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High-strength concrete deep beams with web openings strengthened by carbon fiber reinforced plastics

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Abstract. The objective of this study is to examine the effect of carbon fiber reinforced polymer (CFRP) on the shear strengths of deep beams with web openings. A total of 18 high-strength concrete deep beams with web openings were tested. Twelve were externally wrapped with four layers of CFRP, six of them strengthened in the horizontal direction and the others in the vertical direction. The parameters of the configuration of CFRP, the sizes of the openings and the locations of the openings were covered in this study. The test results indicates the shear strengths of deep beams with openings sized 60×40 mm were about 16% higher than that with openings sized 68×68 mm. For deep beams with openings sized 60×40 mm, the lower the locations of openings the higher the shear strengths were. The test results also indicate the shear strengths of deep beams with web openings strengthened by CFRP wrapped in the vertical direction can be enhanced by about 10%. However, the shear strengths of deep beams with web openings strengthened by CFRP wrapped in the horizontal direction can only be enhanced by about 6%. The shear strengths of deep beam, with different size and location of web openings and strengthened by different configuration of CFRP can be reasonably predicted by the empirical formulas of Kong and Sharp.

Keywords: deep beams; web openings; shear strengths; carbon fiber reinforced plastics (CFRP)

1. Introduction

Openings are frequently placed in the web area of reinforced concrete deep beams to facilitate essential services, such as conduits, network system access, or even movement from one room to another (Yang *et al*. 2007). ACI Code (2011) Section 11.7 specifies deep beams should be loaded on loading points and supports should be placed on reaction points so compression struts can develop between the loads and supports. If the openings interrupt the load paths joining the

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loading and reaction points, it is obvious the simple load paths will change to more complex ones and the shear capacity of the deep beams will be reduced (Kong and Sharp 1973).

Fifteen reinforced concrete deep beams with openings were tested by Yang *et al*. (2007). It was observed the diagonal crack width and shear strength of the tested beams significantly depended on the effective inclined reinforcement factor that ranged from 0 to 0.318 for the test specimens (Yang *et al*. 2007). Twenty-two reinforced concrete continuous deep beams with openings and two companion solid deep beams were tested to failure by Yang and Ashour (2008). It has also been observed higher load and shear capacities were exhibited by beams with web reinforcement above and below openings than those with web reinforcement only above openings (Yang and Ashour 2008).

In recent years, carbon fiber reinforced plastics (CFRP) material usage in strengthening applications gradually became widespread (Anil *et al*. 2012). The application of circumferential wrapping FRP as a new technique for external confinement and strengthening of reinforced concrete columns has been used in recent years (Elwan and Rashed 2011). Although the experimental database is extensive for reinforced concrete members strengthened in flexure (Sobuz *et al*. 2011) with fiber reinforced plastic composites (FRP), further investigations in the domain of shear strengthening are imperative. According to a study of the shear strengthening of reinforced concrete beams (Shuraim 2011), CFRP strengthened beams provide an increase in ultimate strength compared to not-strengthened beams. Chakrabortty and Khennane (2014) present an analysis of the results of an experimental program on the performance of a novel configuration of a hybrid FRP-concrete beam. According to their study, the filament-wound wrap had many benefits such as providing a composite action between the concrete block and the GFRP box, improving the stiffness of the beam, and most importantly, enhancing the load carrying ability through induced confinement of the concrete (Chakrabortty and Khennane 2014).

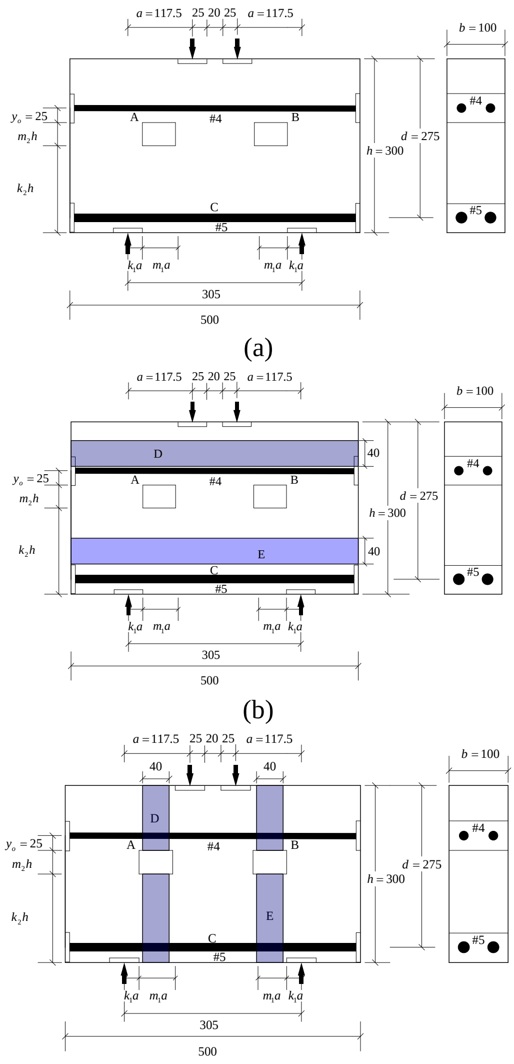
Test results indicate the higher the cross-sectional area of CFRP, the higher is the shear strength of the corbels (Lu *et al*. 2012). It is believed the shear strength of deep beams with web openings can also be enhanced using external CFRP strengthening, but very few, if any, deep beams with web openings that are externally strengthened by CFRP have been studied. Further experimental work on deep beams with web openings strengthened by CFRP should be performed.

2. Experimental study

In this study, 18 high-trength concrete deep beams with web openings were tested under a vertical load. Twelve were externally strengthened with CFRP, six in the horizontal and the others in the vertical direction. Variables examined in the tests included the configuration of CFRP and the size and location of the openings.

2.1 Specimen details

Typical deep beam specimens with web openings are shown in Fig. 1. The width (b), overall depth (h), and effective depth (d) of the tested deep beams were 100 mm, 300 mm and 275 mm, respectively. The compressive strength of concrete (f_c'), the ratio of openings width to shear span, m_1 the ratio of openings depth to overall section depth m_2, the horizontal position coefficient of openings k_1, and the vertical position coefficient of openings k_2 are listed in Table 1. The flexural steels consisting of 2-#5 straight bars were welded to anchored plates at the ends of the beam to



(a)

(b)

(c)

Fig. 1 Typical specimen; (a) Not strengthened (b) Strengthened with CFRP in the horizontal direction (c) Strengthened with CFRP in the vertical direction

prevent local bond failures (Fig. 1). The horizontal bars consisting of 2-#4 straight bars at 25 mm above the openings were welded to anchored plates at the ends of the beam to prevent local bond failures (Fig. 1). The dimensions of the anchored plates were 100×50×6 mm.

The deep beam notation, given in Table 1, includes four parts. The first part refers to the compressive strength of concrete, H for high compressive strength concrete. The second part refers to the size of the openings, S, for deep beams with openings sized 60×40 mm, and L, for deep beams with openings sized 68×68 mm. The third part refers to the location of openings, U, M and D for deep beams with openings located in the high, middle and low positions. The fourth part refers to the configuration of CFRP, H4, for deep beams wrapped with 4 layers of CFRP,

Table 1 Specimen details

Specimen	f_c'(MPa)	Configuration of CFRP[+]	m_1	m_2	k_1	k_2
HSUO0	101.4	-	0.511	0.133	0.213	0.500
HSMO0	101.4	-	0.511	0.133	0.213	0.433
HSDO0	101.4	-	0.511	0.133	0.213	0.367
HSUH4	101.4	H4	0.511	0.133	0.213	0.500
HSMH4	101.4	H4	0.511	0.133	0.213	0.433
HSDH4	101.4	H4	0.511	0.133	0.213	0.367
HSUV4	101.4	V4	0.511	0.133	0.213	0.500
HSMV4	101.4	V4	0.511	0.133	0.213	0.433
HSDV4	101.4	V4	0.511	0.133	0.213	0.367
HLUO0	101.4	-	0.579	0.227	0.145	0.500
HLMO0	101.4	-	0.579	0.227	0.145	0.387
HLDO0	101.4	-	0.579	0.227	0.145	0.273
HLUH4	101.4	H4	0.579	0.227	0.145	0.500
HLMH4	101.4	H4	0.579	0.227	0.145	0.387
HLDH4	101.4	H4	0.579	0.227	0.145	0.273
HLUV4	101.4	V4	0.579	0.227	0.145	0.500
HLMV4	101.4	V4	0.579	0.227	0.145	0.387
HLDV4	101.4	V4	0.579	0.227	0.145	0.273

[+]H4: 4 layers of CFRP strengthened in the horizontal direction
V4: 4 layers of CFRP strengthened in the vertical direction

Table 2 Properties of reinforcement

No.	f_y (MPa)	ε_y [+]	f_u (MPa)	Remark
#4	327 MPa	0.0016	467 MPa	Horizontal reinforcement above the openings
#5	414 MPa	0.0021	579 MPa	Flexural reinforcement of the deep beams

[+] ε_y : yielding strain of reinforcement

Table 3 Properties of concrete

Design strength	Mean strength	Water-cementitious material ratio	Slump	Coarse aggregate	Unit weight
100 MPa	101.4 MPa	0.20	250 mm	13 mm	2491 kg/m^3

Table 4 Properties of CFRP

Tensile strength (MPa)	Thickness (mm)	Modulus of Elasticity (MPa)	Unit weight (g/m^2)	Ultimate strain
3900	0.166	230000	300	0.015

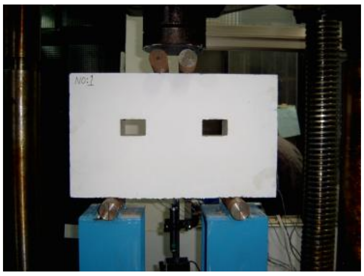


Fig. 2 Testing arrangements for deep beams

strengthened in the horizontal direction (Fig. 1(b)), and V4, for deep beams wrapped with 4 layers of CFRP, strengthened in the vertical direction (Fig. 1(c)).

The yield strength (f_y) and ultimate tensile strength (f_u) of #4 reinforcement are 327 MPa and 467 MPa, while the yield strength and ultimate tensile strength of #5 reinforcement are 414 MPa and 579 MPa (Table 2). The properties of the concrete used in this study are shown in Table 3. The design strength of the concrete is 100 MPa, but the mean strength of the concrete is 101.4 MPa (Table 3). Table 4 shows the tensile strength of CFRP is 3900 MPa, the thickness of each layer of carbon fiber sheet is 0.166 mm and the modulus of elasticity is 230000 MPa.

To avoid premature failure of the CFRP material, caused by shearing at sharp corners, the corners of the specimens were rounded off as smoothly as possible. This study used the procedures proposed by Li *et al*. (2003) for wrapping the CFRP around the concrete cylinder. A thin layer of primer epoxy was first applied to the concrete surface of the test beams. After the primer epoxy on the concrete surface had cured at the ambient temperature for two hours, the carbon fiber sheet was affixed to the concrete surface in the horizontal direction (Fig 1(b)) or vertical direction (Fig 1(c)). For each layer of carbon fiber sheet, two plies of epoxy were applied, one on the concrete surface prior to affixing the sheet, and the other on top of the affixed sheet. A paintbrush was used to fully saturate the carbon fiber with epoxy. The extra epoxy in each layer was squeezed out by compressing the upper surface with a flat plastic scraper (Li *et al*. 2003). After the wrapping procedures were completed, the CFRP were cured in ambient conditions for more than seven days (Li *et al*. 2003).

2.2 Testing procedures

During the test, the strains in the horizontal bars above the openings and flexural bras of the deep beams were measured at locations A, B and C; respectively (Fig. 1), using electrical resistance gauges. For the specimens with CFRP wrapping in the horizontal (Fig. 1(b)) or vertical direction (Fig. 1(c)), the strains in the CFRP were measured at locations D and E using electrical resistance gauges. Prior to testing, both surfaces of the deep beams were whitewashed to aid observation of crack development during the test. The setup for testing the deep beam is shown in Fig. 2. The beams were simply supported and tested in a 1000 kN capacity universal testing machine under two-point loading. The displacement was measured using a linear variable differential transformer (LVDT) mounted on the bottom face at the mid-span of the beam, as seen in Fig. 2. For each load increment, the test data were captured by a data logger and automatically stored.

2.3 Test results

A typical failure for deep beams not strengthened with CFRP is shown in Fig. 3(a); the first cracks appear at the corners of the openings at loads ranging from 20 to 40% of the ultimate loads. As the load increased to greater than 50% of the ultimate loads, a few flexural cracks formed near the mid-span of the deep beams (Fig. 3(a)). Upon further increase in loading, the diagonal cracks appeared above and below the openings. Deep beams do not fail immediately because of the formation of these diagonal cracks. As the applied load increases, more diagonal cracks that were approximately parallel to the original ones developed with simultaneous widening and extension of the existing cracks. After diagonal cracking, the concrete between the upper diagonal cracks can be represented as the upper diagonal compression strut and the concrete between the lower diagonal cracks can be represented as the lower diagonal compression strut. The external shear of the deep beams can thus be transferred by the diagonal compression struts. The ultimate failure mode can be a diagonal compression failure, or a failure initiated by the yielding of the flexural steels. The behavior of deep beams strengthened with CFRP is similar to that of deep beams that are not strengthened with CFRP, except the diagonal cracks do not develop in the area covered by CFRP. Since the CFRP across the diagonal cracks may restrain the propagation and widening of cracks, the amount of cracks in the deep beam horizontally or vertically strengthened with CFRP is fewer than that in deep beams not strengthened with CFRP (Fig. 3).

The observed load-displacement relationships for the 18 specimens are shown in Fig. 4. Basically, the stiffness and ultimate load of deep beams with openings sized 60×40 mm are larger than those of deep beams with openings sized 68×68 mm (Fig. 4). The ultimate load and displacement of deep beams strengthened with CFRP are larger than those of deep beams not strengthened with CFRP (Fig. 4). The observed load versus strain of horizontal steels above the openings for the 18 specimens is shown in Fig. 5. The horizontal steels above the openings of the 16 deep beams had yielded at the ultimate state. However, the horizontal steels above the openings of specimens HSUH4 and HSMH4 had not yielded at the ultimate state (Fig. 5).

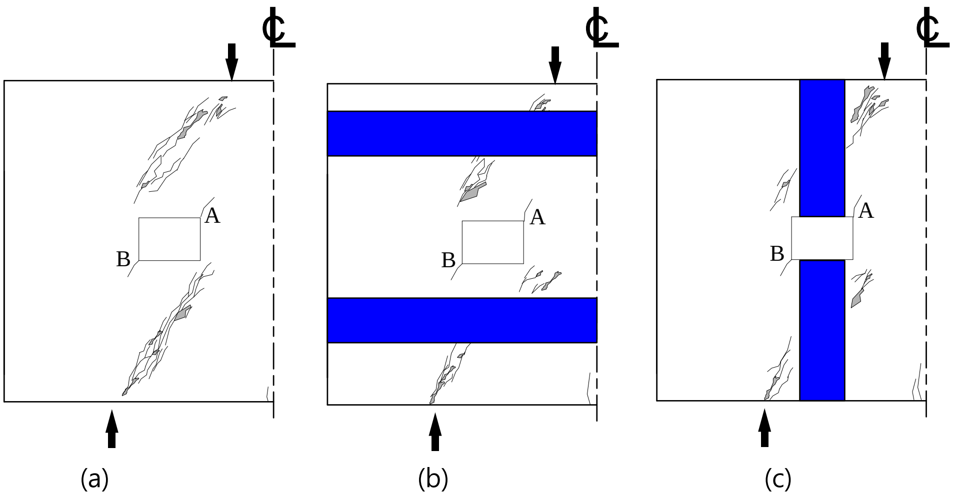


Fig. 3 Typical failure in deep beams tested; (a) Not strengthened (b) Strengthened with CFRP in the horizontal direction (c) Strengthened with CFRP in the vertical direction

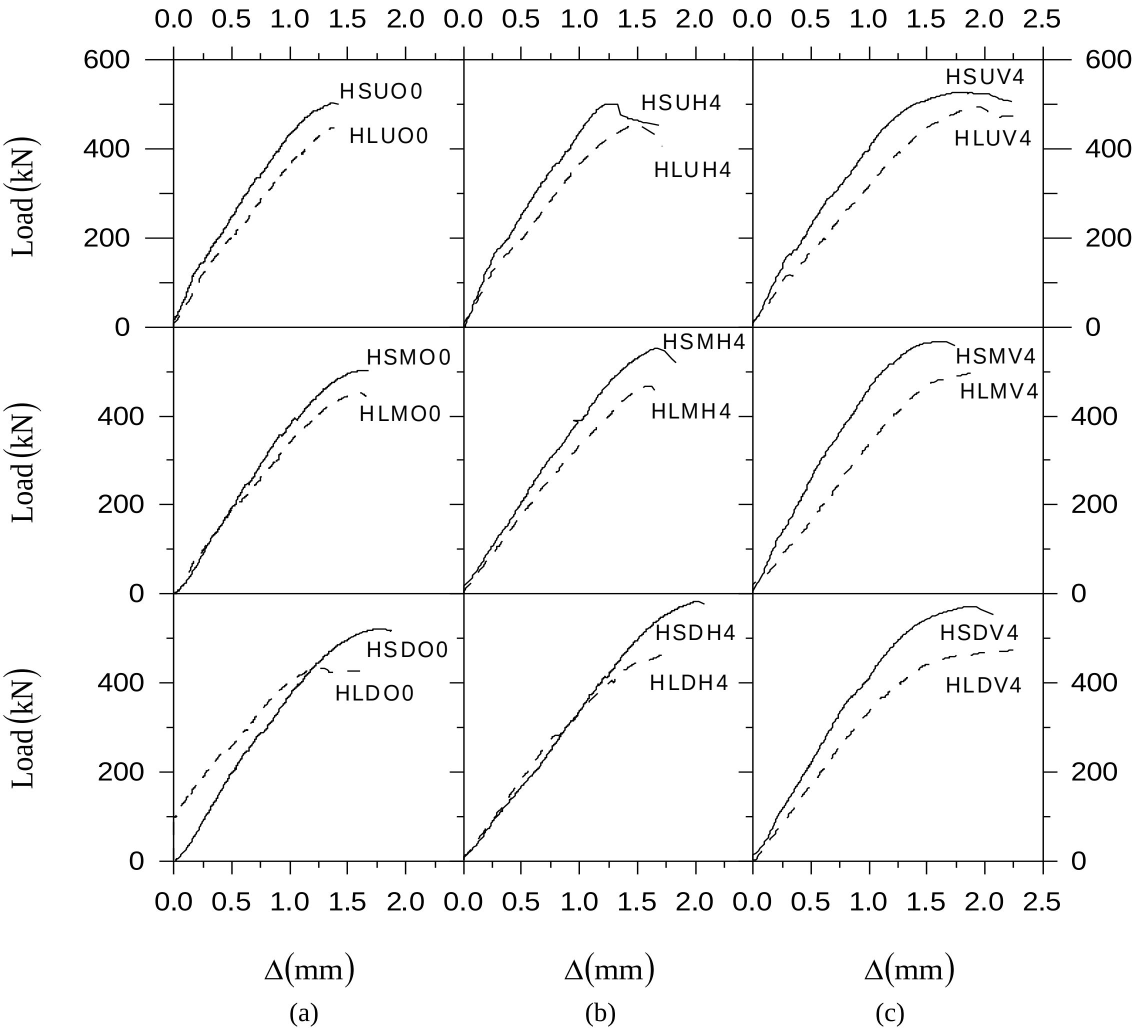


Fig. 4 Load plotted against displacement; (a) Not strengthened (b) Strengthened with CFRP in the horizontal direction (c) Strengthened with CFRP in the vertical direction

The observed load versus strain of the flexural steels for the 18 specimens is shown in Fig. 6. The flexural steels of specimens HLUV4, HSMV4 and HLMV4 had yielded at the ultimate state. However, the flexural steels of the rest specimens had not yielded at the ultimate state (Fig. 6).

The measured shear strengths of the deep beams with web openings, $V_{bv,test}$ for each specimen obtained in the tests, is summarized in Table 5. The major factors influencing the shear strengths of deep beams with web openings are the size of the openings, the location of the openings, and the configuration of CFRP. For deep beams with openings sized 60×40 mm, the lower the locations of openings the higher the shear strengths were (Table 5). For deep beams with openings sized 68×68 mm, the effect of the locations of the openings on the shear strengths of deep beams is not obvious. The failure mode of the deep beams is dominated by shear failure, except for specimens HSMV4, HLUV4 and HLMV4, which failed by flexure (Table 5).

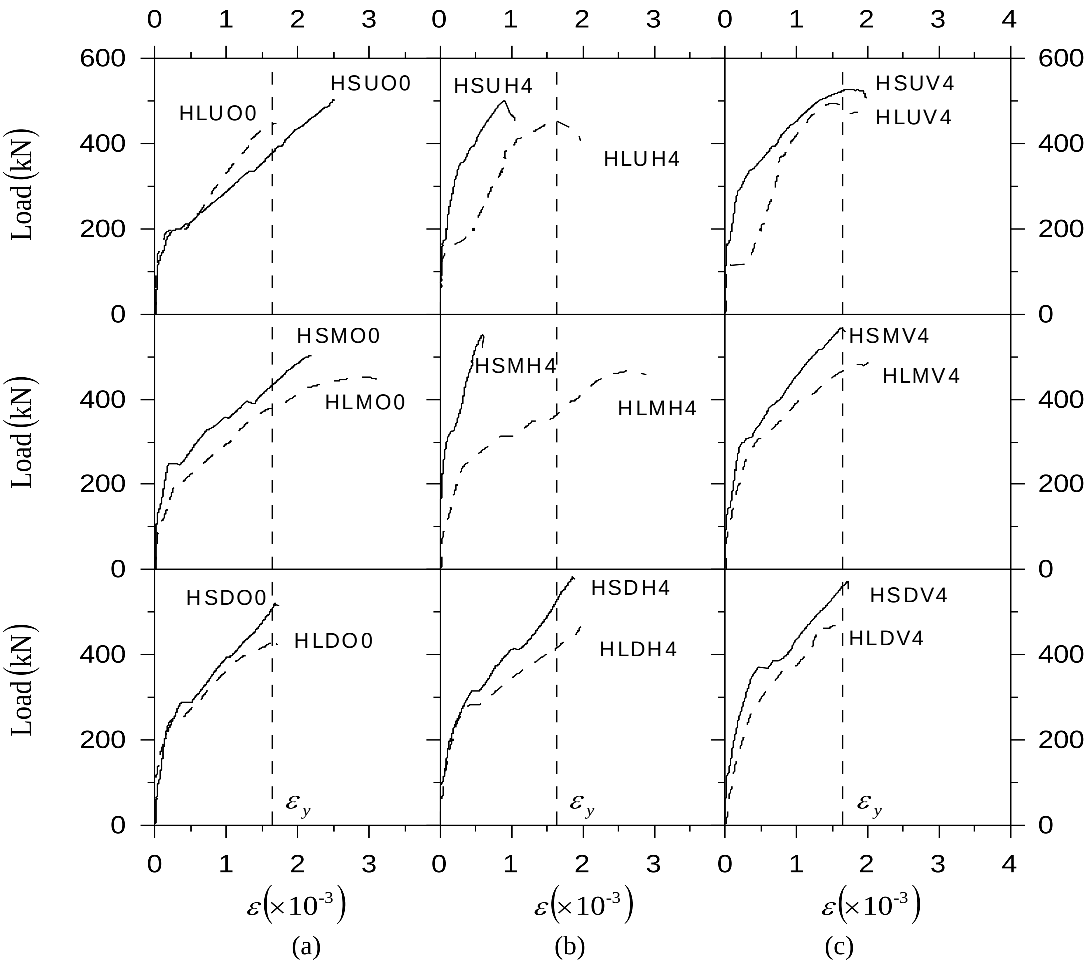


Fig. 5 Load versus strain of horizontal steels above the openings; (a) Not strengthened (b) Strengthened with CFRP in the horizontal direction (c) Strengthened with CFRP in the vertical direction

Table 6 indicates the shear strengths of deep beams with openings sized 60×40 mm were about 16% higher than those with openings sized 68×68 mm. Deep beams in this study are classified into six groups (Table 7). Each group has a controlled beam which is not strengthened with CFRP. The shear strengths of beams in each group are divided by those of the controlled beams. Based on the normalized process, the effect of CFRP on the shear strengths of the deep beams can be further discussed. The shear strengths enhancement of deep beams strengthened with CFRP is shown in Table 8. The shear strengths of deep beams with web openings strengthened by CFRP wrapped in the vertical direction can be enhanced by about 10%. However, the shear strengths of deep beams with web openings strengthened by CFRP wrapped in the horizontal direction can only be enhanced by about 6% (Table 8). This may be due to the readings of ε_{CFRP} of beams strengthened with CFRP in the horizontal direction being smaller than those of beams strengthened with CFRP in the vertical direction.

Table 5 Test results

Specimen	$m_1 a \times m_2 h$ mm	$k_2 h$ [+] mm	Configuration of CFRP[++]	$V_{bv,test}$ (kN)	Failure mode
HSUO0	60×40	150	-	251.4	Shear
HSMO0	60×40	130	-	251.4	Shear
HSDO0	60×40	110	-	260.7	Shear
HSUH4	60×40	150	H4	250.9	Shear
HSMH4	60×40	130	H4	275.4	Shear
HSDH4	60×40	110	H4	291.1	Shear
HSUV4	60×40	150	V4	263.6	Shear
HSMV4	60×40	130	V4	283.2	Flexure
HSDV4	60×40	110	V4	286.2	Shear
HLUO0	68×68	150	-	222.5	Shear
HLMO0	68×68	116	-	225.9	Shear
HLDO0	68×68	82	-	216.1	Shear
HLUH4	68×68	150	H4	226.9	Shear
HLMH4	68×68	116	H4	233.7	Shear
HLDH4	68×68	82	H4	231.8	Shear
HLUV4	68×68	150	V4	247.5	Flexure
HLMV4	68×68	116	V4	248.4	Flexure
HLDV4	68×68	82	V4	236.2	Shear

[+] $k_2 h$: height of openings, measured from the bottom of beam to the bottom of the openings

[++]H4: 4 layers of CFRP strengthened in the horizontal direction

V4: 4 layers of CFRP strengthened in the vertical direction

Table 6 Effect of the openings size on the shear strength of the deep beams

$m_1 a \times m_2 h$ = 60×40 mm		$m_1 a \times m_2 h$ =68×68 mm		$\frac{(V_{bv,test})_{60\times40}}{(V_{bv,test})_{68\times68}}$
Specimen	$V_{bv,test}$ (kN)	Specimen	$V_{bv,test}$ (kN)	
HSUO0	251.4	HLUO0	222.5	1.13
HSMO0	251.4	HLMO0	225.9	1.11
HSDO0	260.7	HLDO0	216.1	1.21
HSUH4	250.9	HLUH4	226.9	1.11
HSMH4	275.4	HLMH4	233.7	1.18
HSDH4	291.1	HLDH4	231.8	1.26
HSUV4	263.6	HLUV4	247.5	1.07
HSMV4	283.2	HLMV4	248.4	1.14
HSDV4	286.2	HLDV4	236.2	1.21
			AVG	**1.16**
			COV	**0.05**

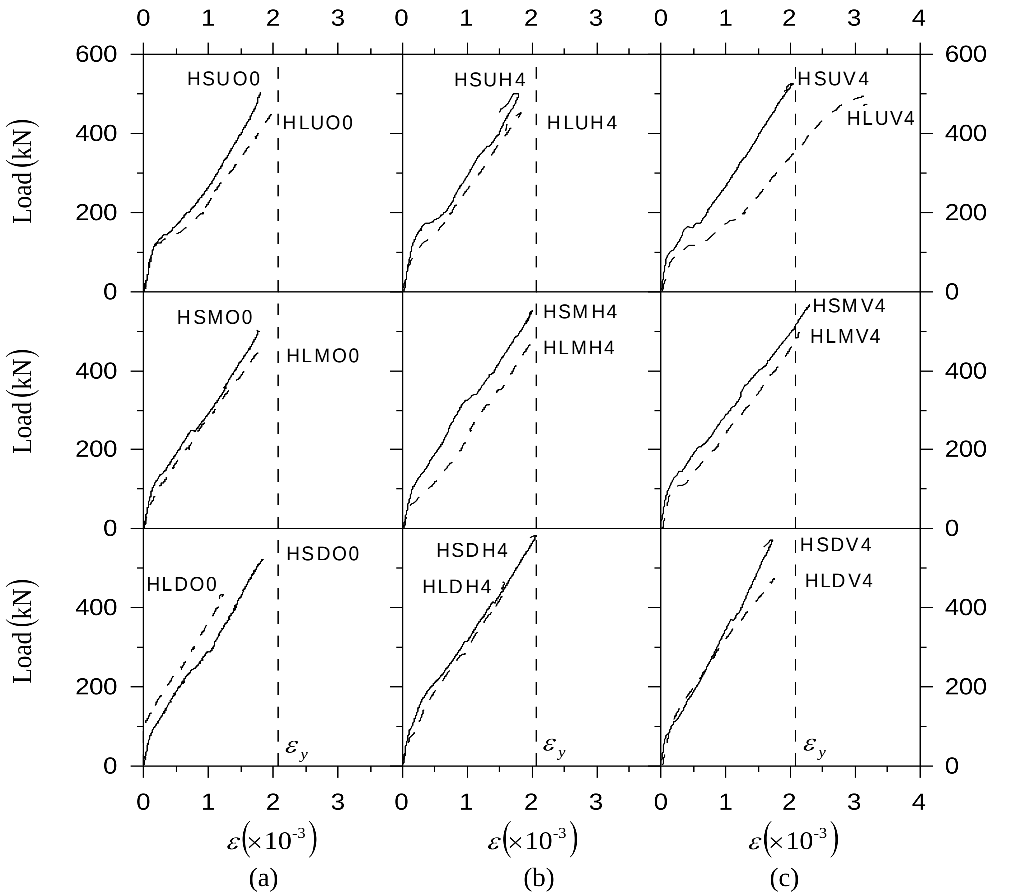


Fig. 6 Load versus strain of flexural steels; (a) Not strengthened (b) Strengthened with CFRP in the horizontal direction (c) Strengthened with CFRP in the vertical direction

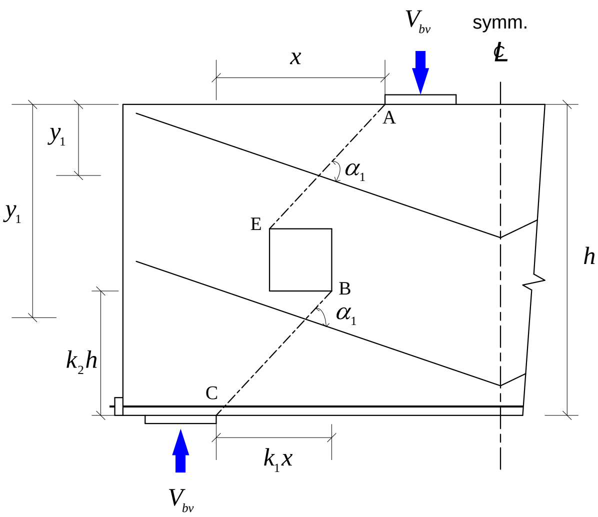


Fig. 7 Meanings on formula of Kong and Sharp (1977)

Table 7 Normalization

Group No.	Specimen	Configuration of CFRP[++]	$V_{bv,test}$ (kN)	Normalization[+++]
1	HSUO0[+]	-	251.4	1.00
	HSUH4	H4	250.9	1.00
	HSUV4	V4	263.6	1.05
2	HSMO0[+]	-	251.4	1.00
	HSMH4	H4	275.4	1.10
	HSMV4	V4	283.2	1.13
3	HSDO0[+]	-	260.7	1.00
	HSDH4	H4	291.1	1.12
	HSDV4	V4	286.2	1.10
4	HLUO0[+]	-	222.5	1.00
	HLUH4	H4	226.9	1.02
	HLUV4	V4	247.5	1.11
5	HLMO0[+]	-	225.9	1.00
	HLMH4	H4	233.7	1.03
	HLMV4	V4	248.4	1.10
6	HLDO0[+]	-	216.1	1.00
	HLDH4	H4	231.8	1.07
	HLDV4	V4	236.2	1.09

[+] Each group has a controlled beam which is not strengthened with CFRP.
[++]H4: 4 layers of CFRP strengthened in the horizontal direction
V4: 4 layers of CFRP strengthened in the vertical direction
[+++] Shear strengths of beams in each group are divided by those of the controlled beams

Table 8 Shear strength enhancement of the deep beams strengthened with CFRP

Specimen	Configuration of CFRP[+]	ε_{CFRP} at D	ε_{CFRP} at E	Shear strength enhancement
HSUH4	H4	0.0005	0.0008	1.00
HSMH4	H4	0.0007	0.0015	1.10
HSDH4	H4	0.0013	0.0014	1.12
HLUH4	H4	0.0015	0.0009	1.02
HLMH4	H4	0.0009	0.0013	1.03
HLDH4	H4	0.0012	0.0015	1.07
Total	AVG	0.0010	0.0012	1.06
	COV	0.36	0.25	0.05
HSUV4	V4	0.0006	0.0028	1.05
HSMV4	V4	0.0014	0.0010	1.13
HSDV4	V4	0.0013	0.0018	1.10
HLUV4	V4	0.0014	0.0018	1.11
HLMV4	V4	0.0012	0.0010	1.10
HLDV4	V4	0.0018	0.0016	1.09
Total	AVG	0.0013	0.0017	1.10
	COV	0.31	0.39	0.02
Total	**AVG**	**0.0011**	**0.0015**	**1.08**
	COV	**0.34**	**0.37**	**0.04**

[+] H4: 4 layers of CFRP strengthened in the horizontal direction
V4: 4 layers of CFRP strengthened in the vertical direction
ε_{CFRP}: the measured strain of CFRP at the ultimate state

3. Comparison with the existing model

The empirical formula of Kong and Sharp (1977) is the most simple existing model in predicting the shear strengths of deep beams with web openings. According to Kong and Sharp (1977), the shear strengths of deep beams with web openings can be calculated as follows

$$V_{bv,calc} = C_1\left(1-\frac{0.35k_1x}{k_2h}\right)f_t b k_2 h + \sum \lambda C_2 A \frac{y_1}{h}\sin^2\alpha_1 \tag{1}$$

where $V_{bv,calc}$ is the predicted shear strength of deep beams with web openings; C_1 is the empirical coefficient, for normal-weight concrete, C_1=1.40, for light-weight concrete, C_1=1.35; k_1 and k_2 are coefficients defining the position of an opening as shown in Fig. 7; x is the clear shear span distance; f_t is the cylinder-splitting tensile strength of concrete; λ is the empirical coefficient, λ = 1.5 for web steels, λ = 1.0 for main steels; C_2 is the empirical coefficient, for deformed bars, C_2=300 MPa, for plain round bars, C_2=130 MPa; A is the area of an individual bar; y_1 is the depth at which a typical bar intersects a potential critical diagonal crack in a deep beam with web openings, idealized as the line EA or CB in Fig. 7; α_1 is the angle of intersection between a typical

Table 9 Comparison with Kong and Sharp (1977)

Specimen	$m_1a\times m_2h$ mm	k_2h +	Configuration of CFRP++	$V_{bv,test}$ (kN)	$V_{bv,calc}$ (kN)	$\frac{V_{bv,test}}{V_{bv,calc}}$
HSUO0	60×40	150 mm	-	251.4	208.3	1.21
HSMO0	60×40	130 mm	-	251.4	198.1	1.27
HSDO0	60×40	110 mm	-	260.7	186.3	1.40
HSUH4	60×40	150 mm	H4	250.9	227.0	1.11
HSMH4	60×40	130 mm	H4	275.4	217.6	1.27
HSDH4	60×40	110 mm	H4	291.1	206.3	1.41
HSUV4	60×40	150 mm	V4	263.6	212.0	1.24
HSMV4	60×40	130 mm	V4	283.2	202.5	1.40
HSDV4	60×40	110 mm	V4	286.2	191.8	1.49
HLUO0	68×68	150 mm	-	222.5	194.6	1.13
HLMO0	68×68	116 mm	-	225.9	175.3	1.27
HLDO0	68×68	82 mm	-	216.1	149.9	1.42
HLUH4	68×68	150 mm	H4	226.9	211.8	1.06
HLMH4	68×68	116 mm	H4	233.7	193.7	1.19
HLDH4	68×68	82 mm	H4	231.8	168.2	1.36
HLUV4	68×68	150 mm	V4	247.5	198.6	1.23
HLMV4	68×68	116 mm	V4	248.4	180.7	1.36
HLDV4	68×68	82 mm	V4	236.2	158.4	1.47
					AVG	**1.29**
					COV	**0.10**

+ k_2h: height of opening, measured from bottom of beam to bottom of opening

++ H4: 4 layers of CFRP strengthened in the horizontal direction
V4: 4 layers of CFRP strengthened in the vertical direction

bar and a potential critical diagonal crack (line EA or CB in Fig. 7). According to the experimental observation in this study, the tension strains of CFRP are about 0.001 at the ultimate state (Table 8). The CFRP across the diagonal cracks may restrain the propagation and widening of cracks, it can thus be regarded as web steels in shear strength calculation of deep beams with web openings. In the case of deep beams strengthened with CFRP, in addition to the area of the horizontal #4 reinforcing bars above the openings, the cross-sectional area (A_{CFRP} = 2×4×0.166 mm×40 mm) of CFRP should be included in the calculation of A when using Equation (1).

The test results for the 18 deep beams with web openings were used to verify the empirical formula of Kong and Sharp (1977). Table 9 compares the measured shear strengths with the predictions using the empirical formula of Kong and Sharp (1977). The accuracy of the empirical formula is gauged, in terms of a strength ratio, which is defined as the ratio of the measured strength to the calculated strength. The comparisons show the shear strengths of deep beam, with different size and location of web openings and strengthened by different configuration of CFRP, can be reasonably predicted by the empirical formulas of Kong and Sharp (1977).

4. Conclusions

A total of 18 high-strength concrete deep beams with web openings were tested in this study. Twelve were externally wrapped with four layers of CFRP, six of them strengthened in the horizontal direction and the others in the vertical direction. Compared with the test results and the predictions using the empirical formula of Kong and Sharp (1977), the following conclusions can be drawn

1. The shear strengths of deep beams with openings sized 60×40 mm were about 16% higher than those with openings sized 68×68 mm.
2. For deep beams with openings sized 60×40 mm, the lower the locations of openings the higher the shear strengths are.
3. The shear strengths of deep beams with web openings strengthened by CFRP wrapped in the vertical direction can be enhanced by about 10%. However, the shear strengths of deep beams with web openings strengthened by CFRP wrapped in the horizontal direction can only be enhanced by about 6%.
4. The shear strengths of deep beam, with different size and location of web openings and strengthened by different configuration of CFRP, can be reasonably predicted by the empirical formulas of Kong and Sharp (1977).

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Notations

A	=	area of an individual bar
A_{CFRP}	=	cross-sectional area of CFRP
b	=	width of the tested deep beams
C_1	=	empirical coefficient, for normal-weight concrete, C_1=1.40, for light-weight concrete, C_1=1.35
C_2	=	empirical coefficient, for deformed bars, C_2=300 MPa, for plain round bars, C_2=130 MPa predicted diagonal compression strength
d	=	effective depth of the tested deep beams
f_c'	=	compressive strength of concrete
f_t	=	cylinder-splitting tensile strength of concrete
f_u	=	ultimate tensile strength of reinforcement
f_y	=	yield strength of reinforcement
h	=	overall depth of the tested deep beams
k_1	=	horizontal position coefficient of opening
k_2	=	vertical position coefficient of opening
k_2h	=	height of opening, measured from bottom of beam to bottom of opening
m_1	=	ratio of opening width to shear span
m_2	=	ratio of opening depth to overall section depth
$V_{bv,calc}$	=	predicted shear strength of deep beams with web openings
$V_{bv,test}$	=	measured shear strengths of the deep beams with web openings
x	=	clear shear span distance
y_1	=	depth at which a typical bar intersects a potential critical diagonal crack in a deep beam with web openings, idealized as the line EA or CB in Fig. 7
α_1	=	angle of intersection between a typical bar and a potential critical diagonal crack (line EA or CB in Fig. 7)
ε	=	strain of reinforcement
ε_{CFRP}	=	measured strain of CFRP at the ultimate state
ε_y	=	yielding strain of reinforcement
Δ	=	displacement of the tested deep beams
λ	=	empirical coefficient, λ =1.5 for web steels, λ =1.0 for main steels

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