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Shear strengthening of reinforced concrete beams with rectangular web openings by FRP Composites

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Abstract. This study presents the experimental results of twenty three reinforced concrete beams with rectangular web openings externally strengthened with Fiber Reinforced Polymers (FRP) composites bonded around openings. All tested beams had the same geometry and reinforcement details. At openings locations, the stirrups intercepted the openings were cut during fabrication of reinforcement cage to simulate the condition of inclusion of an opening in an existing beam. Several design parameters are considered including the opening dimensions and location in the shear zone, the wrapping configurations, and the amount and the type of the FRP composites in the vicinity of the openings. The wrapping configurations of FRP included: sheets, strips, U-shape strips, and U- shape strips with bundles of FRP strands placed at the top and sides of the beam forming a fan under the strips to achieve closed wrapping. The effect of these parameters on the failure modes, the ultimate load, and the beam stiffness were investigated. The shear contribution of FRP on the shear capacity of tested beams with web openings was estimated according to ACI Committee 440-08, Canadian Standards S6-06, and Khalifa *et al.* model and examined against the test results. A modification factor to account for the dimensions of opening chords was applied to the predicted gain in the shear capacity according to ACI 440-08 and CSA S6-06 for bonded Glass Fiber Reinforced Polymers (GFRP) around openings. The analytical results after incorporating the modification factor into the codes guidelines showed good agreement with the test results.

Keywords: GFRP; CFRP; shear strengthening; rectangular web opening; concrete beam

1. Introduction

The inclusion of transverse openings in existing reinforced concrete beams often confronts the structural engineers to pass utility services; especially, when the height of the floor is not sufficient to place the utilities underneath the soffit of the beams. However, the provision of openings in such beams often results in many problems in the beam behavior including reduction in the beam capacity and the beam stiffness, and early cracking around the openings. Thus, the beam's openings need to be externally strengthened. External shear strengthening using Fiber Reinforced Polymer (FRP) has been widely used for reinforced concrete beams (Khalifa *et al*. 1998; Triantafillou and Antonopoulos 2000; Khalifa and Nanni 2002; Micelli *et al.* 2002; Bousselham

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and Chaallal 2006a; Monti and Liotta 2007; Bousselham and Chaallal 2009; Panda *et al*. 2011 ,2012 ,2013; Mofidi and Chaallal 2014), and gained popularity over conventional construction materials because of several reasons including high strength to weight ratio, ease of application, and their non-corrosion characteristics.

The experimental data available in the literature for the study of RC beams with web openings externally strengthened by FRP rather limited. The few studies on the subject investigated the use of Glass Fiber Reinforced Polymer (GFRP) for strengthening T-beams with small circular openings (Abdel Hafez *et al*. 2002), the use of Carbon Fiber Reinforced Polymer (CFRP) for strengthening RC beams with rectangular openings (Abdalla *et al*. 2003; Allam 2005; El Maaddawy and Sherief 2009; Chin *et al* 2012), and the use of CFRP for strengthening deep beams with square openings (El Maaddawy and El-Ariss 2009). Also, the use of externally CFRP rods diagonal to the beam axis along the opening was studied (Pimanmas 2010). It is obvious that the majority of previous research was focus on using the CFRP strengthening material. The lower cost of GFRP in comparison to other types of FRP, CFRP and aramid FRP (AFRP), makes the use of GFRP in strengthening structural elements more attractive. Therefore, the present research focuses on using GFRP as a strengthening material.

This research investigates the shear behavior of full scale rectangular RC beams containing rectangular web openings with different dimensions and locations in the shear zone and externally strengthened with different FRP strengthening system bonded around openings. The parameters in the strengthening system included the wrapping configurations, and the amount and the type of FRP (glass or carbon). The research includes experimental testing and analytical formulation. The experimental part included testing of twenty two RC beams with web openings, in addition to a beam with solid web. In the analytical part, the shear contribution of external bonded FRP in resisting shear force was estimated according to ACI Committee 440-08 (ACI 2008), Canadian Standards S6-06 (CSA 2006), and Khalifa *et al*. model (1998) and compared with the experimental results. These comparisons showed to be satisfactory agreement between the experimental results obtained from strengthening openings by GFRP and the analytical approach on the basis of codes guidelines (ACI 2008 and CSA 2006); the dimensions of the opening chords have to be considered in the shear contribution of GFRP in the beam shear strength. However, a modification factor to account the dimensions of the opening chords was developed and incorporated into the codes guidelines.

2. Experimental test program

2.1 Test specimens

A total of twenty three simply supported reinforced concrete beams were tested in the experimental program of this research. The length of all beam specimens was 2600 mm with a rectangular cross section, 120 mm wide by 300 mm deep. The distance between the supports was 2400 mm and between the two concentrated applied loads was 800 mm. The beams were designed in such a way as to induce shear failure prior to any flexural distress. Reinforcement on the tension side consisted of two 16 mm and two 12 mm diameter deformed bars. Reinforcement on the compression side consisted of two 10 mm diameter deformed bars. Stirrups of 8 mm mild steel were used at 200 mm spacing along the beam length. A clear concrete cover of 15 mm was maintained on all sides. The beam specimens had an effective depth of 263 mm giving a shear

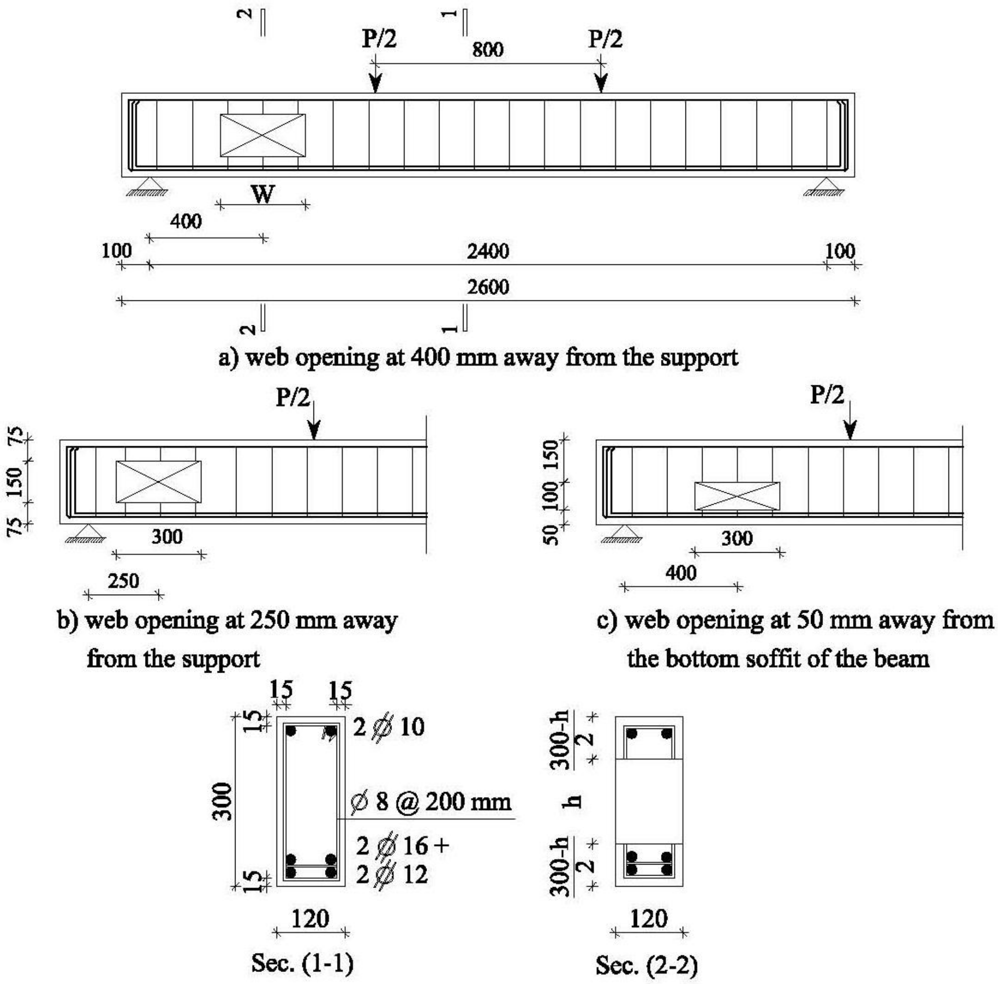


Fig. 1 Longitudinal and cross section details of beam specimens (Note: all dimensions in mm)

span to depth ratio of 3.04. Longitudinal and cross section details of the beam specimens are shown in Fig.1. One opening was created on a side of the test specimens. At opening locations, each opening intercepted one or more of the stirrups. To simulate the condition of inclusion of an opening in an existing beam, these stirrups were cut during fabrication of the reinforcement cage.

The beam specimens are listed in Table 1. The beams consisted of a solid control beam without opening, seven beams with different dimensions and locations of web openings in the shear zone and without strengthening, and fifteen beams were shear strengthened around web openings by externally bonded FRP. The centers of web openings for the un-strengthened beam, as shown in Fig. 1, were placed as follows; five with different dimensions of the opening at the centerline of beam specimen and a distance 400 mm away from the support, one at a distance 250 mm away from the support, and one at a distance 50 mm away from the bottom soffit of the beam. Different strengthening systems were applied to the biggest web opening (150 × 450 mm) and their effects on the structural behavior and the shear gain in the test specimens were evaluated. Other web

Table 1 Test variables and test results

beam specimen	Properties of Openings: Location* (mm)	Width (mm)	Height (mm)	Concrete Strength f_{cu} (Mpa)	Properties of FRP Strengthening: Type	Number of layers	Wrapping Configuration	Ultimate Load (KN)	Mode of Failure
SB	—	—	—	37	—	—	—	185	Flexural Shear Failure
No-10x30-E	0†,400‡	100	300	45	—	—	—	62	Shear at opening
No-15x15-E	0,400	150	150	35	—	—	—	60	Shear at opening
No-15x30-E	0,400	150	300	40	—	—	—	48	Shear at opening
No-15x45-E	0,400	150	450	41	—	—	—	40	Shear at opening
No-20x30-E	0,400	200	300	41	—	—	—	26	Shear at opening
No-10x30-B	50,400	100	300	41	—	—	—	45	Shear at opening
No-15x30-S	0,250	150	300	38	—	—	—	40	Shear at opening
TG1-15x45-E	0,400	150	450	42	Glass	1	Sheets	63	Shear at opening
TG2-15x45-E	0,400	150	450	38	Glass	2	Strips	72	Shear at opening
TG3-15x45-E	0,400	150	450	35	Glass	2	U-Shape Strips**	50	Shear at opening
TG4-15x45-E	0,400	150	450	40	Glass	2	U-Shape Strips ***	60	Shear at opening
TG5-15x45-E	0,400	150	450	37	Glass	3	Strips	80	Shear at opening
TG6-15x45-E	0,400	150	450	36	Glass	4	Strips	82	Shear at opening
TC1-15x45-E	0,400	150	450	44	Carbon	2	Strips	74	Shear at opening
TC2-15x45-E	0,400	150	450	41	Carbon	2	U-Shape Strips**	55	Shear at opening
TC3-15x45-E	0,400	150	450	43	Carbon	2	U-Shape Strips ***	76	Shear at opening
TG-10x30-E	0,400	100	30	42	Glass	2	Strips	140	Shear at opening
TG-15x15-E	0,400	150	150	38	Glass	2	Strips	140	Shear at opening
TG-15x30-E	0,400	150	300	44	Glass	2	Strips	100	Shear at opening
TG-20x30-E	0,400	200	300	44	Glass	2	Strips	57	Shear at opening
TG-10x30-B	50,400	100	300	44	Glass	2	Strips	125	Shear at opening
TG-15x30-S	0,250	150	300	43	Glass	2	Strips	88	Shear at opening

*The location of the center of opening in the vertical direction from centerline of the beam† and in horizontal direction from the support‡
**Wrapped the top chord of the opening
*** U- shape strips with bundles of FRP strands placed at the top and the beam sides

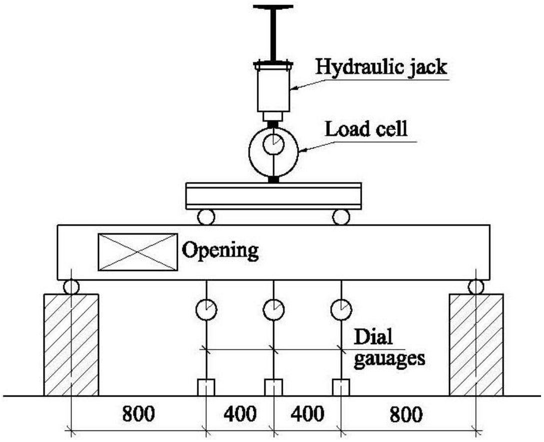


Fig. 2 Schematic view of the test set-up

Table 2 Mechanical properties of FRP composites materials

Mechanical property	Value	
	Glass	Carbon
Weight (g/m^2)	445	230
Fabric Design thickness *(mm)	0.172	0.131
Tensile Strength (Mpa)	2300	4300
Tensile Modulus of Elasticity (Gpa)	76	283
Elongation of break	2.8%	1.8%

* based on fiber content

openings were strengthened by one method and compared with their counterpart un-strengthened openings. The control beam served as a reference to assess the performance of the test specimens with un- strengthened and strengthened web openings.

The control specimen without opening was labeled SB. The designation of the other test specimens can be explained as follows. the first two letters indicate the status of the opening in the tested specimens (NO for un-strengthened opening, TG for strengthened opening by GFRP, TC for strengthened opening by CFRP), the following integer number indicates the FRP strengthening system bonded around the biggest web opening (150 × 450 mm), the numbers in the middle indicates the dimensions of the opening in cm, and the last letter indicates the location of the opening center along the beam specimen (E for opening at the centerline of the beam and a distance 400 mm away from the support, S for opening at the centerline of the beam and a distance 250 mm away from the support, B for opening at a distance 50 mm away from the bottom soffit of the beam and a distance 400 mm away from the support).

2.2 Material properties

The materials used in concrete mixture were ordinary Portland cement (OPC- 42.5 grade), natural sand with 2.65 fineness modulus and crushed dolomite with maximum aggregate size 16 mm. The mix design was carried out for 28-day concrete compressive strength (f_{cu}) = 35 Mpa. The mix design proportional of cement, fine aggregate and coarse aggregate were (1:1.77:3.54). The water cement ratio by weight was 0.45. Three cubes, 150×150×150 mm, were cast at the same time as the specimens and cured alongside the specimens. The concrete compressive strength at the time of testing specimens is shown in Table 1. The longitudinal steel was deformed steel with nominal yield strength of 400 MPa. The stirrups were mild steel with nominal yield strength of 240 MPa.

Unidirectional FRP were used for strengthening the opening region. Table 2 illustrated the mechanical properties of the FRP. The FRP were bonded to the beam specimens with an epoxy resin, Sikdadure 330 (SIKA Egypt 2010). For applying FRP around the web openings in beam specimens, the bonded faces were cleaned until any loose material was removed. Epoxy adhesive was applied to the concrete face in thin layer and pre-cut FRP layer was wrapped over it. The sheet or strips were passed firmly and rolled uniformly by plastic rollers to squeeze out excess epoxy and air bubbles. For applying more layers, epoxy was poured over the last layer and the procedure was repeated.

2.3 Test setup

The load was applied through a hydraulic jack and was transferred to the test beam through a steel spreader beam that was supported on two steel rollers covering the entire width of the beam. The load was measured using load cell under the hydraulic jack of maximum capacity 300 KN. The deflections were measured by three dial gages with displacement up to 150 mm and a least count of 0.01 mm. Two of the dial gages were placed under the two load points and the third one was under the middle of the beam span. Schematic view of the test set-up is shown in Fig. 2. The development and propagation of cracks were marked and the mode of failure was recorded.

2.4 FRP strengthening system

The FRP were bonded to the concrete at all surfaces around the openings such that the principal direction of fibers was oriented to interrupt the potential shear crack. Longitudinal FRP strips with fibers oriented in a direction parallel to the longitudinal axis of the beam were provided above and below each opening. Vertical FRP with different configurations and fibers oriented in a direction perpendicular to the longitudinal axis of the beam were wrapped around the opening chords, and adjacent to each vertical face of the opening. Four wrapping configurations for the vertical FRP, as shown in Fig. 3, were used as follows; sheets, strips covered 50% of the opening chords length, U-shape strips left a clear distance 25 mm at the top of beam to account for the a presence of a concrete slab, and U- shape strips with bundles of FRP strands placed at the top and sides of the beam forming a fan under the strips to achieve closed wrapping. The last two configurations of the vertical FRP were applied to the top opening chords only, while strips wrapped the bottom opening chords. The FRP sheets and strips had an overlap of about 50 mm.

For all strengthened web openings the number of layers for both vertical and horizontal FRP was the same and the width of vertical strips adjacent to the vertical faces of the opening was 75 mm. Different strengthened systems, included the wrapping configurations, the amount of FRP (number of applied layers), and the type of FRP (glass or carbon), were applied to web openings 150 x 450 mm. Other web openings with different dimensions and locations in the shear zone were strengthened by two layers from GFRP strips.

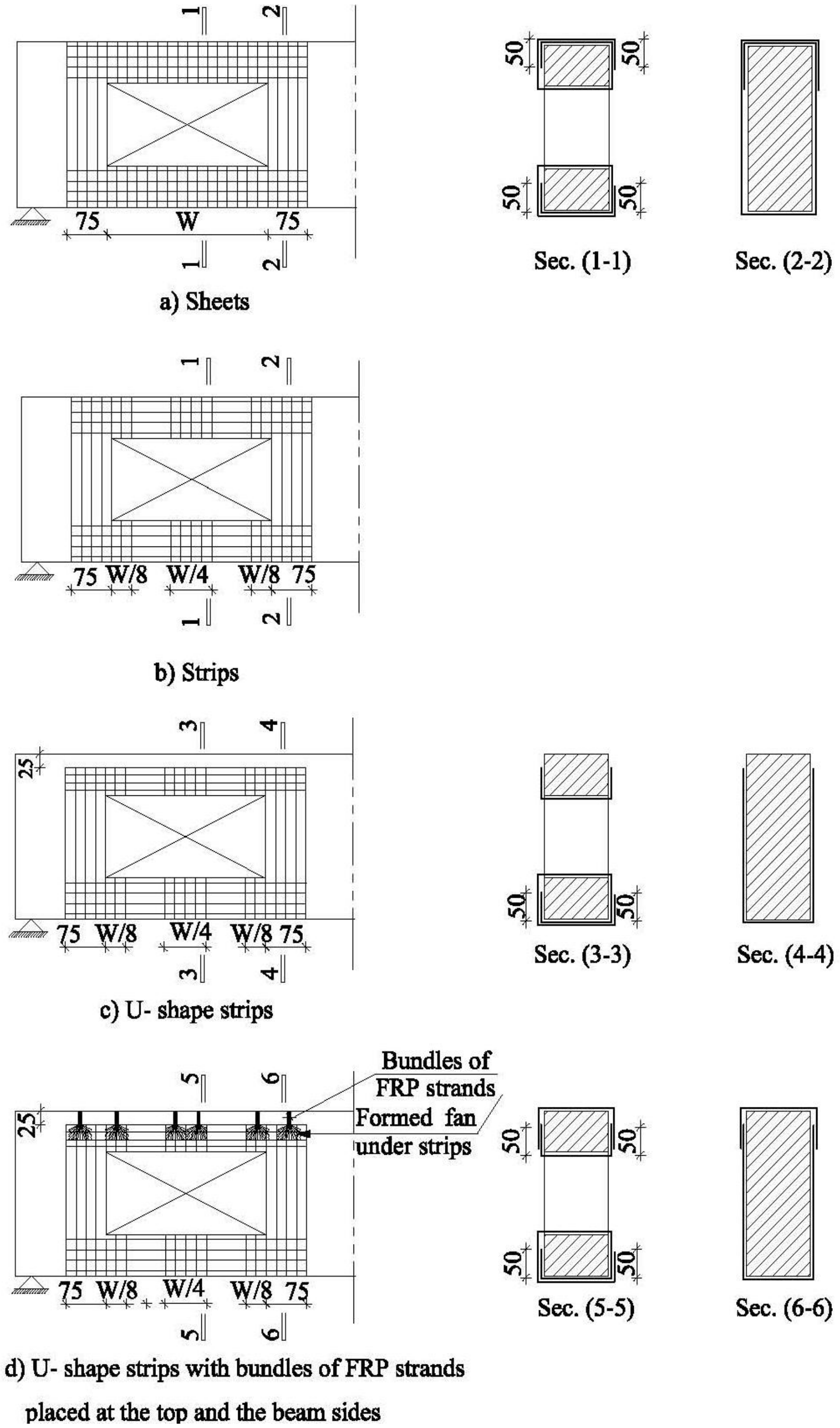


Fig. 3 Description of different FRP wrapping configurations around openings

3. Experimental results and discussions

A brief summary of the test results is given in Table 1. The results of the solid beam are compared with those of beam specimens with un-strengthened and strengthened openings. Analysis and discussion of the results are introduced in the following sections.

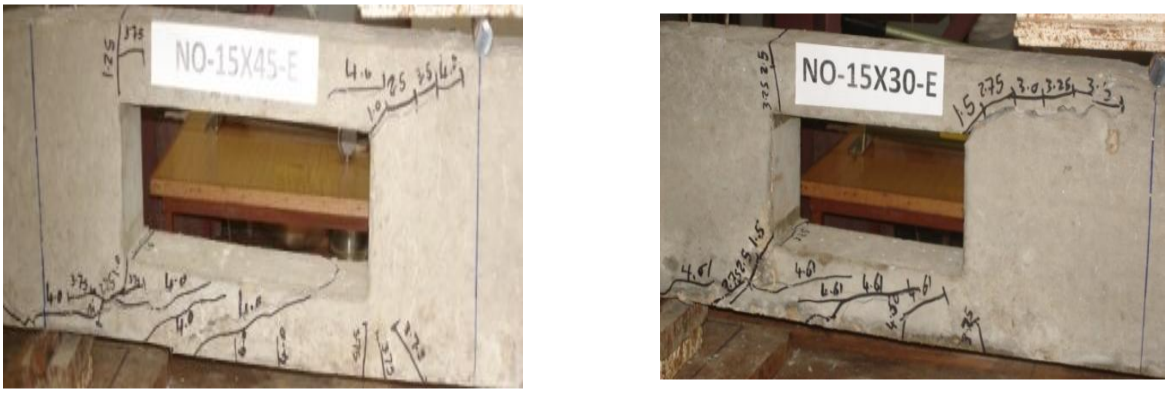
3.1 Failure modes

All beam specimens failed in shear. In the solid beam, crack lines appeared at the tension zone and penetrated vertically up to the neutral axis of the beam. The number of flexural cracks increased and followed by the formation of diagonal cracks. The crack width increased before failure, and the shear failure was sudden and initiated at points of the applied loads to the supports, as shown in Fig. 4.

The shear cracks in the beam specimens with un-strengthened openings, however, appeared much earlier than in the solid beam. The shear cracks initiated at the top corner of the opening near the point load and the bottom corner of the opening near the support followed by the remaining corners of the opening. The beam specimens failed in shear with diagonal cracks initiated from the top corner towards the point load and from the bottom corner towards the support and in the bottom chord of the opening. Fig. 5 shows typical shear failure of beam specimens with un-strengthened openings.

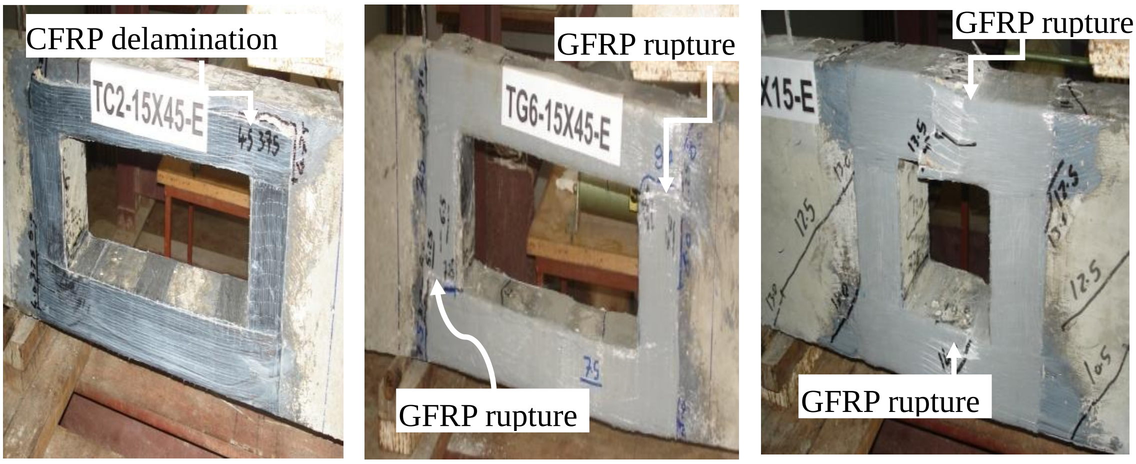
Failure modes of the beam specimens with strengthened opening are shown in Fig. 6. For U-shape strips around the top chord of the openings, in specimens TG3-15X45-E and TC3-15X30-E, the beam failed by peeling the FRP together with concrete cover at the top corner of the opening near the point load. For other strengthened specimens, and with increasing the applied load, diagonal shear cracks formatted between FRP bonded around openings towards the point load and the support. The failure was due to rupture of the FRP.

Fig. 4 Flexural – shear failure of the solid beam



(a) (b)

Fig. 5 Shear failure of beam specimens with un-strengthened openings



(a) (b) (c)

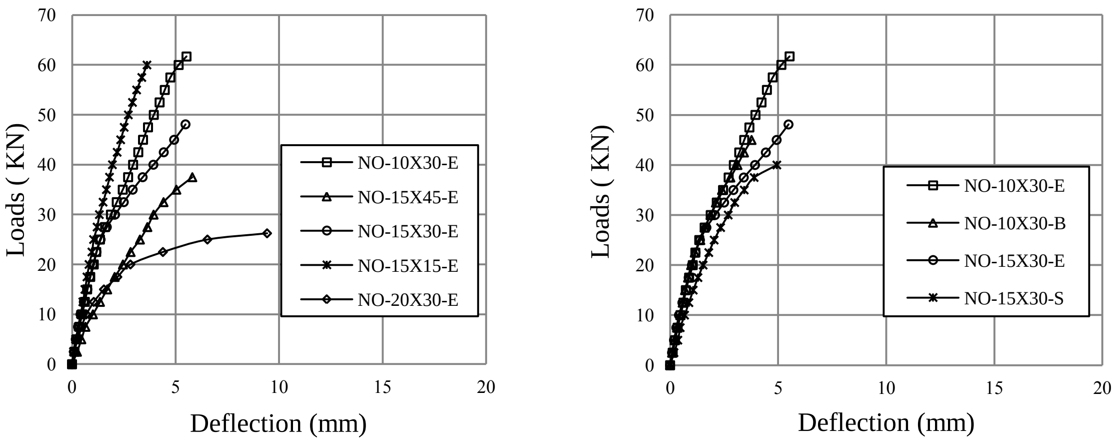
Fig. 6 Shear failure of beam specimens with strengthened openings.

3.2 Load –deflection behavior

Figs. 7-10 show the load versus mid-span deflection of beam specimens according to each variable. The load deflection curve of the solid beam is shown in some figures for comparison purpose.

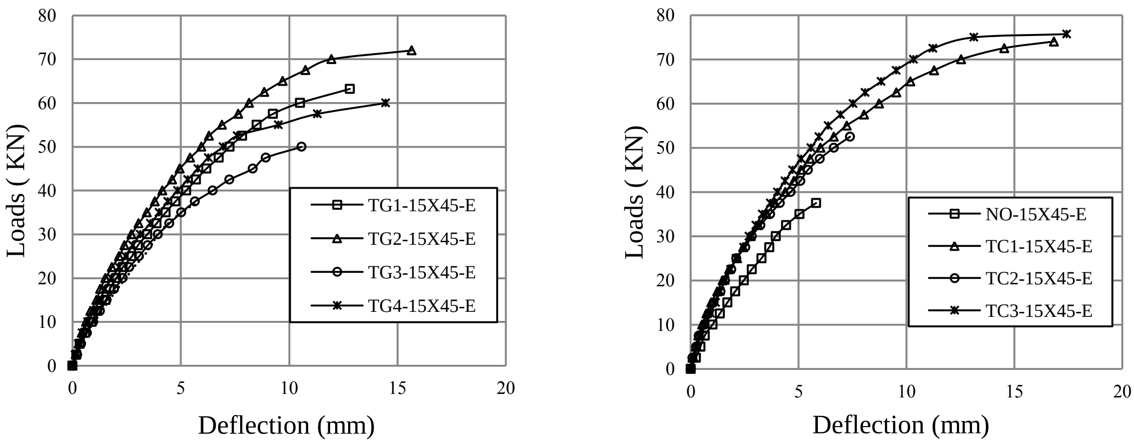
3.2.1 Ultimate load

The results show that having an un-strengthened opening in the shear zone significantly decreases the beam shear strength. For un-strengthened openings with the same width, increasing the opening height to 200 mm (0.67 of the beam height) had the effect of decreasing the ultimate load to 58% of that of the opening height 100 mm (0.33 of the beam height). Increasing the



(a) Openings with different dimensions (b) Openings with different locations

Fig. 7 Load-deflection curves of beam specimens with un-strengthened openings



(a) GFRP (b) CFRP

Fig. 8 Load-deflection curves of beam specimens with different wrapping configurations around openings.

opening width for the same height from 150 mm (0.5 of the beam height) to 450 mm (1.5 of the beam height) a 33% ultimate load reduction was recorded. This is true that the opening height is more affecting than the beam width in the ultimate load capacity of beam with un-strengthened openings. When the web opening 100 × 300 mm shifted near the beam bottom soffit and the height of the bottom chord decreased from 100 mm to 50 mm the ultimate load capacity decreased 27%. While, shifting the web opening 150 × 300 mm along the centerline of the beam towards the support and the distance between the vertical face of the opening and the support decreased from 250 mm to 100 mm had the effect on decreasing the ultimate load 17%. These results indicated that decreasing the bottom chord height of the opening had the effect of decreasing the ultimate load capacity than shifting the opening along the beam length in the shear zone.

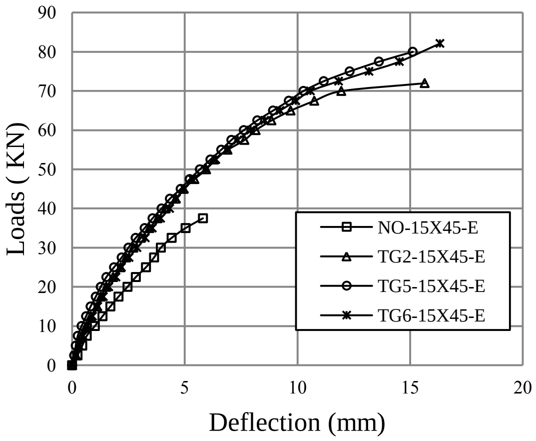


Fig. 9 Load-deflection curves of beam specimens with different amount of GFRP strips around openings

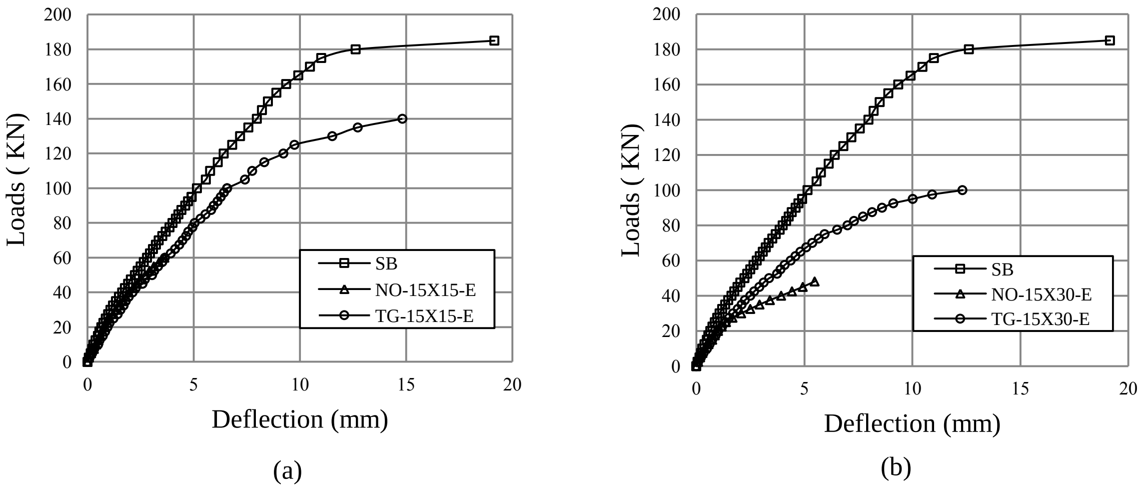


Fig. 10 Comparison between load-deflection curves of beam specimens with un-strengthened openings and their counterparts with strengthened openings

It is evident that FRP shear strengthening around the openings remarkably increased the beam shear strength. Comparing the results of beam specimens having web opening 150 × 450 mm and different wrapping configurations, the ultimate load gain caused by FRP was in the range of 25% - 90%. The lowest load gain was exhibited by beam specimens strengthened by U-shape strips whereas using bundles of FRP strands at the top and the beam sides with the U-shape strips increased the shear strength up to that of specimens with completely wrapped strips. The beam specimen strengthened with two layers of GFRP strips wrapped the half length of the opening chords had higher ultimate load capacity than that strengthened with one layer of GFRP sheet wrapped the entire length of the opening chords. Comparing the results of web openings 150 × 450 mm strengthened with different amount of GFRP strips, it can seen that increasing the number of layers increased the shear strength of beam specimens. However, the shear strength gain was not proportional to the added layers of GFRP strips and increasing the number of layers became insignificant when the number of layers increased more than three layers. Comparing the results of the solid beam with beams having different web openings dimensions and strengthened by two layers of GFRP strips indicated that for small openings size, 150 X150 mm, and small openings height, 100 mm (0.33 of the beam height), the most loss in the ultimate load due to presence of the opening could be retrieved.

3.2.2 Beam stiffness

For un-strengthened specimens, the beam stiffness reduced as the opening size, either the height or the width, was increased. For example, at a 20 KN, the deflection of the specimens was increased about 23% when the opening width was increased from 150 mm to 300 mm with 150 mm opening height. The beam stiffness reduced drastically when the opening width increased from 150 mm to 450 mm with 150 mm opening height and when opening height increased from 100 mm to 200 mm with 300 mm opening width. At a 20 KN, the deflection of beam specimen NO-20X30-E was about 2.7 times the deflection of specimen NO-10X30-E, and the deflection of beam specimen NO-15X45-E was about three times the deflection of specimen NO-15X15-E.

It is seen in Fig. 7(b) that the stiffness of the un-strengthened specimens reduced when the opening shifted near the support and not affected when the opening shifted near the bottom soffit of the beam. For instance, at a 20 KN, the deflection of specimen NO-15X30-S increased about 50% than that of specimen NO-15X30-E.

FRP shear strengthening around the opening resulted in increasing the stiffness of the beam specimens which was remarkable for specimens strengthened by FRP strips and U-shaped strips with bundles of FRP strands at the top and the beam sides. For example, at a 20 KN, the deflection of the strengthened specimens TG2-15X45-E, TG4-15X45-E, TC1-15X45-E and TC3-15X45-E was on average 35% less than that of their counterpart un-strengthened specimen NO-15X45-E. The stiffness of strengthened specimens was not affected by the amount of GFRP strips around the openings, as shown in Fig. 8.

GFRP shear strengthening around the openings resulted in a pronounced improvement in the beam stiffness as the opening size was increased. For instance, at a 20 KN, the deflection of the strengthened specimens TG-10X30-E and TG-20X30-E was on average 10% and 45%, respectively less than that their counterparts specimens NO-10X30-E and NO-20X30-E that had the same opening size but not shear strengthened with GFRP strips.

4. Analytical study

The free-body diagram through the center of opening is shown in Fig. 11. For the applied moment (*M*) and shear (*V*) at the center of opening, the actions in the cord members are the axial forces and the shear forces. The applied moment equals to $N\,Z$ and the applied shear distributes between the openings chords. Kennedy and Abdella (1992) suggested that the applied shear force distributed between the top and bottom chords using the area ratio, inertia ratio, and the root ratio. The shear force carried by the bottom chord, V_b, is given by

$$\frac{V_b}{V} = \frac{\sqrt{A_b I_b}}{\sqrt{A_b I_b} + \sqrt{A_t I_t}} \tag{1}$$

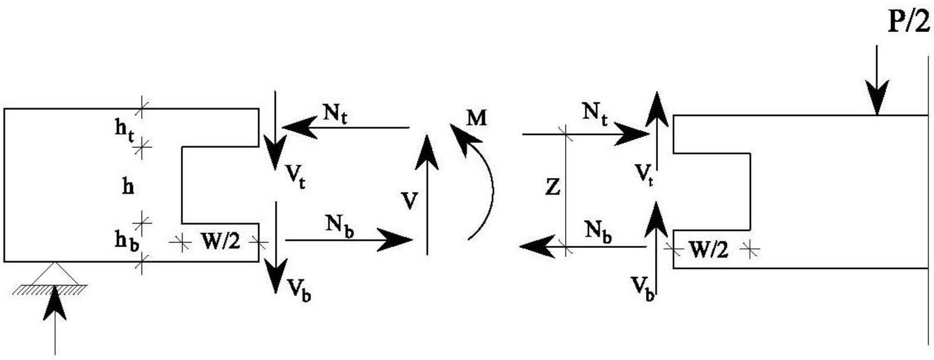


Fig. 11 Free body diagram at opening for beam under bending and shear

Table 3 Predicted shear contribution of FRP from analytical models in the shear strength of test specimens

beam specimen	V_c^* (KN)	Experimental		ACI 440.2R-08		CSA S6-06		Khalifa et.al Model	
		V_t^{**} (KN)	$V_{f,exp}^{***}$ (KN)	$V_{f,\text{ACI}}$ (KN)	$\frac{V_{f,exp}}{V_{f,ACI}}$	$V_{f,CSA}$ (KN)	$\frac{V_{f,exp}}{V_{f,CSA}}$	$V_{f,khal.}$ (KN)	$\frac{V_{f,exp}}{V_{f,khal.}}$
TG1-15×45-E	13.9	31.5	17.6	10.7	1.64	12.5	1.40	18.3	0.96
TG2-15×45-E	13.2	36	22.8	12.3	1.85	14.3	1.59	20.9	1.09
TG3-15×45-E	13.2	25	11.8	6.1	1.92	7.2	1.64	10.4	1.12
TG4-15×45-E	13.6	30	16.4	12.3	1.34	14.3	1.14	20.9	0.78
TG5-15×45-E	13.1	40	26.9	18.4	1.46	21.5	1.25	31.3	0.86
TG6-15×45-E	12.9	41	28.1	24.5	1.15	28.6	0.98	41.8	0.67
TG-10×30-E	19.7	70	50.3	16.3	3.08	19.1	2.63	27.8	1.80
TG-15×15-E	13.2	70	56.8	12.3	4.63	14.3	3.96	20.9	2.71
TG-15×30-E	14.2	50	35.8	12.3	2.92	14.3	2.49	20.9	1.71
TG-20×30-E	9.5	28.5	19.0	8.2	2.32	9.5	1.99	13.9	1.36
TG-10×30-B	18.9	62.5	43.5	16.3	2.66	19.1	2.28	33.6	1.29
TG-15×30-S	14.1	44	29.9	12.3	2.44	14.3	2.09	20.9	1.43
Mean					2.28		1.95		1.32
Standard deviation					0.97		0.83		0.56
TC1-15×45-E	14.2	37	22.8	29.2	0.78	34.1	0.66	35.2	0.67
TC2-15×45-E	13.7	27.5	13.8	15.9	0.86	18.7	0.73	19.2	0.71
TC3-15×45-E	14.07	38	23.93	29.2	0.81	34.1	0.70	35.2	0.68
Mean					0.82		0.69		0.67
Standard deviation					0.05		0.04		0.02

* V_c is the sum of the concrete shear strength of the top and the bottom chords of the opening (Eq. (5), (6)).
** V_t = 0.5 ultimate load.
*** $V_{f,exp} = V_t - V_c$ (The steel shear strength is nglected since it is assumed that there are no closed stirrups in the opening chords).

In which A_b, A_t are the cross- sectional areas of bottom and top chords, respectively; I_b, I_t are the moments of inertia of bottom and top chords, about their centroidal axes, respectively. The shear force carried by the top chord, V_t, is given by

$$V_t = V - V_b \tag{2}$$

The mode of failure of un-strengthened beam specimens with web openings was due to shear at opening chords. For beam specimens with strengthened openings, the applied shear force carried by the top and the bottom chords of the openings. The shear strength of each strengthened chord is computed by adding the contribution of the FRP (V_f) to the contribution of the concrete (V_c), the contribution of lateral reinforcement in resisting shear is neglected since it is assumed that there are no closed stirrups in each chord. Therefore, the shear strength of the bottom and the top chords are given by

$$V_{nb} = V_{cb} + V_{fb} \tag{3}$$

$$V_{nt} = V_{ct} + V_{ft} \tag{4}$$

In which V_{nb}, V_{nt} are the shear strength of the bottom and the top chords, respectively; V_{cb}, V_{ct} are the shear strength provided by concrete in the bottom and the top chords, respectively; V_{fb}, V_{ft} are the shear strength provided by FRP strengthened the bottom and the top chords, respectively. The concrete contribution to the shear resistance in the openings chords can be calculated using ACI 318-05 (ACI 2005), in SI unites, as follows:

$$V_{ct} = \frac{1}{6}\sqrt{f_c'}\, b_w d_t \tag{5}$$

$$V_{cb} = \frac{1}{6}\sqrt{f_c'}\, b_w d_b \tag{6}$$

In which f_c' is the cylindrical concrete compressive strength; b_w is the beam width; d_b, d_t are the effective depth of the bottom and the top chords, respectively, taken as 0.8 the total height of the chord in this research.

The FRP contribution to the shear resistance in the openings chords can be calculated by different analytical models developed by researchers and codes guidelines. Previous research indicated that the contribution of the horizontal FRP strips to the shear strength of the opening chords is negligible (Zhang *et a*l. 2004), and hence only vertical FRP were considered in the analysis. In this study, three analytical models were used to predict the shear strength of FRP strengthened the openings chords: ACI committee 440-08; Canadian Standard S6-06; and model developed by Khalifa *et al*. (1998). The results from analytical models were compared with the experimental results. However, before discussing the results of this comparison, a brief summary of the contribution of FRP to the shear resistance by these analytical models is first reviewed.

4.1 ACI 440.2R-08

An additional reduction factor, ψ_f is applied to the FRP contribution in shear strength, V_f as follows:

$$\psi_f = \begin{cases} 0.95 & \text{for full FRP wrap} \\ 0.85 & \text{for U- wraps or two sides bonded} \end{cases} \tag{7}$$

The shear strength contribution from FRP (V_f), in SI unites, is estimated from:

$$V_f = \frac{A_f E_f \varepsilon_{fe} (sin\alpha + cos\alpha) d_f}{S_f} \tag{8}$$

In which α is the angle between the principal fiber orientation and longitudinal axis of the opening chord, equal to 90° in this research. Eq. (8) then becomes as follows:

$$V_f = \frac{A_f E_f \varepsilon_{fe} d_f}{S_f} \tag{9}$$

In which A_f is the cross –sectional area of FRP, and is given by:

$$A_f = 2nt_f w_f \tag{10}$$

Where d_f is the effective depth of the FRP shear reinforcement, which equal to 0.9 the effective depth of the beam for full FRP wrapped sections and 0.9 the height of FRP on the side of the beam for U- wrapped sections; E_f is elastic modulus of FRP; S_f is center- to- center of FRP strips; t_f is the thickness of FRP; n is the number of FRP layers; w_f is the width of FRP strip, which equal to S_f for continuous FRP; ε_{fe} is the effective strain in FRP and is assumed the smaller than the ultimate strain, ε_{fu} , this can be computed as

$$\varepsilon_{fe} = \begin{cases} 0.004 \le 0.75\ \varepsilon_{fu} & \text{for full FRP wrap} \\ \varepsilon_{fu} \le 0.004 & \text{for U- wraps or two sides bonded} \end{cases} \tag{11}$$

$$K_V = \frac{K_1 K_2 L_e}{11900 \varepsilon_{fu}} \le 0.75 \tag{12}$$

Where L_e is the active bond length, which is the length over which the majority of the bond stress is maintained. This length is given by:

$$L_e = \frac{23300}{\left(nt_f E_f\right)^{0.58}} \tag{13}$$

$$K_1 = \left(\frac{f'_c}{27}\right)^{2/3} \tag{14}$$

$$K_2 = \begin{cases} \dfrac{d_f - L_e}{d_f} & \text{for U- wraps} \\ \dfrac{d_f - 2L_e}{d_f} & \text{for two sides bonded} \end{cases} \tag{15}$$

4.2 CSA S6-06

The provisions of Canadian Standards S6-06 for the FRP contribution to shear strength are similar to those in ACI Committee 440. The FRP contribution, V_f, computed from the following:

$$V_f = \frac{A_f d_f E_f \varepsilon_f e(\cot\theta + \cot\alpha)\sin\alpha}{s_f} \tag{16}$$

Where θ is the angle of inclination of the strut in the truss model, which taken as 42° for top or bottom chord with height not greater than 250 mm according to Canadian Standards A23.3-04 (CSA 2004)(clause 11.3.6.2).

The CSA S6-06 follows the shear design method used in ACI 440 to calculate the effective strain, ε_{fe}, except the factor K_2 related to the FRP configuration which is given by:

$$K_2 = \frac{d_f - L_e}{d_f} \quad \text{for U- wraps or two sides bonded} \tag{17}$$

4.3 Khalifa et al. model

The contribution of externally bonded FRP in shear strength may be computed in ACI code format for the contribution of the steel shear reinforcement.

$$V_f = \frac{A_f f_{fe}(\sin\theta + \cos\alpha)d_f}{S_f} \tag{18}$$

In which f_{fe} is the effective tensile stress of the FRP in the direction of principle fibers, which was replaced with the effective strain times the modulus of elasticity ($\varepsilon_{fe}E_f$) in American and Canadian guidelines. The FRP effective stress calculated as a fraction of the ultimate tensile stress of the FRP (f_{fu}) using a reduction factor (R), which may be assumed as the lowest of the following three values according to the type of failure between the concrete and bonded FRP

$$R = \begin{cases} \dfrac{0.006}{\varepsilon_{fu}} & \text{(failure governed by the ultimate shear crack width in concrete)} \quad \text{(19-A)} \\[2ex] 0.5622\,(\rho_f E_f)^2 - 1.218\,(\rho_f E_f) + 0.778 & \text{(failure governed by FRP rupture)} \quad \text{(19-B)} \\[2ex] \dfrac{0.0042(f_c')^{2/3} w_{fe}}{(t_f E_f)^{0.58}\varepsilon_{fu} d_f} & \text{(failure governed by FRP delamination)} \quad \text{(19-C)} \end{cases}$$

Where Eq. (19-B) valid for $\rho_f E_f \leq 0.7$; E_f in GPa; ρ_f is the FRP reinforcement ratio; and w_{fe} is the effective FRP width which are given by:

$$\rho_f = \frac{2nt_f}{b_w}\frac{w_f}{s_f} \tag{20}$$

$$w_{fe}\begin{cases} d_f - L_e & \text{for U-wraps} \\ d_f - 2L_e & \text{for two sides bonded} \end{cases} \tag{21}$$

For beams full wrapped with FRP, the Eq. (19-C) may be disregarded.

The contribution of FRP in the shear capacities of the beam specimens strengthened around opening were estimated according to these models and presented in Table 3.

4.4 Comparison between experimental and analytical results

Comparing the results in Table 3, it can evident that the considered analytical models provide FRP shear strength lower than those obtained from the experimental program for strengthened openings by GFRP. Otherwise, these models results for strengthened openings by CFRP are higher than the experimental results. For GFRP strengthened openings, it is evident that the gap between the shear force obtained from the analytical models and that from the experimental program increases as the opening size decrease. This can be attributed to the opening chords behave as deep beams when the chord width is small compared with the chord height. Zhang *et al*. (2004) reported for deep beam externally strengthened by FRP that the shear contribution of the vertical FRP either strips or U-shaped strips decreased as the shear span to the effective depth of the deep beam decreased, and suggested applying a reduction factor to reduce the ultimate tensile stress of FRP when calculating the shear strength of strengthened beam. To express the effect of width to height ratio of the opening chords (*w/h*) on the predicted shear force for openings strengthened with GFRP, the ratio of the experimental results ($V_{f,exp}$) to the predicted results by CSA S6-06 ($V_{f,CSA}$) plotted versus the *w/h* ratio, as shown in Fig. 12.

Fig. 12 shows that the $V_{f,CSA}$ is well correlated with modification factor K_o (a dimensionless factor), as shown in the following equation:

$$K_0=7.9(w/h)^{-1} \tag{22}$$

Table 4 Predicted shear contribution of GFRP from codes guidelines including factor K_o in the shear strength of test specimens

beam specimen	$V_{f,,exp}$ (KN)	ACI 440.2R-08		CSA S6-06	
		$V_{f, ACI}$* (KN)	$\frac{V_{f, exp}}{V_{f, ACI}}$	$V_{f, CSA}$* (KN)	$\frac{V_{f, exp}}{V_{f, CSA}}$
TG1-15×45-E	17.6	14.1	1.24	16.5	1.07
TG2-15×45-E	22.8	16.1	1.41	18.8	1.21
TG3-15×45-E	11.8	8.1	1.46	9.4	1.25
TG4-15×45-E	16.4	16.1	1.02	18.8	0.87
TG5-15×45-E	26.9	24.2	1.11	28.3	0.95
TG6-15×45-E	28.1	32.3	0.87	37.7	0.74
TG-10×30-E	50.3	43.0	1.17	50.2	1.00
TG-15×15-E	56.8	48.4	1.17	56.5	1.00
TG-15×30-E	35.8	24.2	1.48	28.3	1.26
TG-20×30-E	19.0	10.8	1.77	12.6	1.51
TG-10×30-B	43.5	43.0	1.01	50.2	0.87
TG-15×30-S	29.9	24.2	1.23	28.3	1.06
Mean			1.24		1.06
Standard deviation			0.25		0.21

*V_f from codes guidelines multiplied by K_o

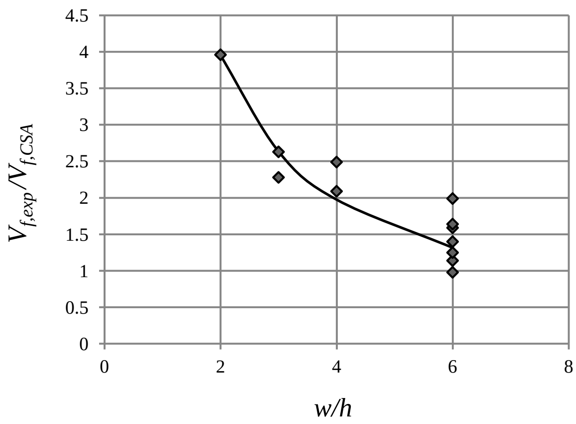


Fig. 12 The ratio (Vf,exp /Vf,CSA) of the strengthened specimens with GFRP around openings versus width to height ratio of the opening chords

It should be mentioned that Fig. 12 shows the *w/h* ratio up to 6. Since the design equations of CSA S6-06 for FRP contribution to shear strength are similar to those in ACI 440-08, the proposed factor K_0 can be incorporated into the shear capacity equations of CSA S6-06 and ACI 440-08 for predicting the ultimate shear force for web openings strengthened with GFRP. The factor K_0 is applicable for the ratio of width to height for the opening chords up to 6. Table 4 shows that incorporating K_0 into the codes guidelines results in enhanced accuracy of the predicted shear force.

5. Conclusions

This research presents the results of an experimental investigation on twenty three simply supported RC rectangular beams involving one solid control beam and the rest beams with shear web openings. Seven beams with un-strengthened web openings were included in the experimental program to study the effect of openings dimensions and location in the shear zone and to compare with their counterpart strengthened beams, and fifteen beams were strengthened in the vicinity of the openings with externally bonded FRP. Different strengthened systems, includes the wrapping configurations and the amount and the type of FRP, were applied to the largest web opening considered in the experimental program. The FRP shear contribution of the strengthened beams calculated from three analytical models were compared with the experimental results. Based on the findings in this research, the following conclusions can be made.

- The presence of an un-strengthened web opening in the shear zone of RC beams causes a significant reduction in the beam capacity. The losses in the beam capacity increases with increase of opening height to opening width. Also, it is found that the losses in the beam capacity due to the location of the opening in the shear zone are affected more with shifting the opening near the bottom soffit of the beam than shifting the opening near the support.
- The stiffness of the beams with un-strengthened web openings significantly decreases with increasing the opening size. Shifting the opening near the support decreases the beam stiffness.

- The failure modes of RC beams with strengthened web openings depend on the wrapping configurations around openings. At failure, the U-shaped strips wrapped the top chord of the openings were detached from the concrete surface near the point load. For sheets, strips, and U-shaped strips with bundles of FRP strands at the top and beam sides, the FRP ruptured at the onset of failure. For all tested beams the shear failure was accompanied by diagonal shear cracks between FRP bonded around the openings and the point load and the support.
- FRP strengthening around the web openings of RC beams remarkably increased the beam strength, and the most beam capacity may retrieve for relatively small openings. The shear strength gain by FRP for opening 150 × 450 mm was in the range 25% -90% according to the wrapping configurations and type of FRP in the vicinity of the openings. The shear strength gain is a minimum using the GFRP U-shaped strips wrapped the top chord of the openings and a maximum using CFRP completely wrapped the opening chords either strips or U shape strips with bundles of FRP strands at the top and the beam sides. Increasing the amount of GFRP strips increases the beam strength but the additional gain in the beam strength was not proportional to the added amount of GFRP strips and increasing the amount of GFRP become insignificant after certain amount of GFRP strips, which are three layers for web opening 150 × 450 mm.
- FRP strengthening around the web openings of RC beams results in a remarkably increase in the stiffness espacially when the size of the opening is relatively big. Completely wrapping of FRP around the opening chords increaeses the beam stiffness more than U-shape strips. The stiffness of the strengthened beams not affected by increasing the amount of GFRP bonded around openings.
- Based on the comparison of the experimental result with different theoretical models discussed in this research to predict the shear capacity of RC beams with openings strengthened in shear, the theoritical models underestimate the shear capacity of GFRP strengthened openings, and on the contrary these models overestimate the shear capacity of CFRP strengthened openings
- A modification factor (K_o) to address the effect of the dimensions of openings chords on the contribution of GFRP to shear resistance of strengthened web openings is defined as a function of chord width to chord height. Incorporating K_o into the predicted gain in the shear capacity equations from ACI 440-08 and CSA S6-06 guidelines results in a significantly improved correlation of the experimental results with the predicted results from the codes guidelines.

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