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GFRP COMPOSITES: A MATERIAL TO STRENGTHEN REINFORCED CONCRETE BEAMS WITH WEB OPENINGS FOR SHEAR

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Abstract

Buildings that require mechanical and electrical services must have utility pipes and ducts. The services include air conditioning, power supply, telephone lines, network cables, sewerage lines, water supply and etc. A reinforced concrete (RC) deep beam with web openings experiences excessive cracking and deflection, as well as a decrease in beam stiffness. Enlargement of these openings near supports would reduce beams' capacity for shear. Hence, analysis and design of such beams require careful consideration, particularly with regard to their performance. In addition, design compliance to relevant codes and standards, and selection of suitable material properties and construction techniques are needed. When such an enlargement is unavoidable, strengthening of beam for shear and flexure is necessary. In this study, the use of GFRP (Glass-Fiber Reinforced Polymer) composites for strengthening of RC beams with openings is experimentally investigated. As compared to the control beam, test results showed that using GFRP was found to be effective in increasing the shear strength of beams with openings by 40% to 60%. Test results of beams with web openings exhibited higher shear strength than the predicted values whereas for strengthened beams with GFRP, code predictions are found conservative.

Keywords: *Deep beams; RC; strengthening; GFRP; web openings*

Introduction

In modern building construction, for the passage ways of mechanical, electrical, networking and plumbing services, the need of considering ducts are important. This avoids the use of extended dropped ceilings and minimized associated costs. For such purposes, openings in the transverse direction are often provided through beams. These openings can be of circular, square or rectangular with different shapes and sizes which significantly affect the structural capacity of reinforced-concrete (RC) structures. One of the reliable materials for the strengthening of such structures is the use of fiber reinforced polymer (FRP) sheets. Strengthening of RC beams using FRP sheets requires better understanding of material properties and accurate modeling of the stress-strain behavior of FRP- concrete is necessary. Related researchers have been carried out to determine the effect of FRP sheets on capacity of strengthened members. Moreover, the structural behavior of FRP-reinforced concrete structures can also be modeled using a variety of numerical tools that have been developed by researchers.

ACI 318-02 defines deep beams for flexure if span to depth ratio is below 1.25 for simply supported beams and the limit is 2.5 for continuous beams. For shear classification, the ratio is less than 4 (in order for compression struts to form between loads and supports, for simply

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supported beams, the beams are loaded on one face and supported on the other face) [1]. However, deep beams are defined by the European standard if the ratio is less than 3 [2].

Practically, there are two major types of openings in structures; pre-planned and post- planned openings. If the depth or diameter of openings in a beam is less than 25% of its overall depth (*h*), openings may be classified to be a small opening [3]. In some cases, 40% is a limit for depth or diameter of an opening to beam depth ratio [4]. The performance of beams with openings depends on shape and size of openings. Such openings shall be located in places where the impact on the strength of the member is small [4]. Openings and their effects on the shear resistance of the member need to be considered in the design. In the case of pre-planned opening, the design is followed based on the strut-tie model and reinforcements equivalent to the zone that the opening interrupts must be provided [5]. Among the most well-known methods for strengthening of reinforced concrete structures, section enlargement and increasing area of reinforcements are some of the conventional options [6]. Externally applied FRP have become increasingly popular in recent years and have proven to be an effective method for renovating and restoring damaged reinforced-concrete structures, including buildings and bridges [7]. Test results showed that use of externally bonded FRP enhanced the shear capacity of deep beams by 24% to 43% [8, 9].

Numerical analysis was used to evaluate the structural behavior of composite beams and steel plate girders with web openings [10]. Composite beams were strengthened with ultra-high-performance fiber-reinforced concrete (UHPC) and CFRP laminates were used to strengthen the steel girders. The findings demonstrated a significant increase in shear capacity [10-12]. The effects of steel strips around web openings in composite beams were also tested, and load-carrying capacity was increased by 40% to 60% [10].

For RC beams with web openings and strengthened by CFRP, a recent study showed an improvement in shear capacity of beams ranging from 30% to 47% [13]. Furthermore, circular web openings with diameters ranging from 50mm to 80mm [14] and square opening sizes ranging from 40mm to 70mm [15] were provided in RC beams. Premature cracking with 20% to 40% capacity reduction was observed for circular and square web openings, respectively [12, 15]. A study was also performed in which the transversal reinforcement ratio was varied, and a 60% reduction in shear capability was reported [15].

Furthermore, an experimental study was conducted on specimens with simply supported beams to examine the shear strength of RC deep beams. The result demonstrates that the placement and quantity of shear reinforcement have an impact on the deep beams' ultimate strength and that the concentrated bars in the shear span's center region are more efficient in strengthening deep beams. Moreover, both the vertical and horizontal shear reinforcement bars can improve deep beams' shear strength. As the shear span-to-depth ratio increases, horizontal reinforcing bars becomes less effective [16]. Under four-point loading, various simply supported beams with and without openings were tested considering the impact of opening size at various locations on failure mode, maximum deflection, and ultimate failure load [16-18]. It is also investigated that performance of deep beams with openings depends on shape, size and location of openings [4]. Test results showed that the ultimate capacity of RC beams with web openings was reduced significantly at the shear zone and the reduction in capacity was minimum at the flexure zone. The ultimate load capacity reduction due to the presence of rectangular openings is higher than square openings by 4.1%, while in the case of circular openings, the capacity was reduced by 8% [17]. Research has been done on RC beams with web openings that are strengthened by CFRP sheets [19] and FRP rods which are externally installed [20]. The results showed that the capacity of beams was found to be more effective for inclined FRP rods than vertical ones, if the FRP rods were extended to a minimum length of 67% of the beams' depth [20] whereas use of CFRP sheets increased the capacity by 10% to 40% [19]. Moreover, the use of FRP sheets around web openings significantly improves the ultimate displacement by 66-77% [21]. Steel plates with thicknesses ranging from 4mm to 8mm, as well as studs arround the openings, were used to increase the shear capacity of beams by up to 10% [22, 23].

Replacement of coarse aggregate by polystyrene balls were used to study the shear behaviour of RC beams with web openings. The use of polystrene foam balls reduces the weight of the beam by 30% while the beams behave similarly to the control beam if the depth of the openings varies from 20% to 40% of the effective depth of the beam [24].

RC deep beams with web openings made of 100% recycled concrete aggregates and steel fibres with volume fraction of 1.2 to 3% were evaluated, and the beams exhibited an increase in shear capacity by 39-84% [25]. Internal reinforcing bars were also found to be useful in resisting ultimate load carrying capacity in RC beams with pre-planned web openings [26, 27]. Numerical simulation was used to strengthen RC beams with openings using pretressed iron-based shape memory alloy (Fe-SMA) bars. When compared to a solid beam, installation of Fe-SMA bars improved load-carrying capacity by up to 12% for small openings [28]. Furthermore, external horizontal prestressed strands on the top and bottom parts of the openings were employed, which increased the shear capacity of beams with large web openings by 32-53% [29].

Several recent studies have found that strengthening of deep beams with web openings using various methods (GFRP, CFRP, FRP rods, FRP composites, PC strands and etc) improves beams'shear capacity [13, 19, 20, 23, 29-34], however, the use of GFRP with two layers (mat and weaved fiber glasses) and comparison of experimental results with code provisions were limitted. Furthermore, in most studies, web openings were provided near one side of the beam support [19, 35, 36] and strengthening were made near the openings [13, 19, 21, 23, 28, 30, 35, 36].

Hence, in this research, the efficiency of GFRP composites to strengthen RC beams with openings for shear was experimentally investigated. In the test, a full-depth GFRP sheet was wrapped throughout the entire length of the beam. From the experimental result, remarkable amount of strength gain was observed and it is suggested to use GFRP sheets to strengthen the shear capacity of beams with web openings.

Estimation of Shear Capacity of Beam with Web Openings

Different researchers have developed basic empirical equations to estimate shear capacity of beams with web openings. Based on Mansur (1998), shear capacity of RC beams with small openings can be estimated using Eq. (1). In this case, the ACI simplified method is modified using the concrete net depth. If diagonal bars around the openings have been provided, the shear strength provided by shear reinforcement at an opening is enhanced [4].

$$V_n = V_c + V_s = \frac{1}{6}\sqrt{f_c'}\,b_w(d - d_o) + \frac{A_v f_{yv}}{s}(d_v - d_o) \tag{1}$$

where:

V_n : nominal shear strength

V_c : nominal shear strength provided by concrete with flexural bars

V_s : nominal shear strength provided by stirrups

b_w : web width

d : effective depth

d_o : diameter of the opening

d_v : distance between the top and bottom longitudinal rebar

A_v : area of stirrups per spacing. s

f_{yv} : yield strength of stirrups

In the Architectural Institute of Japan (AIJ), a formula to evaluate the shear capacity, V_n, of beams with opening was proposed by Hirosawa and the empirical equation as obtained from [37] is given in Eq. (2). In the equation, to account for the size effects in shear, the term k_u has a value ranges from 0.72 to 1.0 and is a function of the effective depth d [37].

$$V_s = \left[\frac{0.092k_u k_p(f'_c + 17.7)}{k + 0.12}\left(1 - \frac{1.61d_o}{h}\right) + 0.846\sqrt{\rho_w f_{yv}}\right] b_w d_v \quad (2)$$

$$k = M/Vd \leq 3$$
$$k_p = 0.82(100A_s/b_w \mathrm{d})^{0.23} \text{ and} \quad (3)$$
$$\rho_w = A_v(sin\alpha + cos\alpha)/b_w d_v$$

where:
h : overall depth of the beam
d_o : diameter of the circular opening or in the case of square openings, it is the diameter of the circumscribed circle $\leq h/3$
M : bending moment at the center of the opening
V : shear force at the center of the opening
ρ_w : web reinforcement ratio placed within a distance $d_v/2$ from the center of the opening
A_s : area of tension reinforcement
α : angle of inclination of web reinforcement

For $\rho_w < 0.012$, Eq. (4) is used to compute the nominal shear strength provided by the concrete [38] and the corresponding shear strength of reinforced concrete beams with web openings is computed using the modified Mansur model considering the concrete net depth [4] and nominal shear strength provided by steel stirrups.

$$V_c = (0.07 + 8.3\rho_w)\sqrt{f'_c}\, b_w d \quad (4)$$

GFRP Composite Material Properties

When two or more distinct fundamental materials are combined, one or more of the materials serve as reinforcements and the other material acts as the matrix to create composite materials [7]. Fiber glass is a type of fiber-reinforced polymer, consisting of fine glass fibers embedded in a plastic matrix. Fiber-reinforced polymers (FRP) composite resembles reinforced concrete in that it uses a polymer (polymer resin matrix, like epoxy or polyester) as the concrete and a fiber (like glass, carbon, etc.) as the reinforcement [39].

GFRP Strengthening of Reinforced Concrete Members

A study through experiments on the behavior of high-performance deep beams that have web openings and how to strengthen them using glass fiber around the openings was conducted [31, 40]. If an opening in an RC deep beam is planned or designed, there is no need for strengthening the member. In such cases, the sizes and location of the opening need to be specified clearly and sufficient detailing for the reinforcement should be provided. However, for post-planned opening, strengthening of RC deep beam is required [41-43].

Fiber contribution to shear strength

The shear capacity of fiber strengthened member is estimated by considering the contribution of GFRP to shear strength of un-strengthened beams. The fiber contribution equations to shear strength according to different codes and researches are given in Eqs. (5), (6) and (7).

i) ACI-400.2R-08 [44]

$$\psi_f V_f = \psi_f \frac{A_{fv} f_{fe}(\sin\alpha + \cos\alpha) d_{fv}}{S_f} \quad (5)$$

where:
V_f : fiber contribution to shear strength
ψ_f : reduction factor (=0.95for completed U-wrapped and 0.85 for two sides bonded)
α : angle between the longitudinal axis of the opening and principal fiber orientation
A_{fv} : cross –sectional area of FRP (=$2nt_fw_f$)
d_{fv} : effective depth of the fiber (=$0.9d_v$)
E_f : elastic modulus of FRP
S_f : center- to- center spacing of FRP strips (= w_f , for continuous FRP)
t_f : thickness of FRP
n : number of FRP layers
w_f : width of FRP strip (for continuous FRP, $w_f= S_f$)
f_{fe} : effective tensile stress in the FRP (=$\varepsilon_{fe}\times E_f$)
ε_{fe} : effective strain in FRP (=0.004for two sides bonded $\leq 0.75\ \varepsilon_{fu}$)
ε_{fu} : ultimate strain

*ii) Canadian Code, CSA S*6-06 [45]

$$V_f = \frac{A_{fv}E_f\varepsilon_{fe}\left(\cot\theta + \cos\alpha\right)\sin\alpha\, d_{fv}}{S_f} \tag{6}$$

In the truss model, θ represents the strut's angle of inclination, and it is considered as 42° for top or bottom chord when the maximum height is 250 mm [32, 5].

iii) Khalifa et al. model [33]

$$V_f = \frac{A_{fv}f_{fe}(\sin\theta + \cos\alpha)d_{fv}}{S_f} \tag{7}$$

The effective tensile stress ratio of FRP for modes of failures governed by rupture and de-lamination are given in Eqs. (8a) and (8b), respectively.

$$R = 0.5622\left(\rho_f E_f\right)^2 - 1.218\left(\rho_f E_f\right) + 0.778 \tag{8a}$$

$$R = \frac{0.0042(f_c')^{2/3}w_{fe}}{\left(t_f E_f\right)^{0.58}\varepsilon_{fu}d_{fv}} \tag{8b}$$

where:
f'_c : cylindrical compressive strength of concrete
ρ_f : FRP reinforcement ratio (=$2nt_fw_f / b_w s_f$) and $\rho_f E_f \leq 0.7$
R : effective tensile stress ratio of FRP ≤ 0.5 ($f_{fe} = R\times f_{fu}$)
w_{fe} : effective FRP width (=d_{fv}-L_e for U-wraps and = d_{fv}-$2L_e$for two sides bonded)
f_{fu} : ultimate tensile stress of the FRP
L_e : active bond length =$23300/(nt_fE_f)^{0.58}$

Generally, the shear strength of FRP strengthened beam is computed using Eq. (9) [33, 44].

$$V_n = V_c + V_s + V_f \tag{9}$$

Materials and Methods

Materials

Cement

Pozzolanic Portland Cement (PPC) with a specific gravity of 3.15 was used.

Aggregates

The coarse aggregate used in this research was natural gravel with a nominal aggregate size of 25 mm. A natural siliceous sand which was clean, free from impurities and silt was used as fine aggregate. Properties of fine and coarse aggregates were tested and fulfils the requirements set on ACI-E1-99 [46] and it is shown in Table 1 [47].

Table 1. Aggregate properties

Properties	Fine aggregate	Coarse aggregate
Unit weight (kg/m^3)	1,332.20	1,425.20
Silt content (%)	1.33	-
Moisture content (%)	1.62	1.52
Specific gravity	2.34	2.51
Absorption capacity (%)	1.82	1.54
Fineness	2.70	-

Reinforcement bar

Deformed bars of diameters 8, 10 and 12 mm have been used. In Table 2, the corresponding yield and ultimate tensile strength of reinforcement bars are listed [47].

Table 2. Experimental result of reinforcing bars

Diameter (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)
8	558.68	662.65
10	536.41	630.98
12	564.98	641.79

Glass fiber

Two types of glass fibers; mat and weaved fiber glass have been used. The materials are produced by VITRULAN company and their properties are shown in Table 3 [34, 48]. In Fig. 1, samples of the two types of glass fibers used in this study are shown. Moreover, adhesive material such as gel-coat, general purpose resin and Butanox M-50 (as a catalyst) have been used [47].

Table 3. Properties of glass fiber

Typical properties	Mat	Weaved/ Fabric
Density (g/cm^3)	2.60	2.50
Young's modules (GPa)	30	40
Ultimate tensile strength (GPa)	0.60	0.90
Tensile elongation (%)	2.40	2.90

Methods

Mix design

The mix proportion of concrete used in this study is as per ACI mix design procedure and it is shown in Table 4 [49]. The 28th days cubic compressive strength of the concrete is found to be 37.6 MPa.

Table 4. Concrete mix design

Materials	Cement	Fine aggregate	Coarse aggregate	Water
Qty (kg/m^3)	387.55	734.04	942.82	180.66

a)

b)

Fig. 1. Samples of GFRP a) mat fiber glass b) weaved fiber glass

Test specimens

In this study, nine reinforced concrete beams with 500 ×100 mm (h × b) and overall length of 1200 mm were prepared using 2 ϕ12 and 2 ϕ10 deformed bars on the bottom and top surfaces, respectively. Diameter 8 mm deformed bars with a spacing of 90 mm were provided as shear stirrups. The effective span of the beam is 1000 mm and the openings are spaced at 700 mm apart. In all specimens, a 15 mm concrete cover was provided [47]. The web openings of the test beams are classified as small openings since the definition of Somes and Corley has been satisfied [3]. Detailing of beams were provided as per the recommendation of ACI Committee 318 [1]. For positive bending moment, flexural reinforcements are uniformly positioned over a vertical distance of 0.25h-0.05L using bars of comparatively small in size.

Circular web openings of 110 mm and 160 mm in diameter and square web openings of sizes 110 mm and 160 mm were provided. The openings were arranged symmetrically and placed at the middle of half of the deep beam. Even if the openings are pre-planned, no special reinforcement detailing provisions were done around the holes. A single layer of woven and mat fiber glass with a total thickness of 3 mm was used. Table 5 below shows designation of test specimens.

Table 5. Beam designation

No.	Designation	Beam specimens
1	CB	Control Beam without web opening
2	B1	Beam with circular openings of diam.110 mm
3	B2	Beam with circular openings of diam.160 mm
4	B3	Beam with square openings of size 110 mm
5	B4	Beam with square openings of size 160 mm
6	C1	Beam with circular openings of diam. 110 mm and laminated with GFRP
7	C2	Beam with circular openings of diam. 160 mm and laminated with GFRP
8	C3	Beam with square openings of size110 mm and laminated with GFRP
9	C4	Beam with square openings of size160 mm and laminated with GFRP

Surface preparation

In order to guarantee a strong bond between the gel-coat and the concrete surface, the concrete's surface was thoroughly cleaned and chiseled. For external strengthening of beams with web openings, GFRP sheets are attached to the concrete surface using an epoxy-based adhesive (Sika 161) and the manufacturer's recommendations for mixing are followed [50]. Following the gel-coat application, Butanox M-50 was added to the epoxy resin (this is done to extend the curing time as per the manufacturer's instructions) [50]. The mixed gel was applied on the concrete surface. Finally, the fabrics are layered atop the resin coating and compressed using a roller to remove air bubbles and achieve a consistent GFRP thickness. Fig. 2 shows strengthened beam specimens with GFRP.

Fig. 2. Strengthened beams with GFRP

Experimental Setup

Before the testing began, all instrumentation and devices were calibrated and prepared. Every beam specimen was installed with a single point loading arrangement and was simply supported. A single point load was applied at the mid span and deflection is measured using linear variable displacement transducer (LVDT). The experimental set-up of beam specimen with web openings is shown in Fig. 3.

Fig. 3. Experimental setup

Results and Discussion

Beam without Web Opening (Control Beam)

In this section, a detailed discussion of the behaviors observed during the experiments is given. Finally, comparison between the different types of web openings and strengthening methods are put and are briefly discussed. For the control beam specimen, at the load of 120kN, the first crack was appeared and it failed in shear at a load of 329.13kN. Diagonal shear mode of failure was the primary characteristic of control beam's failure, as shown in Fig. 4, where the cracks propagated to the loading point corresponding to the increment of the load.

Beam with Web Openings

The load-deflection diagram of the control beam and un-strengthened beams with web openings shown in Fig. 5 showed that circular web openings have good performance as compared to that of square openings of the same dimension. This result is in good agreement with research conducted by Nishitha and Kavitha [41].

Samples of shear failure of un-strengthened beams with circular and square openings are shown in Fig. 6. Cracks have been seen at the corners of the openings in addition to diagonal cracks that have been developed along the upper and lower chords. The test results showed that, as shown in Fig. 5, as the diameter/ depth of the openings of un-strengthened beams is increased by 54.4%, the load carrying capacities of beams were reduced by 27.2% and 39.1% for circular and square openings, respectively.

Fig. 4. Cracking pattern of control beam

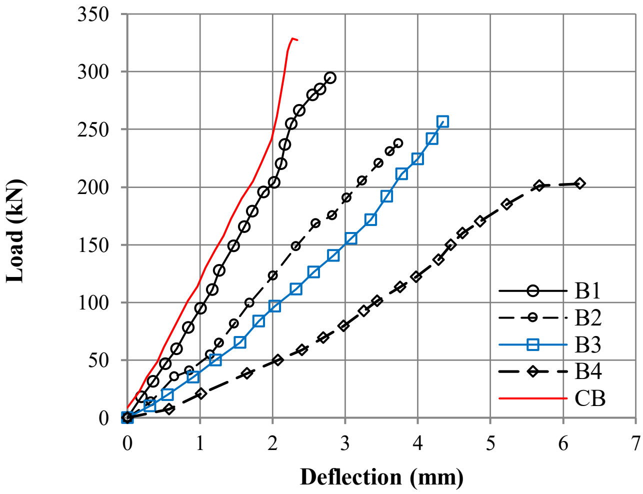

Fig. 5. Load-deflection diagram of beams with openings

(a) (b)

Fig. 6. Crack propagation of beams with a) circular openings b) square openings

GFRP Strengthened Beams

Load carrying capacity of beams with circular and square openings are measured after the beams have been strengthened with externally bonded GFRP systems and the load deflection diagrams are shown in Fig. 7. In the figure, it is observed that for square and circular openings, the strength increased by applying GFRP sheets ranged from 2% to 10% (C3 and C4) and from 4.3% to 30.1% (C1 and C2), respectively. The result of this study is in line with related studies, which showed increments in beam capacity ranging from 8.1 to 45.6% [51] and from 12% to 38% [52].

As discussed earlier, it is obvious that circular web openings are performed well as compared to that of square openings of same dimension. Fig. 8 shows de-lamination and rupture of GFRP sheet of beam specimens C3 and C4. In addition, tiny cracks on the inside of the openings were noticed.

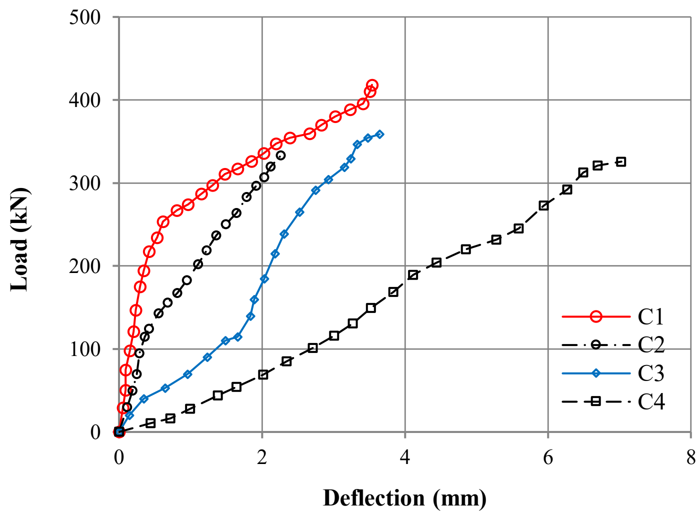

Fig. 7. Load-deflection diagram of GFRP strengthened beam specimens

(a)

(b)

Fig. 8. De-lamination and rupture of beams with square openings a) 100mm and b) 160mm

Comparison of Strengthened and Un-strengthened Beams

Load-deflection curves for beam specimens with circular openings (B-1, B-2, C-1 and C-2) is shown in Fig. 9 and the corresponding ultimate loads are found to be 299.4kN, 241.3kN, 425.1kN and 340.1kN. When compared to un-strengthened beams with circular openings, the load carrying capability of strengthened beams is enhanced by 42.5% and the ultimate deflection was reduced by 39%. Moreover, the load-mid span deflection curve for beams with square openings (B-3, B-4, C-3 and C-4) is shown in Fig. 10. From Fig. 10, it is observed that the ultimate loads are 264.6kN, 201.1kN, 362.4kN and 334.3kN, respectively. When compared to un-strengthened beams, the load carrying capability of strengthened beams with web openings is enhanced by 66.2% and the ultimate displacement was improved by 16%.

The load carrying capacity of deep beams reinforced with GFRP has increased dramatically, even in the presence of openings. This is especially the case for beam C-1, where an increment of 30% to 42% was achieved in comparison to CB and beams with circular opening of dia. 110mm. The result is in good agreement with related research [8]. In terms of shape of openings, square openings which have four sharp corners are vulnerable to high stress concentration and hence they have a significant reduction in capacity as compared to circular openings. In case of square openings, if beam specimen B4 was strengthened with GFRP, an increase of 31% was achieved. According to test results of this study, even when reinforced with GFRP sheets, beams with square openings could not resist more load than the control beam could. In such circumstances, to minimize the reduction in load carrying capacity, diagonal bars must be provided for pre-planned web openings, and the area around the openings must be properly detailed [4].

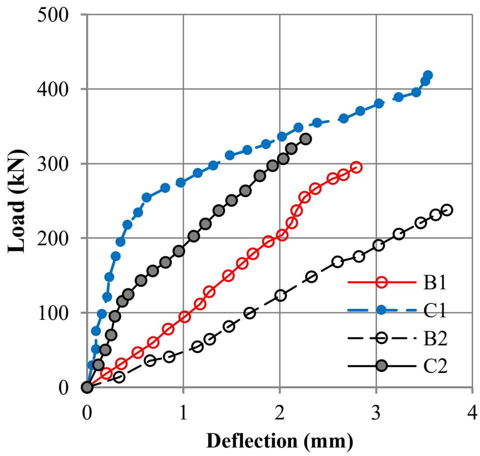

Fig. 9. Load- deflection curves for beams with circular openings

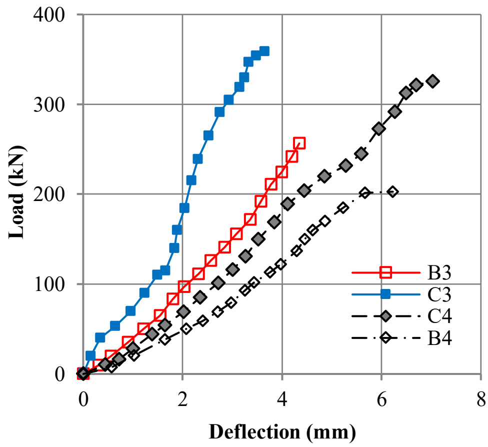

Fig. 10. Load- deflection curves for beams with square openings

Comparison of Test Results with Prediction Models

Comparison of shear capacity of solid beam, strengthened and un-strengthened beams with circular and square openings are made. Moreover, test results with that of prediction equations stipulated in codes and standards are compared and the results are summarized in Tables 6 and 7. From Table 6, it is indicated that the test results show strong agreement with the Mansur prediction equation whereas the Hirosawa's and Mansur-2 approaches underestimate the shear capacity.

Table 6. Test results and code predictions for unstrengthened beams

Beam designation	Experiment result (kN) (1)	Predicted shear strength for unstrengthened beams (kN)			Ratio		
		Mansur (2)	Hirosawa (3)	Mansur-2 (4)	(1)/(2)	(1)/(3)	(1)/(4)
CB	329.13	334.96	229.40	203.76	0.98	1.43	1.62
B1	299.37	254.07	163.37	156.17	1.18	1.83	1.92
B2	241.35	217.30	133.36	134.54	1.11	1.81	1.79
B3	264.61	220.57	136.02	136.46	1.20	1.95	1.94
B4	201.08	212.40	129.36	131.66	0.95	1.55	1.53

Table 7. Test results and code predictions for strengthened beams

Beam designation	Experiment result (kN) (1)	Predicted shear strength for strengthened beams (kN) ACI (2)	CSA (3)	Khalifa (4)	Ratio (1)/(2)	(1)/(3)	(1)/(4)
C1	425.13	499.01	569.93	418.40	0.95	0.75	1.02
C2	340.14	412.23	533.17	381.64	0.83	0.64	0.89
C3	362.41	415.50	536.43	384.90	0.87	0.68	0.94
C4	334.29	407.33	528.26	376.73	0.82	0.63	0.89

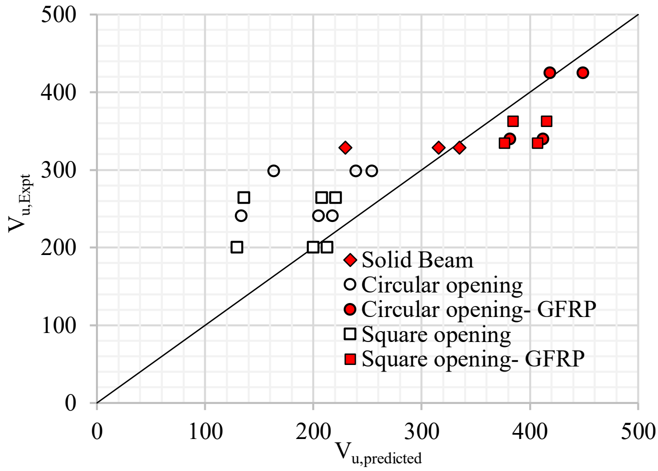

Fig. 11. Comparison of test results with code predictions

As shown in Table 7 and Fig, 11, for GFRP strengthened beams with web openings, experimental results are in good agreement with ACI-440 and Khalifa prediction models whereas the CSA model overestimates shear capacity of GFRP strengthened beams. For comparison of test results with code predictions, the fiber contribution to shear strength models given in Eqs. (5) to (7) are used along with the shear strength model proposed by Mansur, Eq. (1) as it was found a good prediction model with less deviations from the experimental result (see Table 6).

Conclusions

The use of GFRP to strengthen RC beams with web openings is a common practice in structural engineering as they are relatively easy to install. Related studies demonstrated that using a different strengthening method around the areas where web openings are provided increased the ultimate shear capacity of RC beams by up to 60% and that the shear capacity is significantly influenced by the size and shape of the openings. In this study, a full-depth mat and fabric type GFRP materials are selected and the entire length of the beam was wrapped. Hence, based on the study, the following conclusions are drawn:

- The presence of square openings cause disturbances in the stress distribution pattern which has a significant impact on beam performance and results in a 39.1% reduction in shear capacity. It also produces excessive stress concentration and early cracking at their corners. As a result, if openings cannot be avoided, the best shape recommended for openings in reinforced concrete beams is circular.
- To improve the shear strength of deep beams with openings, GFRP sheets have been found to be very effective in which an incremental of load carrying capacity in the range

of 40% to 60% was achieved. Moreover, the experimental resilt of the study revealed that the ultimate displacement of beams with web openings was improved by 14 to 39%.

- To enhance the shear capacity of beams with openings, provision of enough shear strength to the chords of the opening is required. This will reduce the propagation of cracks around the openings and enhances the beam's capacity.
- The experimental result was found to be in good agreement with code predictions given in Mansur's equation for un-strengthened beams and ACI and Khalifa models for GFRP strengthened reinforced concrete beams with web openings.

Future Directions and Limitations

The current research work was limited to study the use of GFRP wraps to strengthen RC beams with circular and square web openings. In the future, it is recommended to investigate the performance and behaviour of beams with web openings for repeated and cyclic loading in the case of bridges and other structures built in seismic prone areas. Furthermore, a parametric study on the use of various strengthening techniques with variable material properties and different opening shapes should also be included in future studies.

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