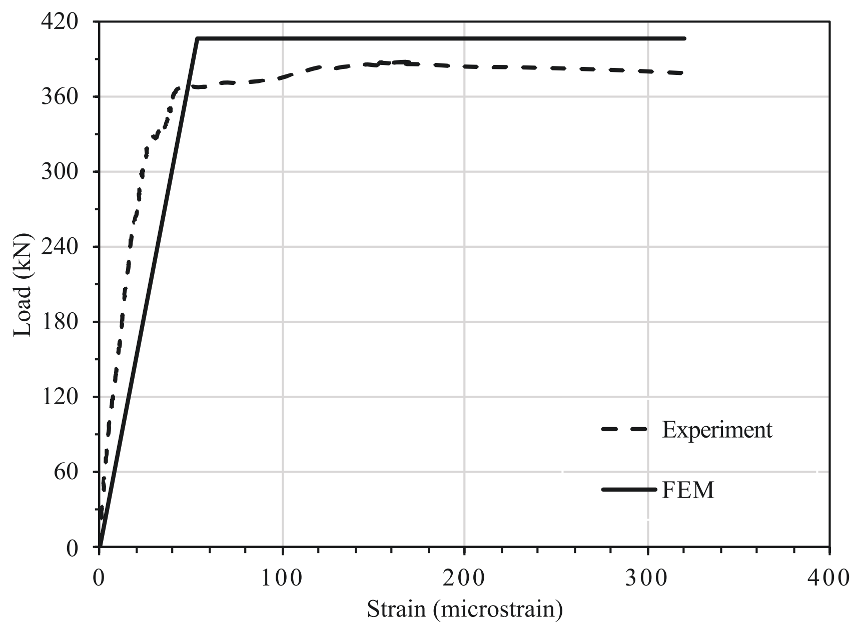
Figure 6. Sample load-deflection curves. Note: CFRP = carbon-fiber-reinforce polymer; FEM = finite element model. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

in the lower ultimate loading capacity obtained in the physical tests compared with that of the S1-1-450 specimen.

Figure 6 shows a sample of load-deflection curves, the results of which suggest that the developed finite element model could satisfactorily predict the behavior of the nonstrengthened and strengthened prestressed concrete hollow-core slabs in terms of the initial stiffness, the ultimate failure load, and the deflection at failure. In addition, the load-strain relationships illustrated in **Fig. 7** indicate that the developed finite element model could accurately predict the compression in the concrete and the tension in the CFRP sheets. Based on



Load versus longitudinal concrete compressive strain at the top surface of S2-2-450



Load versus longitudinal tensile strain in CFRP sheets in the middle web of S2-2-450

Figure 7. Relationship between applied load and strain in concrete and carbon-fiber-reinforced-polymer sheets. Note: CFRP = carbon-fiber reinforced; FEM = finite element model; S2-2-450 = specimen with two layers of CFRP at 450 mm length for medium prestressing series. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

these, the finite element model developed in the current study was considered to be capable of simulating the behavior of the control and the strengthened prestressed concrete hollow-core slabs over the entire loading process. It was also applied to carry out additional parametric studies as a supplement to the physical tests.

Parametric study

The effects of three important parameters associated with the configurations of the strengthening technique are discussed in this section based on the experimental and numerical simulation results. These parameters include the thickness (one, two, or three layers), the length (300 or 450 mm [12 or 18 in.]), the width of the strengthening material (arc lengths of 90, 120, or 150 degrees), and different prestressing levels (low or medium). The study of three layers of CFRP and width ranges of 90 or 120 degrees were only performed in the numerical simulation, not experimentally.

Effect of strengthening thickness

Comparing the ultimate loading capacity of the control specimens with those strengthened by one layer and two layers of CFRP sheets (Table 2) shows that installing CFRP sheets along the perimeter of the slab voids considerably enhances the shear capacity of prestressed concrete hollow-core slabs. The load-carrying capacity increases when more layers of CFRP sheets are applied. Although in the case of the S1 series, the experimentally obtained ultimate load of the two S1-2-450 specimens was lower than that of the S1-1-450.

As previously explained, this was mainly caused by the preexisting fine cracks that may be been caused by strand slippage in those two specimens. Both the experimental and the numerical results show that a 22% to 23% increase of the ultimate load can be achieved in the S1 series prestressed concrete hollow-core slabs strengthened with one layer of CFRP sheet. The finite element results also indicate another 6% improvement in the loading capacity (393 kN [88.4 kip]), or a total of 29%, by adding one more layer of CFRP sheet. A clearer trend of the strengthening thickness effect can be observed from the results of the S2 series specimens, of which the increases in the ultimate load obtained from the experimental test and numerical simulation were respectively 17% and 15% with the installation of one layer CFRP sheet; whereas for the two-layer CFRP sheet configuration, average increases of 35% and 36% were found by using these two approaches, respectively. In addition, the installation of three layers of CFRP sheets was simulated with the developed finite element model, which with an ultimate load of 457 kN (103 kip) gave a 53.4% increase compared with the control specimen. Results of the S2 series specimens suggest that each layer of CFRP sheet led to about a 50 kN (11 kip) increase in the shear capacity of the prestressed concrete hollow-core slabs.

Alternatively, based on the ductility index shown in Table 2, S1-2-450 series specimens had less ductility improvement than the S1-1-450 series, which was caused by the more considerable slippage of prestressing strand during loading. Nevertheless, the ductility of all strengthened S1 series specimens increased significantly compared with that of the control specimen. Furthermore, in the S2 series specimens, by increasing the thickness of the applied CFRP sheets, the ductility index showed reasonable improvement, which proves that the proposed technique could also enhance the ductility of prestressed concrete hollow-core slabs.

Figure 5 illustrates the effect of strengthening thickness on the load-deflection behavior of the experimental specimens. The control and the strengthened specimens had similar behavior in the elastic range, and the specimens strengthened by more layers of CFRP sheets manifested higher loading capacity and larger deformation.

Effect of strengthening length

The effect of the length of the strengthening material was evaluated based on the results of the S2-C, S2-2-300, and three S2-2-450 experimental and numerical simulation specimens. Table 2 gives the ultimate load and ductility indexes of these specimens. Compared with the control specimen, the one strengthened with two layers of 300 mm (11.8 in.) long CFRP sheets showed an 11% increase in its ultimate load in the experimental test, whereas the one strengthened by two layers of 450 mm (17.7 in.) CFRP sheets showed an average 35% increase. The increases in the ultimate load of these two strengthening configurations predicted by the finite element simulation are 12% and 36%, respectively. The ductility index also shows a similar trend compared with the ultimate load results. The S2-2-300 specimen showed marginal improvement of the ductility index. However, the S2-2-450-series specimens had an average ductility index improvement of about 34% compared with the control specimen. Figure 5 shows the effect of strengthening length on the behavior of prestressed concrete hollow-core slabs where the installation of longer strengthening material enhances both the loading capacity and the ductility of the strengthened specimen.

Effect of strengthening width

Because the maximum shear stress of prestressed concrete hollow-core slabs occurs at the midheight of the web, the development length and anchorage of the CFRP sheets around midheight is important. Therefore, it is worth studying the effect of the strengthening width on the performance of the prestressed concrete hollow-core slabs. This part of the study was conducted with numerical simulation using the developed finite element model for the S2-2-450 specimen. Three scenarios of strengthening width were studied, with the CFRP sheets covering an arc range of 150, 120, and 90 degrees, respectively, along the perimeter of the slab voids (**Fig. 8**). **Table 5** shows that the specimens with a strengthening width of 150- and 120-degree arc range showed almost

Table 5. Finite element simulation results of S2-2-450 with different strengthening width

Strengthening width, degrees	Failure load, kN	Reduction, %*
150	405	n/a
120	402	0.7
90	389	3.9

Note: n/a = not applicable.

*The 150-degree case is the reference base.

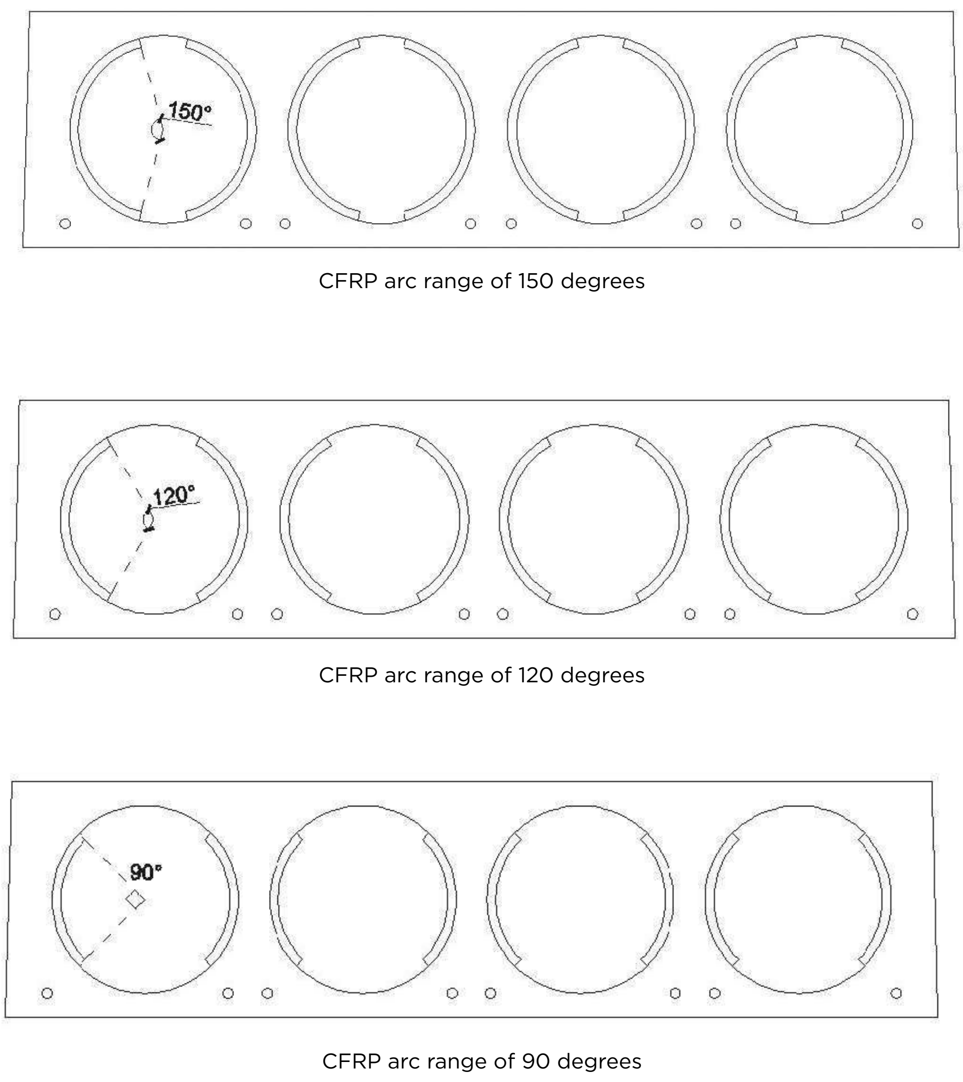


Figure 8. Three studied scenarios of strengthening width effect on prestressed concrete hollow-core slabs.
Note: CFRP = carbon-fiber-reinforced polymer.

the same ultimate capacity, whereas that with a narrower strengthening width of 90 degrees only dropped by 3.9% compared with the 150-degree case. This set of simulation results suggests that a width of CFRP sheets corresponding to a 120-degree arc range could adequately provide satisfactory anchorage length for the CFRP sheets. With the current installation configuration of CFRP sheets, decreasing the strengthening width would only slightly reduce the ultimate shear capacity of prestressed concrete hollow-core slabs. Even with a strengthening width corresponding to a 90-degree arc range, a considerable shear-capacity enhancement of 32% can still be achieved compared with the nonstrengthened case of 298 kN (70 kip). Furthermore, reducing the strengthening width of CFRP sheets would reduce costs and make the proposed shear-strengthening technique more economical and easier to apply.

Effect of prestressing level

Table 6 compares the ultimate load of the S1 (low prestressing level) and S2 series (medium prestressing level) specimens. It can be concluded that the medium prestressing specimen strengthened with two layers of 450 mm (17.7 in.) long CFRP sheets (S2-2-450) showed higher shear capacity than the low prestressing one (S1-2-450). However, in the case of the specimens strengthened with one layer of 450 mm long CFRP sheet, the low prestressing specimens resisted larger load. This is consistent with Yang's[18] finding that a higher prestressing level might not necessarily help to enhance the shear capacity of prestressed concrete hollow-core slabs. **Figure 9** shows the effect of the prestressing level on the load-deflection behavior of the prestressed concrete hollow-core slabs. Both sets of results indicate that the prestressing level of prestressed concrete

Table 6. Ultimate load of the specimen under different prestressing levels

Specimen	Prestressing level, MPa	Experiment		Finite element simulation	
		Failure load, kN	Increase, %	Failure load, kN	Increase, %
S1-C	2.7 (low)	291	-3.4	304	-2.0
S2-C	5.4 (medium)	281	-3.4	298	-2.0
S1-1-450	2.7 (low)	356	-7.9	374	-8.5
S2-1-450	5.4 (medium)	328	-7.9	342	-8.5
S1-2-450	2.7 (low)	332	17.2	393	3.5
S2-2-450	5.4 (medium)	387	17.2	405	3.5

Note: 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

hollow-core slabs may not necessarily affect the effectiveness of the proposed shear-strengthening technique.

Economy of the proposed technique

Results obtained from the current study clearly suggest that the proposed strengthening technique could considerably improve the shear capacity of the 305 mm (12 in.) thick prestressed concrete hollow-core slabs. Therefore, the economy of the proposed technique should be further explored.

Taking one layer of 450 mm (17.7 in.) long CFRP sheet (covering an arc range of 150 degrees) as an example, the one layer 450 mm CFPR sheet helped improve the ultimate shear capacity of the medium prestressing level (eight prestressing strands) prestressed concrete hollow-core slab by 17%. This configuration requires approximately 1.15 m^2 (12.4 ft^2) of CFRP sheets to strengthen the four voids of a 305 mm (12 in.) thick prestressed concrete hollow-core slab. According to the information provided by the manufacturer, the cost of the carbon fiber sheets used in the current study is \$70/m^2 (\$6.50/ft^2), whereas the cost of the epoxy is approximately \$22.30/m^2 (\$2.07/ft^2) for saturating the fibers and \$5.70/m^2 (\$0.53/ft^2) as primer for the concrete surface. Therefore, the cost of the one-layer, 450 mm technique will be approximately \$226 per slab (including both side of the slab). Similarly, applying two layers of 450 mm CFRP sheets will cost \$438 per slab but provide 38% improvement of shear capacity.

Based on the manufacturer's design tables, the cost of strengthening the shear capacity of a single 1.2 × 12.0 m (3.9 × 39.3 ft) prestressed concrete hollow-core slab using the proposed technique would be approximately \$12/m^2 (\$1.15/ft^2) for the covered area. It is not recommended that the manufacturer open the core of prestressed concrete hollow-core slabs during fabrication and fill all middle cores with solid concrete if the factored shear exceeds the shear capacity of the prestressed concrete hollow-core slabs. This would slow the fabrication process and increase the labor cost. Therefore, most suppliers may choose to increase slab thickness to satisfy the shear requirement. For example, the difference between fabricating a 305 mm (12 in.) prestressed concrete hollow-core slab and a 355 mm (14 in.) prestressed concrete hollow-core slab is \$10.7/m^2 (\$0.99/ft^2), which means that the proposed shear-strengthening technique is barely 12% more expensive than the traditional method. However, other factors should also be considered, such as savings in the self-weight of the whole structure, reservations in the headroom, conserving limited natural resources by using less aggregates, as well as reducing cement consumption and therefore greenhouse gas emissions. To further improve the economy of the proposed strengthening technique, the possible application of a less expensive strengthening material, such as glass-fiber-reinforced polymer, is currently under investigation.

Conclusion

A new shear-strengthening technique for prestressed concrete hollow-core slabs by installing externally bonded CFRP sheets to each void of the full-width prestressed concrete hollow-core slab is proposed. To evaluate the feasibility and effectiveness of this new method, the behavior of 10 full-width prestressed concrete hollow-core slab specimens, two unstrengthened and eight strengthened with CFRP sheets externally bonded along the circumferential direction of the surface of the prestressed concrete hollow-core slab voids, were investigated using experimental testing and numerical simulation. The developed finite element model was validated by the experimental results. The studied parameters include the length, width, and thickness of the applied CFRP sheets and the prestressing level of the prestressed concrete hollow-core slab. The results show that by applying the proposed shear-strengthening technique, a considerable enhancement of the shear capacity of the prestressed concrete hollow-core slabs can be achieved. Some strengthened specimens also showed sizable improvement of the ductility before failure. These results clearly indicate that the proposed technique is effective in strengthening the shear capacity of prestressed concrete hollow-core slabs. The main findings obtained from the current study are the following:

- Increasing the strengthening thickness by applying more layers of CFRP sheets can improve the shear capacity of prestressed concrete hollow-core slabs. The role of the CFRP sheets can be considered to be similar to the

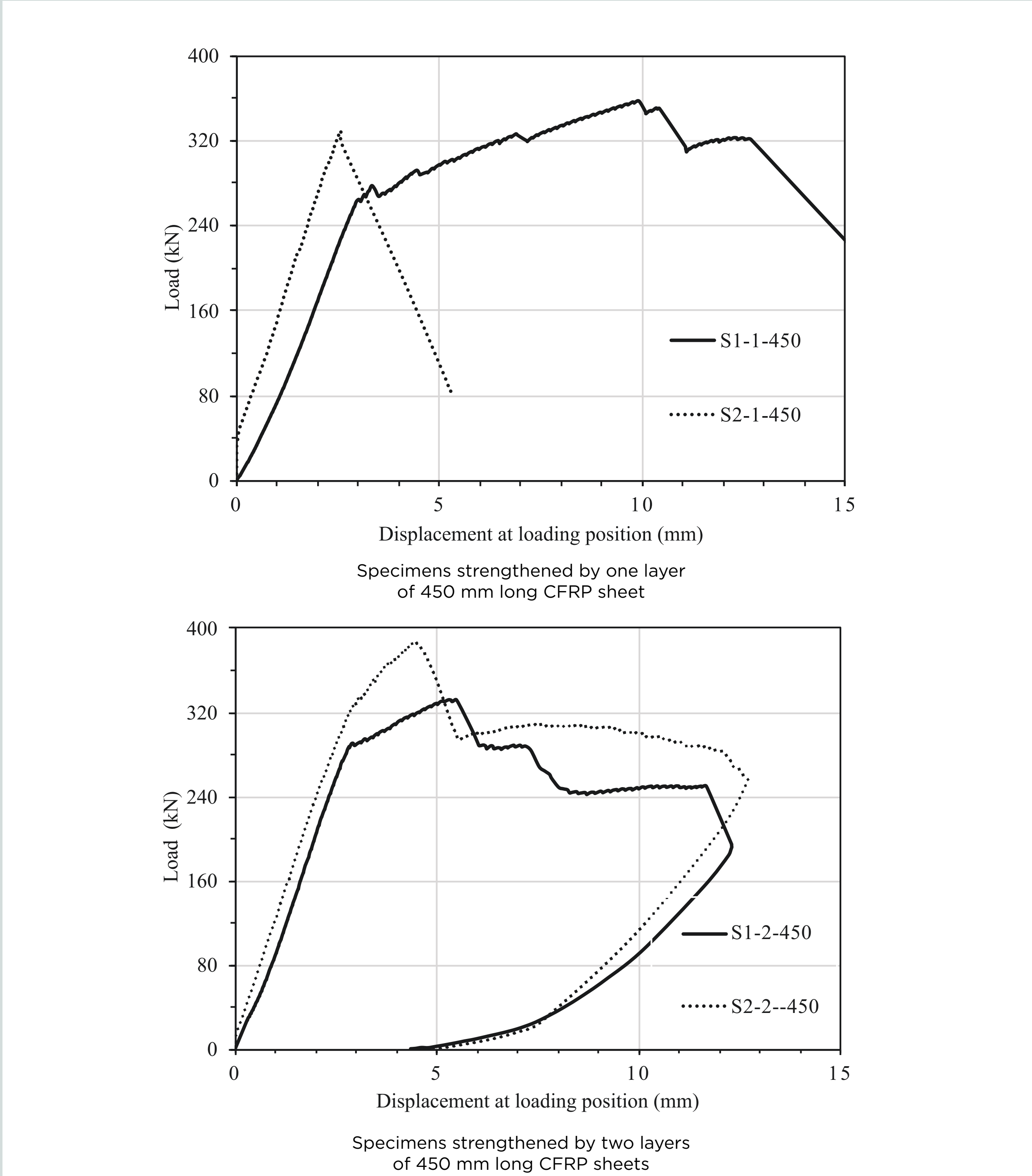


Figure 9. Effect of prestressing level on the load-deflection relation of prestressed concrete hollow-core slab specimens for S1 (low prestressing) and S2 (medium prestressing) series. Note: CFRP = carbon-fiber-reinforced polymer; S1-1-450 = specimen with one layer of CFRP at 450 mm length; S1-2-450 = specimen with two layers of CFRP at 450 mm length; S2-1-450 = specimen with one layer of CFRP at 450 mm length; S2-2-450 = specimen with two layers of CFRP at 450 mm length. 1 mm = 0.0394 in.; 1 kN = 0.225 kip.

shear stirrup. Numerical simulation results show that the average contribution of each layer of the applied CFRP sheet to the ultimate loading capacity was about 50 kN (11 kip). The limit of the number of layers that can be applied practically was not studied.

- A longer strengthening length by CFRP sheets can lead to higher shear resistance capacity because it can better cover the critical shear-tension region. The shear-capacity enhancement of the strengthened prestressed concrete hollow-core slabs was 11% for the S2-2-300 specimen and 34% for the S2-2-450 series, respectively. These results were validated by finite element simulation.

- The effect of strengthening width on the proposed shear-strengthening technique was only investigated by numerical simulation. The results show that with a certain strengthening length and thickness, reducing the width of the applied CFRP sheets from 150 to 120 degrees has a marginal impact on the shear performance of prestressed concrete hollow-core slabs. In addition, it was found that CFRP sheets with a width covering an arc range of 90 degrees are sufficient to strengthen the critical shear portion of each web in the prestressed concrete hollow-core slabs and showed 32% shear resistance improvement.

- A higher prestressing level might not necessarily help to enhance the shear capacity of prestressed concrete hollow-core slabs. The shear capacity of nonstrengthened and strengthened prestressed concrete hollow-core slabs is mainly related to the concrete property of prestressed concrete hollow-core slab itself and the applied CFRP material.

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Notation

a = span

d = depth

E_c = Young's modulus of concrete

f'_c = ultimate compressive strength of concrete

f_t = average tensile strength of concrete

h = depth of slab

About the authors

Xianzhe Meng, MASc, obtained his master's degree from the Department of Civil and Environmental Engineering at the University of Windsor in Windsor, ON, Canada.

Shaohong Cheng, PhD, PEng, is a professor in the Department of Civil and Environmental Engineering at the University of Windsor.

Amr El Ragaby, PhD, PEng, is an assistant professor in the Department of Civil and Environmental Engineering at the University of Wisconsin in Platteville, Wis., and an adjunct assistant professor at the University of Windsor. He received his PhD in structural engineering from the Université de Sherbrooke in Sherbrooke, QC, Canada. His research interests include analysis, design, large-scale experimental testing, finite element modeling, and structural health monitoring of reinforced and precast/prestressed concrete structures reinforced and/or strengthened with steel and fiber-reinforced-polymer composite materials. He is a member of the Canadian Precast/Prestressed Concrete Institute, the American Concrete Institute, and the American Society of Civil Engineers.

Abstract

Precast, prestressed concrete hollow-core slabs are widely used for floor decks in office and residential buildings and in parking structures. Although they are generally designed to resist bending moments under uniformly distributed loads, in some cases, shear failure can occur at the region close to support due to a large concentrated or line load. The manufacturing process for this type of member does not allow shear reinforcement to be arranged in the slab webs during fabrication. Therefore, the web shear resistance is only provided by the concrete itself, which governs the member capacity. The objective of this study was to explore the feasibility and effectiveness of a novel shear-strengthening technique using externally bonded carbon-fiber-reinforced polymer (CFRP) composite sheets along the internal perimeter of slab voids. Both experimental tests and numerical simulations were conducted to investigate the behavior of ten full-sized prestressed concrete hollow-core slabs: eight specimens strengthened with CFRP and two control specimens. The studied parameters included the length, width, and thickness of the applied CFRP sheets and the prestressing level of the prestressed concrete hollow-core slabs. The results show that the proposed shear-strengthening technique not only considerably enhances the shear capacity of prestressed concrete hollow-core slabs but also sizably improves the ductility.

Keywords

Carbon-fiber-reinforced polymer sheet, hollow-core slab, numerical validation, shear capacity, shear strengthening.

Review policy

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