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EXPERIMENTAL STUDY OF RC WALLS WITH OPENING STRENGTHENED BY CFRP

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ABSTRACT

Structural wall panels often experience eccentric loads due to a range of loading conditions including: corbel elements applied to the wall, imperfections in construction, uneven loading conditions on top of the wall and temporary loading during operation and/or maintenance. Openings in these walls are frequently required as a result of changes to a buildings function, architectural or mechanical necessities. This is typically for the provision of doors and windows or for services including ventilation and air-conditioning ducts. In recent years, strengthening and retrofitting of structural members using bonded Carbon Fibre Reinforced Polymer (CFRP) materials has gained a great deal of attention. The superior properties of composite materials, including: high elastic modulus, high strengths, light weight as well as excellent durability, have made them a suitable alternative for steel plates in strengthening applications. Experimental tests have been undertaken on RC opening walls supported by two types of restraint conditions with and without FRP strengthening. The study found that walls with CFRP greatly change the ultimate capacity of the walls under various support conditions.

KEYWORDS

RC wall, retrofitting, carbon fibre reinforced polymer, eccentricity.

INTRODUCTION

In the past, Reinforced Concrete (RC) wall panels were considered non-load bearing elements resulting in limited research on these components. In recent years, largely as a result of tilt-up concrete wall panel popularity and the use of concrete cores in tall buildings, RC walls have become as important as beams, columns, and slabs. Considerable effort has been advocated to find the behaviour of RC walls (Seddon 1956; Saheb and Desayi 1989; Doh 2002, Doh and Fragomeni 2005) and empirical or semi-empirical formulas have been derived for the ultimate load design. A wall panel hinged at the top and bottom carrying in-plane vertical loads developing a curvature along the loading direction is known as one-way action. The wall panel supported on three sides develops a curvature diagonally from three restrained corners to the centre and then horizontally along the loading direction to free restrained edge. In RC walls with openings, as a result of removing a considerable amount of steel and concrete, the load bearing capacity decreases. A similar crack pattern has been observed in

RC walls with opening in one-way action, however, in three side restrained condition, a curvature develops diagonally from three restrained corners to the openings and then horizontally along the loading direction from the opening to the unrestrained edge. Several studies have been done on this area (Saheb and Desayi 1990; Doh and Fragomeni 2006) and introduced some formula for finding the ultimate load of RC walls under eccentric axial load. Some of studies investigate the influence of opening size, location, and slenderness ratio of the walls (Lee et al. 2008)

The Current American concrete code (ACI318-2014) wall design equations are intended for load bearing walls supported at the top and bottom only. However, in the Australian Standard AS3600-2009 the effects of side restraints are also included. AS3600-2009 is restricted to walls with slenderness ratios less than 30. Despite some investigations into walls with three side restraints, based on the knowledge of the authors, there is no comprehensive formula for finding the ultimate load of walls with three sides restrained.

The issue of deteriorating infrastructure has received enormous attention in different countries. The deterioration of structures is largely influenced by: environmental effects, poor initial construction or a lack of required maintenance (Täljesten et al. 2003). There have been a significant number of studies assessing the usage of composite materials in civil engineering projects. It is reported that FRP composite materials have excellent corrosion resistance to environmental agents, as well as stiffness-to-weight and strength-to-weight ratios (Täljesten et al. 2003). Numerous researchers have investigated strengthening of structural elements such as slabs and beams with cut-out openings using CFRP (Casadei et al. 2003; Smith and Kim 2009). The use of CFRP to strengthen existing slabs with openings is becoming increasingly popular (Enochsson et al. 2007).

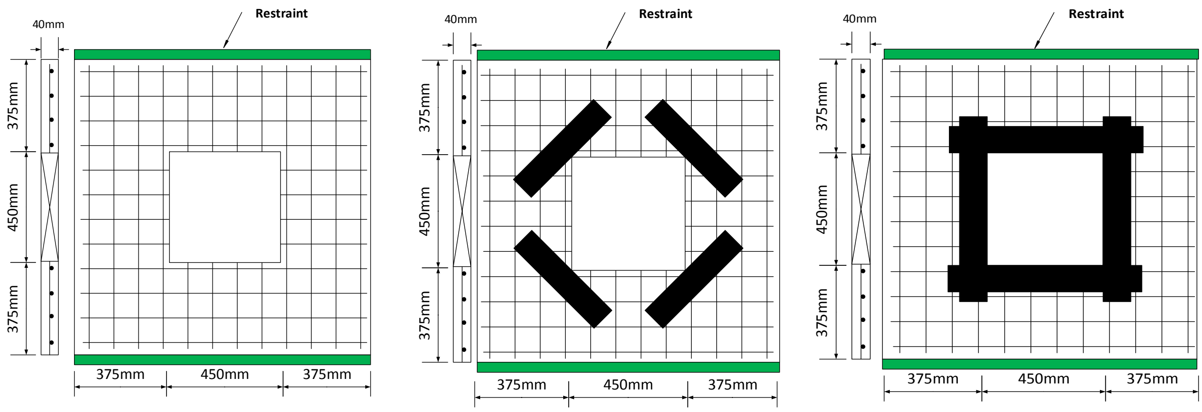
Despite extensive research on the behaviour of walls with and without openings, little has been conducted to investigate the strengthening of these walls using CFRP. Mohammad et al. (2013) claimed that even though CFRP is widely used as a strengthening material for existing structures, no research work has been carried out on CFRP as a strengthening material for RC walls with openings under axial eccentric loading, prior to their research. They reported that using CFRP increased the ultimate strength of RC wall and proposed an empirical formula for concrete walls with a slenderness ratio of 20 and two types of CFRP pattern applications (alongside openings and 45^0 to the opening). However, based on the knowledge of authors, the current research is the first investigation into the use of CFRP strengthening of RC walls with high slenderness ratios under one-way action and with three sides restrained.

In real structures, when CFRP is used for strengthening of RC wall with openings, it is common to anchor the CFRP. This would typically involve attachment to some rigid point both above and below the structural element being strengthened. When these walls experience eccentric axial loading, the CFRP will effectively induce tensile forces as a result of the anchoring, therefore supporting the wall until failure. However, when the CFRP was not attached to any rigid element, the effectiveness of the CFRP may be compromised due to its application being parallel to the loading direction. This confinement is an important aspect of CFRP investigations.

In order to better understand CFRP strengthened RC wall behaviour, an experimental program has been undertaken on six (6) half-scale RC walls with various support conditions. All panels with a slenderness ratio of 30 were subjected to uniformly distributed axial loads with an eccentricity of $t_w/6$. To compare the effects of CFRP strengthening; two types of CFRP layout have been investigated.

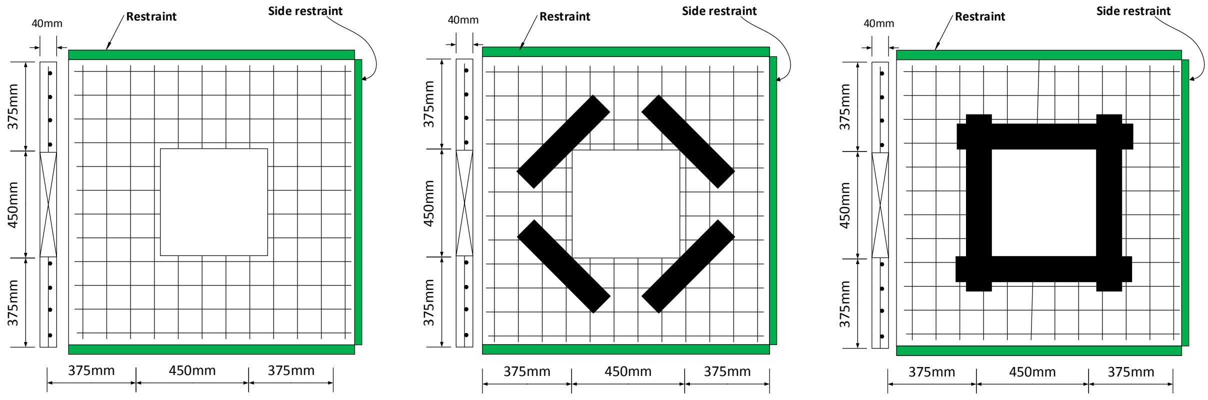
EXPERIMENTAL WORK

An experimental test was undertaken on RC walls with and without CFRP, working under one-way and two-way action. Six (6) half-scaled wall panels supported on two and three sides, with identical opening dimensions and locations, were tested to failure. Details of test specimen dimensions are shown in Figure 1 and 2. The panels have been designated as: 1) OW- one way buckling with two sides supported; 2) TW3S- two-way buckling with three sides supported; 3) NF - no CFRP; 4) AF using CFRP Alongside the opening and 5) DF using CFRP diagonal to the opening. For all wall series, aspect ratio (H/L), slenderness ratio (H/ t_w), and thinness ratio (L/t_w) were 1, 30 and 30, respectively. The percentage of the opening in this research was 14%, warranting the intervention of CFRP. The test procedures adopted were those described by (Doh and Fragomeni 2006). All walls were axially loaded at an eccentricity of $t_w/6$. The opening size and location is shown in Figure 1. The restraints of all panels have been shown by green colour (Figure 1). As the primary purpose of this investigation was to analyse the influence of strengthening patterns and the structural behaviour of one-way and three side restraints, the reinforcement ratios were kept constant for all walls. Single F41 mesh (4 mm diameter, 100 mm spacing and f_y = 450 MPa) was placed centrally in the cross section of the panels. The reinforcement ratios conformed to the minimum requirements of the Standards. Walls were loaded up to failure and crack patterns, load vs deflections were recorded.



(a) OW-NF (b) OW-DF (c) OW-AF

Figure 1. RC wall panels in one way action and CFRP layout



(a) TW3S-NF (b) TW3S-DF (c) TW3S-AF

Figure 2. RC wall panels with three sides restraint and CFRP layout

CFRP CONFIGURATION

A simplified method proposed by Enochsson et al. (2007) has been applied to CFRP strengthening in wall panels. The method was to investigate the replacement of reinforcement in the vicinity of the opening of the two-way RC slab to the minimum CFRP sheet surrounding the opening region. They suggested the traditional method according to BBK 04 (The Swedish Building Administration's Handbook on Concrete Structures), in order to calculate the required steel reinforcement for slabs or walls with openings. The CFRP material properties are listed in Table 1 and the minimum amount of CFRP sheet was determined as indicated in Table 2. Figure 1 and 2 illustrate the typical CFRP layout for current test specimens. The resign used in the application of CFRP was Sikadur 330, with the dry method used for application. The procedure was based on the technical product data sheet provided by Sika Pty. Ltd.

Table 1. Properties of CFRP: SikaWrap – 230C (SIKA Australia Pty. Ltd)

Areal weight g/m^2	Thickness mm	Density g/cm^3	Tensile Modulus N/mm^2	Tensile Strength N/mm^2	Elongation at Failure (%)
230±10	0.128	1.8	234000	4300	1.8

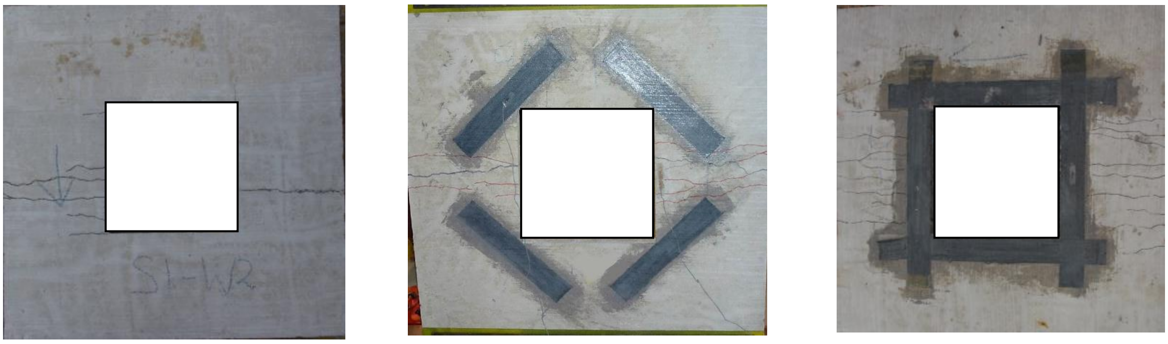
Table 2. Dimensions of the applied CFRP sheets

Length of opening (mm)	Width of opening (mm)	AF		DF	
		Width of CFRP (mm)	Length of CFRP (mm)	Width of CFRP(mm)	Length of CFRP (mm)
450	450	105	770	105	450

RESULTS AND DISCUSSION

Crack Patterns

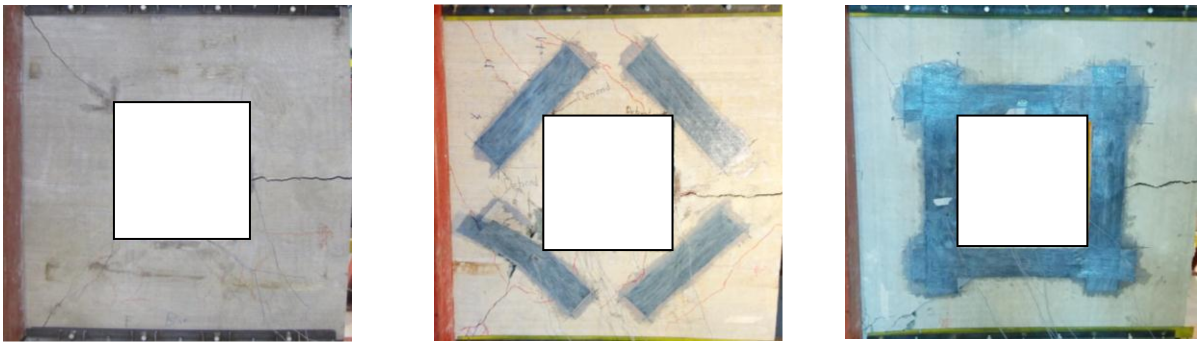
The crack patterns observed on the tension face of the wall panels tested, after failure, are presented in Figure 3 and 4. The crack patterns of all one-way action walls were horizontal with failure occurring near the centre of the panels, typical significant bending failure. In general, there was no evidence of the failure mode on the confinement between CFRP and concrete. In NF appplication, a catastrophic failure happened, with major cracking observed at the centre. In DF and AF layouts, distributed cracks were observed and the failures were not catastrophic.



(a) OW-NF (b) OW-DF (c) OW-AF

Figure 3. Crack pattern of one-way action panels

Based on previous research by Doh et al. (2010), for two-way action walls with three sides restrained, the panel experienced biaxial bending. It was reported that that major crack propagated diagonally from the restrained corner to the opening and then horizontally from the opening to unrestrained edges. This unique cracking mode indicates typical two-way behaviour close to the restrained ends and one-way behaviour between unsupported edges (Doh et al. 2010). The application of the CFRP changed the load path and therefore changed the shape of the crack patterns due to the resistance of the CFRP provided. The CFRP was bonded with the substrate until the failure load was achieved (Figure 4b). The crack patterns on the tension face, of the RC walls with three sides retrained, are presented (Figure 4). In walls strengthened with CFRP, the failure was not catastrophic and distributed cracks were observed.



(a) TW3S-NF (b) TW3S-DF (c) TW3S-AF

Figure 4. Crack pattern of three-side restrained walls

Ultimate Strength:

The experimental test results including the ultimate loads and the axial strength ratios, $N_u / (f'_c L t_w)$, together with the concrete strengths are presented (Table 4).

Table 4. Ultimate load of RC wall panels

Designation	Ultimate Load N_{u0} (kN)	f'_c (MPa)	$\frac{N_{u0}}{f'_c L t_w}$	Increase of ultimate load %
OW-NF	273.9	54.72	0.104	1.0
OW-DF	315.2	55.07	0.119	15.1
OW-AF	348.5	54.72	0.133	27.2
TW3S-NF	450	60	0.156	1.0
TW3S-DF	699	60.5	0.241	55.3
TW3S-AF	660.6	58.5	0.235	46.8

It is obvious that the failure loads for three-side restrained walls are much higher than the corresponding specimens of one-way action panels (Table 4).

Table 4 indicates that for the one-way panels, the ultimate strengths of OW-NF to DF and AF wrapping patterns have led to a strength increase of 15.1% and 27.2% respectively. It is evident that the CFRP wrapping pattern on the concrete wall has an obvious influence on the ultimate strengths. However, this observation contradicts the results obtained by Mohammad et al. (2013). Their study presented CFRP pattern DF as achieving higher load capacities.

For the two-way action panel, with three sides restrained, the CFRP wrapping has a significant effect on wall strengths, however, the DF wrapping wall panel led to slightly higher strength increases than the corresponding AF panel. The wall strengths increased by 55.3% and 46.8 % for DF and AF, respectively. This finding shows that for the DF pattern, as CFRP was applied perpendicular to the crack direction, the load carrying capacity increased more than pattern AF. The flexural behaviour of unstrengthened RC walls were presented in previous research (Doh et al. 2010, Doh and Fragomeni 2006) and the results in strengthened walls show the enhancement of flexural strength due to CFRP application.

CONCLUSIONS

An experimental study was undertaken on six RC walls with openings under one-way action and with three sides restrained. The walls were loaded with an eccentricity of $t_w/6$, and these half-scale specimens exhibited a high slenderness ration of 30. Two different CFRP patterns were applied and results showed the load carrying capacity of RC walls with openings strengthened with CFRP has been improved in one-way action. The application of CFRP alongside the opening (AF) has had a better results than CFRP application at 45^0 (DF). However, for two-way action walls with three sides restrained, the application of CFRP in 45^0 (DF), increased the load carrying capacity of the wall more than the alongside application (AF). This study found that CFRP application greatly changed the strength of wall panels with various support conditions and CFRP layouts. Further investigations are required to determine the behaviour of RC walls with two-way action and all four sides restrained using alternative CFRP layouts.

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