CFRP Composites for Strengthening of Reinforced Concrete Walls with Openings

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ABSTRACT

This paper presents the results of a research work aimed at investigating the potential used of externally bonded Carbon Fiber Reinforced Polymer (CFRP) composite sheets as a strengthening solution for uniaxial rectangular concrete walls with central rectangular in-plane openings. Seventeen of 1/3 scale rectangular concrete walls with and without central rectangular in-plane openings of different sizes (5%, 10%, 20% and 30% of wall areas) are tested. In thickness direction, one central layer of steel fabrics was used to reinforce the concrete walls. The walls were subjected to uniaxial loading aligned with the longest edge of the concrete walls. The loading was applied eccentrically (t/6) with respect to the mid-plane of the walls. Two different patterns were used to fix the CFRP to both surfaces of the walls which are parallel to the mid-plane of the wall segments. The first pattern consisted of applying four strips of CFRP parallel to the four edges of the opening such that they framed the opening. In the second pattern, CFRP strips were used to reinforce the walls in the vicinity of the opening edges only, i.e. four CFRP strips were applied close to the corners of the openings, in an angle of 45 degrees with both adjacent edges of the opening. From the results of the research work, it was found that CFRP strips applied at an angle of 45 degrees to both adjacent edges of the opening yielded a better compressive strength compared to the CFRP strips that framed the openings.

***Keywords*-Reinforced concrete wall, opening, ultimate load, Carbon Reinforced Polymer, CFRP, stress concentration, strengthening**

I. INTRODUCTION

Reinforced concrete wall panels are commonly used as a load bearing structural elements. Uniaxial action walls are defined as laterally supported and restrained against deflection along top and bottom supports. It is designed to resist in-plane vertical loads acting downward from the top of the wall and it, also transfers loads in one direction to supports at the top and bottom. The wall panels often undergo accidental eccentric loads due to the imperfections in construction. Due to architectural or mechanical requirements and/or change in the building's function; cut-out new openings for provision of doors and windows or to accommodate essential services such as ventilation and air-conditioning ducts is frequently required. Large openings in RC wall panels cause disturbance in the stress path when considerable amount of concrete and reinforcing steel have to be removed. Most of the investigations on uniaxial reinforced concrete wall panels are on solid walls and have led to certain design recommendations such as American Concrete Institute code ACI318-02 [1] and Australian Standard AS3600-01[2]. Hence, there are some researchers that have contributed to the developments of empirical formula for RC wall panels with openings [3-10].

The structural effect of small openings is often not considered due to the ability of the structure to redistribute stresses. However, for larger openings the static system may be altered when a considerable amount of concrete and reinforcing steels have to be removed. This leads to a decreased ability of the structure to resist the imposed loads [11]. The presence of the openings in the panels determines the load paths and creates stress concentrations around the opening, which encourages cracks to occur first at the corners of the opening [12 and 13]. Therefore, the openings in the wall panels need to be strengthened. The traditional strengthening methods for cut-outs in the literature are mostly by providing embedding of reinforcing bars or steel plates [14, 15]. On the other hand, advanced composites as an externally bonded reinforcement have been extensively tested on their use for strengthening of beams and girders in flexure, shear and even to some extent in torsion. The use of Carbon Fiber Reinforced Polymer (CFRP) to strengthen existing slabs with openings is becoming increasingly popular [11].

This research mainly focuses on the application of carbon fibers as the strengthening materials. A few researchers have studied the strengthening of structural elements such as slabs and beams with cut-outs using CFRP (eg:[11], [14],[15] and

[16]). Even though CFRP is widely used as strengthening materials of existing structures, yet to the best knowledge of the authors, currently no research work has been carried out on CFRP as a strengthening material to strengthen wall panel with cut-out openings. Advantages of using FRP have been reported by other researchers [17-23].

The latest studies of uniaxial reinforced concrete walls with openings by Saheb, and Desayi [5] led to developments of empirical equations to determine their ultimate strength. They carried out test on twelve panels; six were supported only at the top and bottom and the others were supported on four sides. Each panel was provided with a window or a door opening in different regions. The test panels were subjected to in plane vertical loads applied at an eccentricity. Empirical equations were developed for panels with openings by modifying the ACI formula and had introduced a reduction parameter that allowed for the geometry of the openings. The equations of ultimate loads for the wall panels with openings under in-plane uniaxial load (equation 1) proposed by S. M. Saheb and P. Desayi [5] are;

$$P_{uo}^{c} = (k_1 - k_2\alpha)P_{uc}^{c} \quad (1)$$

where,

k_1 & k_2 = (constants) $k_1 = 1.25; k_2 = 1.22$

P_{uc}^{c} = The ultimate load of an identical wall panel without opening under uniaxial action from Madina Saheb, S. and Desayi, P. [24]

α = Opening geometry parameter

The equations 2,3 and 4 for ultimate loads of wall panels without openings under uniaxial load were defined in S. M. Saheb and P. Desayi [24] as,

$$P_{uc}^{c} = 0.55\phi\left[A_g f_c' + (f_{yv} - f_c')A_{sv}\right]\left[1 - \left(\frac{h}{32t}\right)^2\right]\left[1.20 - \right.$$

$h10L$ for $hL<2.0$ (2)

and

$$P_{uc}^{c} = 0.55\phi\left[A_g f_c' + (f_{yv} - f_c')A_{sv}\right]\left[1 - \left(\frac{h}{32t}\right)^2\right] \quad \text{For } \frac{h}{L} \geq 2.0 \quad (3)$$

The opening geometry parameter, α defined as

$$\alpha = \frac{A_o}{A} + \frac{a}{L} \quad (4)$$

where

$$A_o = L_o t;\ A = Lt;\ a = \left[\left(\frac{L}{2}\right) - \bar{a}\right];\ \bar{a} = \frac{\left(\frac{L^2 t}{2} - L_o t a_o\right)}{(Lt - L_o t)};$$

where

L_o and h_o = the dimensions of the opening

a =the distance between centers of the gravity of panel section in plan with and without an opening

a_o and ā = distances of the centers of gravity of the opening and of a panel without an opening from the left edge of the panel, respectively. However, the empirical equations are subjected to wall panels with concrete strength < 35MPa, slenderness ratio (H/t) < 12, aspect ratio (H/L) <0.67, thinness ratio (L/t) <18 and opening aspect ratio (H_o/L_o) is 1~2. Comparisons between normal compressive strength and high strength solid wall panels tested in uniaxial and biaxial action had been reported by Doh and Fragomeni [25]. Walls in uniaxial action are characterized by horizontal cracking at mid-span at failure, while walls in biaxial action feature biaxial cracking. The crack pattern of normal strength wall panel on the tension face is horizontal (perpendicular to the loading direction) with failure occurring near the centre of the panel, signifying bending failure being intensified by buckling. In contrast, high strength panel developed a single large crack, commencing at the tension face splitting in two separate parts. This indicates that the high strength concrete panels possessed a more brittle failure mode, with some yielding of reinforcement taking place before concrete failure. This suggests that the use of very slender and high strength concrete wall panels may become dangerous in practice, when only minimum reinforcement is provided, as abrupt failure may occur [25]. In uniaxial walls with openings, it was noted that vertical and inclined cracks formed in the beam strips while horizontal cracks formed in column strips. [10, 24].

II. RESEARCH SIGNIFICANCE

This paper presents an analysis of the related formulas suggested by researchers with the experimental results. The test panels for this research are designed with concrete strength <25MPa, slenderness ratio (H/t) < 16, aspect ratio (H/L) <2, thinness ratio (L/t) <8, and opening aspect ratio $(H_o/L_o) \approx 1.8$. This paper also reports the crack patterns of the test panels and suggested the best strengthening pattern for wall panels with openings strengthened with CFRP.

III. EXPERIMENTAL WORK

3.1 Test Panels

A total of sixteen 1/3 scale reinforced concrete wall panels with openings comprising four identical series of four specimens each are casted. Tables 1 and 2 show the dimensions of wall panels and openings. All the test panels are 400mm width and 800mm height. Series one designated WO1-WO4, are 50mm thick and 3 other series were 40mm in thickness. Series one and two designated as WO1-WO4 and WO1a-WO4a, respectively are tested without CFRP; while series three and four designated as WO1b-WO4b and WO1c-WO4c, respectively are tested with CFRP strengthened wall openings. Wall panels are tested with different sizes of openings. Opening sizes increase by percentage of wall area of 5%, 10%, 20% and 30%. Aspect ratio (H/L), slenderness ratio (H/t) and thinness ratio (L/t) are 2, 16 and 8 respectively for wall series one. For series two, three, and four, aspect ratio (H/L), slenderness ratio (H/t) and thinness ratio (L/t) are 2, 20 and 10, respectively.

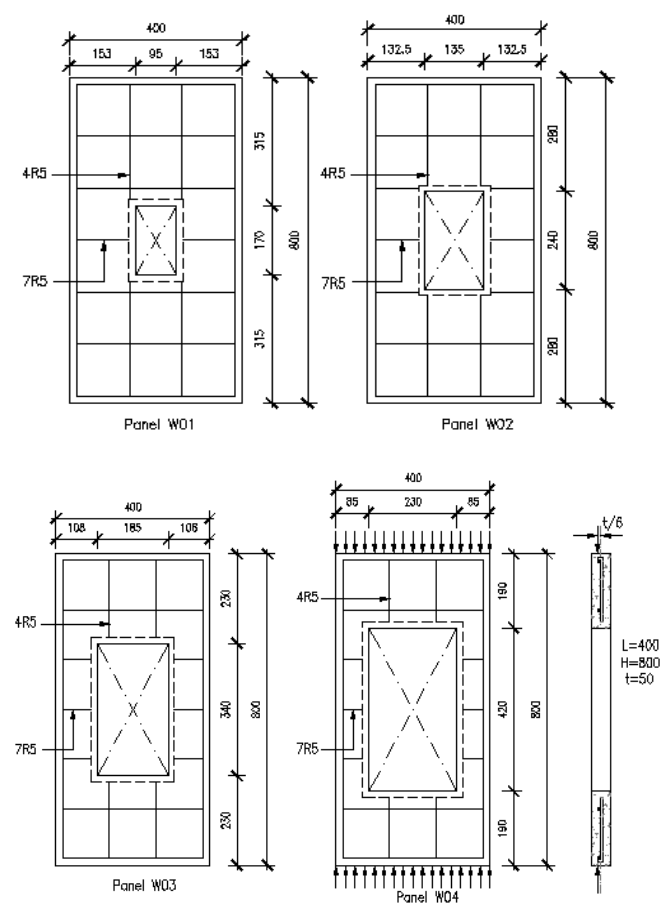
Figures 1 shows the detail of the wall panels in series. The percentages of reinforcements are kept the same in all the specimens. The purpose is to study the influences of opening sizes on the strength and the behavior of wall panels tested in uniaxial action. The panel reinforcements are in one layer placed centrally within the panel cross-section. The reinforcement ratios ρ_v and ρ_h for wall series one are 0.004 and 0.007, respectively while for series two, three, and four are 0.005 and 0.009, respectively. These reinforcement ratios satisfy the minimum requirements in the ACI 318-02[1]. Figure 2 shows a solid wall, SW2 size 400x800x40 mm as a control wall for comparison of CFRP application. Reinforcement ratios for SW2 are the same as series 2, 3 and 4.

TABLE 1: DIMENSIONS OF WALL PANELS SERIES 1

Wall	% of wall opening	Wall Size (mm)			Opening Size (mm)	
		H	L	t	Ho	Lo
WO1	5	800	400	50	170	95
WO2	10	800	400	50	240	135
WO3	20	800	400	50	340	185
WO4	30	800	400	50	420	230

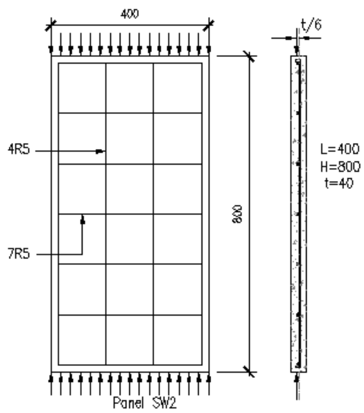
TABLE 2: DIMENSIONS OF WALL PANELS SERIES 2, 3, 4 AND SOLID WALL.

Wall	% of wall opening	Wall Size (mm)			Opening Size (mm)	
		H	L	t	Ho	Lo
SW1	-	800	400	50	-	-
WO1a,b,c	5	800	400	50	170	95
WO2a,b,c	10	800	400	50	240	135
WO3a,b,c	20	800	400	50	340	185
WO4a,b,c	30	800	400	50	420	230



Note: 1. Dimensions in millimeters.
2. Series two, three, and four with 40mm thickness

Fig. 1: Series one (panels with opening, details of reinforcement and schematic loading on one specimen)



Note: Dimensions in mm.

Fig. 2: Details of reinforcement and schematic loading of solid wall panel.

3.2 CFRP Strengthened Wall Panel Opening

CFRP are applied around panel openings to strengthen the wall panels. The method to calculate the required sectional areas of CFRP for strengthening panel openings has not been developed in design code. Enochsson et al.[11] have introduced a simplified method to estimate the amount of CFRP required to strengthen the openings in biaxial concrete slabs. The outcome of the work can also be used for cast and made openings in uniaxial concrete slabs and in concrete walls. They suggested that traditional method followed BBK 04 (The Swedish building administration handbook of concrete structures) is used to calculate the required steel reinforcement for slabs or walls with openings. The additional steel reinforcement replace the cut-out reinforcement are given at least the same length, as it would have had if the opening had not exist. The simplified method is to convert the calculated designed required steel reinforcements to necessary amount of CFRP. Required area for CFRP are given as equation 5 below, assuming concrete and reinforcement have a perfect bond, so that the expression for the sectional area of CFRP becomes only dependent on the level arms and the elastic modulus of the steel.

$$A_f = \frac{E_{s2}}{E_f}\left(\frac{t-u-x}{t-x}\right)^2 A_{s2} \quad (5)$$

$$x = \frac{a}{0.85} \quad (6)$$

$$a = \frac{A_{s2} f_{yv}}{0.85 f_c^{'} L} \quad (7)$$

$$width\ of\ required\ CFRP = \frac{CFRP\ sectional\ \ Area\ , A_f}{thickness\ \ of\ CFRP} \quad (8)$$

where;
E_{s2} = Modulus of elasticity for additional steel reinforcement.
E_f = Modulus of elasticity for CFRP .
t = Depth of the slab or thickness of the wall.
u = Distance from the bottom tensile side to the centre of gravity of the steel bars.
x = Distance from the top compression side to neutral axis
A_{s2} = Area of additional steel reinforcement
a = Depth of the equivalent rectangular stress block
f_{yv} = yield strength of steel
$f_c^{'}$ = concrete compressive strength
L = width of wall

Anchorage length of CFRP is defined from the outermost crack of the wall (un-cracked section) which is at the corners of the openings. Effective anchorage length, $l_{b,max}$ defined as equation 9 by fib Bulletin 14 [26]. An increase in anchorage length $l_{b,max}$ does not result in resisting tensile stresses due to the limitation of fracture energy [26]. CFRP is used to strengthen wall panel openings in two patterns, which is along the opening corners and 45° to the opening corners. Length and width of the applied CFRP are shown in Tables 3 and 4. Figure 3 shows the CFRP pattern used to strengthen the wall panel's opening.

$$l_{b,max} = C\sqrt{\frac{E_f t_f}{\sqrt{f_{cu} f_{ctm}}}} \ \text{(mm)} \quad (9)$$

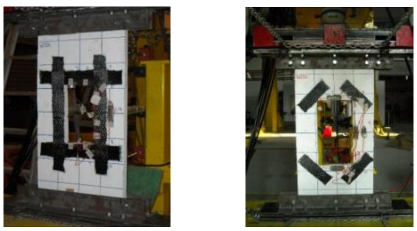
where;
C = 1.44 ; constant
E_f = Modulus of elasticity for CFRP, MPa
t_f = Thickness of CFRP, mm
f_{cu} = Characteristic value of the concrete compressive strength
f_{ctm} = Mean value of the concrete tensile strength, MPa.

TABLE 3: WIDTH AND LENGTH OF THE APPLIED CFRP SHEETS ALONG (0/90°) PANEL OPENING (SERIES 3).

Wall	Length of opening (mm)	Width of opening (mm)	Width of CFRP (mm)	Length of CFRP 0° along the opening (mm)	Length of CFRP 90° along the opening (mm)
WO1b	170	95	60	345	420
WO2b	240	135	60	385	490
WO3b	340	185	60	400	590
WO4b	420	230	60	400	670

TABLE 4: WIDTH AND LENGTH OF THE APPLIED CFRP SHEETS AT THE CORNER (45°) OF PANEL OPENING (SERIES 4).

Wall	Length of opening (mm)	Width of opening (mm)	Width of CFRP (mm)	Length of CFRP (mm)
WO1c	170	95	60	95
WO2c	240	135	60	135
WO3c	340	185	60	185
WO4c	420	230	60	230



(a) CFRP pattern 1 (b) CFRP pattern 2
Fig. 3: CFRP patterns used to strengthen wall panel openings.

3.3 Materials

The concrete used for all the specimens in this research were having the mixture proportions of (cement: fine aggregate: coarse aggregate: water) 1:2.638:2.149:0.63. Ordinary Portland Cement (OPC) Type I which conforms to the requirement of ASTM C 150-04 was used in the concrete mix. The coarse aggregates used were graded 10 mm maximum sized crushed stone. Average concrete slumps for the concrete is approximately 75 mm which is medium slump. Compressive strength (f_{cu}) of 100 mm cubes at the age of testing the wall panels is shown in Table 5. Cylinder strength is taken to be equal to 0.8 x f_{cu}. Compressive test is conducted just before the wall panels are tested. Average concrete tensile strength taken from splitting tensile strength test of concrete cylinder for Series two, three, and four is 1.46 MPa. The concrete compressive and splitting strengths are the mean values of three test cubes and cylinders respectively. Modulus of elasticity and Poisson ratio of the concrete cylinders are 21GPa and 0.21, respectively.

Reinforcements used are 5mm in diameter steels with average proof yield strength of 478 MPa and modulus of elasticity of $2.05\text{x}10^5$ MPa. Clear cover of 15mm is given over the reinforcements. Table 6 shows material properties of the CFRP sheets. The wall panels are tested on the 14th day of curing by wet gunny bag. The wall panels strengthened with CFRP are cured with the gunny bag for 7 days, and applied with the CFRP on the 7th day. The wall panels with applied CFRP then air cured with humidity of 70-75% and temperature of 28°C-33°C.

TABLE 5: COMPRESSIVE STRENGTH OF THE TEST CUBES ON TESTING DAY.

Wall Series No.	wall	Average Compressive Strength for Concrete Cube, f_{cu} ,MPa	Average Compressive Strength for Concrete Cylinder, f'_{cu},MPa (0.8xf_{cu})
1	WO1	21.09	16.87
	WO2	22.11	17.68
	WO3	23.01	18.40
	WO4	24.80	19.84
2	SW2	18.32	14.66
	WO1a	19.99	15.99
	WO2a	17.43	13.94
	WO3a	19.46	15.57
	WO4a	19.73	15.79
3	WO1b	18.71	14.97
	WO2b	21.35	17.08
	WO3b	22.79	18.24
	WO4b	18.83	15.06
4	WO1c	18.39	14.72
	WO2c	19.55	15.64
	WO3c	20.45	16.36
	WO4c	21.29	17.04

TABLE 6: Material Properties of CFRP Sheet (MAPEWRAP C UNI-AX 300/40)

Product	Fabric Thickness (mm)	Tensile Strength (MPa)	Tensile Modulus of Elasticity (GPa)	Elongation at Breaking Point (%)
UNI-AX 300/40	0.167	4800	230	2.1

Note: UNI-AX denotes uni-directional continuous carbon fibre fabric, 300 denote mass per cross sectional area (g/m^2) and 40 denote height in cm for 50m rolls packed in carton boxes.

3.4 Test Set Up

The wall panels are tested using a hydraulic jack of 30 tone capacity. The hydraulic jack transmits a uniformly distributed load across the top through a top plate to a 20 mm diameter steel bar at an eccentricity of t/6. The arrangements are to ensure a distributed loading at an eccentricity with pinned conditions. Figure 4 shows a two point load arrangement. The wall panels are similarly supported at the bottom. Details of the simply supported top pinned edge are shown in Figure 5. Surface strains and lateral deflections are measured at selected locations at each stage of loading using strain gauges and Linear Variable Differential Transformers (LVDT) respectively. Positions of LVDTs are shown in Figure 6. LVDTs are placed midway between the edges of the wall panel and the edges of opening. Every attempt is made to develop pinned-ended condition at the top and bottom of the walls. One additional LVDT is placed at the top edge to ascertain the amount of panel movement within the frame in order to check the pinned- ended condition. Strain gauges are placed at the corners and sides of the openings to record the strains during the testing. Arrangements of strain gauges on both faces are shown in Figure 7.

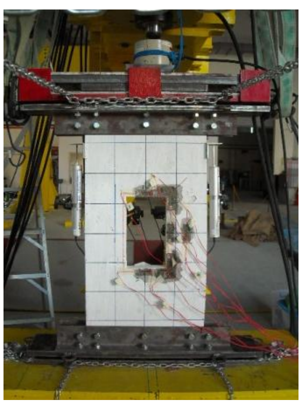


Fig. 4: Arrangement for Two Point Load Distribution

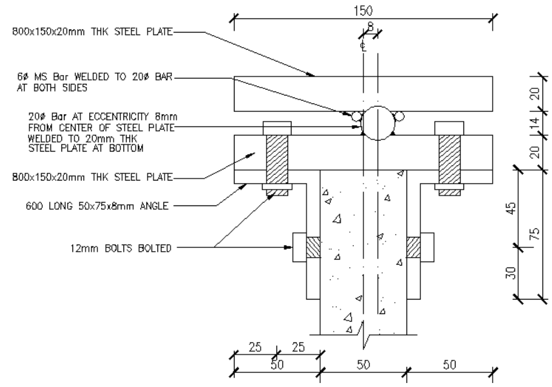


Fig. 5: Top and bottom restraint

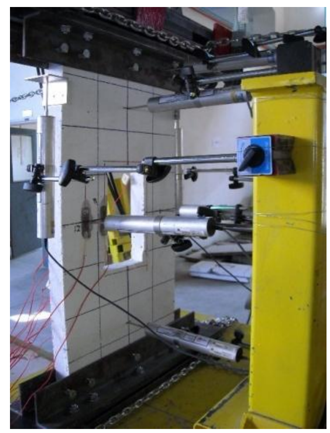


Fig. 6: Arrangement of LVDT

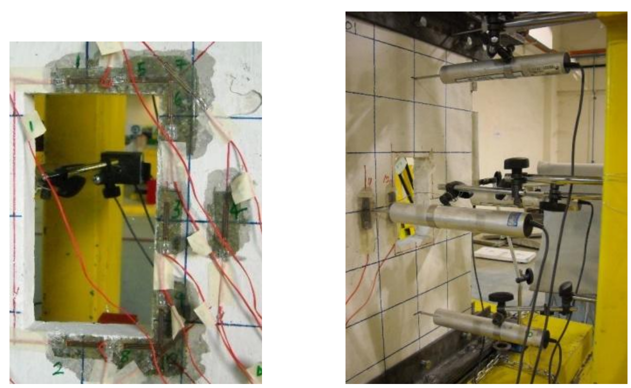


Fig. 7: Arrangements for Strain Gauges

IV. RESULTS AND DISCUSSIONS

4.1 Failure Load of Wall Panels with Openings in in-plane Uniaxial Action

Table 7 shows the theoretical failure loads, P_{uo}^{c} and the experimental failure loads, P_{uo}^{e}. The theoretical failure loads are calculated from the empirical formula by Saheb and Desayi [5] in equation 1. P_{uc}^{c} for the test panels are calculated from equation 3 for $\phi = 1$ (ϕ is capacity reduction factor). $P_{uo}^{c}/P_{uo}^{e} < 1$ which the theoretical failure loads are less than experimental failure loads and it is conservative to use in design.

TABLE 7: P_{uo}^{e} AND P_{uc}^{c} FOR TEST PANELS.

Wall	$\propto$	P_{uo}^{e}	P_{uo}^{c}	P_{uo}^{c}/P_{uo}^{e}
WO1	0.2375	210.0	147.99	0.70
WO2	0.3375	203.8	134.80	0.66
WO3	0.4625	179.8	114.33	0.64
WO4	0.5750	172.6	97.92	0.57
SW2	-	110	95.08	0.86
WO1a	0.2375	100.0	94.02	0.94
WO2a	0.3375	95.3	81.16	0.85
WO3a	0.4625	85.0	65.62	0.77
WO4a	0.5750	73.7	52.40	0.71

Note: P_{uc}^{c} of the WO1-4 =179.84kN; P_{uc}^{c} of the WO1a-4a =97.96kN.

Table 8 shows the theoretical failure loads, P_{uo}^{c} and the experimental failure loads, P_{uoc}^{e} of test panels strengthened with CFRP. The theoretical failure loads are calculated from the empirical formula by Saheb and Desayi [5] in equation 1 for test panels without CFRP. P_{uo}^{c} / P_{uo}^{e} ratios show that application of CFRP had increased the load capacity of the test panels, where the experimental values of test panels with applied CFRP are larger than experimental values of test panels without CFRP. It shows that test panels with applied CFRP along the corners increased the load capacity by roughly 34% and applied CFRP 45^{o} at the corners of the test panels increased the load capacity by 55%.

TABLE 8: P_{uo}^{e} AND P_{uc}^{c} FOR TEST PANELS.

Wall	$\propto$	P_{uoc}^{e}	P_{uo}^{c}	P_{uo}^{e}	P_{uo}^{c} / P_{uoc}^{e}	P_{uoc}^{e} / P_{uo}^{e}
WO1b	0.2375	149.9	94.02	100.0	0.63	1.50
WO2b	0.3375	139.1	81.16	95.3	0.58	1.46
WO3b	0.4625	108.0	65.62	85.0	0.61	1.27
WO4b	0.5750	82.0	52.40	73.7	0.64	1.11
WO1c	0.2375	175.4	94.02	100.0	0.54	1.75
WO2c	0.3375	157.2	81.16	95.3	0.52	1.65
WO3c	0.4625	138.5	65.62	85.0	0.47	1.63
WO4c	0.5750	84.8	52.40	73.7	0.62	1.15

Note: P_{uc}^{c} of the WO1a-4a =97.96kN.

4.2 Crack Patterns of Wall Panels with Openings in in-plane Uniaxial Action

Crack patterns for the tested panels were observed. The solid wall panel has deflected in a single curvature with the maximum deflection occurring at the centre of the wall panel and failure near the centre of the wall panel. The cracks were observed horizontally near centre of the wall panel. Figure 8 shows crack pattern of 40 mm thick solid wall on the tension face after failure.

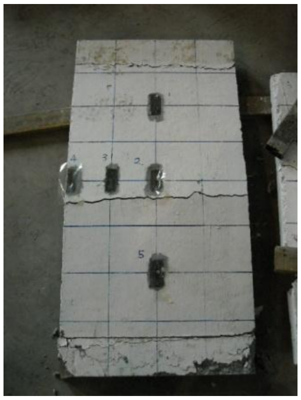


Fig. 8: Crack pattern of 40mm thick solid wall on the tension face after failure.

On the other hand, the wall panels with an opening tested under in-plane uniaxial action deflected in a single curvature with a maximum deflection occurring near the middle of the wall panels. The cracks initiate from the centre of the opening, parallel with the loading direction towards the applied loads. Followed by that is a crack from the centre of the opening, parallel with the loading direction towards the bottom of the wall panel. Besides that, the cracks also occurred near the middle of the wall panels, perpendicular to the loading direction which leads to the failure of the wall panels.

Portions of the panel above and below the opening behave as beam strips and those adjacent to an opening as column strips. The behavior was noticed through the crack patterns on the tested wall panels. Horizontal crack patterns developed on the column sections, while vertical and inclined cracks were formed in the beam strips. A horizontal crack was formed at the corner of the opening in where changes of smaller cross section area. Failure in all panels was mostly due to the buckling of slender column strip of the panel. The crushing of concrete on the compression faces of the column strips of the specimens is noticed in all specimens along the failure section. Figure 9 shows some figures of the concrete crushed in the compression face. Crushing of the compression face is noticed mostly in wall panels with small openings. Cracks before failure are not very obvious in wall panels with big opening. Sudden and explosive types of failure are observed in all the test panels. It can be observed that the major horizontal cracks that leads to failure of the walls for small opening (5% and 10%) forms at the column strips near middle of the wall. On the other hand, the major horizontal cracks for large opening walls (20% and 30%) initiated from the corners of the openings. Figure 10 shows some samples of the crack patterns.

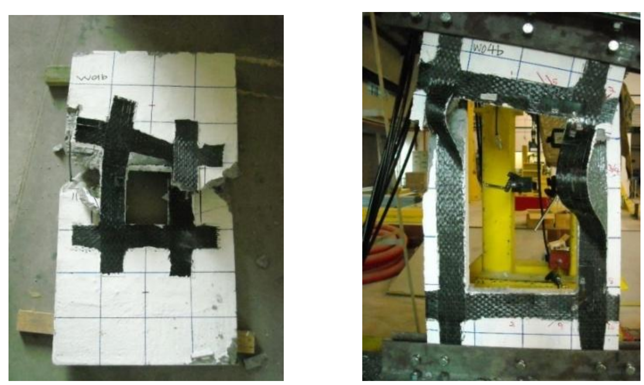
Fig. 9: Crushing of concrete in compression face.

WO2 WO4a

Fig. 10: Crack patterns on the tension face after failure of the wall panels with openings.

Wall panels with openings strengthened with CFRP displayed different crack pattern compared to the wall panels without CFRP. Different patterns of CFRP strengthening.

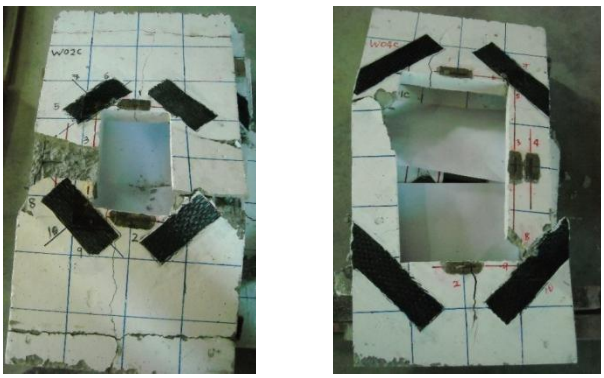
Method show different crack patterns as well. Figure 11 shows some crack patterns for the wall panels with openings strengthened with CFRP pattern 1, where the CFRP applied along the wall panel opening. The failures occurred in tension face whereby the CFRP will either be ruptured or torn from the concrete when the force applied is greater than the CFRP tension capacity. The failure of concrete took place after the CFRP have been torn from the concrete surface. The advantages of applying CFRP along the wall panel opening is that the wall panels will only fail in column strips, either near the centre of the wall or horizontally from the opening corner.



WO1b WO4b

Fig. 11: Crack patterns on the tension face after failure of the 40mm thick wall panels with openings strengthened with CFRP pattern 1.

Figure 12 shows some crack patterns for wall panels with openings strengthened with CFRP pattern 2. The crack patterns for wall panels in this batch are similar to wall panels with openings without CFRP. The cracks were initiated vertically from the top or bottom of the wall panel opening towards upper or lower support, followed by horizontal cracks at the column strips. The cracks at the column strips were not originated from the opening corners. The cracks that happened near the applied CFRP will went around the CFRP because the CFRP resisting the force.



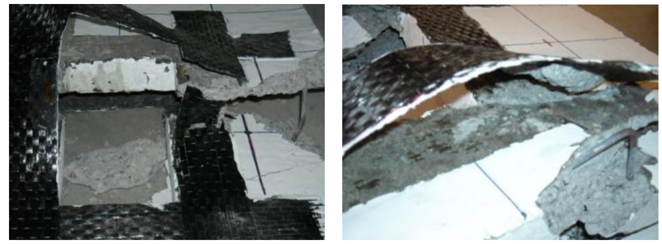
WO2c WO4c

Fig. 12: Crack patterns on the tension face after failure of the 40mm thick wall panels with openings strengthened with CFRP pattern 2.

4.3 Failure Modes of Bond between Concrete and CFRP-strip

Wall panels with openings strengthened with CFRP have been tested with 2 patterns. Pattern 1 is where the CFRP is applied along the wall panels opening with a certain anchorage length while CFRP pattern 2 is applied 45 degree to the wall opening corners. Failure modes of both CFRP pattern were observed and compared to the failure modes mentioned in Technical Report *fib* [26].

Figure 13 shows the failure mode of wall panels with openings strengthened with CFRP pattern 1. It shows where full composite action of concrete and FRP is maintained until the concrete reaches crushing in compression or the FRP fails in tension [26]. De-bonding in the adhesive also happen as the tensile and shear strength of the adhesive (epoxy resin) is usually higher than the tensile and shear strength of concrete, failure will normally occur in the concrete. In this case, a thin layer of concrete (a few millimetres thick) will remain on the FRP reinforcement [26].



(a) (b)

Fig. 13: Failure mode of wall panels with openings strengthened with CFRP pattern 1 in tension face.

CFRP in the compression face is normally either peeled off or fractured due to the compression force. The CFRP is weak in compression and is easily peeled off when the tension face has reached the failure. Figure 14 shows a few sample of failure in compression face.

Fig. 14: Failure mode of wall panels with openings strengthened with CFRP pattern 1 in compression face.

Figure 15 shows some failure mode of wall panels with openings strengthened with CFRP pattern 2. The cracks happened around the CFRP since the CFRP has strengthened the crack path.

Figure 16 (a) shows another failure mode of wall panels with openings strengthened with CFRP pattern 2 on the tension face. The wall panel experienced de-bonding in the adhesive. This is also one of the failure modes of the bond between concrete and CFRP-strip described by Schilde and Seim [27]. The concrete wedge was clearly seen on the peeled CFRP. Figure 16 (b) shows the CFRP-strip that was clean from any concrete wedges. There was just a thin layer a few millimetres thick of concrete remained on the CFRP. This failure mode met another failure mode that was mentioned by Karsten Schilde and Werner Seim [27] which was failure of the adhesive over the whole bond length.

(a) (b)

Fig. 15: Failure mode of wall panels with openings strengthened with CFRP pattern 2 in tension face.

(a) (b)

Fig. 16: Failure mode of the wall panels with openings strengthened with CFRP pattern 2 in (a) tension face and (b) compression face.

V. CONCLUSIONS

The following can be concluded from this paper.

a. The ultimate loads of the wall panels decreased as the opening sizes increased.
b. Saheb and Desayi [5] existing empirical equation shows that theoretical failure loads are less than experimental failure loads and it is conservative to use in design.
c. The experimental failure loads of the wall panels show that wall panels with openings strengthened with CFRP increase the load capacity. The wall panels with openings strengthened with CFRP resisted axial load more than solid wall.
d. It shows that test panels with applied CFRP along the corners increased the load capacity by roughly 34% and applied CFRP at the corners of the test panels increased the load capacity by 55%.
e. The wall panel openings strengthened with CFRP at 45° to the opening corners resisted higher axial load compared with the pattern which was strengthened around the wall panel openings.
f. Crack patterns
   (i) The solid wall panel deflected in a single curvature with the maximum deflection occurring at the centre of the wall panel. The cracks were observed horizontally near centre of the wall panel.
   (ii) The wall panels with openings deflected in a single curvature with a maximum deflection occurring near the centre of the wall panels. Portion of the panels, above and below the openings behaved as beam strips and those adjacent to the openings as column strips. The behavior was noticed through the crack patterns on the tested wall panels. Horizontal cracks developed on the column strips, while vertical and inclined cracks were formed in the beam strips. Failure in all panels was mostly due to the buckling of slender column strips.
   (iii) The wall panels with openings strengthened with CFRP applied along the openings experienced failures in tension face whereby the CFRP will either be fracture or torn from the concrete. The failure of the concrete took place after the CFRP were torn from the concrete surface. One of the advantages of applying CFRP along the wall panel openings is that the wall panels will only fail in column strips, either near the centre of the wall or horizontally from the opening corners.
   (iv) The Wall panels with openings strengthened with CFRP applied at 45° to the opening corners had a similar crack patterns to wall panels with openings without CFRP. The cracks at the column strips were not originated from the opening corners. The cracks that occurred near the applied CFRP would go round the CFRP because the CFRP was resisting the force.
g. Failure mode
   (i) Wall panels with openings strengthened with CFRP around the openings showed that full composite action of concrete and FRP was maintained until the concrete reached crushing in compression or the CFRP failed in tension.

(ii) Wall panels with openings strengthened with CFRP 45° at the opening corners experienced the yielding of the tensile reinforcement followed by crushing of the concrete while the CFRP was still intact to the concrete. The failure occurred at the place which was not strengthened by CFRP.

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