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Experimental study on reinforced concrete walls with opening strengthened by externally bonded CFRP

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Abstract:

Reinforced Concrete (RC) walls with opening under eccentric axial loads exhibit cracks around the opening leading to reduction in the ultimate strength of wall. These cracks are mainly due to changes in load path within the wall and stress concentration around the opening. Strengthening is usually required to enhance the ultimate strength of the wall and Carbon Fibre Reinforced Polymer (CFRP) is a suitable option for this purpose. In this paper, eighteen (18) one-third scaled RC walls with opening were strengthened using seven distinct Externally Bonded (EB) CFRP layouts and were loaded up to failure under various support conditions. These walls, were subjected to a uniformly distributed axial load with an eccentricity of one sixth of the wall's thickness. Crack patterns, failure modes, ultimate strength, and typical strain measurement of CFRP-concrete interface are presented and discussed in detail. The experimental outcomes revealed that CFRP layout enhance the ultimate strength of RC walls between 14.0-59.7% and 3.0-40.8% for walls under one-way and two-way actions, respectively. The efficiency of each CFRP layout is also investigated to prioritise the appropriate layouts for each specific support condition.

Keywords: CFRP; RC wall; de-bonding; strengthening; supports.

Introduction:

Reinforced Concrete (RC) structures require strengthening/retrofitting due to deterioration caused by environmental effects, poor initial construction, excessive loading, or a lack of required maintenance. RC walls often experience eccentric loading conditions due to imperfections in construction, corbel elements attached to the wall, uneven loading conditions on top of the wall, or temporary loading during/after construction. Presence of an opening within RC wall under eccentric axial load results in cracks around the opening and a reduction in load carrying capacity.

Load bearing walls with free vertical edges that are only restrained on top and bottom behave in one-way action (see Fig. 1 (a)). In core of tall buildings, axially loaded walls behave in two-way action when restrained on three sides (Fig. 1 (b)) or four sides (see Fig. 1 (c)). A typical crack pattern and curvature scenario for a wall with single opening behaving in one-way action and two-way action is also depicted in Fig. 1. By providing side supports, the wall exhibits double curvature behaviour in both parallel and perpendicular directions shown as X-axis and Y-axis in Fig. 1 (a).

Carbon Fibre Reinforced Polymer (CFRP) is a suitable option for strengthening RC walls by enhancing the ultimate strength. National codes and standards devote separate chapters for FRP applications in RC members (ACI 440- 2008; FIB-14 2001; JSCE 2000; TR 55 2012). The behaviour of RC walls without FRP strengthening scheme has been investigated considering various material properties, geometry, and support conditions (Ho and Doh, 2018; Ho et al. 2017; Popsecu et al. 2015, 2016; Sabau et al. 2016; Doh and Fragomeni 2005; Doh and Fragomeni 2006; Fragomeni et al. 2012; Saheb and Desayi 1989, 1990) and guidelines have been provided to design the RC walls (ACI-318 2014; AS3600 2009). However, limited study has been conducted on the behaviour of CFRP strengthened RC walls.

Mohammed et al. (2013) proposed design equations based on experiments of eight RC walls under one-way action with two different CFRP layouts. Various opening (window) sizes (5, 10, 20, 30 percentage) were considered at the centre of the RC wall. The specimens had an aspect ratio (H_w / L_w), slenderness ratio (H_w / t_w) and thinness ratio (L_w / L_w) of 2, 20, and 10, respectively. The test outcomes indicated that the Externally Bonded (EB) CFRP applications on RC walls in one-way action would increase the ultimate strength of walls between 8% and 90%, depending on the opening size and CFRP layout. Mohammed et al. (2013) reported that applied CFRP layout with 45 degree angle to the opening corners resulted in a higher contribution to ultimate strength in comparison to cases where CFRP were applied all around the opening.

Lima et al. (2016) completed a FE analysis on CFRP strengthened RC walls with opening in one-way action with two different CFRP patterns. It was evident that the CFRP has greater contribution in ultimate strength of the wall when the opening size increases and more CFRP is applied. The investigation also revealed that for wall with one-way action, the application of CFRP layout with 45^0 to the opening corners resulted in a lower enhancement in ultimate strength in comparison to the case of wall with CFRP applied all around (0/90 degree) the opening. This finding was in contradict with the outcome presented by Mohammed et al. (2013). Unlike the experiment's outcome presented by Mohammed et al. (2013), the FEM simulation showed that the wall with CFRP applied all around (0/90 degree) the opening had a better effect on the strength of the RC wall, as the weakest part of the wall was strengthened.

Popescu et al. (2016) conducted an experimental investigation on FRP strengthened RC walls with door-opening with four sides restraints (TW4S). The FRP was wrapped around the opening with a mechanical anchorage system. Some specimens were pre-cracked by loading up to 75% of the wall axial capacity and some other were un-cracked. FRP-confinement and mechanical anchorages increased the axial capacity of walls with small (25%) and large (50%)

openings by 34-50% and 13-27%, respectively. This enhancement in ultimate load is equivalent up to 94.8% and 63.4% of the corresponding solid wall, respectively. Concrete crushing of wall and de-bonding of FRP sheet was observed at ultimate load.

Popescu et al. (2017) proposed a formula to calculate the ultimate load of fully wrapped CFRP walls under axial (in-plane) loading. The contribution of CFRP was calculated indirectly, by updating the concrete model with an enhanced compressive strength as a result of confining the piers (the sides of opening).

A summary of previous experiments outcome is presented in Table 1 in form of dimensionless quantity, i.e. the axial strength ratio and the numbers in the parentheses represents the enhancement (in percentage) of the axial strength ratios between the control walls (without CFRP) and CFRP-strengthened walls for each specimen. For more detailed description about the experiments and findings, the original articles can be referred.

Even though, a few studies have been conducted on CFRP strengthened RC walls, these investigations have some shortcoming that are outlined herein:

a) Previous design formulae for CFRP strengthened walls in one-way action are not applicable for various CFRP layouts. Also, the current formula for CFRP strengthened RC walls in two-way action is only applicable for specimens with fully wrapped CFRP.
b) Unlike the experiment's outcome (Mohammed et al. 2013), the study conducted by Lima et al. (2016) confirmed that the specimen of CFRP layout with 45 degree angle to the opening corners resulted in a lower contribution to the ultimate strength in comparison to that with CFRP applied all around the opening for walls under one-way action. The current research is aimed to clarify the previous findings.

Hence, additional studies were required to obtain a better understanding of the RC walls' behaviour strengthened with various CFRP layouts and tested under different support conditions. Since only the axial load capacities of CFRP strengthened concrete walls with opening was of interest in this study, neither horizontal in-plane nor lateral forces were applied during the experiment. The walls were subjected to a uniformly distributed in-plane axial load with an eccentricity of $t_w / 6$ which is the limit scope of the AS3600 (2009).

Test walls and test set up

Test walls

Experiments were undertaken on RC walls with and without CFRP layouts, under one-way action ((OW, Fig. 1 (a)) and, two-way action with three sides restrained (TW3S, Fig. 1(b)) and two-way action with four (all) sides restrained (TW4S, Fig. 1(c)). In total, eighteen (18) RC walls were tested up to failure load. The walls are designated as: 1) **OW**: one-way buckling with supported top and bottom only; 2) **TW3S:** two-way buckling with three-side supports; 3) **TW4S:** two-way buckling with four-side supports. The nomenclature for seven distinguished CFRP were designated as: NF- no CFRP (Control wall); AF- alongside the opening; DF- diagonal to the opening; CF- a combination of AF and DF; WF- a combination of DF and wrapped around the opening's corners; PF- parallel to the opening; MF- a mix of diagonal and parallel layouts to the opening, and FWF-: fully wrapped around the opening. NF, AF, DF, CF, and WF layouts were tested for walls with OW, TW3S, and TW4S. PF and MF layouts were tested for walls with OW and TW3S, respectively. The walls dimensions and CFRP layouts are detailed in Fig. 2.

The dimension of RC walls was 1200 mm ×1200 mm × 40 mm $(H_w \times L_w \times t_w)$. For all wall series, slenderness ratio (H_w / t_w) was 30 and all walls were axially loaded at an eccentricity of $t_w / 6$. In the current AS3600 (2009), the effects of openings can be neglected for TW4S if the total area of the openings is less than 10% of the area of the wall and the height of any opening is less than 1/3 of the height of the wall. Therefore, in this study the opening ratio of the wall was selected as 14% which is beyond the limit of AS3600 (2009) for walls with TW4S to be considered as wall with opening. The size of the opening was constant within all RC walls in order to investigate the efficiency of CFRP layouts between various support condition.

CFRP layouts were selected and applied considering the expected behaviour of the wall and observed crack patterns in previous investigations (Fig. 1). Horizontal crack pattern was reported within OW walls, therefore the CFRP was applied perpendicular to the crack direction (AF and CF layouts). However, a CFRP layout was applied 45 degree to the opening to investigate the discrepancy between the outcomes of finite element analysis (Lima et al, 2016) and experimental analysis (Mohammad et al. 213). The effect of the extended CFRP layout was the main focus in wall OW-PF. The wall with MF layout was strengthened by applying CFRP with 45^{o} near the side support and alongside opening at the free-edge in which the layouts were applied perpendicular to the crack direction. In CF layout, a combination of CFRP layouts in 45^{o} and alongside opening was applied. The effect of fully wrapped CFRP around the opening is investigated in wall TW3S-FWF where the wall behaves as a slender-column at the free-edge.

Strain gauges were installed at critical positions to investigate the potential de-bonding between concrete and CFRP layout in all RC walls. As the primary purpose of this investigation was to analyse the influence of strengthening patterns and the structural behaviour of walls under one-way, and two-way actions, the reinforcement ratios were kept constant for all walls. Single F41 mesh (4 mm diameter, 100 mm spacing and nominal tensile strength, ($f_y = 500$ MPa) was placed centrally in the cross section of the walls. This reinforcement ratio was taken approximately the minimum level required by the AS3600 (2009)

The concrete was provided by a local ready mix supplier using general purpose cement, sand, and 10 mm aggregates. No admixtures were used in concrete mixes. The initial concrete compressive strength for design was equal to 50 MPa. Walls were cast horizontally in specially made timber moulds with reinforcement secured at the centre of the cross-section using tie wires on 20 mm high chairs. High density polystyrene foam was placed in specific positions on the timber moulds to ensure openings were formed in the places required. Walls were cast in batches of six, to maximise the usage of moulds and concrete delivered.

CFRP amount and size

A simplified method proposed by Enochsson et al. (2007) was utilised to determine the amount of required CFRP for strengthening of RC walls. The concept of their method is to replace the cut reinforcement within the opening with equivalent CFRP sheet around the opening. This method is based on the Swedish Building Administration's handbook on concrete structures BBK04 (2004). Fig. 2 illustrates the CFRP layout for all walls. The width and anchorage length of CFRP layout was calculated based on the following formulae (Eqs. 1-4):

$$a = \frac{A_{s2} f_{sy}}{0.85 f_c' L_w} \quad \text{Eq. 1}$$

$$x = \frac{a}{0.85} \quad \text{Eq. 2}$$

$$A_f = \frac{E_{s2}}{E_f}\left(\frac{t_w - u - x}{t_w - x}\right)^2 A_{s2} \quad \text{Eq. 3}$$

$$W_f = \frac{A_f}{t_f} \quad \text{Eq. 4}$$

where: f_c' is concrete compressive strength; L_w is concrete wall length; f_{sy} is steel yield stress; t_w and t_f are the thickness of wall and CFRP, respectively; E_s and E_f are modulus of elasticity of steel and CFRP, respectively; u is concrete cover of reinforcement; A_{s2} and A_f are the area of additional steel reinforcement and CFRP cross sectional area, respectively; a is the depth of the equivalent rectangular stress block, and W_f is the width of the required CFRP.

The width of CFRP layout was 105 mm for all test walls, except for the wall TW3S-FWF where a width of 450 mm was used to fully wrap the opening. In order to have an estimation of the effective anchorage length ($L_{b\,max}$) of CFRP, a proposed formula (Eq. 5) for concrete beams was used (*CEB-FIP* 1993). Based on the recommendation provided in FIB Bulletin 14 (2001), an increase in anchorage length does not result in an increase in resisting the tensile stress due to the limitation of fracture energy.

$$L_{bmax} = c\sqrt{\frac{E_f t_f}{\sqrt{f_{ctm} f'_c}}} \qquad \text{Eq.5}$$

Where, $c = 1.44$ (constant) and f_{ctm} is the tensile strength of the concrete. The effective anchorage length was added to the opening size to calculate the total length of required CFR. An additional length was also added to the CFRP layer to provide a cross coverage of two perpendicular layers. The CFRP material properties are listed for reference in Table 2. The minimum amount of required CFRP sheet is presented in Table 3. For all CFRP applications, the width of layout was the same, while the width of the FWF layout was equal to the opening length.

Application of CFRP layouts

An epoxy system consisting of two parts, resin and hardener in a weight ratio of 4:1 was used in a dry-layup process. Initially, the well mixed Sikadur-330 [Sika 2014] was applied to the prepared substrate by lamb skin roller. Later, Sika Wrap-230C [Sika2014] was placed onto the resin coating. Finally, the fabric was carefully worked into the resin with a plastic roller until the resin was squeezed out between the rovings. The walls were then left to dry for 14 days as was specified by the supplier. The CFRP layouts were applied on the tension side of the RC walls, except for FWF and WF patterns in which CFRP layer was totally wrapped around the opening or a u-shaped pattern was applied around the corner of opening.

Test set-up

The test set-up arrangement is presented in Fig. 3. The test frame was designed to support three independent hydraulic jacks able to apply loads up to 800 kN individually. The hydraulic jacks applied a uniformly distributed load across the top of the wall at an eccentricity of $t_w / 6$. The 250UC72 supporting beam on the strong floor was identical to the loading beam at top. The top and bottom hinged support conditions were each simulated by placing a 40 mm diameter high strength steel rod on an 8 mm thick steel plate of 150 mm width. Two 40×40 mm equal angles were clamped to the thick plate using bolts. The steel rod was welded along the steel plate at an eccentricity of $t_w / 6$. Details of the simply supported top hinged edge are presented in Fig. 3(b). To achieve the hinged side support conditions for two-way action, the edges of the walls had to be effectively stiffened in the perpendicular direction to prevent rotation around the X-axis while allowing rotation around the Y-axis (X and Y axes are shown in Fig. 1). To achieve this, two 150 Parallel Flange Channels (PFC) separated by a Square Hollow Section (SHS) extending along the height of both sides of the test wall were used (Fig. 3(c)). The side restraints were tied up with high tensile bolts (with 16 mm diameter at 100 mm span) through the SHS, to take advantage of the stronger axis of the section. Dial gauges were used to measure the deflections of the walls during testing (Fig. 3(a)). The position of dial gauges on the walls during the experiments is presented in Fig. 4. Four dial gauges were positioned midway between the edges of the panel and the edges of the opening to measure out-of-plane deflections. A single dial gauge was also installed to measure the vertical shortening or in-plane deflection of the RC wall. Strain gauges were also installed to monitor the critical points such as the corner of the wall openings, top of the CFRP and at the CFRP-concrete interface for detecting any potential de-bonding. In Fig. 2, the location and type of strain gauges for each test sample is presented. The Rossete strain gauges were installed on the corner of the opening (Fig, 2(a)). For clarity, the Rossete strain gauges are not shown on the CFRP strengthened walls. The orange and blue colours are representing the concrete and CFRP strain gauges, respectively.

Test procedure

A static loading regime was adopted for the experiment. A load cell was positioned at the centre of the hydraulic jacks on top of the loading beam. Load was applied per hydraulic jack incrementally at 4.9 kN up to failure (force controlled). Due to lack of equipment and facility for completion of test using displacement control, the force control approach was utilised.

Experimental results and discussion

Crack Patterns

One-way action (OW)

Provided restraints at top and bottom, the RC walls experience horizontal cracks throughout the middle of the opening, as shown in Fig. 5 (a). For the OW-NF wall without CFRP, similar bending failure for RC walls with opening under eccentric axial loading has been reported in the previous studies (Doh and Fragomeni 2006; Fragomeni et al. 2012).

The crack patterns after failure, observed on the tension face of the walls tested under one-way action, are presented in Figs. 5(b), 5(c), 5(d), 5(e), and 5(f). In most cases, more distributed cracks were observed for strengthened walls compare to corresponding control sample.

Wall OW-DF presented a few large cracks on the tension face, similar to the failure mode observed for the wall OW-NF. This indicates that the DF layout in walls under one-way action did not provide sufficient contribution to the performance of the wall accompanying a brittle failure. In contrast to the findings in Mohammed et al. (2013) which reported above 50% increase in ultimate load for a similar size of opening, the results revealed only a 15% increase in the ultimate strengths between OW-DF and OW-NF walls. The CFRP application alongside the opening for OW-AF, OW-CF, and OW-PF walls resulted in more distributed cracks within the RC walls around the opening on the tension side in compare to OW-DF and OW-NF. This observation indicates that these CFRP layouts enhanced the performance and ultimate strength of the walls. Although bending failure was predominant in these walls, there was adequate evidence to confirm that some compressive crushing failure also occurred.

For OW-WF wall, a catastrophic collapse was observed with some reinforcements yield. The failure pattern for this wall was still a flexural bending failure. The brittle nature and failure across the thickness of the wall is due to load transferring between compression and tension faces of the walls as the u-shaped CFRP was wrapped around the corner of the opening.

As shown in Figs. 5(b), 5(c), 5(d), 5(e), and 5(f), on the tension side of the walls, there was no evidence of de-bonding between CFRP and concrete before ultimate load was reached. For walls OW-DF and OW-WF, there was no evidence of de-bonding even after failure load (Figs. 5(b) and 5(e)). Further details are presented in strain gauge data measurement section.

Two-way action with three sides restrained (TW3S)

The tested TW3S walls exhibited crack patterns and failure modes that were consistent with the expected behaviour of walls supported on three sides. Biaxial curvature was evident as idealised in Fig. 1(b). It is evident that the majority of cracking propagated diagonally from the restrained corners to the opening and then horizontally from the opening to the unrestrained edge. This unique cracking mode indicates a typical two-way behaviour close to the restrained ends and one-way behaviour close to free edge. Similar crack patterns were reported in the experimental tests conducted by Doh et al. (2010) as highlighted in Fig. 6 (a),

The application of the CFRP changed the load path and therefore changed the shape of the crack patterns due to the resistance provided by CFRP (Figs. 6(b), 6(c), 6(d), 6(e), 6(f), and 6(g)). Walls with CFRP perpendicular to the crack direction (TW3S-DF, -CF, -WF and -MF) represents more ductile behaviour with more distributed. In TW3S-AF wall, three large cracks were observed within the wall propagating from the restrained corners on tension side towards the corner of the opening, accompanied by a single horizontal crack that propagates toward the free edge. This observation indicates a brittle failure mode with possible yielding of some reinforcement. In contrast, TW3S-FWF wall presented more ductile behaviour with a few parallel cracks. As no CFRP layer was used perpendicular to the crack direction near the restrained corners, the crack pattern was analogous to that observed on walls without CFRP. In this case, the fibre orientation was parallel to the crack propagation in the free edge.

Two-way action with all four sides restrained (TW4S)

The crack patterns on the tension face of wall TW4S walls are presented in Fig 7. The TW4S-NF wall showed typical double curvature bending failure characterised by diagonal cracking from the wall's corners propagating towards the corner of the opening, similar to the ideal scenario as shown in Fig. 1(c).

A distinct difference was also observed in failure modes of TW4S walls strengthened with CFRP layouts where more smeared diagonal cracks were evident within the tension side of the wall propagating from the restraints towards the corner of the opening (Figs. 7 (b) and 7(e)).

It should also be noted that the diagonal crack patterns were slightly changed due to wall irregularities and loading condition; however, the anticipated crack pattern was generally observed in most cases. In these cases, the CFRP was also bonded with the substrate until the failure load was achieved.

Deflection measurement

The loads versus out-of-plane and in-plane deflections for all walls are presented in Figs. 8 to 10. The vertical in-plane deflections were also recorded to investigate shortening of the walls. The maximum deflections were obtained just prior to the failure load being reached. The failure behaviour in most of the walls was brittle mode and the deflection at the last stage of loading was not recorded due to sudden failure. Thus, in these figures, the absolute maximum failure loads and the corresponding maximum deflections are not shown.

For walls with OW and TW3S, the maximum out-of-plane deflection was reported at the midway between the free edge of the wall and the edges of the opening (shown as Right Gauge in Fig. 4). As shown in Figs. 8, 9, and 10, the maximum shortenings (in-plane vertical deflection) were generally smaller than the maximum out-of-plane deflection in most of the RC walls. Smaller vertical shortenings (in-plane deflection) were recorded in RC walls under one-way action in comparison to TW3S and TW4S walls at the same load level (Figs. 8, 9, and 10).

For OW walls, the recorded out-of-plane deflection at the left side of the opening was similar to that at the right side. The out-of-plane deflection at the top of the opening was slightly greater than that on the bottom of the RC walls. This observation is due to the proximity of the portion of wall to the loading cell at top of the opening. The maximum out-of-plane deflection of strengthened RC walls was increased by various amounts for alternative CFRP layouts. The out-of-plane deflection profile of OW walls showed a fairly uniform curvature along the height with the maximum deflection at the mid-height. Generally, the profile of all the tested walls under one-way action showed similar behaviour in which, in early stages of loading, slight out-of-plane deflections were produced and then more pronounced deflections observed as the test walls were progressively loaded to failure.

The distinct advantages of TW3S walls compared to OW walls are also evident with less out-of-plane deflections being achieved for the same load level. The deflections near unrestrained support (Right Gauge) indicate that a greater deflection occurred for all cases in wall TW3S in comparison to that with OW. The vertical shortening (in-plane deflection) of walls TW3S was recorded where greater deflections were observed compared to TW4S walls at the same load level. The out-of-plane deflection profiles for the free edge of walls TW3S were similar to that of walls with OW. Based on out-of-plane deflection profiles, it is obvious that the CFRP layer assisted the walls to sustain greater deflections compared to walls without CFRP. A similar behaviour was observed for some of the walls with four sides restrained (TW4S).

Generally, in TW4S walls the out-of-plane deflections at the left and right gauges were similar to observed deflections at the top and bottom gauges. This was obvious as the side, top, and bottom-quarter points should have moved, approximately, by the same amount due to the curvatures taking place in both the vertical and horizontal directions. However, an irregular vertical (in-plane) deflection was observed for the wall TW4S-CF (Fig. 10(d)), where the CFRP layout provided a robust lateral support around the opening and the major failure mechanism was concrete crushing at the top restraint. For this case, given the restraint conditions, the CFRP layout was covered large portion of wall and prevented the wall to rotate appropriately. This condition was resulted in excessive stress concentration within the top edge of the wall and localised crushing near support.

Strain gauge data measurements

Strains were also measured to monitor the critical points such as the corner of the wall openings, top of the CFRP and at the CFRP-concrete interface for detecting any potential de-bonding. Strains were recorded at each load increment for all RC walls. The tested wall had a brittle mode and the sudden failure of these walls made it difficult to record strain precisely, at the last step of loading. Based on the obtained data and observation, the CFRP was bonded with the substrate until the failure load was achieved. Generally, an abrupt change was noticed in the obtained strain data during the last stage of loading. A few of these outcomes are selected and presented in this section. Fig. 11 presents the location of the strain gauges on top of the CFRP layer and concrete (interface) for OW-CF and Fig. 12 depicts the load versus strain diagram. The measurement of strain on top of the CFRP layout was identical to that of the gauge located at the CFRP-concrete interface. This was further evidence that the concrete and CFRP were intact and fully bonded until the ultimate load was achieved. The loads versus strain were linear for initial loading stages, and then a non-linear trend was observed where strain rapidly increased approaching failure phase. For OW-CF wall, the load-strain curve exhibits a linear behaviour up to a loading stage at approximately 30% of the ultimate load. A similar observation was made for TW3S-CF (Figs. 13 and 14) and TW4S-CF (Figs. 15 and 16). For TW3S-CF and TW4S-CF walls, the load-strain curves were essentially linear up to 70-80% of the ultimate load where a low strain and brittle behaviour was recorded for these walls.

The strain gauges that were installed on top of the CFRP layer did not reveal any abrupt changes in the obtained strain data during testing and before the last stage of loading and failure. Figs. 17, 18, 19 and 20 present the location of the strain gauges and load versus strain curves for walls under OW, TW3S and TW4S strengthened with CF and WF layouts. As shown in Figs. 18 and 20, it is noticeable that the CFRP layer enhanced the ultimate strength of walls and it also remained bonded to the concrete.

Ultimate strength

The ultimate strength of the walls were recorded and are presented as a dimensionless quantity, i.e. the axial strength ($N_{uo} / f'_c.L_w.t_w$), shown in Table 4. In this section, the effect of support conditions and the contribution of CFRP layout in enhancement of the ultimate strength of RC walls are discussed.

In Table 3, the numbers in the parentheses represents the enhancement (in percentage) of the axial strength ratios between the control walls (without CFRP i.e. NF) and CFRP-strengthened walls for each support condition. A comparison between the ratio of ultimate loading of walls under various support condition (N_{uo}(OW)/N_{uo}(TW3S) and N_{uo}(OW)/N_{uo}(TW4S)) are also presented in Table 4.

The ultimate strength of RC walls in one-way action was approximately 60% and 40% of that of TW3S and TW4S walls, respectively. The results are similar to the experimental tests obtained by Doh et al. (2010) which indicates that adding side supports increases the load capacity of walls irrespective of any type of CFRP layout.

Alternate CFRP applications resulted in various enhancements in ultimate strength (Table 4). The ultimate strengths of walls under one-way action (OW) with DF, AF, WF, CF and PF layouts resulted in an enhancement of the ultimate strength up to 15.5%, 26.2%, 25.4%, 59.7%, and 14.0%, respectively. However, this observation contradicts the results obtained by Mohammad et al. (2013); they claimed that greater enhancement of ultimate strength is achievable by applying DF pattern rather than AF for OW walls. Although, based on the finding of the current experiment, the higher contribution of CFRP in ultimate strength of OW-AF wall is due to the CFRP application around the weakest part of the wall and it is consistent with the outcomes obtained in a finite element analysis conducted by Lima et al. (2016).

Furthermore, for TW3S walls, the ultimate strength was enhanced up to 28.2%, 40.8 %, 33.2%, 40.8%, 32.9%, and 3.0% for DF, AF, WF, CF, MF, and FWF, respectively. The maximum enhancement was observed in RC walls strengthened with AF and CF pattern. This is mainly due to the CFRP application around the opening and close to free-edge where the wall has similar behaviour to OW walls. The least contribution in ultimate strength was recorded in RC walls strengthened with FWF layout; this insignificant contribution is mainly due to the fibre orientation which was parallel to crack propagation at the free-edge of the wall.

For TW4S walls, the CFRP layout contributed an average of 21.4% gain in ultimate strength. The increases in ultimate strengths were up to 18.4%, 19.3%, 23.0%, and 24.9% for DF, AF, WF, and CF layouts, respectively. The maximum contribution in ultimate strength was observed for RC walls strengthened with WF and CF layouts. This observation was mainly due to the application of CFRP perpendicular to the crack direction.

The study revealed that the axial strength ratio of the walls with CF layout is the largest value that represents the maximum enhancement in ultimate strength of RC walls. This indicates that CF layout may be the best strengthening or retrofitting pattern for walls under any support conditions.

The amount of the applied CFRP was also investigated and compared with the corresponding gain in ultimate strength. For more clarification, the efficiency of each CFRP layout was considered as the ratio of ultimate strength enhancement (%) to the total length of CFRP layout *(L_{CFRP})*.

The findings indicated that the WF pattern resulted in the least efficient layout and minimum enhancement in ultimate strength considering the amount of used CFRP in all three categories of walls under OW, TW3S, and TW4S.

For OW walls, the greatest efficiency was obtained for RC walls strengthened with CF layout where ultimate strength was significantly enhanced up to 59.7%. The AF and DF layouts resulted in similar efficiency while the lowest efficiency was observed for the walls with PF and WF layouts.

For TW3S walls, the maximum efficiency was obtained in walls with DF layout in which the minimum amount of CFRP was utilised. Also, the maximum usage of CFRP was for the FWF pattern, the lowest efficiency was reached in this case. Noteworthy, both DF and WF layouts resulted in identical enhancements in ultimate strength, while the amount of applied CFRP for the WF pattern was triple than that for DF layout. The AF and CF pattern improved the capacity of RC walls identically (by 40.8%); however, the efficiency of DF pattern is clearly superior to that of AF.

Generally, an identical enhancement in ultimate strength was observed for TW4S walls; however, the DF layout resulted in the optimum efficiency in enhancement of ultimate strength.

Conclusions

Fifteen CFRP strengthened and three reference RC walls with opening were constructed and tested under eccentric axial loads. Seven types of CFRP layouts were considered and the effect of these layouts on the behaviour of RC walls was examined under three distinct support conditions. The conclusion of this research is outlined herein:

- Various level of enhancement in ultimate strength of RC walls was achieved under different support conditions and CFRP layouts. For OW walls, an enhancement of ultimate strength between 14.0-59.7% was observed, while this range for walls under TW3S and TW4S was between 3.0-40.8% and 18.4-24.9%, respectively.
- The ultimate strength of OW walls was approximately 60% and 40% of that with TW3S and TW4S, respectively.
- CFRP application changed the load path around the opening and provide more rigidity to the walls around the opening and ease the load transferring to the bottom restraint. This condition altered the crack patterns due to the resistance of the CFRP provided. This was more obvious in cases where the CFRP was applied perpendicular to the typical cracks direction resulted in more distributed cracks.
- Generally, more deflection was observed in CFRP strengthened RC walls compared to that without CFRP. However, due to brittle failure of the walls, the deflection at last step was not recorded.
- De-bonding was not an issue before failure load. This conclusion is based on the obtained data and observations during the test. This finding indicates that additional amount of EB-CFRP for anchoring purposes might not be essential for strengthening RC walls.
- The efficiency investigation of CFRP layouts was also completed. FWF layout was the least efficient pattern of strengthening while it was totally wrapped around the wall. The CF and DF were the most effective layouts for walls under one-way and two-way action, respectively. Application of CFRP perpendicular to the crack direction significantly enhanced the ultimate strength of the wall in compare to the case where the CFRP was not applied perpendicular to the crack direction.

Further research is required to determine the behaviour of RC walls with various opening sizes and locations using alternative CFRP layouts. The outcomes of this study provide a platform to establish a future reliable FEM model to conduct parametric studies considering the effects of various factors.

Acknowledgments

The authors wish to acknowledge an in-kind contribution from SIKA Australia Pty. Ltd by providing the CFRP material and epoxy. The authors also express their thanks to the concrete lab technicians at Griffith University, School of Engineering. The authors wish to acknowledge an in-kind contribution from Dr Mojtaba Ale-Mohamamdi for proofreading of this paper.

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NOTATION

a	= the depth of the equivalent rectangular stress block
A_f	$= \dfrac{E_{s2}}{E_f}\left(\dfrac{t_w - u - x}{t_w - x}\right)^2 A_{s2}$, the CFRP cross sectional area
A_{s2}	= the area of additional steel reinforcement
e	= the load eccentricity (mm)
E_f	= the modulus of elasticity of CFRP in principal direction
E_s	= elastic modulus of steel
f_{ctm}	= the tensile strength of the concrete
$f'c$	= the yield strength of concrete in MPa
f_{sy}	= steel yield stress
f_y	= the yield strength of steel in MPa
H_o	= the dimension of the opening height in mm
HSC	= High Strength Concrete

H_w = the height of the wall in mm

$L_{b\,max}$ = $c\sqrt{\dfrac{E_f t_f}{\sqrt{f_{ctm} f'_c}}}$,effective anchorage length

L_{CFRP} = the length of CFRP layout

L_o = the dimension of the opening length in mm

L_w = the length of the wall in mm

N_{AF} = the ultimate load of CFRP strengthened RC walls using AF layout

N_{CF} = the ultimate load of CFRP strengthened RC walls using CF layout

N_{DF} = the ultimate load of CFRP strengthened RC walls using DF layout

N_{NF} = the ultimate load of CFRP strengthened RC walls using NF layout

N_{uo} = the ultimate design axial strength of wall per unit length (in N/mm)

N_{WF} = the ultimate load of CFRP strengthened RC walls using WF layout

OW = one-way buckling with two sides supported

t_f = CFRP thickness

t_i = the resin thickness

t_w = the wall thickness

TW3S = two-way buckling with three sides supported;

TW4S = two-way buckling with four sides supported

u = concrete cover of reinforcement (mm)

W_f = A_f / t_f, width of the required CFRP

Table 1-summary of previous study on CFRP-strengthened RC walls

Refs	Specimen	Geometrical Dimension (mm)			Opening Dimension (mm)		Type of Opening	Wall Condition	Type of CFRP application	f'_c [3] (MPa)	Capacity N_{uo} [4] (kN)	Axial strength ratio $N_{uo}/(f'_c.L_w.t_w)$
		Height H_w	Width L_w	Thickness t_w	Height H_o	Width L_o						
Popsecu (2016)	II-S	1800	1350	60	1050	450	Door	P-C[1]	Fully wrapped CFRP with mechanical anchor	62.8	2241	0.330 (49%)
	II-L	1800	1350	60	1050	900	Door	P-C		62.8	1487	0.219 (26%)
	III-S1	1800	1350	60	1050	450	Door	U-C[2]		64.4	2178	0.311 (42%)
	III-S2	1800	1350	60	1050	450	Door	U-C		64.4	2009	0.289(31%)
	III-L1	1800	1350	60	1050	900	Door	U-C		64.4	1334	0.191 (10%)
	III-L2	1800	1350	60	1050	900	Door	U-C		64.4	1482	0.213 (22%)
Mohamamd et al (2013)	Wo1b	800	400	40	170	95	window	U-C	EB-CFRP alongside of the opening	15.0	150	0.626 (60%)
	W02b	800	400	40	240	135	window	U-C		17.1	139	0.509 (20%)
	W023b	800	400	40	340	185	window	U-C		18.2	108	0.370 (12%)
	W04b	800	400	40	420	230	window	U-C		15.1	82	0.340 (17%)
	W01c	800	400	40	170	95	window	U-C	EB-CFRP with 45^0 to the opening's corners	14.7	175	0.745 (90%)
	W02c	800	400	40	240	135	window	U-C		15.6	157	0.628 (48%)
	W03c	800	400	40	340	185	window	U-C		16.4	139	0.529 (60%)
	W04c	800	400	40	420	230	window	U-C		17.0	85	0.311 (8%)

Note: [1] P-C: Pre-Cracked; [2]U-C: Un-Cracked; [3] f'_c: Concrete compressive strength; [4] N_{uo} :Ultimate strength of RC walls

Table 2. Properties of CFRP: 230C [Sika 2014]

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

Table 3. Location, width and length of the applied CFRP sheets

CFRP layout	Location in relation to edges of the opening / (confinement, tension or compression side)	Width (mm)	Length (mm)	
			Individual	Total
NF	-	-	-	-
DF	In corner (45^0) / tension	105	450	1800
AF	Along ($0/90^0$) / tension	105	770	3080
WF	In corner (45^0) and wrapped ($0/90^0$) / tension and compression	105	450 and 440	5320
CF	In corner (45^0) and along ($0/90^0$)/ tension	105	450 and 770	4880
PF	Along (90^0)/ tension	105	1480	2960
MF	In corner (45^0) and along (90^0)/ tension	105	1480, 1380	4240
FWF	Fully wrapped around opening / confinement	450	850	1700

Table 4. Ultimate load of RC wall panels

Wall designation	Curing duration	f_c' [1] (MPa)	t_w [2] (mm)	N_{uo} (kN)	$\frac{N_{uo}(OW)}{N_{uo}(TW3S)}$ or $\frac{N_{uo}(OW)}{N_{uo}(TW4S)}$	Axial strength ratio $N_{uo} / f'_c.L_w.t_w$	Efficiency [Increase of ultimate load (%) to L_{CFRP} (m)]
OW-NF	86	54.7	40.0	266	-	0.101	-
OW-DF	113	55.0	40.0	309	-	0.117(15.5%)	8.6
OW-AF	86	54.7	40.0	336	-	0.128(26.2%)	8.5
OW-WF	73	62.6	43.5	415	-	0.127(25.4%)	4.8
OW-CF	73	62.6	46.0	559	-	0.162(59.7%)	12.2
OW-PF	84	64.9	40.0	360	-	0.1165(14.0%)	4.8
TW3S-NF	82	60.0	40.0	440	0.7	0.153	-
TW3S-DF	68	57.0	44.0	589	0.6	0.196(28.2%)	15.7
TW3S-AF	68	58.5	43.0	650	0.6	0.215(40.8%)	13.2
TW3S-WF	74	62.3	46.0	700	0.6	0.204(33.2%)	6.3
TW3S-CF	68	62.3	40.0	643	0.8	0.215(40.8%)	8.4
TW3S-MF	84	65.0	40.0	633	-	0.203(32.9%)	7.8
TW3S-FWF	69	58.4	40.0	441	-	0.157(3.0%)	1.8
TW4S-NF	67	57.6	40.0	647	0.4	0.234	-
TW4S-DF	67	57.6	40.0	766	0.4	0.277(18.4%)	10.2
TW4S-AF	67	56.2	40.0	753	0.5	0.279(19.3%)	6.2
TW4S-WF	75	64.7	40.0	894	0.4	0.288(23.0%)	4.3
TW4S-CF	75	63.2	40.0	887	0.6	0.293(24.9%)	5.1

Note: [1] f_c': Concrete compressive strength; [2] t_w: Wall panel thickness; [3] N_{uo}: Ultimate strength of RC walls

Fig 1

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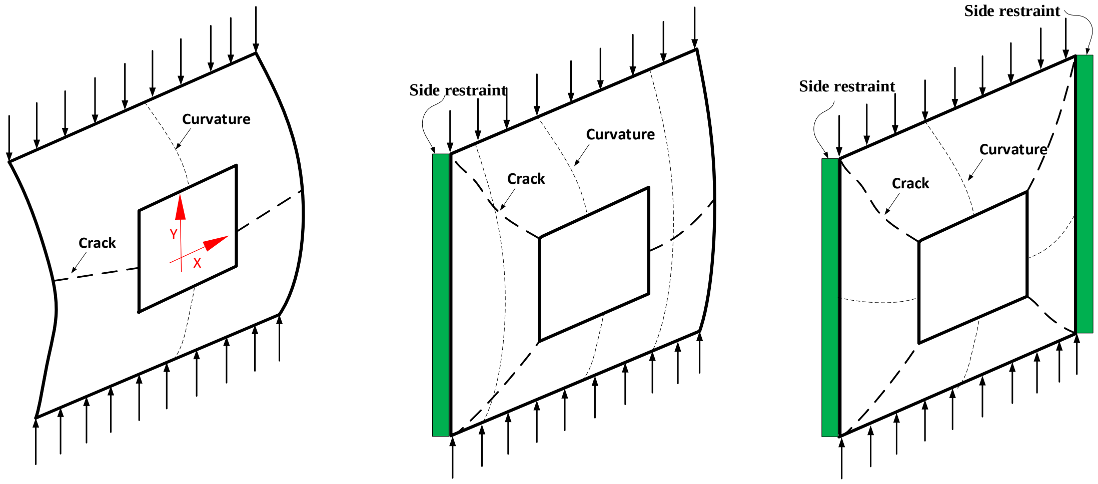


(a) OW (b) TW3S (c) TW4S

Fig. 1. Walls with and without side supports

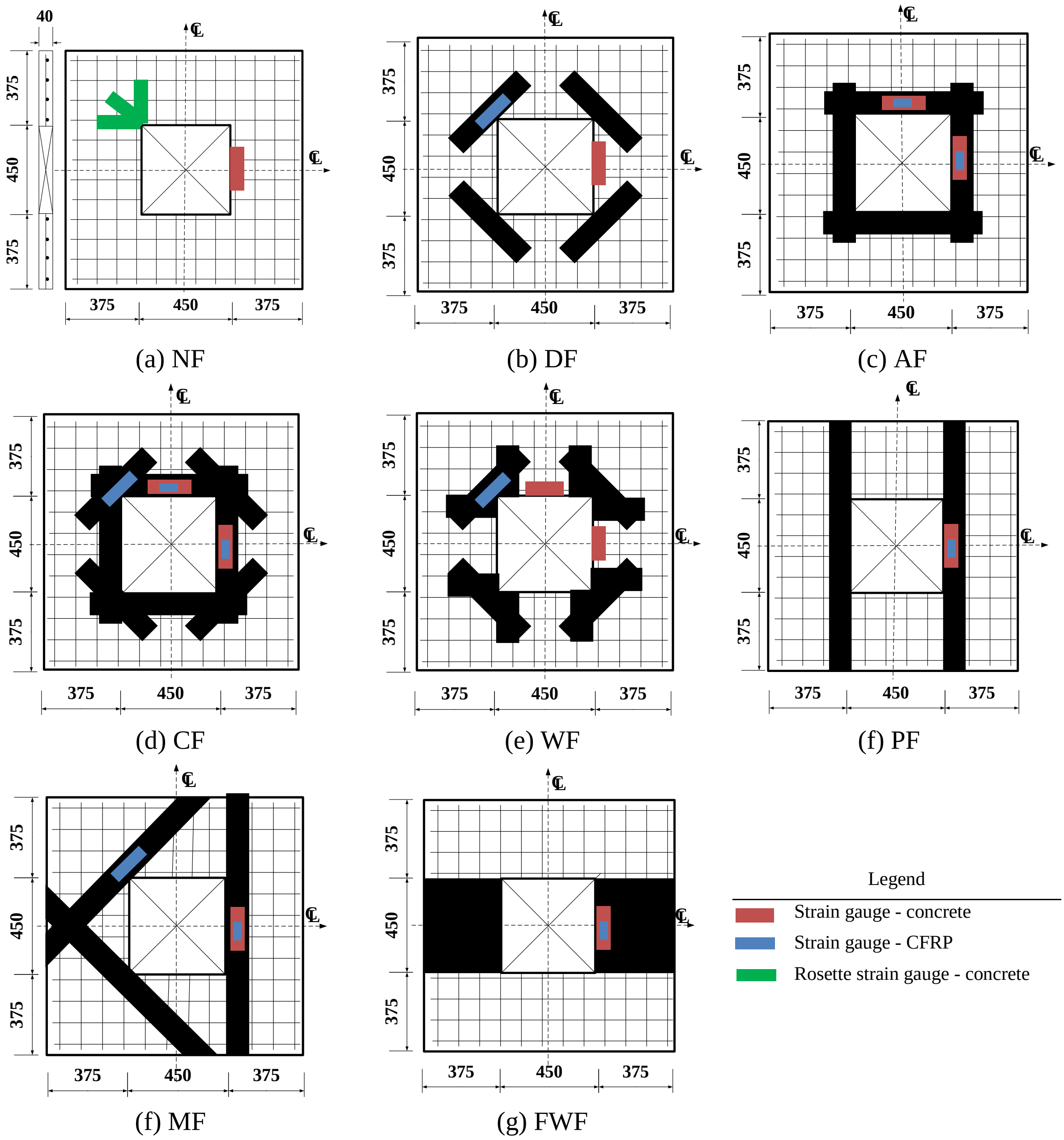
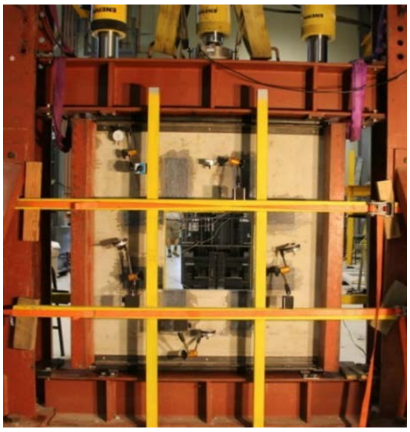
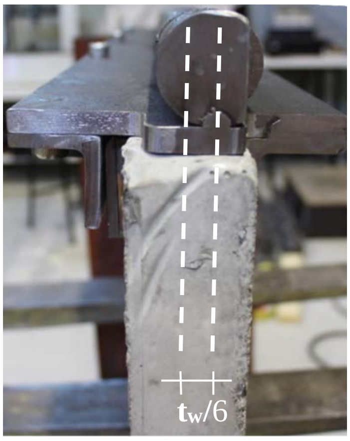


Fig. 2. RC wall panels with/without CFRP layouts and strain gauges (all dimensions are in mm)



(a) Protective shield and dial gauge placement for TW4S-WF



(b) Top and bottom restraint

(c) Top view of side restraint

Fig. 3. Test frame arrangement

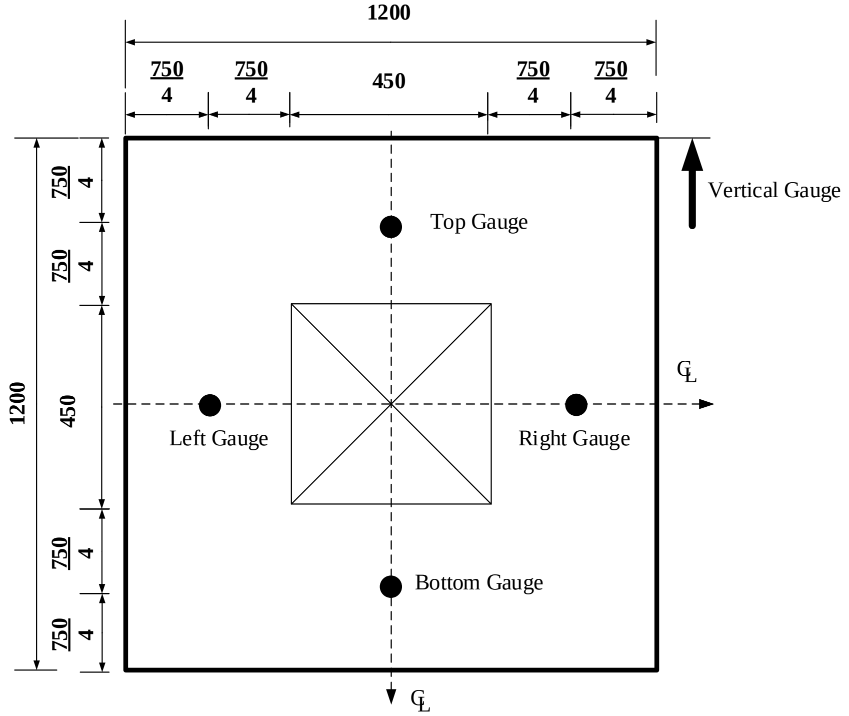
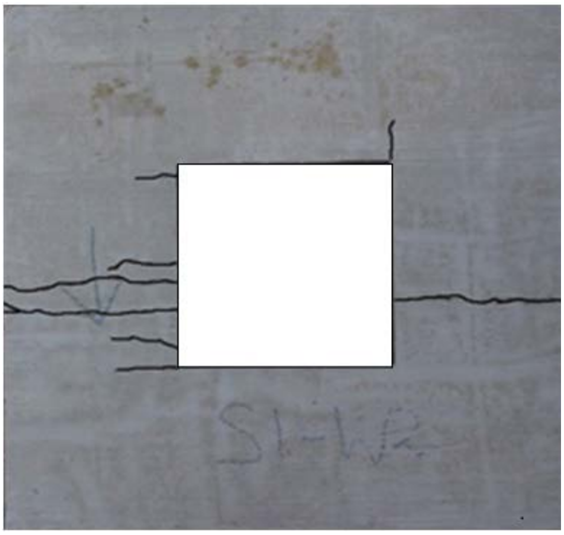
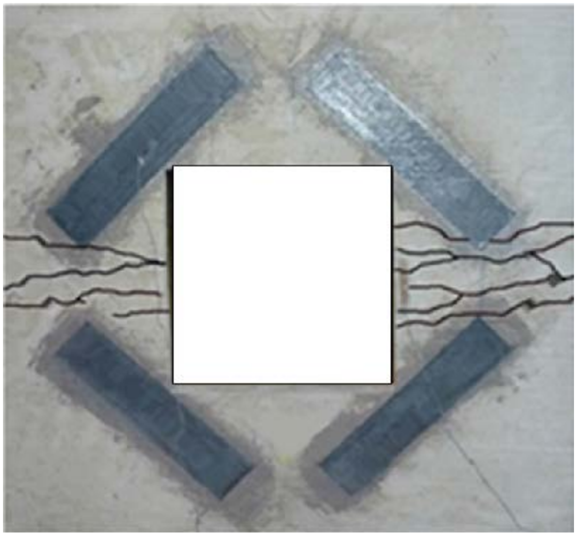


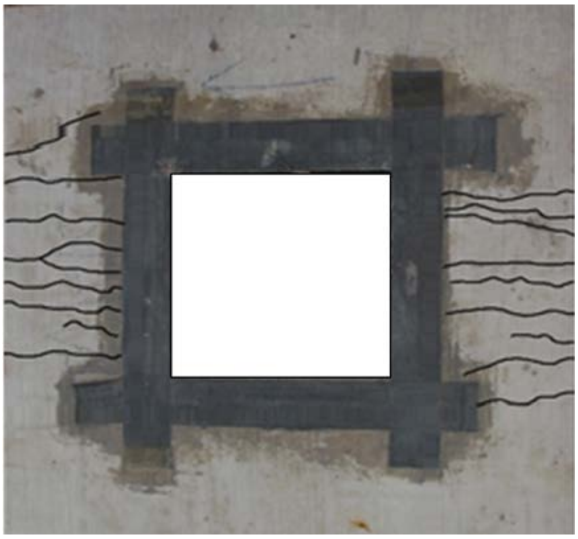
Fig. 4. Typical dial gauge locations on wall panels on the compression side (all dimensions are in mm)



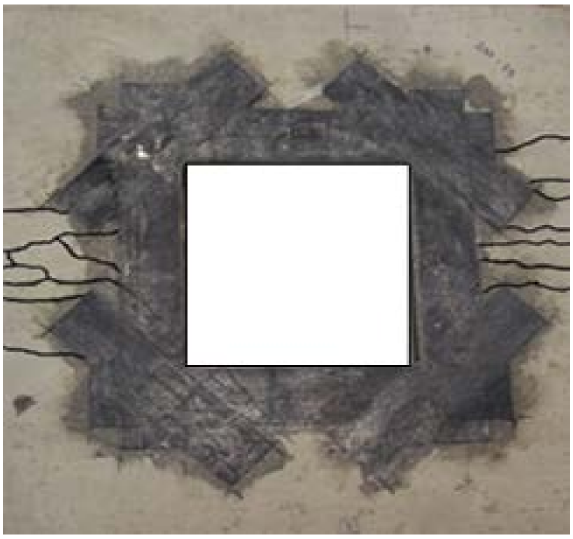
(a) OW-NF



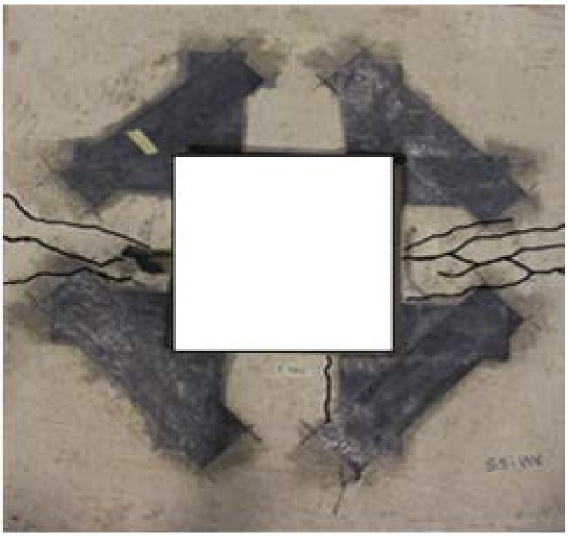
(b) OW-DF



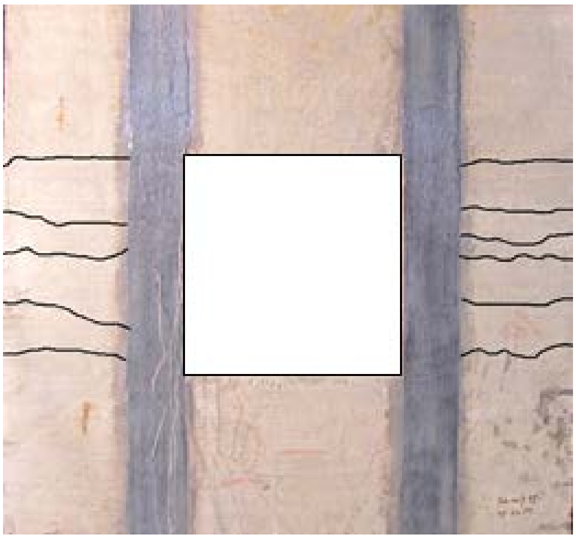
(c) OW-AF



(d) OW-CF

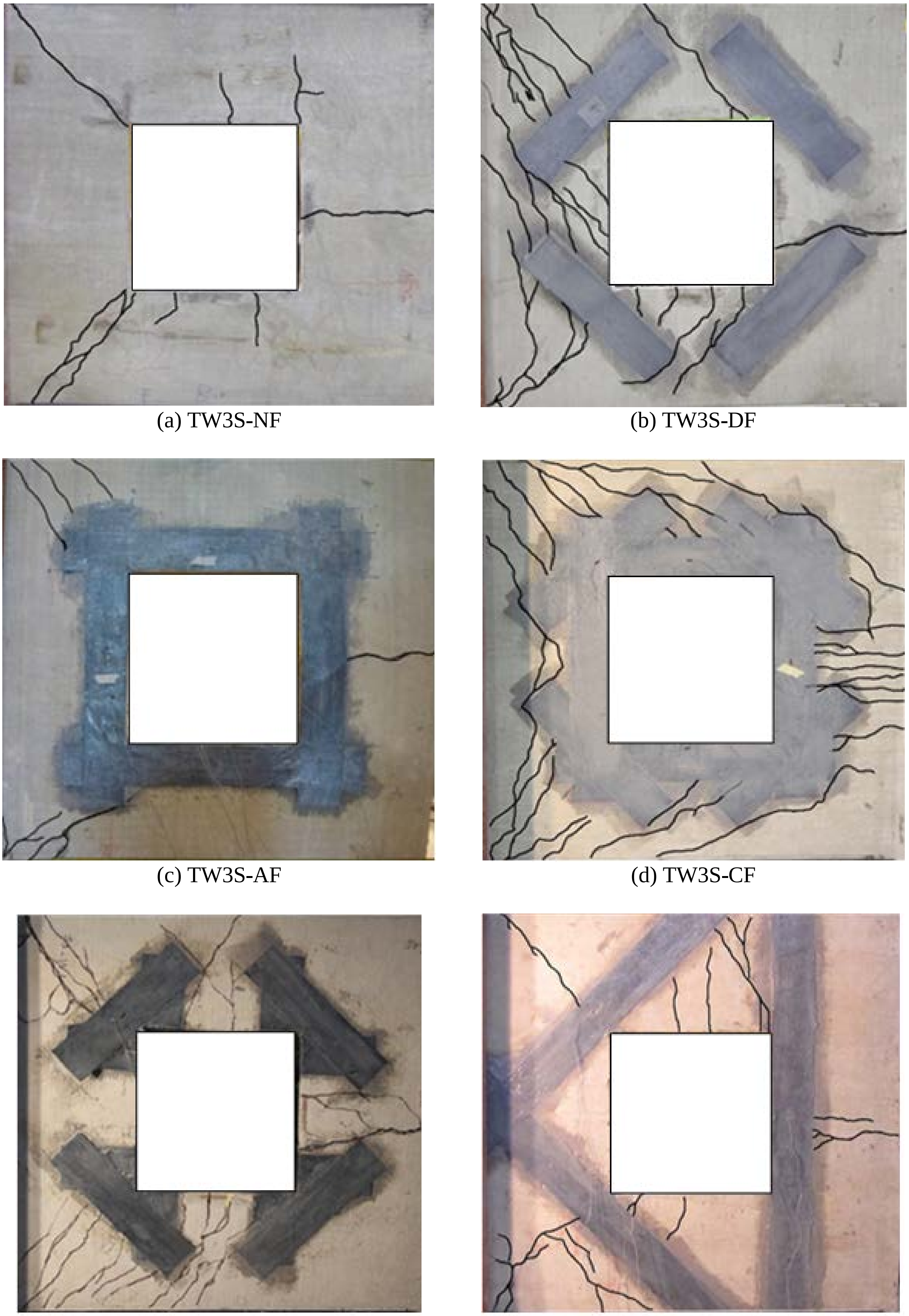


(e) OW-WF



(f) OW-PF

Fig. 5. Crack patterns on tension side of walls with OW

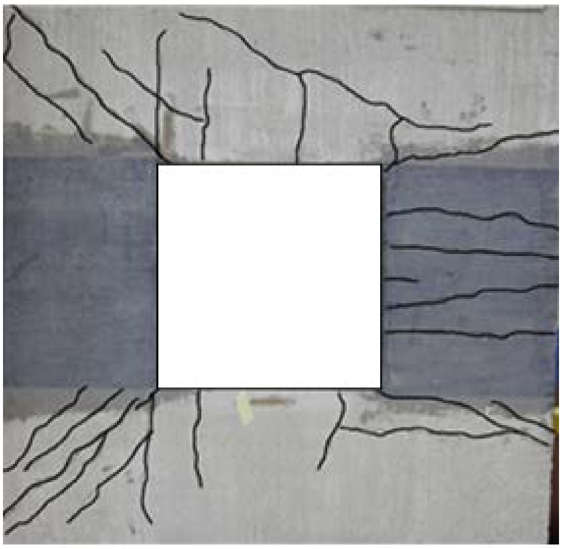


(a) TW3S-NF (b) TW3S-DF

(c) TW3S-AF (d) TW3S-CF

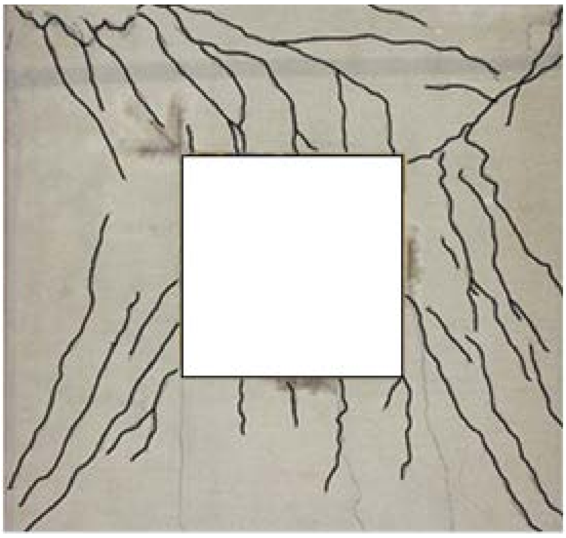
(e) TW3S-WF (f) TW3S-MF

Fig. 6. Crack pattern on tension side of walls with TW3S

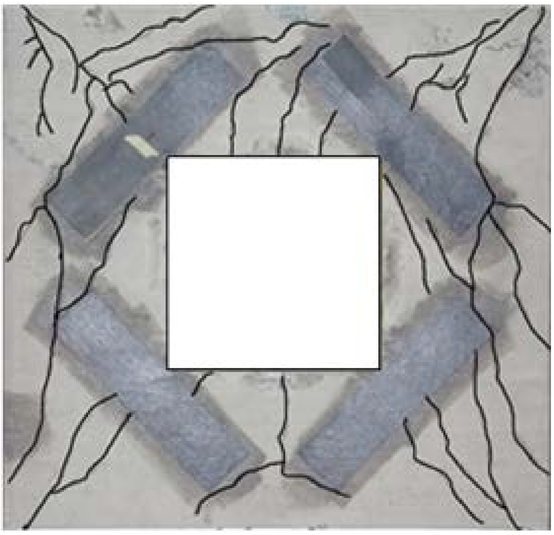


(g) TW3S-FWF

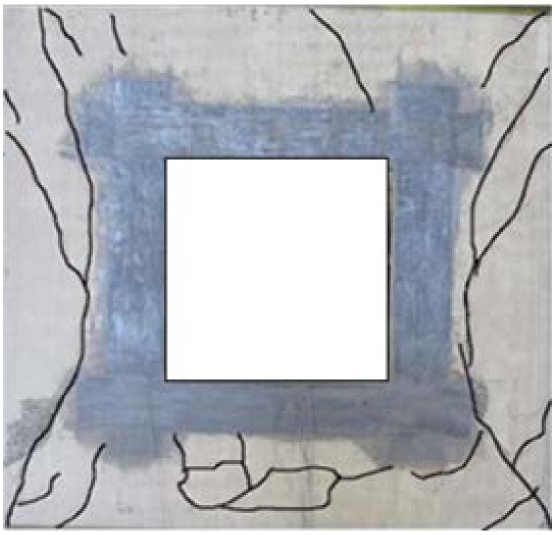
Fig. 6 (continued). Crack patterns on tension side of wall with TW3S



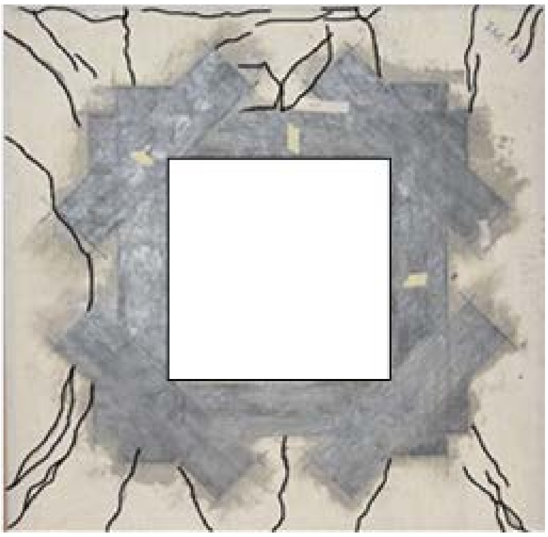
(a) TW4S-NF



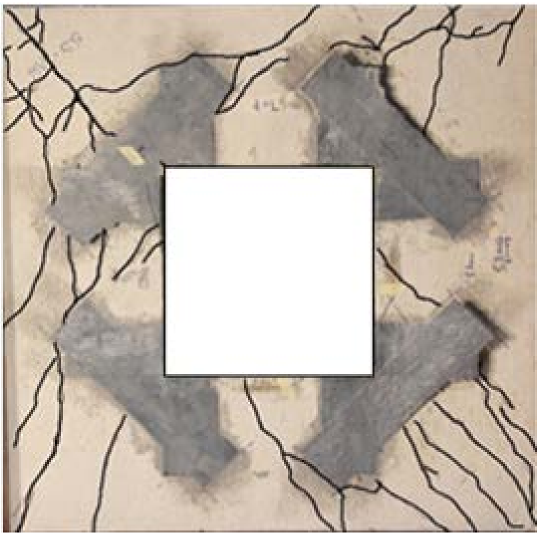
(b) TW4S-DF



(c) TW4S-AF



(d) TW4S-CF



(e) TW4S-WF

Fig. 7. Crack patterns on tension side of walls with TW4S

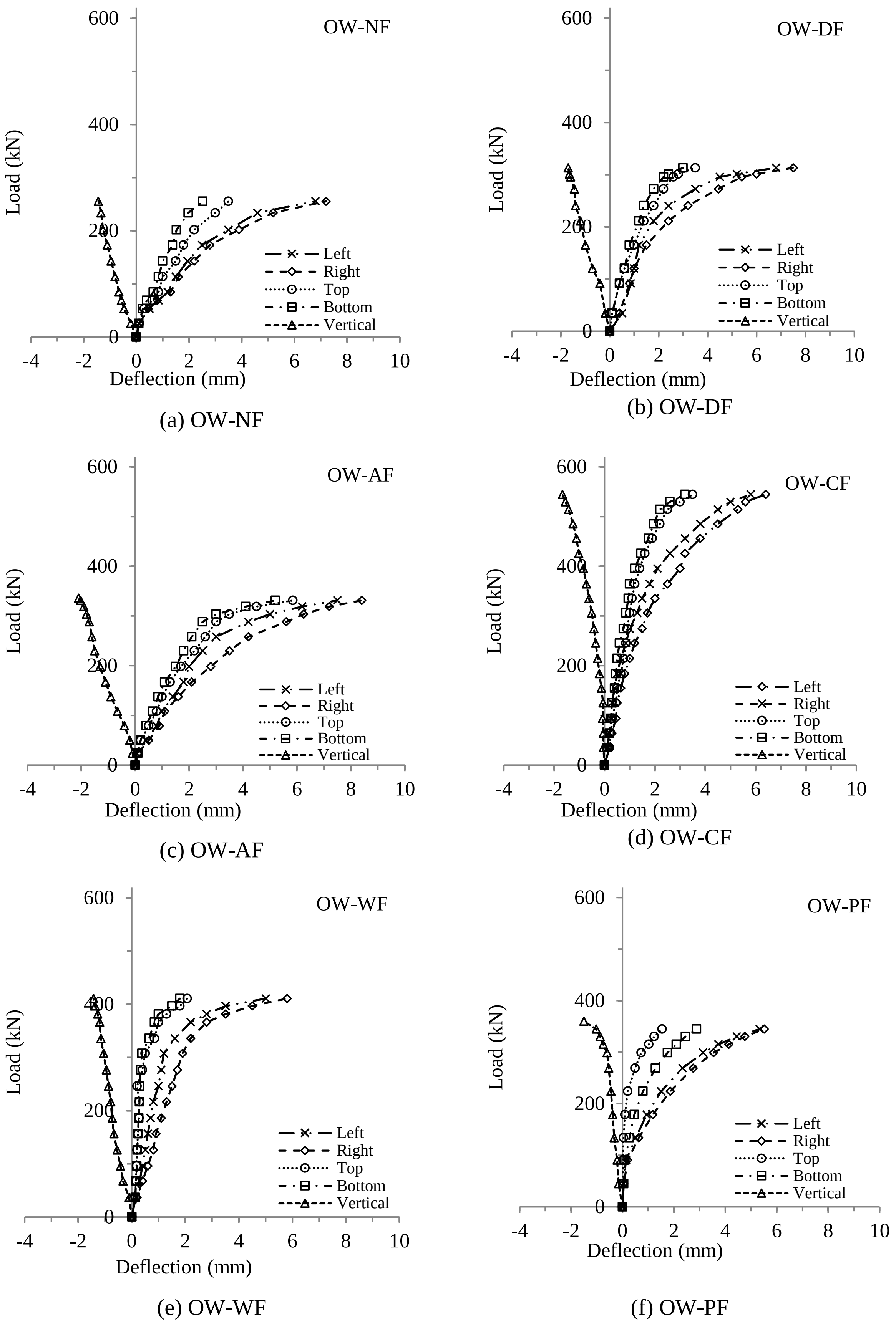


Fig. 8. Load versus out-of-plane and in-plane deflection curves of walls with OW (refer to Fig. 4 for gauge locations)

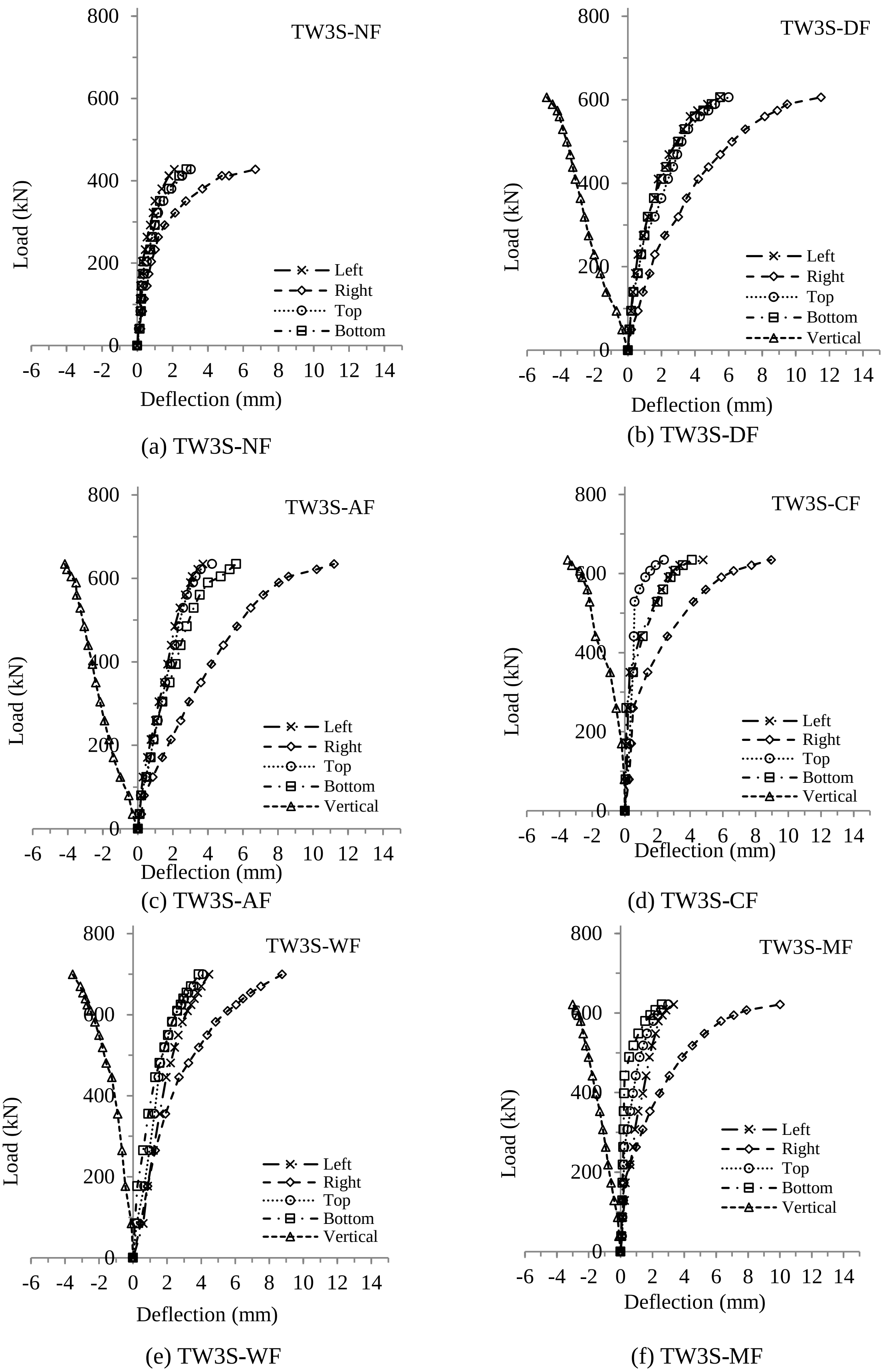
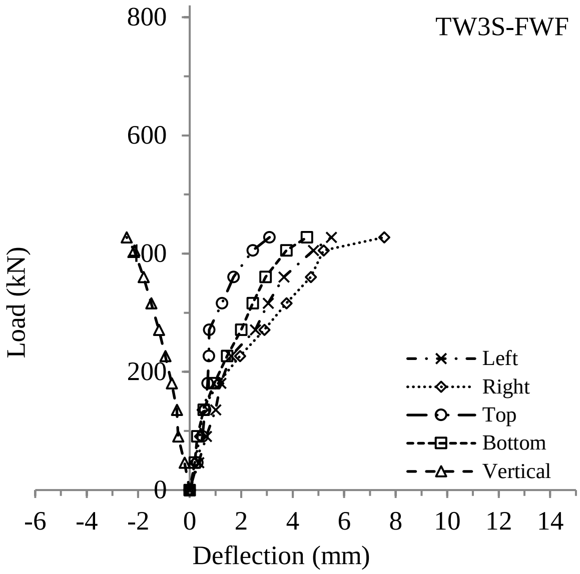
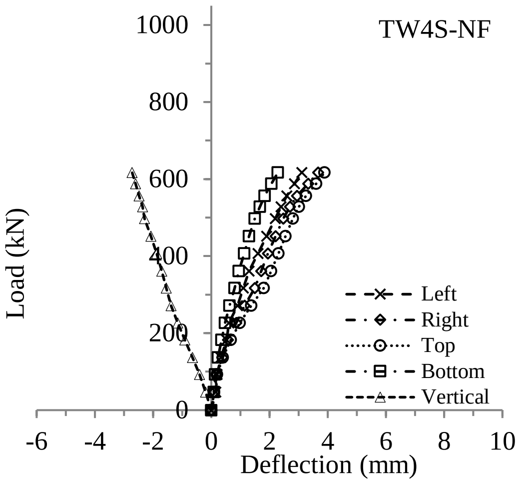


Fig. 9. Load versus out-of-plane and in-plane deflection curves of walls with (refer to Fig. 4 for gauge locations)

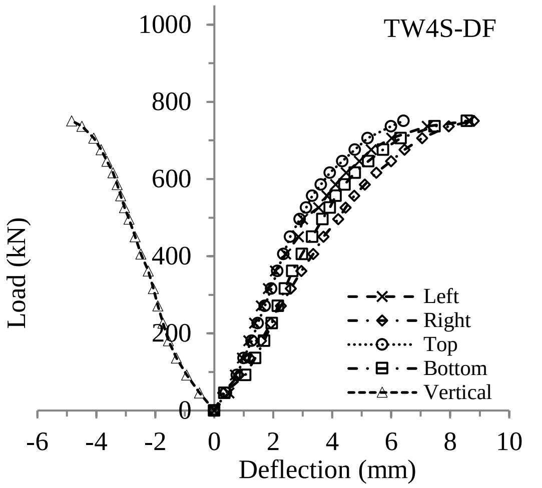


(g) TW3S-FWF

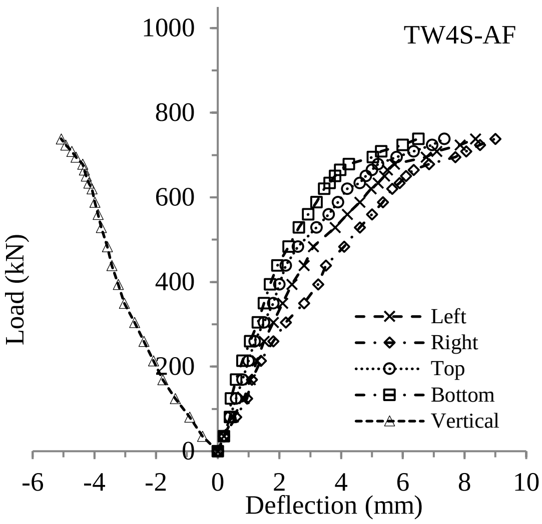
Fig. 9 (continued). Load versus out-of-plane and in-plane deflection curves of walls with TW3S (refer to Fig. 4 for gauge locations)



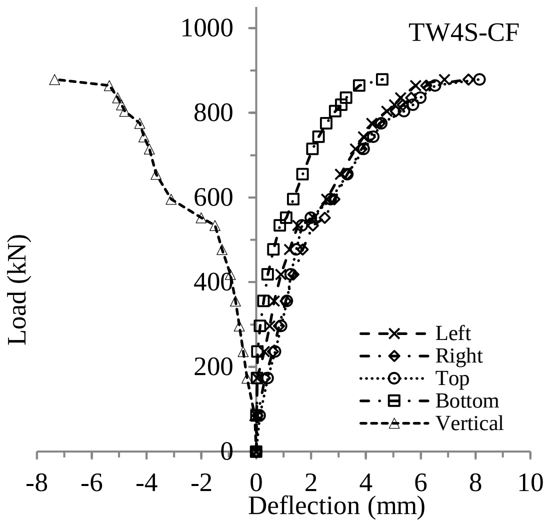
(a) TW4S-NF



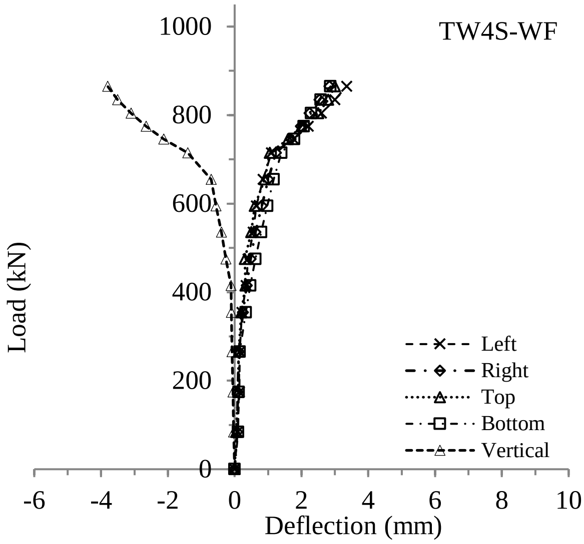
(b) TW4S-DF



(c) TW4S-AF



(d) TW4S-CF



(e) TW4S-WF

Fig. 10. Load versus out-of-plane and in-plane deflection curves of walls with TW4S (refer to Fig. 4 for gauge locations)

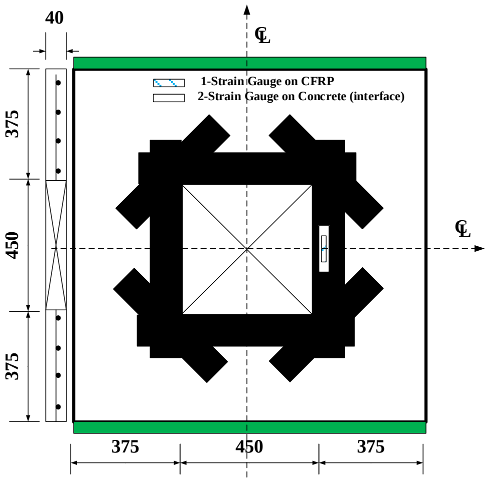


Fig. 11.. Location of strain gauges on top of CFRP and concrete (interface) of wall OW-CF

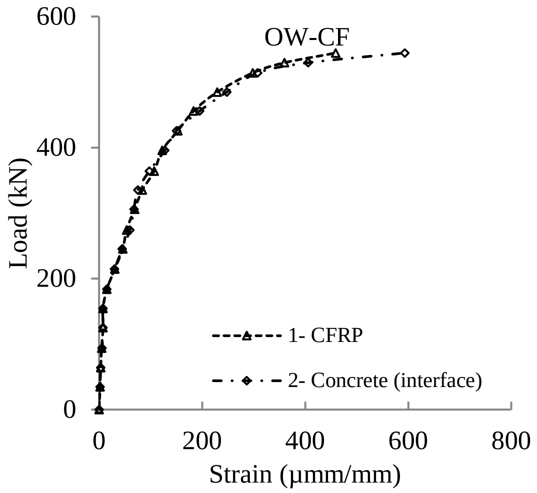


Fig. 12. Load versus strain curves of wall OW-CF

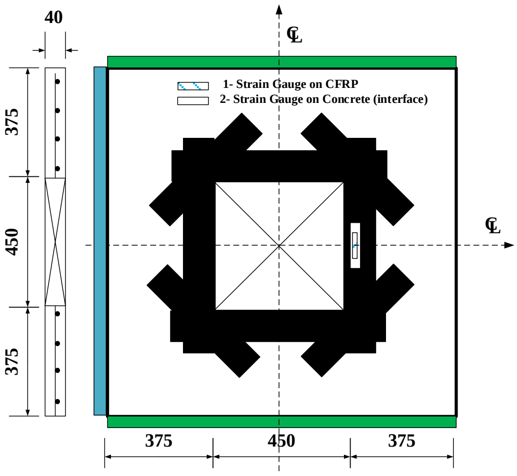


Fig. 13. Location of strain gauges on top of CFRP and concrete (interface) for wall TW3S-CF

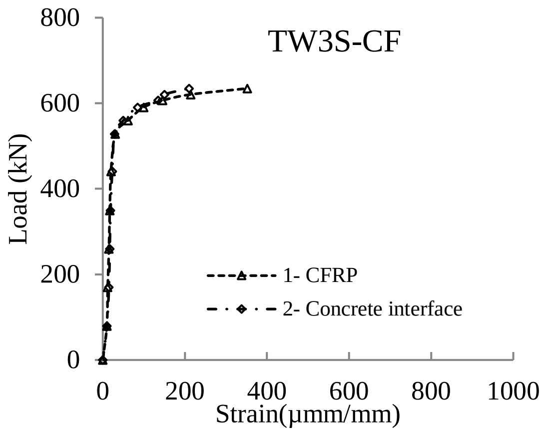


Fig. 14. Load versus strain curves of wall TW3S-CF

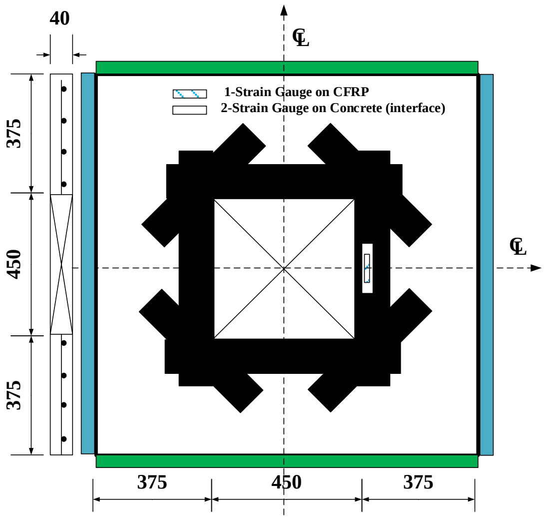


Fig. 15. Location of strain gauges on top of CFRP and concrete (interface) for wall TW4S-CF

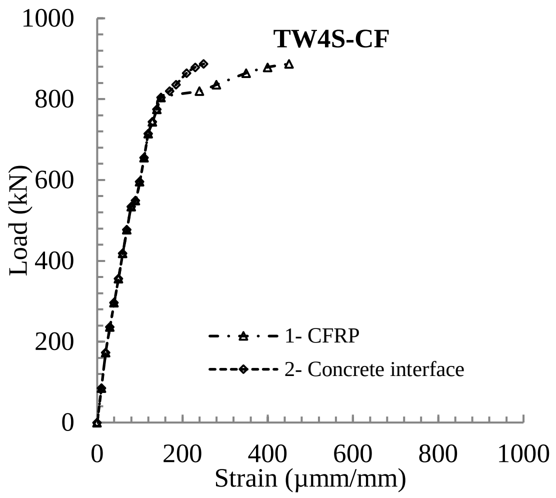


Fig. 16. Load versus strain curves of wall TW4S-CF

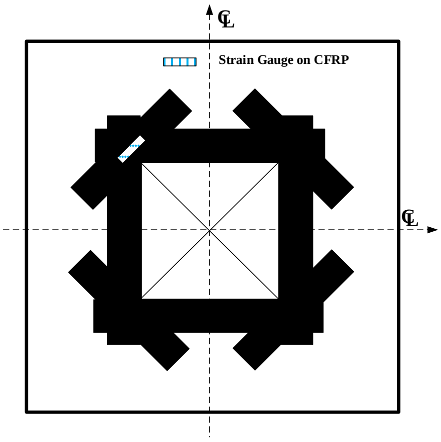


Fig. 17. Location of strain gauge on top of CFRP for walls with CF layout

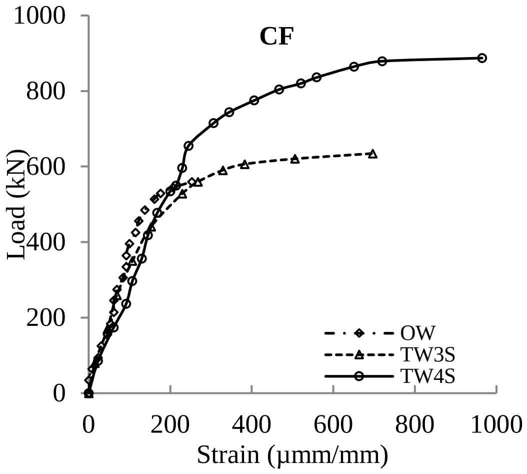


Fig. 18. Load versus strain curves of walls with CF layout

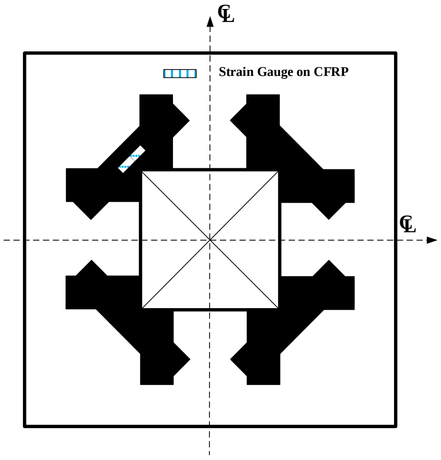


Fig. 19. Location of strain gauge on CFRP for walls with WF layout

Fig 20 Click here to download Figure Fig 20.pdf

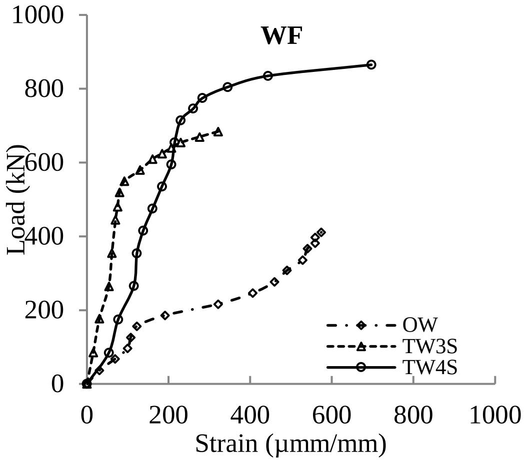


Fig. 20. Load versus strain curves of walls with WF layout

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