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Strengthening of Squat RC Shear Walls with Square Openings by FRP under Monotonic Loading

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***Abstract**: Reinforced concrete (RC) shear walls are considered to be one of the most major elements in the lateral force resisting systems. The existence of openings in RC shear walls becomes essential in some cases that relate basically to architectural or mechanical requirements although they are not preferred to be constructed from the structural point of view. In this current work, massive numbers of numerical models are conducted using the well-known finite element software (ANSYS) for achieving an obvious conclusion about the influence of positions and dimensions of openings on the nonlinear behavior of shear walls under lateral monotonic loads. Furthermore, the efficiency of a proposed configuration of CFRP strips in retrofitting these RC walls with openings is investigated.*

***Keywords:** Shear Walls; Monotonic Lateral Loads; Nonlinear Behavior; Strengthening; CFRP sheets.*

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I. Introduction

High-rise reinforced concrete buildings contribute a considerable share of the real estates all over the world. In order to resist lateral loads; either wind or seismic loads, different structural systems are used such as reinforced concrete (RC) moment resisting frames, braced frames and shear walls. RC moment resisting frames are popular forms of construction in multi-story buildings. This system resists lateral forces depending on the fixed connections between girders and columns that work on distributing the moment between them according to their relative stiffness. On the other side, RC braced frames depend on the existence of vertical truss systems. Beside the economic and safety issues, there is no doubt that the used lateral force resisting system has to achieve all architectural and mechanical requirements. Accordingly, when the frames systems are insufficient, uneconomical or in conflict with architectural needs, reinforced concrete (RC) shear walls are the suitable structural systems for improving the ability of high-rise RC buildings in resisting lateral forces.

RC shear walls are vertical structural elements in the lateral forces resisting system. Due to their in-plane rigidity, they transmit lateral forces from diaphragms above to the foundation. These walls are usually located regularly in plan and in elevation to minimize the torsion's effects in each story due to the existence of an offset between the center of mass and the center of rigidity of the building. The height-to-length ratio (aspect ratio) of RC shear walls affects mainly the mode in which these walls fail. For slender walls with aspect ratio equals (3 to 4), the main behavior is flexural behavior. Moderately slender walls have aspect ratio ranges between 1.5 and 3 their nonlinear behavior tends essentially to the flexure with a limited contribution of the shear behavior. In case of squat shear walls that have aspect ratio less than 1.5, the nonlinear shear deformation is the reason for the highest percentage of walls' lateral displacement. [1]

In the last few decades, the behavior of RC shear walls-without openings- was studied for the first time after the design codes had recognized the urgent need for considering the effects of seismic loads on the buildings especially RC high-rise buildings. The life safety of residents of these buildings was the main concern as the structural design of buildings without including seismic forces had caused thousands of people to die during strong seismic strikes all over the world. Researchers [7]studied experimentally RC shear walls with different aspect ratios under a constant axial loading and lateral incremental loads; they aimed to put design guidelines of shear walls and figure out the nonlinear response of shear walls under different regimes of lateral cyclic loads. “The existence of transverse confining stirrups in shear walls improves obviously the seismic performance of structural walls under quasi-static loading”; this was the conclusion that researchers[8] had obtained. Other researchers[9]developed special reinforcement system (concealed steel frame and steel truss); the proposed system improved ductility, strength and energy dissipation of the tested shear walls.

The usage of Fiber Reinforced Polymers (FRP) in retrofitting and repairing a lot of structural elements occupied a top priority in research topics. The remarkable pursuit of achieving the maximum benefits of FRP regards to its unique advantages like corrosion resistance, non-magnetic properties, high tensile strength, light weight and ease of handling. One of the most precious contributions in evaluating the effect of FRP sheets on seismic performance of shear walls was Lombard and Hiotakis' experimental researches [10]. Researchers [12] studied the hysteresis behavior of strengthened shear walls using X-shaped diagonal strips of FRP. Other researchers [13] were interested in studying the nonlinear response of GFRP reinforced shear walls. A research[14] was conducted for investigating the ability of FRP in strengthening deficient shear walls with insufficient shear reinforcement, poor confinement at boundary zones and lap splices at plastic hinge. Researchers [15][16] studied analytically the retrofitting of shear walls with steel plates and CFRP sheets. Other researchers [17] used numerical models for studying the effect of confining of slender walls' boundary zones on the nonlinear behavior of shear walls.

Regarding the probability the existence of openings in RC shear walls for achieving architectural or mechanical requirements, the effect of these openings on the seismic response of walls was a vital topic for researches. The behavior of RC shear walls with staggered openings was studied experimentally**[18**] under quasi-static loads. Other researchers,[19], proposed a strengthening scheme for RC shear walls with openings using information of conducted strut-and-tie with two different positions of opening.

The objective of the current work is to study; analytically, the effects of openings on the nonlinear performance of reinforced concrete shear walls under vertical and lateral loads. A massive parametric study is conducted for figuring out the effect of changing openings' size, location and aspect ratio on the wall's lateral load carrying capacity, lateral drift and shear stress distribution of RC shear walls. Also this work aims to analyze the feasibility of using CFRP sheets for retrofitting these shear walls with different openings' location.

II. Numerical Modelling

The numerical simulations provide excellent tools for conducting accurate parametric studies instead of the traditional build-and-break models. In the current work, the well-known finite element software ANSYS-V14.5will be used. ANSYS is a large scale multipurpose program ; after it has been in commercial use in 1970, it has been recommended in the analytical scientific researches due to its ability for solving static, dynamics, steady state, transient heat transfer and mode-frequency analyses. It considers the effect of creep, large deflection, contact, large strain, swelling and plasticity. Besides, ANSYS supports the nonlinear analysis for structural elements using iterative process (the Newton-Raphson approach)[21].

III. Model verification

In order to investigate the ability of the used numerical modeling in predicting the nonlinear behavior of RC shear walls, two distinguished experimental researches have been simulated using ANSYS. The analytical and experimental results are compared with each other in order to verify the reliability and the accuracy of the modeling to provide the basis on which the parametric study will be conducted.

A. First verificatioun example

Moderately slender RC shear wall that was tested experimentally by G.V. Ramo [23] and has been simulated in this numerical modeling is subjected to lateral monotonic load and a constant vertical load of 160kN. It is constructed with M30 grade concrete and Fe-415 steel reinforcement. Dimensions of the tested shear wall and the arrangement of longitudinal and transversal reinforcement are shown in Fig. 1.

All detailed information about the test procedure and the mechanism of applying lateral loads can be obtained from G.V. Ramo [22]. The tested RC shear wall has been simulated numerically as a volume with the same dimensions as those of the experimentally tested one; longitudinal and transversal reinforcement have been modeled as lines (Fig. 2). Before meshing all structure's components, we aim to subdivide the whole volumes with the steel bars (lines) for ensuring a full bond between reinforcement and concrete.

Solid65 is the most convenient element type for simulating the properties of concrete [23]. In addition to its ability to consider the nonlinearity of materials, Solid65 is capable of cracking in tension and crushing in compression. This element type is defined by eight nodes having three degrees of freedom at each single node (translation in X, Y and Z directions). Link180 has been used as the element type for modeling the reinforcing steel bars; it is a uniaxial tension-compression element that has three degrees of freedom at each node (translation in X, Y and, Z directions). It considers plasticity, creep and large strain with neglecting bending of the element (Fig. 3).

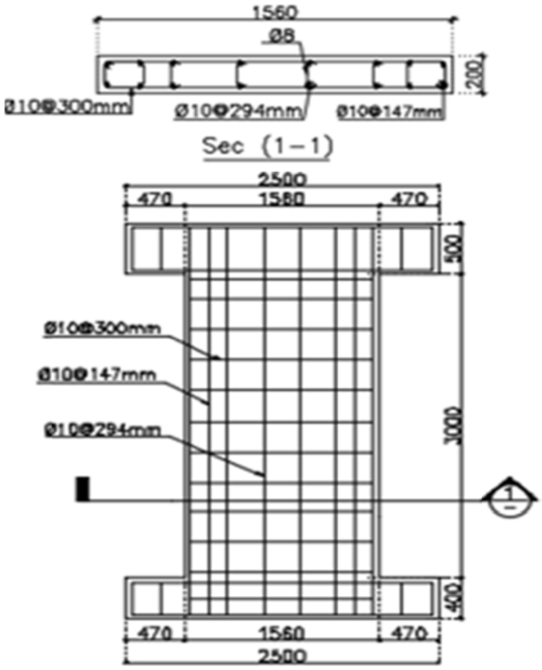


Fig. 1: Section plan and elevation of the shear wall.

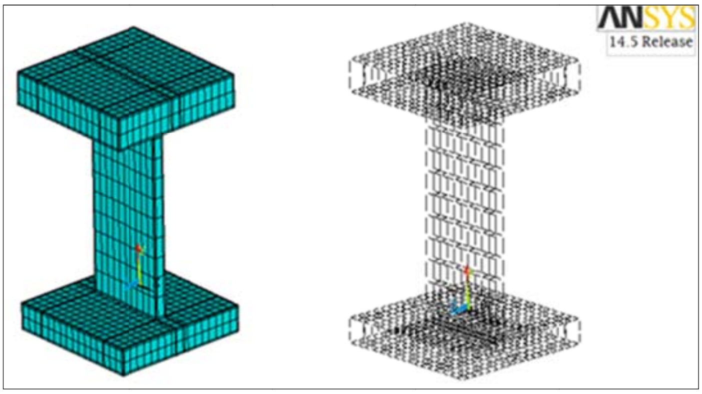
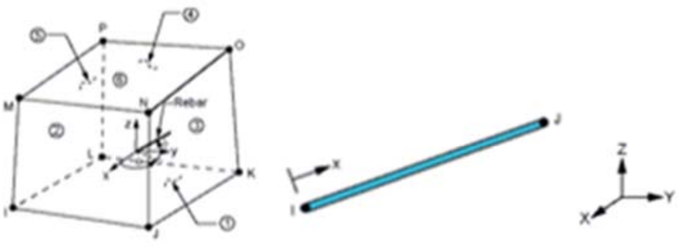


Fig. 2: Simulation of the RC wall and reinforcement.



(a) Solid65 element. (b) Link180 element.

Fig. 3: Geometry of (a) solid65 element and, (b) link180 element.

The load has been applied to the wall and the relation between the load and the lateral displacement has been obtained and plotted in figure 4. According to the figure, it can be seen that the numerical model can predict with an acceptable percentage. The nonlinear response of RC wall under gradually increasing lateral load besides the applied concentrated axial load has been successfully predicted. The modeled wall can with stand up to a lateral load of 192kN with a corresponding lateral displacement of 60.9mm. On the other hand, the experimental results indicated that the tested wall achieved an ultimate lateral displacement of 64mm when the applied lateral load was increased to 206kN (Fig. 4).

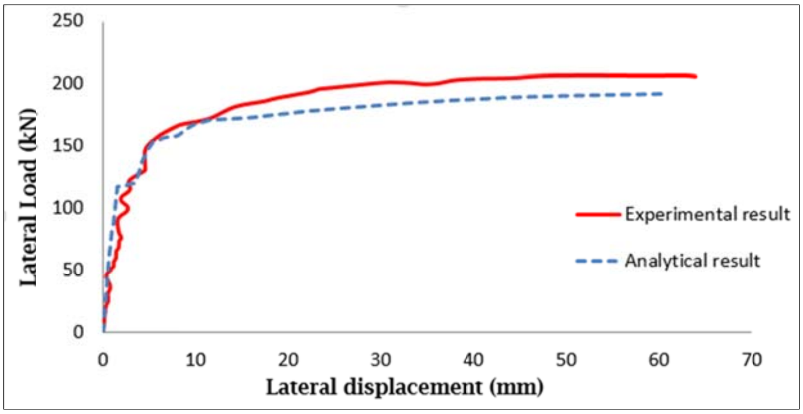


Fig. 4: Experimental and analytical lateral load-lateral displacement curves for the reference wall. (Reference [23]).

B. Second verification example

S. Qazi's experimental work [24] includes a strengthened squat RC shear wall and a normal one with the same dimensions, material properties and reinforcement ratio. The performance of walls has been investigated under the application of lateral monotonic load and a vertical constant load of 110kN. Dimensions of the tested shear walls and the arrangement of reinforcement are as shown in Fig. 5; the configuration of CFRP sheets that used in the strengthened specimen is shown in Fig. 6.The rebar average yield strength, ultimate strength and modulus of elasticity were evaluated to be equivalent to 500MPa, 570MPa, and 200GPa, respectively. CFRP fabric which was used had a tensile strength of 825MPa, tensile modulus equal to 70.5MPa and an ultimate strain of 0.85%. The previous modeling procedure is applied in the numerical simulation of S. Qazi's walls using ANSYS. Solid65 has been used for concrete and link180 for reinforcement steel as shown in Fig. 7. Shell181 has been used as the element type for modeling the CFRP sheets; it is a four- node element that has six degrees of freedom at each node (translation in X, Y and Z directions and rotation about X, Y and, Z axes), Fig. 8. Sensitivity analysis has been conducted on the meshing size for obtaining the most accurate analytical behavior of the RC shear wall; three sizes of meshing have been considered and the meshing size of (100x100) mm achieves the most appropriate performance of the wall that matches with the experimental results (as can be noticed from Fig. 9). The experimental work showed that the reference wall collapsed at a lateral load of 158kN and an ultimate displacement of 5.90mm, while the strengthened wall could resist until a lateral load of 219kN with achieving a lateral displacement of 8.20mm. On the other hand, the obtained results from ANSYS has indicated that the normal wall can resist lateral load up to 154kN and the ultimate lateral displacement was 6.5mm.The strengthened wall has confirmed the validity of the proposed finite element models; as the wall has achieved an ultimate load of 211kN and a maximum lateral displacemt at failure of 9.1mm (Fig. 9 and Fig. 10).

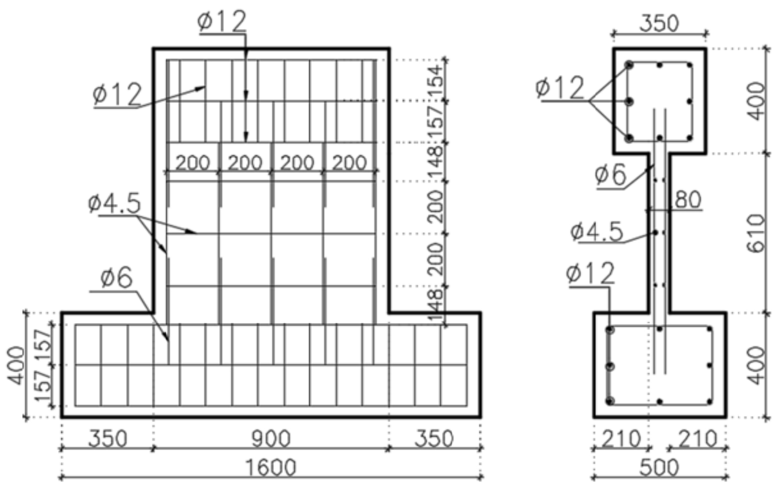


Fig. 5: Geometry and reinforcement details of RC shear walls. (Reference [23]).

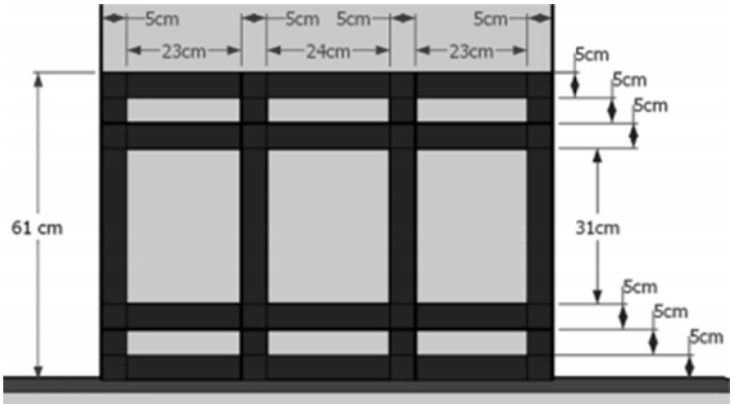


Fig. 6: Configuration of CFRP sheets (Reference [23]).

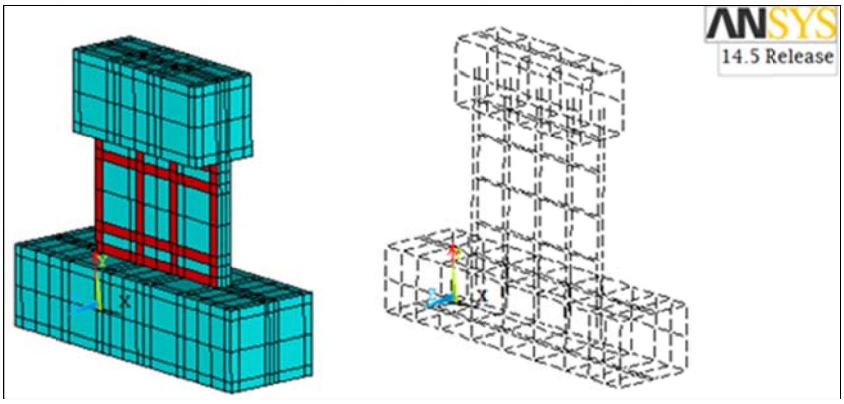


Fig. 7: Simulation of the RC wall, CFRP sheets and, steel bars.

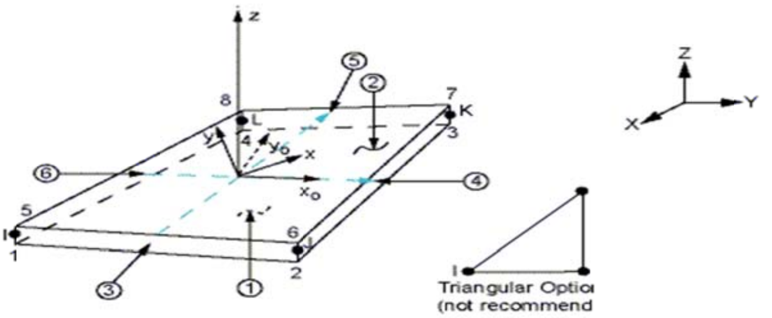


Fig. 8: Geometry of Shell181.

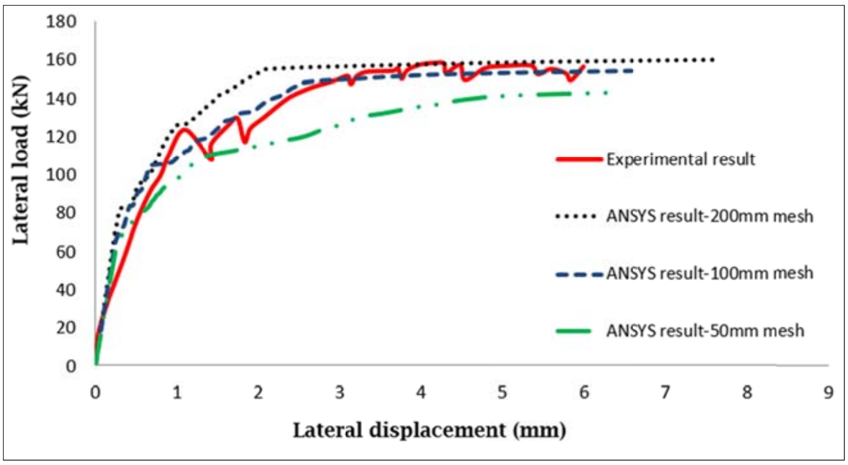


Fig. 9: Experimental and analytical lateral load-lateral displacement curves for the un-strengthened wall that was tested by S. Qazi et al., Reference [25].

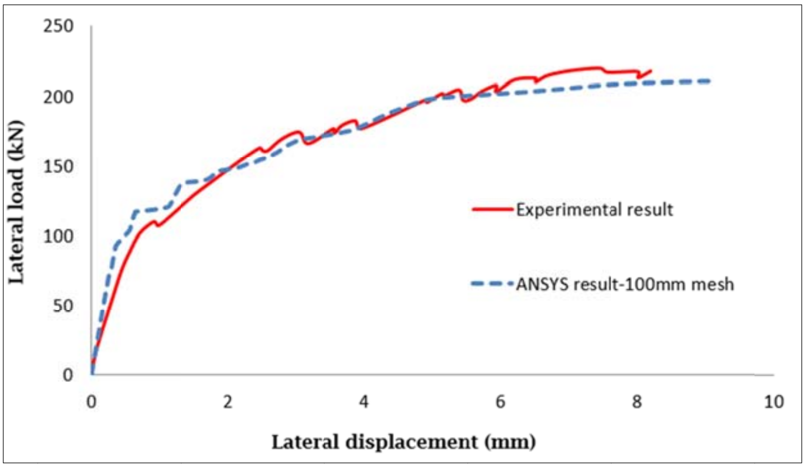


Fig. 10: Experimental and analytical lateral load-lateral displacement curves for the strengthened wall that was tested by S. Qazi, et al., Reference [25].

The previous verification examples have verified the accuracy of the modeling process and hence, the reliability of the used modeling technique to be extended to be used in conducting a comprehensive parametric study in order to reveal the key factors that affect the behavior of RC walls with openings when subjected to lateral monotonic loading conditions.

IV. Parametric Study

A. Details of the reference RC shear wall

The nonlinear behavior of a reference squat RC shear wall has been investigated under the application of monotonically increased lateral load along with the existence of a constant vertical pressure. The reference wall has dimensions of 900mm in height, 900mm in width and 100mm thick. A rigid footing is conducted with dimensions of 1500x700x300 mm^3; a constant vertical load of 150kN has been applied on the RC slab that has dimensions of 900x700x300 mm^3. Two layers of longitudinal and transversal reinforcement have been used in the reference specimen; 10mm-diameter bars with spacing of 200mm have been used for the wall and 12mm-diameter bars were the used for the RC slab and footing Fig. 11.

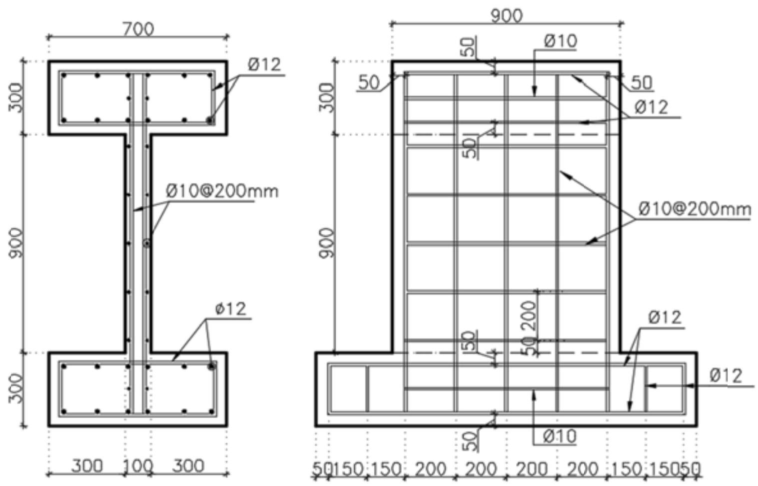


Fig. 11: Geometry and reinforcement details of the control RC shear wall that has been used in the parametric study.

B. Configuration of the unstrengthened shear walls with opening

A large number of models has been numerically simulated for figuring out the accurate performance of the squat RC shear walls in case of the existence of openings. The target is obtaining a conclusion for the influence of openings' size and location on the wall's capacity and lateral drift of the squat shear walls. Eight sizes of openings have been implemented in this study; each opening size has nine positions in the RC wall that has the same dimensions, percentage of reinforcement steel and loading procedure as the reference wall. The nine positions of each opening size and arrangement of steel reinforcement are illustrated in Fig. 12; and the opening's data for all models are explained in0 Fig. 13 shows an illustration for the used notations in the table.

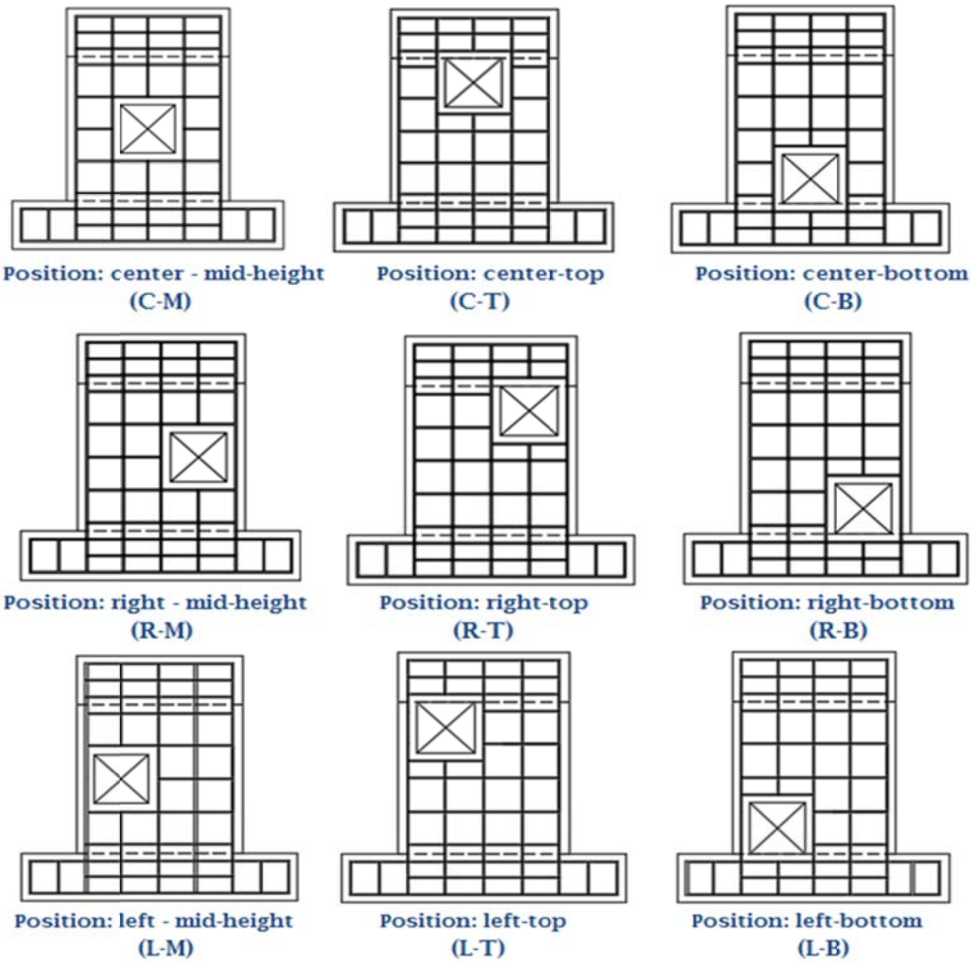


Fig. 12: Studied positions for each opening.

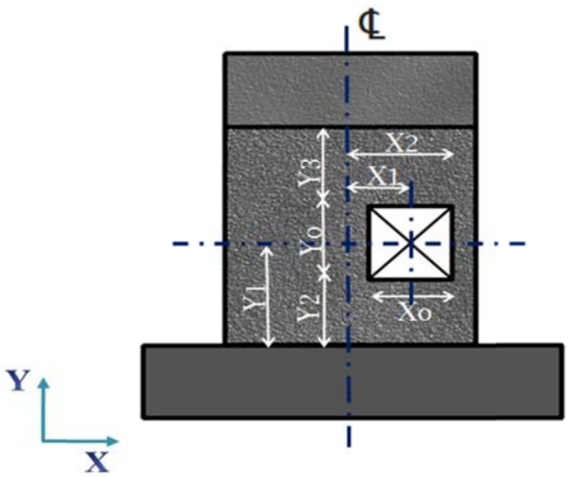


Fig. 13: Details of openings sizes and locations.

Table I: Details of openings' sizes and locations.

	Model code	Xo (mm)	Yo (mm)	X1 (mm)	Y1 (mm)	Opening area to Wall area
Control Wall	CON-Wall	-	-	-	-	-
Opening (200x200)mm	C-M	200	200	0	450	**4.94%**
	C-T	200	200	0	800	
	C-B	200	200	0	100	
	R-M	200	200	250	450	
	R-T	200	200	250	800	
	R-B	200	200	250	100	
	L-M	200	200	-250	450	
	L-T	200	200	-250	800	
	L-B	200	200	-250	100	
Opening (300x300)mm	C-M	300	300	0	450	**11.11%**
	C-T	300	300	0	750	
	C-B	300	300	0	150	
	R-M	300	300	200	450	
	R-T	300	300	200	750	
	R-B	300	300	200	150	
	L-M	300	300	-200	450	
	L-T	300	300	-200	750	
	L-B	300	300	-200	150	
Opening (350x350)mm	C-M	350	350	0	450	**15.12%**
	C-T	350	350	0	725	
	C-B	350	350	0	175	
	R-M	350	350	175	450	
	R-T	350	350	175	725	
	R-B	350	350	175	175	
	L-M	350	350	-175	450	
	L-T	350	350	-175	725	
	L-B	350	350	-175	175	
Opening (400x400)mm	C-M	400	400	0	450	**19.75%**
	C-T	400	400	0	700	
	C-B	400	400	0	200	
	R-M	400	400	150	450	
	R-T	400	400	150	700	
	R-B	400	400	150	200	
	L-M	400	400	-150	450	
	L-T	400	400	-150	700	
	L-B	400	400	-150	200	

C. Configuration of the strengthened shear walls with openings

In the present study, a single strengthening proposal has been used for improving the nonlinear response of RC shear walls with openings that has been demonstrated previously in Table I. Every RC wall has been retrofitted using bi-directional CFRP sheets; in the proposed strengthening scheme, 100mm-wide CFRP sheets with a thickness of 1mm have applied vertically and horizontally around the opening in both sides of every shear walls. The configuration of CFRP sheets with the different positions of openings is illustrated in Fig.14.

D. Material properties

Modified Hognestad equation [25] has been used to define the nonlinear behavior of concrete while the well-known nonlinear steel model that proposed by K. J. Thompson and R. Park [26] has been used for defining the material properties of reinforcing steel. Only the elastic behavior of the bi-directional CFRP sheets has been considered; mechanical properties of the used materials are presented in Table II.

E. Finite element models

As mentioned previously, the numerical modeling is the backbone of the current work; all of the obtained results and recommendations of this work have been concluded based on the numerical models that have been studied with ANSYS. It is worth to mention that the procedure of simulation that has been used in constructing the verification models is the same one as that has been used in the parametric study. The type of the current analysis has been considered to be static; all numerically tested walls have been solved under a vertical constant load equals to 150kN then lateral monotonic loads have been applied at four joints at corners and have been increased; till failure, Fig. 16.

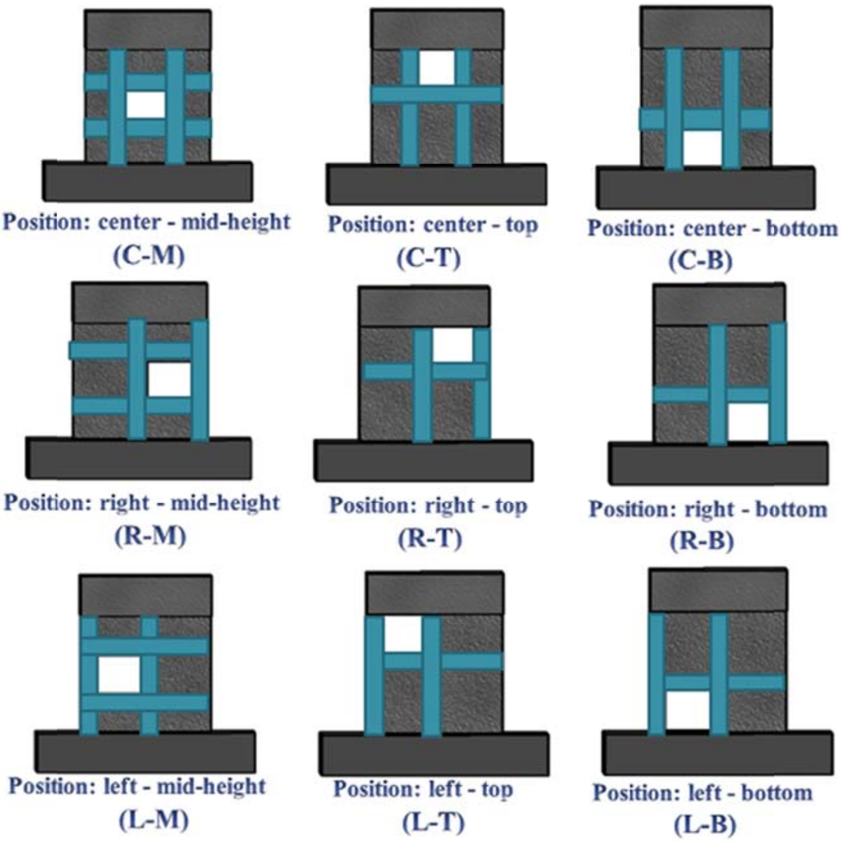
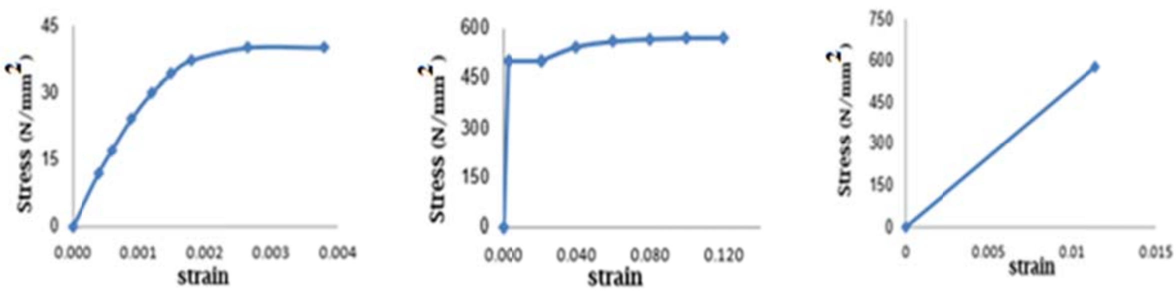


Fig. 14: Configuration of CFRP sheets for each opening position.

Table II: Mechanical properties of concrete, reinforcing steel and, CFRP sheets.

Cubic strength (Fc') of concrete (MPa)	**Tensile strength (f_t) of concrete (MPa)**	**Elastic modulus (E) of concrete (MPa)**
40	4.43	30075.2
Yield strength (Fy) of RFT (MPa)	**Ultimate stress (Fu) of RFT (MPa)**	**Elastic modulus (E) of RFT (MPa)**
500	570	200,000
Ultimate stress (Fu) of CFRP (MPa)	**Ultimate strain of CFRP**	**Elastic modulus (E) of CFRP (MPa)**
579	1.14%	48351



(a) Concrete (b) Reinforcing steel (c) CFRP

Fig. 15: Stress-strain relations for concrete, reinforcing steel and, CFRP sheets.

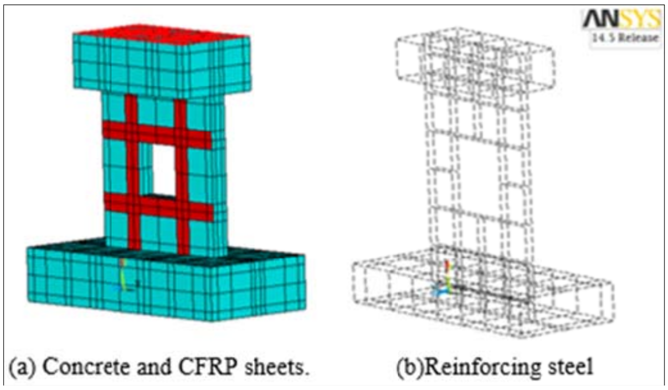


Fig. 16: Simulation of the RC wall with opening, CFRP sheets and, reinforcing steel bars.

V. Results and Discussion

Step-by-step nonlinear static analysis has been carried out for all of the studied models. Material as well as geometric nonlinearities have been considered in the analysis. After triggering the analysis, the results have been obtained and plotted for each group of models as will be explained in the following items.

*A. **The effect of opening'slocation on the shear capacity of the shear wall.***

For the same opening size, the behavior of the wall for the nine positions of the opening has been observed. The following sections demonstrate the lateral load-lateral displacement curves for the nine positions of different four openings' sizes.

A.1. Effect of the vertical location of the opening on the shear capacity of the wall .

A.1.1 Openingis horizontally located at the wall's center line.

The behavior of the RC wall when the opening is horizontally centered in the wall's width; x1 = 0 mm, has been investigated for four different sizes of the openings. The minimum opening size has been set to 200 x 200 mm^2 representing about 5% of the area of the wall in elevation. The size of the opening has been increased to 300 x 300 mm^2, 350 x 350 mm^2 and, 400 x 400 mm^2 representing about 11%, 15% and, 20% of the walls area in elevation, respectively. The studied cases are C-M, C-T and, C-B cases and their obtained behaviors have been compared to the original wall (CON-Wall) where no openings have been applied.

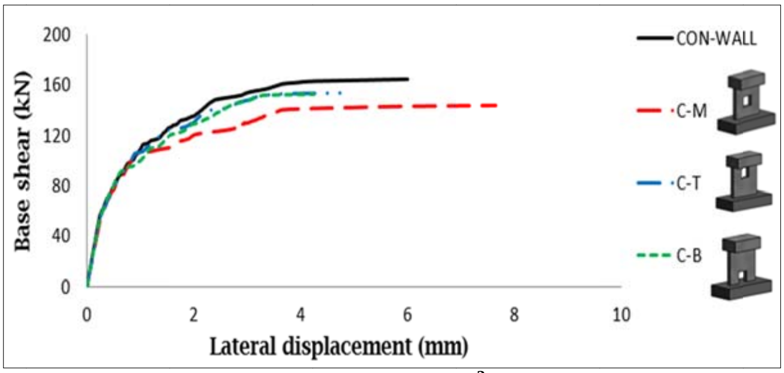


Fig. 17: Behavior of wall with opening (200x200 mm^2) - horizontally centered-(X1=0mm).

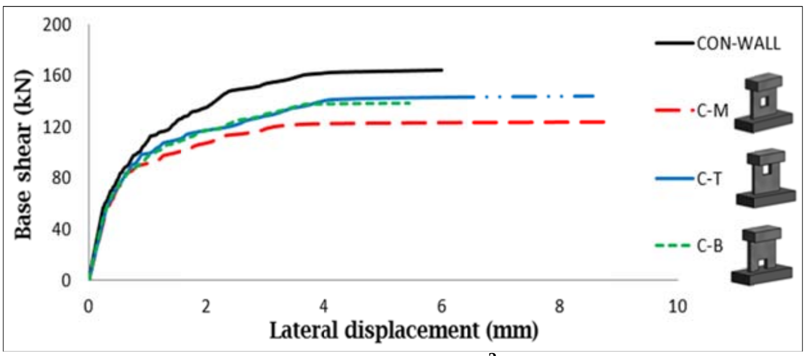


Fig. 18: Behavior of wall with opening (300x300 mm^2) - horizontally centered-(X1=0mm).

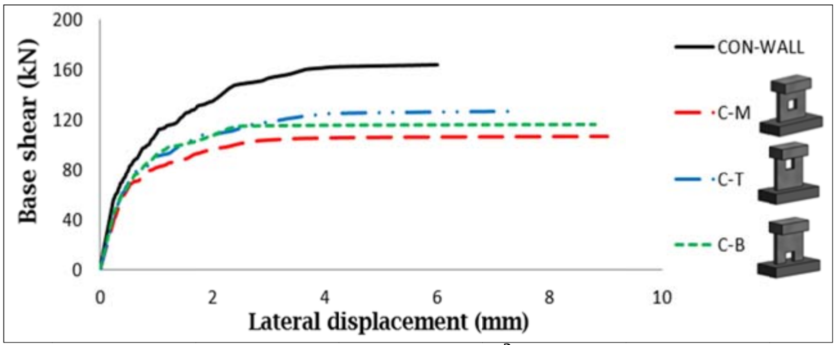


Fig. 19: Behavior of wall with opening (350x350 mm^2) - horizontally centered-(X1=0mm).

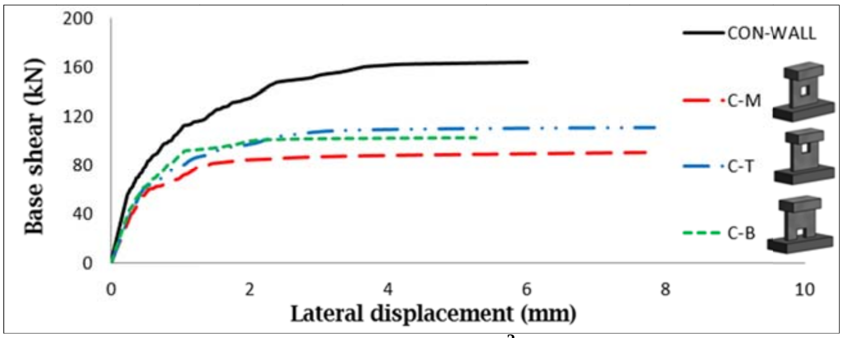


Fig. 20: Behavior of wall with opening (400x400 mm^2) - horizontally centered-(X1=0mm).

Regarding the obtained results of the shear walls with openings that are horizontally centered in the wall (X1=0 mm), it has been found that the walls with opening located in the top position (C-T) can withstand till a higher load level than those with opening in the bottom and mid-height locations(C-B and C-M). On the other hand, openings located in the mid-height position cause the most harmful reduction in the shear capacity of the wall. The reduction percentage of the shear capacity for shear walls with opening in the position of (C-T) is about (7-32%) while openings in the position of (C-M) cause a reduction in the shear capacity ranges between 12% and 44%. A reduction percentage of (7-38%) in the base shear is caused due to the existence of opening in the position of (C-B) (Fig. 17 to Fig. 20). Figure 21 shows the shear stress distributions and deformed shapes for shear walls with opening (300x300mm^2) in C-M, C-T and C-B locations as a sample.

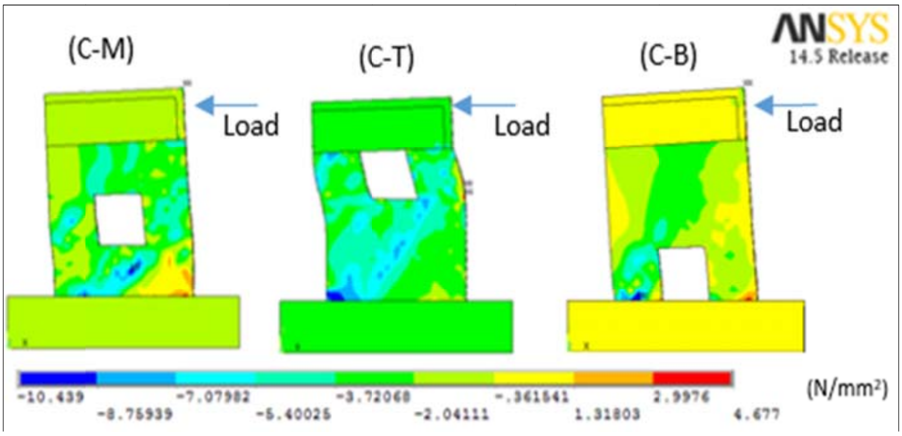


Fig. 21: Shear stress distribution-opening (300x300 mm2)-(X2=0mm).

A.1.2. Openings with different elevations (Y) and have the same offset (X2=350mm)- (in the right side)

The previous openings have been used to study the behavior of walls with openings in the right position (X2 = 350 mm). The studied cases are R-M, R-T and, R-B cases and their obtained behaviors have been compared to the original wall (CON-Wall) where no openings have been applied.

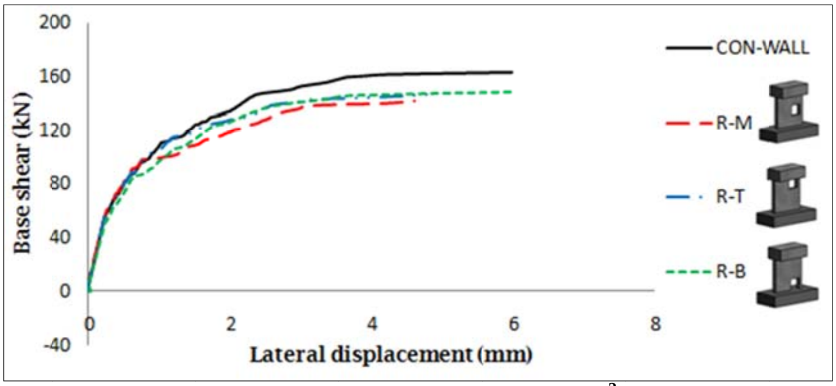


Fig. 21: Behavior of wall with opening (200x200 mm^2) - (X2 = 350mm).

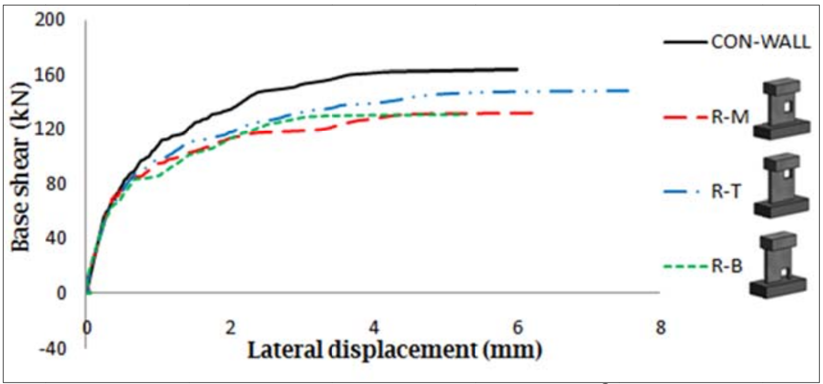


Fig. 22: Behavior of wall with opening (300x300 mm^2) - (X2 = 350mm).

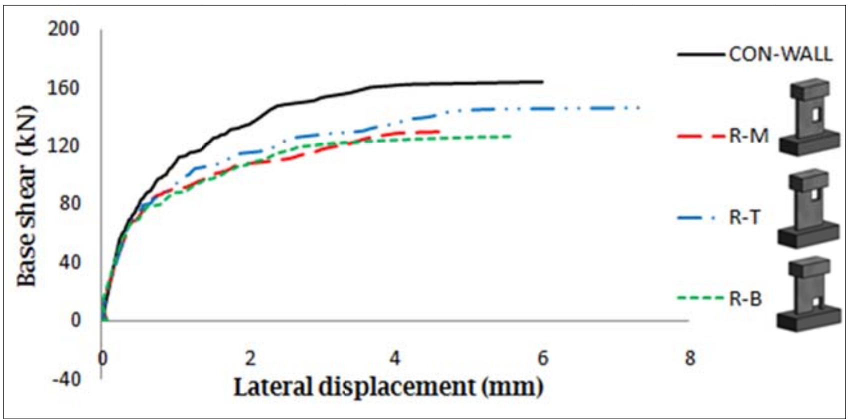


Fig. 23: Behavior of wall with opening (350x350 mm^2) - (X2 = 350mm).

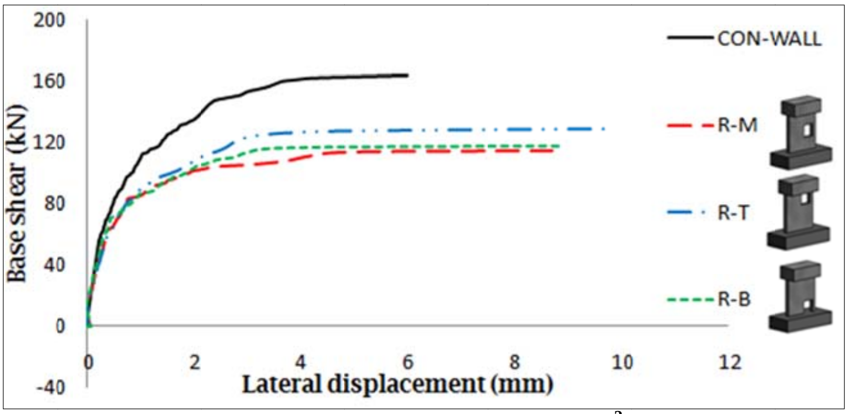


Fig. 24: Behavior of wall with opening (400x400 mm^2) - (X2 = 350mm).

Focusing on the nonlinear performance of the shear walls with openings that located in the right side (X2=350mm) (Fig. 17 to Fig. 20), locating the opening at the top of the wall (R-T) causes the lowest reduction in the shear capacity of the wall; the reduction percentage ranges between 6% and22%. The bottom and mid-height positions of openings (R-B and R-M) has affected the stiffness of the wall with almost the same percentage. Position of (R-M) has reduced the base shear by a percentage of 10 to 30 %; openings in the location of (R-B) have caused a reduction in the value of maximum base shear by a percentage of 9 to 28%. A sample for the shear stress distribution for shear walls with an opening of (300x300mm^2) for the three different locations R-M, R-T and, R-B are shown in Fig. 25.

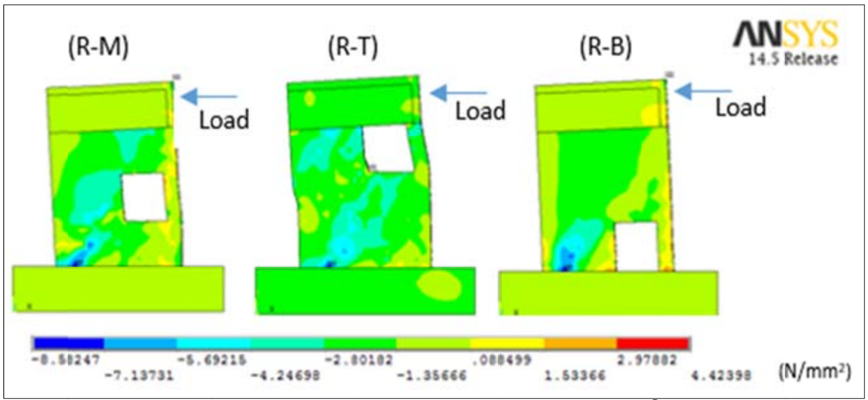


Fig. 25: Shear stress distribution -opening (300x300 mm^2) - (X2=350mm).

A.1.3. Openings with different elevations (Y) and have the same offset distance (X2=-350mm)-(Left side)

Finally, The four square openings (200x200 mm^2 , 300x300 mm^2, 350x350mm^2 and 400x400mm^2) have been used to study the behavior of walls with openings in the left position (X2 = -350 mm). The studied cases are L-M, L-T and, L-B and their obtained behaviors have been compared to the original wall (CON-Wall) where no openings have been applied.

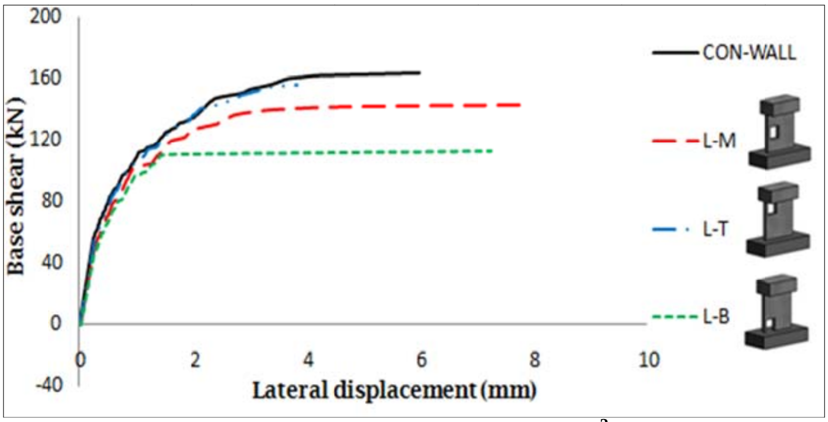


Fig. 26: Behavior of wall with opening (200x200 mm^2) - (X2 = -350mm).

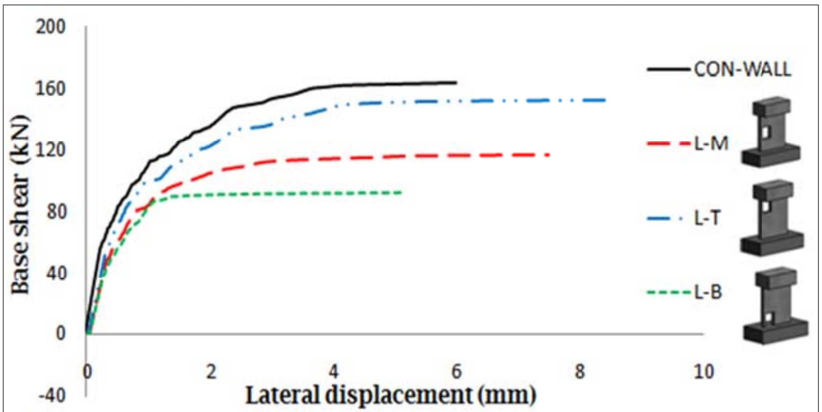


Fig. 27: Behavior of wall with opening (300x300 mm^2) - (X2 = -350mm).

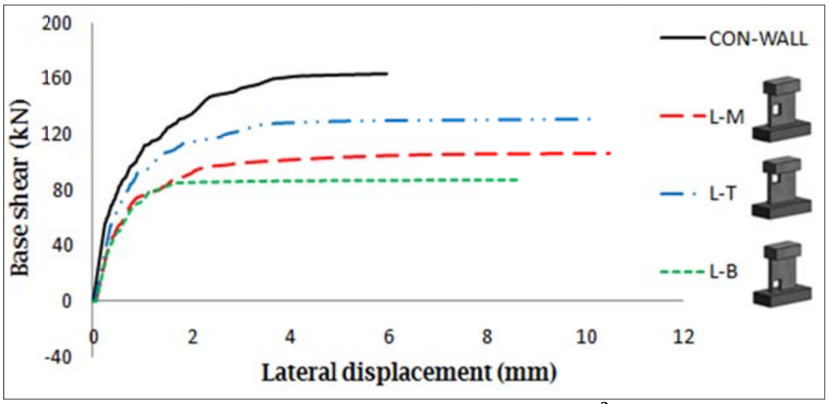


Fig. 28: Behavior of wall with opening (300x300 mm^2) - (X2 = -350mm).

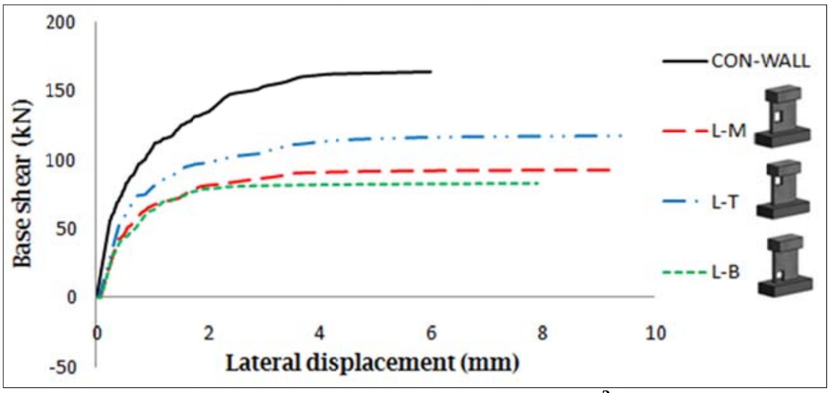


Fig. 29: Behavior of wall with opening (300x300 mm^2) - (X2 = -350mm).

The conducted numerical analysis of the shear walls with different opening sizes in the left side has indicated that locating the opening at top (L-T) causes the lowest reduction in the shear capacity of RC walls. The (L-T) located openings decrease the value of the lateral load that shear wall can resist by (5-28) %. As expected, the most harmful effect on the nonlinear behavior of RC shear walls has been resulted from the existence of opening in the bottom position (L-B). It is not recommended to construct any opening in the position of (L-B) whatever the architectural requirement. Openings in the (L-B) position have decreased the shear capacity of the wall by a percentage of 31 to 49% (Fig. 26 to fig.29); the distribution of shear stress due to the existence of openings in the left side is shown in Fig. 30.

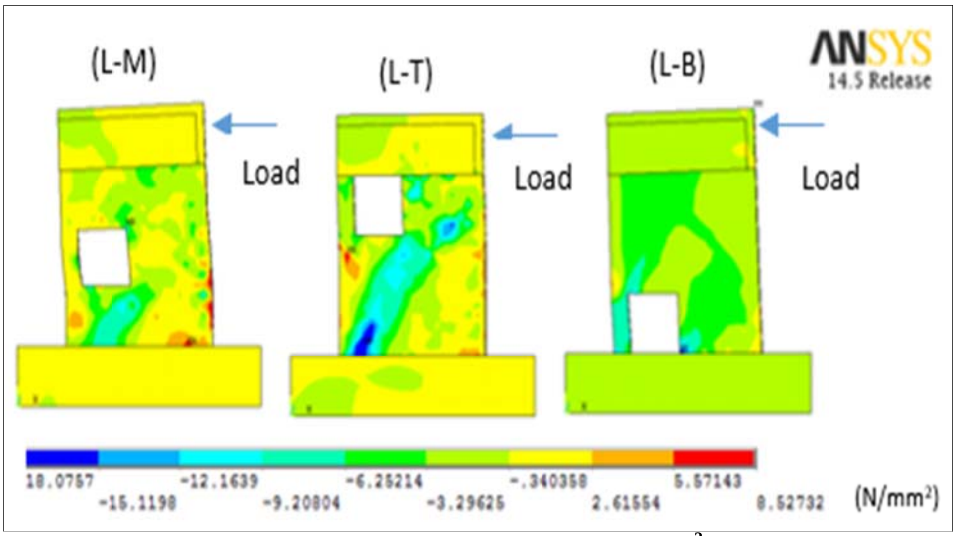


Fig. 30: Shear stress distribution - opening (300x300 mm^2) - (X2=-350mm).

A.2. Effect of the horizontal location of the opening on the shear capacity of the wall.

The results of the four studied opening's sizes when locating the opening at different locations have been rearranged and re-plotted. This is to provide a good judgment on the effect of the horizontal location of the opening on the shear capacity of the wall.

A.2.1. Openings with different offset distances from the center line of the wall and have the same elevation (Y1=450mm)-(at mid-height)

The results of shear walls that have an opening in the mid-height location show that the right side position of the opening (R-M) has resulted in a reduction in the shear capacity of the wall by 10 to 30%.Openings that located in the left or center side (L-M and C-M) has caused the same amount of reduction in the shear capacity; openings in the (L-M) position has decreased the shear capacity of the wall by a percentage of 13% to 44% while C-M located openings has led to a reduction of 12% to 44%, (Fig. 31 to Fig. 34). The comparison between the distributions of shear stress in the mentioned shear walls are shown in Fig. 35.

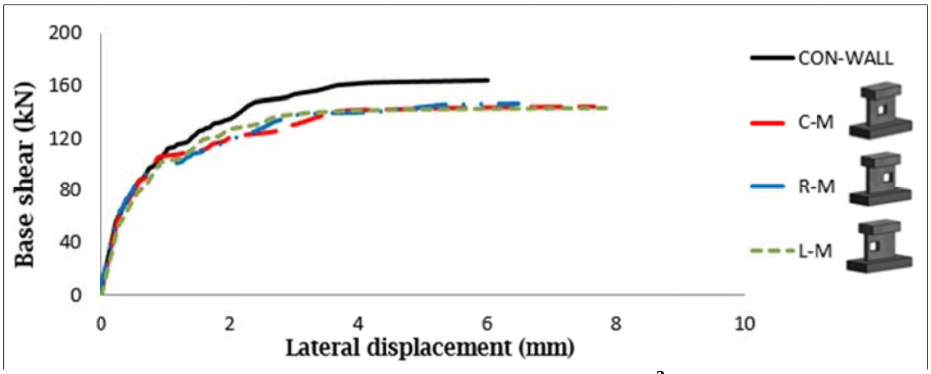


Fig. 31: Behavior of wall with opening (200x200 mm^2) - (Y1 = 450mm).

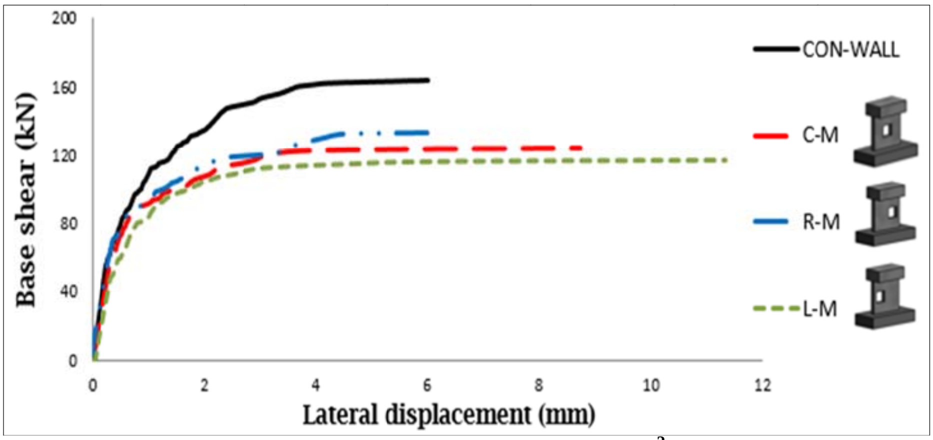


Fig. 32: Behavior of wall with opening (300x300 mm^2) - (Y1 = 450mm).

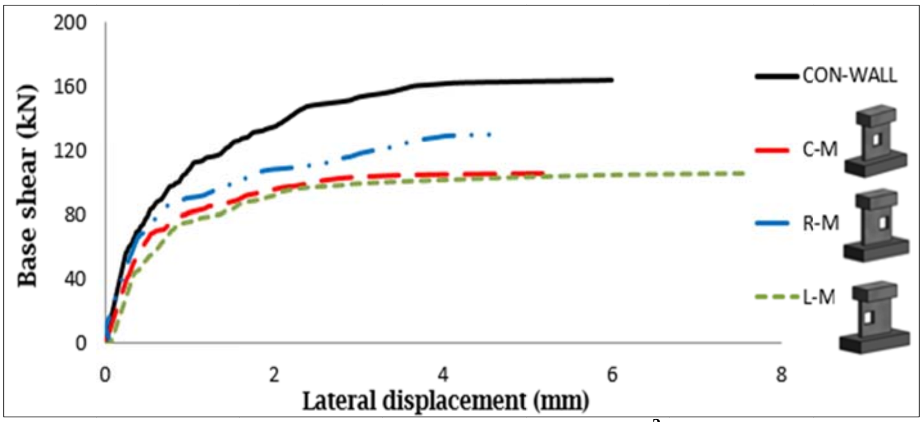


Fig. 33: Behavior of wall with opening (350x350 mm^2) - (Y1 = 450mm).

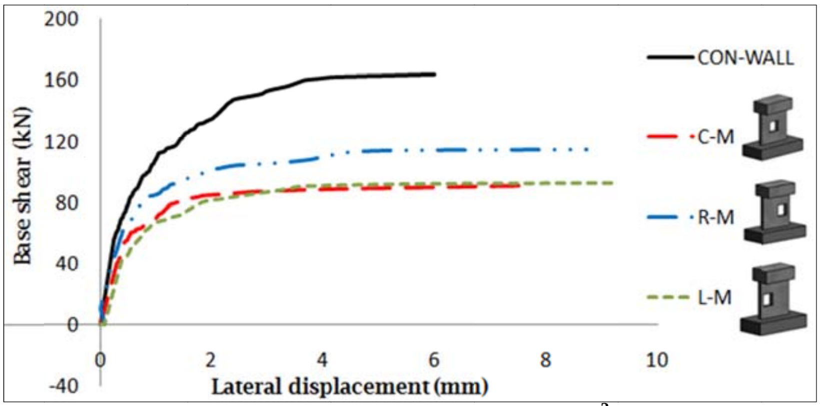


Fig. 34: Behavior of wall with opening (400x400 mm^2) - (Y1 = 450mm).

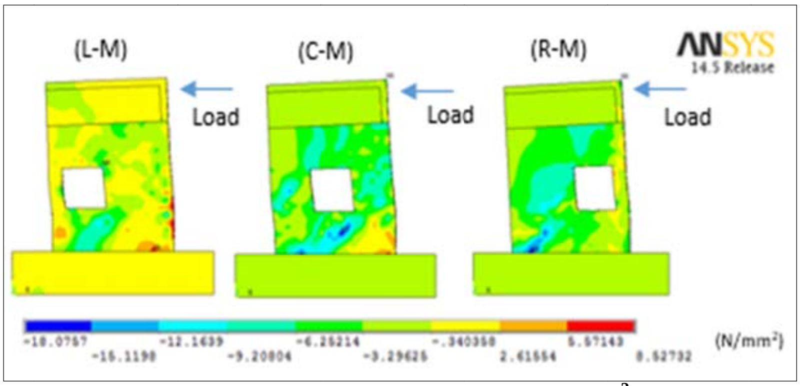


Fig. 35: Shear stress distribution - opening (300x300 mm^2) - (Y1=450mm).

A.2.2. Openings with different offset from the center line of the wall and have the same elevation(Y2=0mm)-(in the bottom zone)

Locating the opening at the right and at the center of the wall, (R-B) and (CB), have led to almost the same effect on the nonlinear response of the wall but the (R-B) position achieves a higher load level in the existence of large-size openings. It is generally noticeable that openings in the left side (L-B) are the most undesirable openings in shear walls under lateral static loading (Fig. 31 to Fig. 39). This can be due to the fact that when the opening is located at the tension zone, the shear stresses are resisted by the reinforcement only. Accordingly, the effect of locating the opening at this zone will be lower than the case in which the opening is located at the zone where the stresses are resisted by both of concrete and reinforcement. The distribution of shear stresses for the openings that have been located at the bottom of the wall is illustrated in Fig. 40.

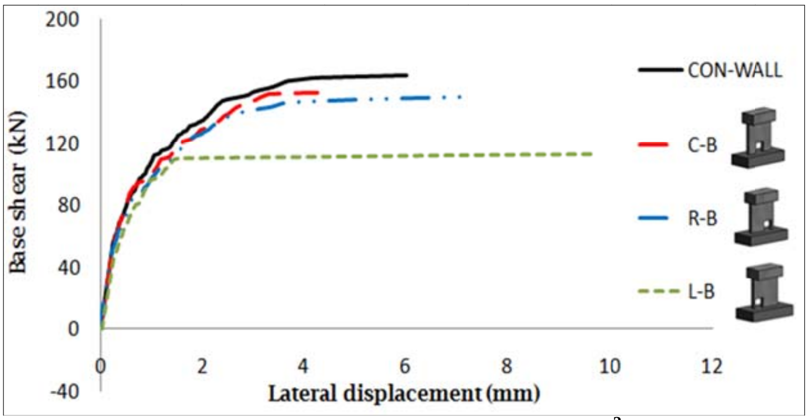


Fig. 36: Behavior of wall with opening (200x200 mm^2) - (Y2=0mm).

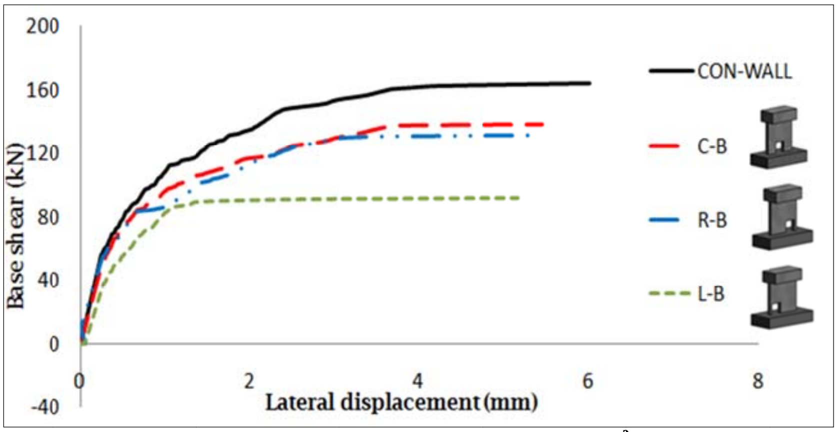


Fig. 37: Behavior of wall with opening (300x300 mm^2) - (Y2 = 0mm).

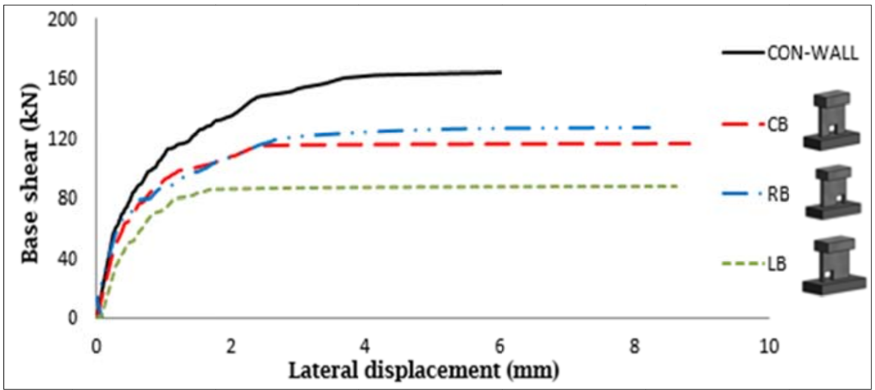


Fig. 38: Behavior of wall with opening (350x350 mm^2) - (Y2 = 0mm).

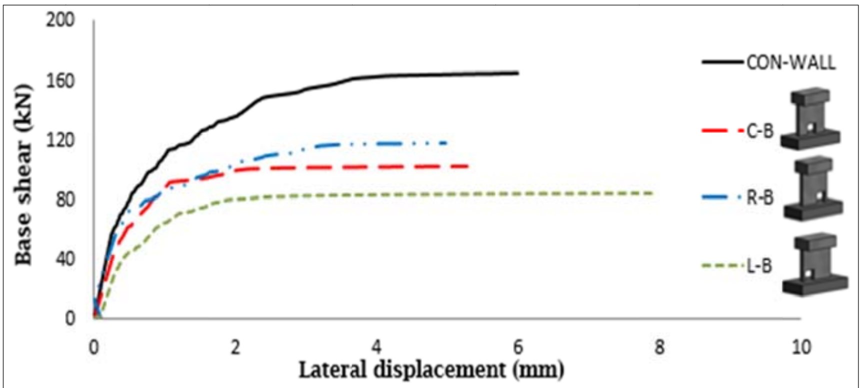


Fig. 39: Behavior of wall with opening (400x400 mm^2) - (Y2 = 0mm).

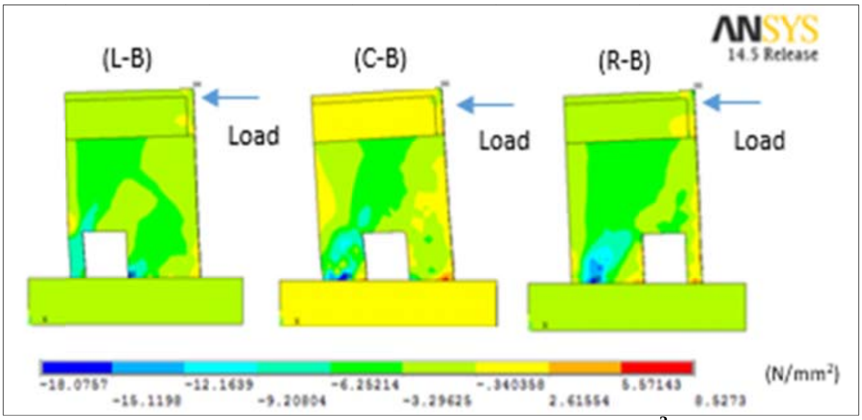


Fig. 40: Shear stress distribution- opening (300x300mm^2) - (Y2=0mm).

A.2.3. Openings with different offset distances from the center line of the wall and have the same elevation (Y3=0mm) -(at the top zone)

Finally, Fig. 41 to Fig. 44 show that openings in the right, left and center positions; R-T, L-T and, C-T, have the same impact on the performance of shear walls. By increasing the openings size, the shear wall with openings located at the right side, R-T, have the lowest decrease in their stiffness in comparison with those having openings in the position of R-B or C-T. Fig. 45 demonstrates the shear stresses distributions for shear walls with openings in the top positions.

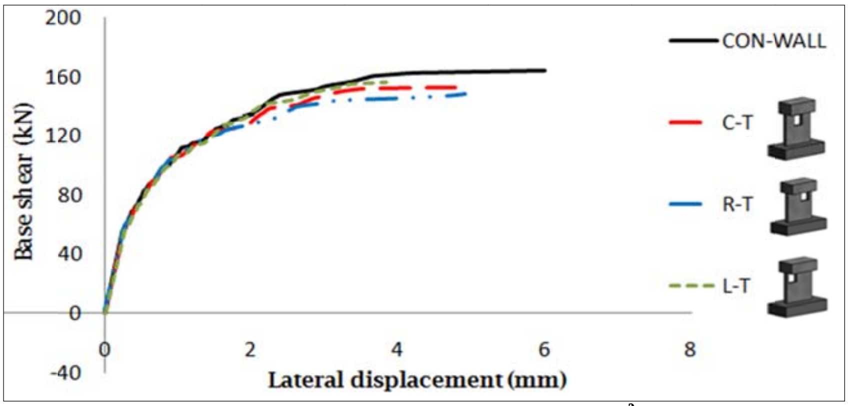


Fig. 41: Behavior of wall with opening (200x200 mm^2) - (Y3 = 0mm).

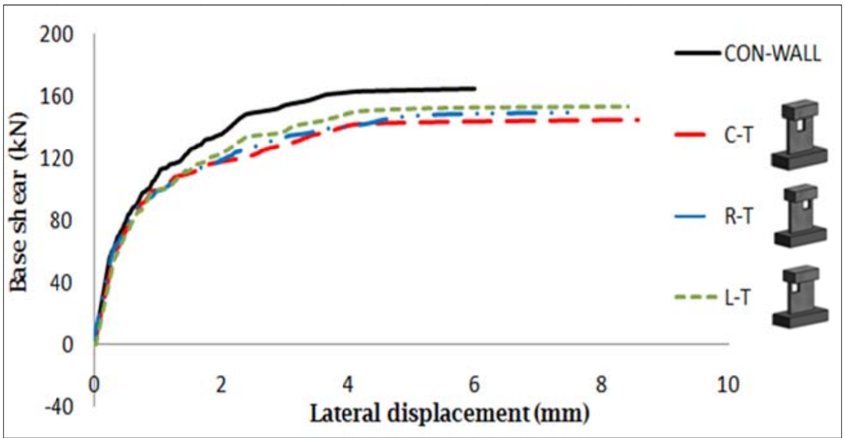


Fig. 42: Behavior of wall with opening (300x300 mm^2) - (Y3 = 0mm).

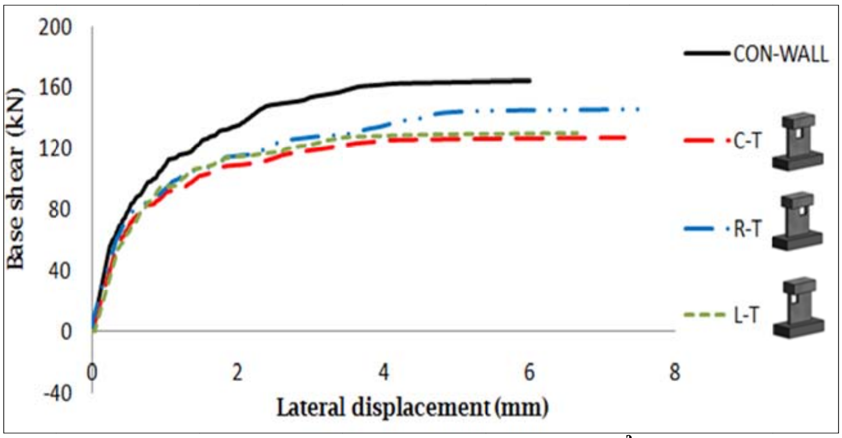


Fig. 43: Behavior of wall with opening (350x350 mm^2) - (Y3 = 0mm).

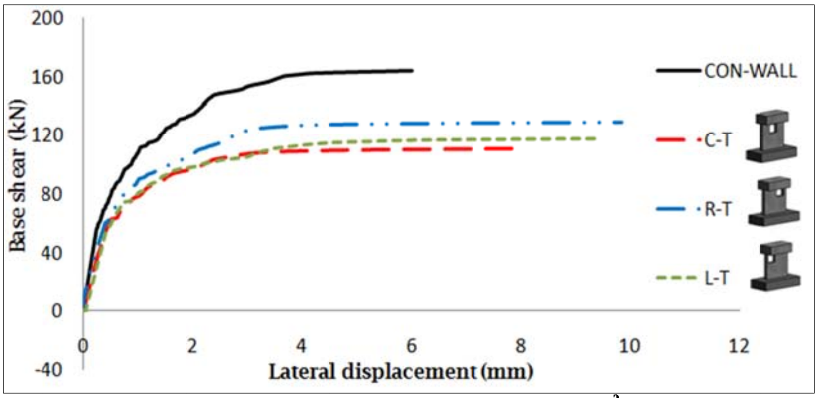


Fig. 44: Behavior of wall with opening (400x400 mm²) - (Y3 = 0mm).

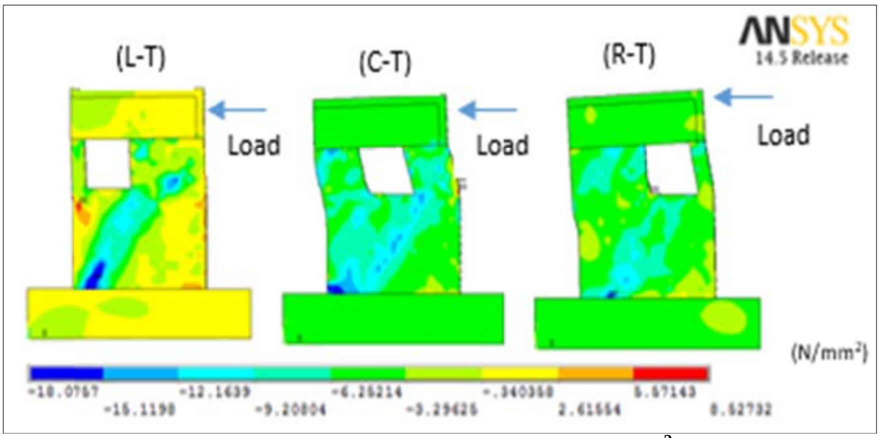


Fig. 45: Shear stress distribution-opening (300x300mm²) - (X2=0mm).

All previously obtained nonlinear responses of RC shear walls; that our parametric study has involved, are result of the way that a squat wall behave under the application of step-by-step lateral load. The main idea of predicting the influence of an opening located in any position on the stiffness of squat walls is tracing the path of strut that formed in such walls that have a height-to-width ratio (aspect ratio) less than 1.50. Fig. 46 shows the shear stress distribution among the reference wall just before its failure. So it becomes significantly clear why the most undesirable location of opening is the left-bottom (LB) position where the maximum compression stresses concentrate. This position of opening causes the greatest reduction percentage in the shear capacity of squat walls as explained before. On the other hand, the compression stresses in the position of left-top (L-T) almost equal to zero so openings that located in this location affects the capacity of shear walls by the lowest percentage as illustrated in Fig. 26 to Fig. 29 and Fig. 41 to Fig. 44Fig. 44.

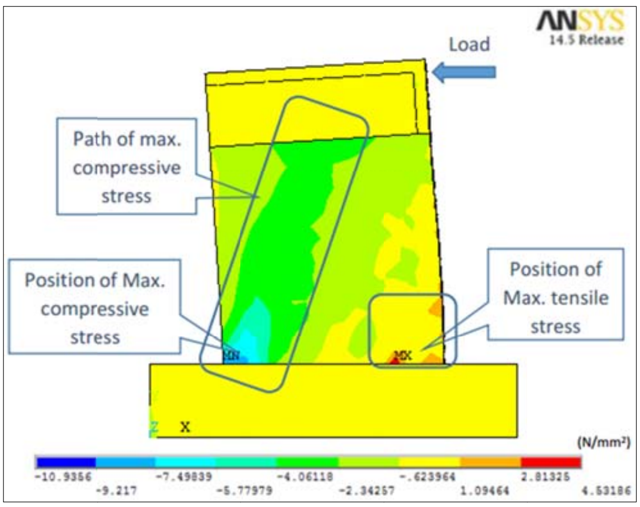


Fig. 46: Distribution of (X-Y) stresses in the reference wall under the application of lateral loads.

B. The efficiency of using CFRP sheets for retrofitting squat shear walls with opening

In this study, four different square openings are constructed at nine different positions in the reference squat wall (Fig. 14) with CFRP strips of 100mm width are applied around these openings for retrofitting the shear walls with opening that subjected to lateral static loads.

B.1. Openings located in the center- mid-height position (C-M):

The results of numerical analyses that have been conducted on RC shear walls with square opening in the position of center- mid-height (C-M) indicate that the shear capacity of the wall has decreased by a percentage ranges between 12% and 44%; these reduction percentages correspond to an increase in the size of the opening from 5% to 20% of the whole area of the reference wall. The proposed configuration of CFRP sheets makes an acceptable improvement in the lateral load carrying capacity of shear walls with opening; the average percentage of improvement is about 15% of the maximum base shear that obtained from the normal walls with opening, as can be seen from Fig. 47, Fig. 48 and, Table III.

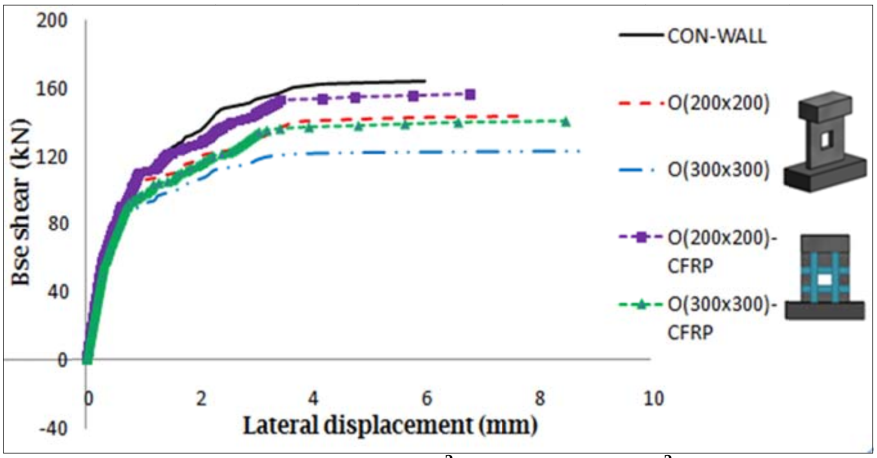


Fig. 47: Openings (200x200mm^2) and (300x300mm^2) - (C-M).

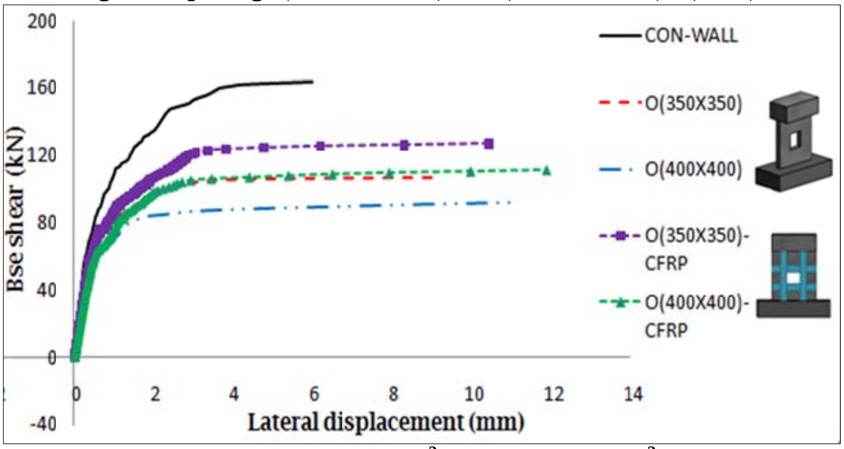


Fig. 48: Openings (350x350mm^2) and (400x400mm^2) - (C-M).

B.2. Openings located in the center-top position (C-T):

Regarding the shown figures; Fig. 49 and Fig. 50, the creation of openings in the position of (C-T) decrease the value of the wall's capacity by a percentage of (7-32%) depending on the size of the constructed opening. The applied CFRP sheets improve the shear capacity of these walls by an average percentage of 17%. As a result, the performance of retrofitted walls with openings (200x200mm^2 and 300x300mm^2) is better than the reference wall.

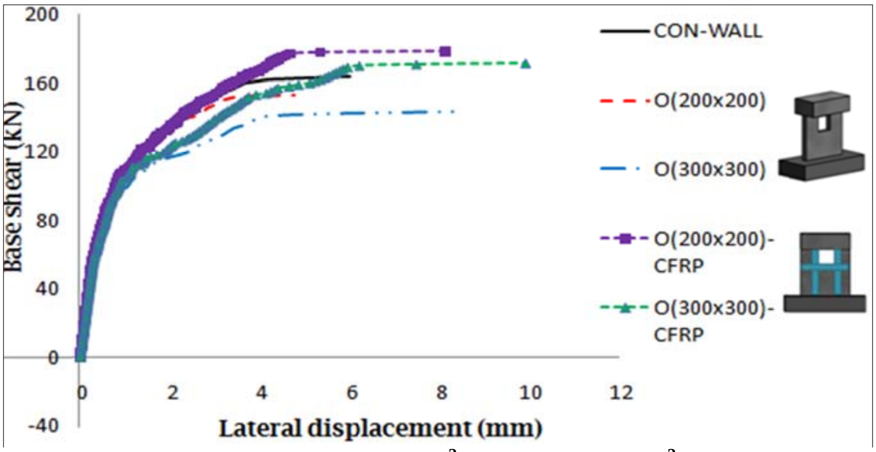


Fig. 49: Openings (200x200mm^2) and (300x300mm^2) - (C-T).

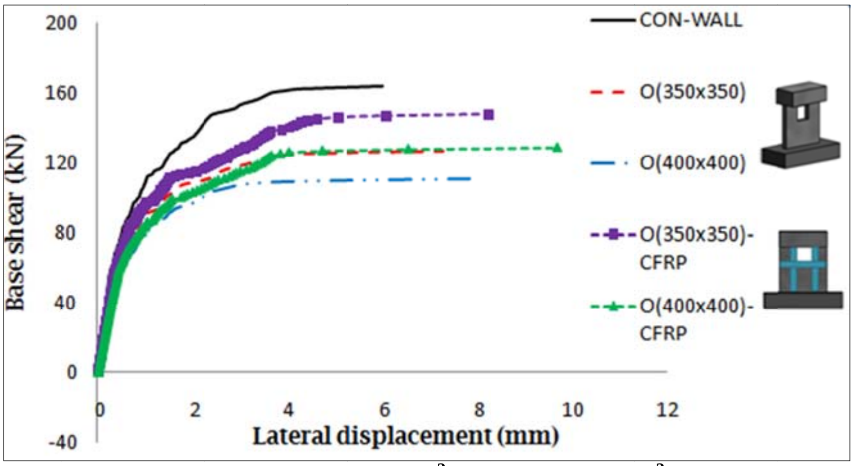


Fig. 50: Openings (350x350mm^2) and (400x400mm^2) - (C-T).

B.3. Openings located in the center-bottom position (C-B):

For the center-bottom position (C-B), increasing the size of the opening from (200x200mm^2) to (400x400mm^2) has decreased the shear capacity of the wall by a percentage ranges between 7% and 38%. The proposed retrofitting technique has enhanced the lateral load carrying capacity of the wall as can be noticed from Fig. 51, Fig. 52 and, Table III. The maximum capacity of the wall has increased by about 7%.

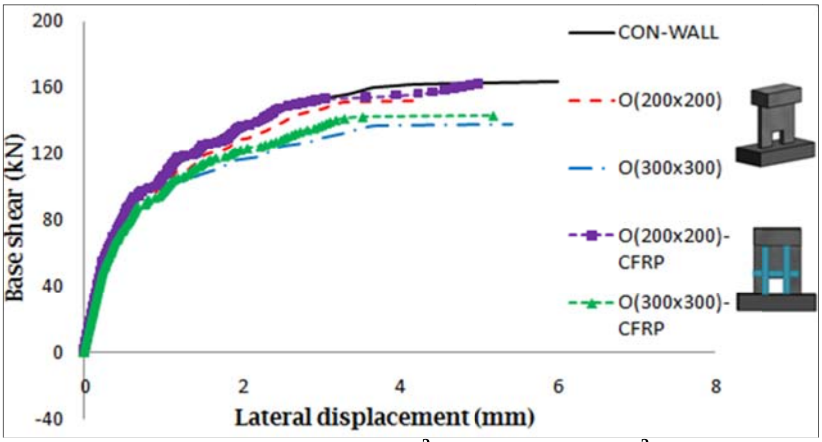


Fig. 51: Openings (200x200mm^2) and (300x300mm^2) - (C-B).

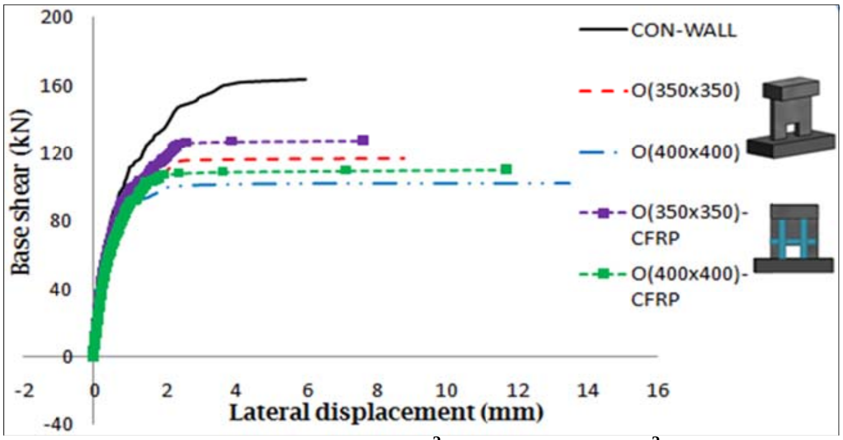


Fig. 52: Openings (350x350mm^2) and (400x400mm^2) - (C-B).

B.4. Openings located in the right- mid-height position (R-M):

It is found that square openings in this location reduce the obtained base shear by percentages range from 11% to 30%. Moderate improvements occur in RC walls with opening due to the application of CFRP sheets. In this case, the enhancement in the load carrying capacity ranges between 9.1% and about 22% comparing to the corresponding un-strengthened wall. Furthermore, some decrease in the wall's maximum displacement can be noticed in the cases of small openings as can be seen from Fig. 53 and Fig. 54.

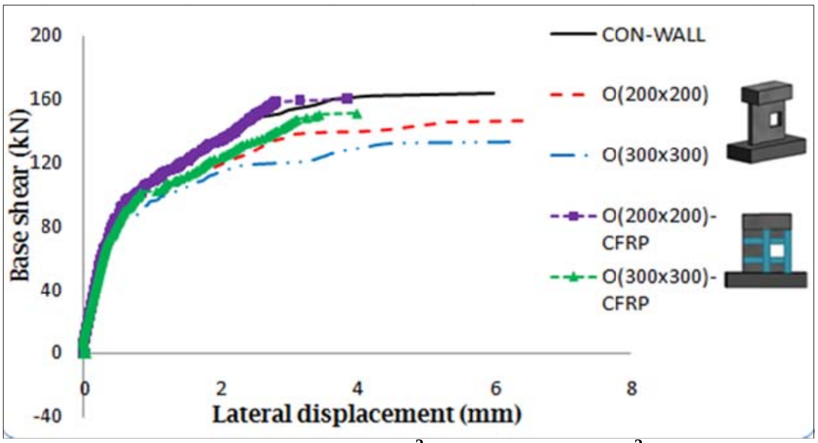


Fig. 53: Openings (200x200mm^2) and (300x300mm^2) - (R-M).

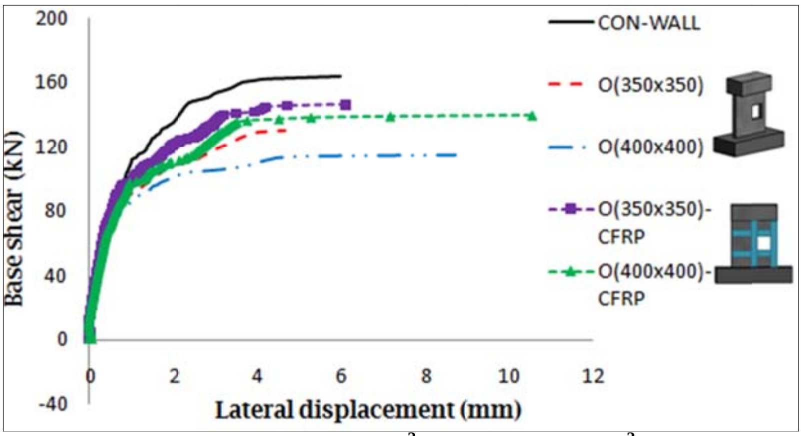


Fig. 54: Openings (350x350mm^2) and (400x400mm^2) - (R-M).

B.5. Openings located in the right-top position (R-T):

According to Fig. 55, Fig. 56 and, Table III, small reduction percentages have been obtained due to openings in the position of right-top (R-T); maximum reduction percentage of shear capacity (22%) has been occurred during the numerical analysis of the shear wall with a square opening of ($400x400mm^2$). Applying 10mm-wide sheets of CFRP has increased the maximum obtained base shear with an average percentage of 15%.

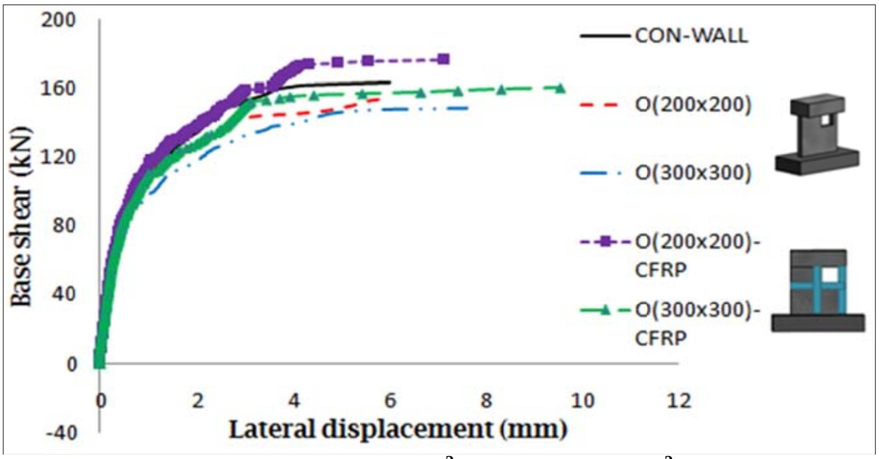


Fig. 55 Openings ($200x200mm^2$) and ($300x300mm^2$) - (R-T).

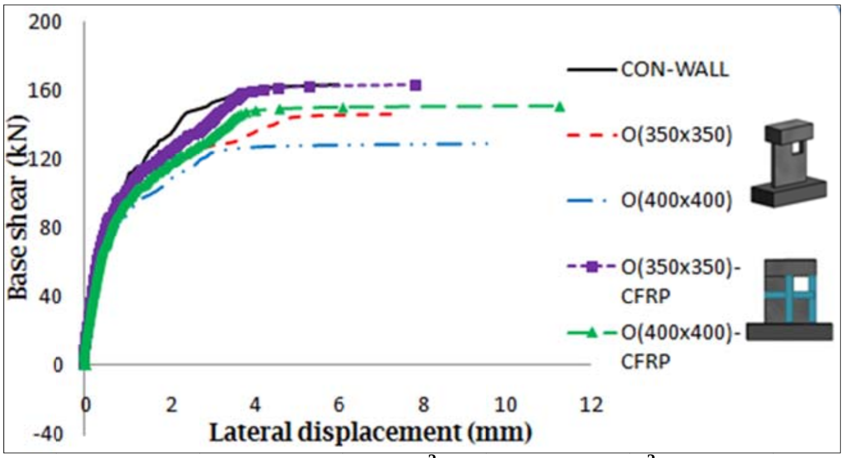


Fig. 56 Openings ($350x350mm^2$) and ($400x400mm^2$) - (R-T).

B.6. Openings located in the right-top position (R-B):

Openings in this position cause a reduction in the lateral load capacity of shear walls by percentages start from 9% to 28% (in case of constructing the 400mm-square opening). The proposed strengthening scheme achieves the greatest improvement in the nonlinear behavior of shear walls in comparison with all other positions. The obtained values of the base shear are higher than those of un-strengthened walls by a percentage of 24% in average, Fig. 557 and Fig. 58.

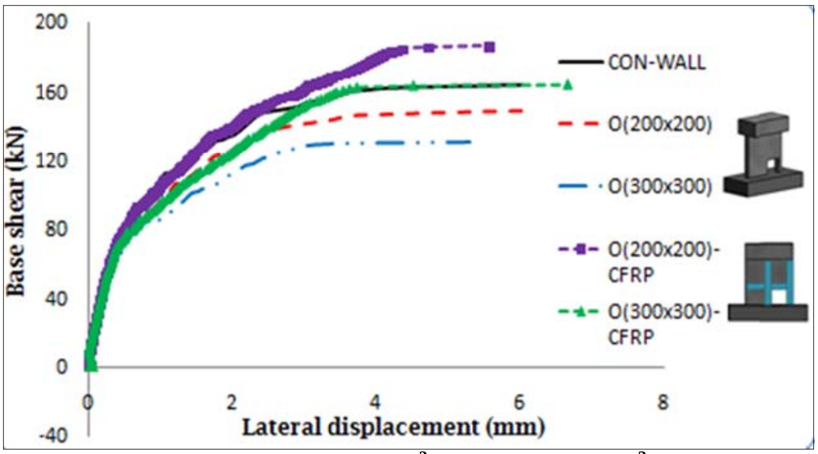


Fig. 57: Openings ($200x200mm^2$) and ($300x300mm^2$) - (R-B).

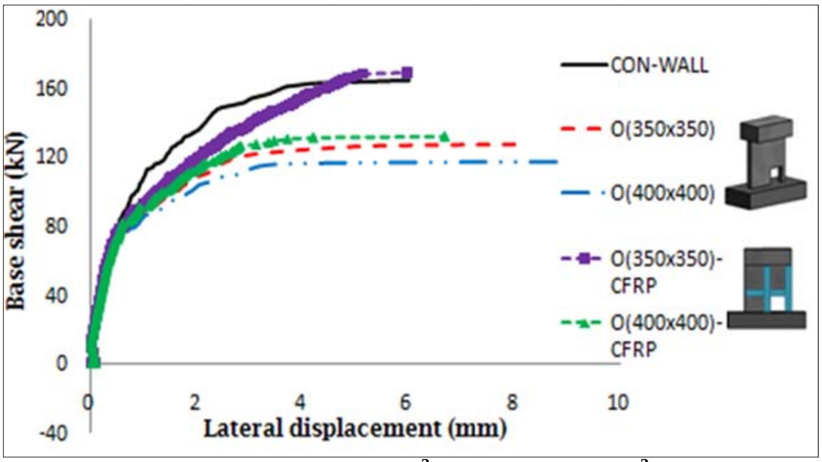


Fig. 58: Openings (350x350mm^2) and (400x400mm^2) - (R-B).

B.7. Openings located in the left- mid-height position (L-M):

In the case of locating the opening at the left-mid-height position of the wall, the shear capacity of the wall's section has increased by about 17% to 21% comparing to the un-strengthened one. It is worth to mention that in the case of small opening (200x2000mm^2), the strengthening system has succeed to recover the walls capacity. Refer to Fig. 59, Fig. 60 and, Table0 III.

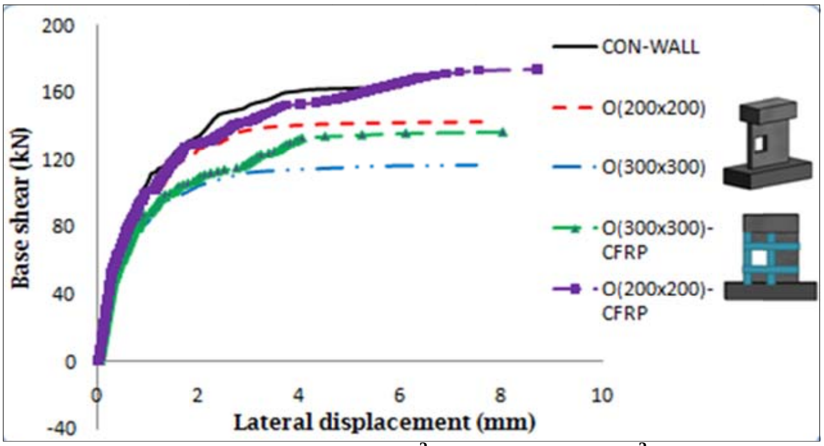


Fig. 59: Openings (200x200mm^2) and (300x300mm^2) - (L-M).

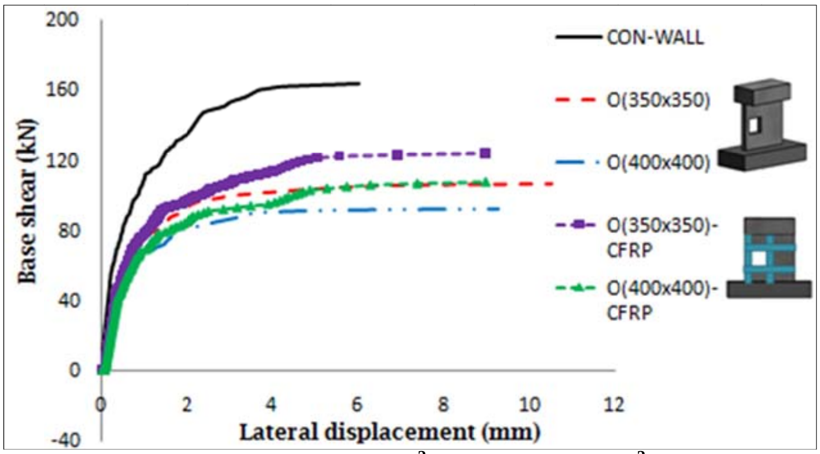


Fig. 60: Openings (350x350mm^2) and (400x400mm^2) - (L-M).

B.8. Openings located in the left- top position (L-T):

Regarding the shown Fig. 55, Fig. 56 and, Table III, the influence of openings (200x200mm^2 and 300x300mm^2) that located in the position of left-top is not significant. Increasing the openings size to

(350x350mm^2 and 400x400mm^2), results in a loss in the wall's capacity by 21% to 28%. The CFRP sheets produce a little improvement in the capacity in this case by about 12%.

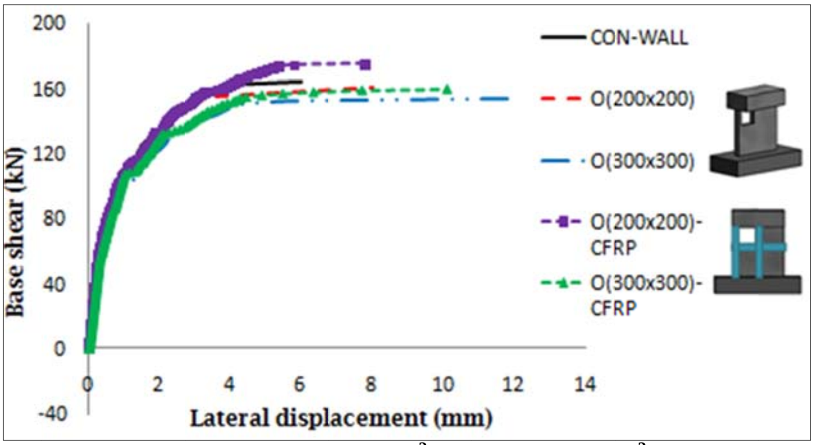


Fig. 61: Openings (200x200mm^2) and (300x300mm^2) - (L-T).

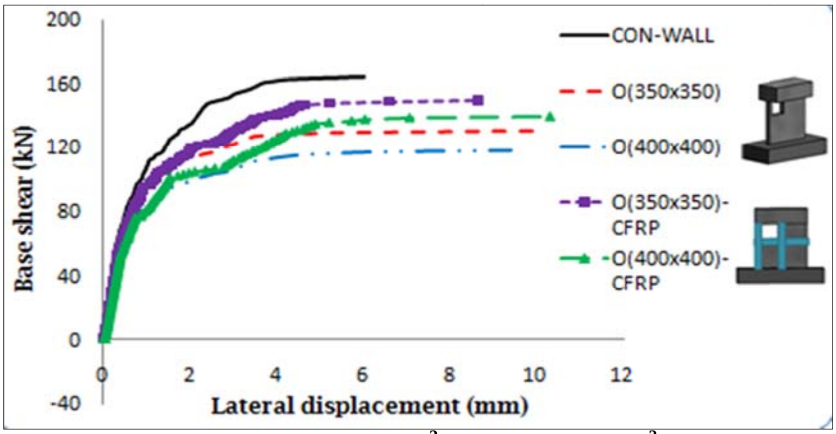


Fig. 62: Openings (350x350mm^2) and (400x400mm^2) - (L-T).

B.9. Openings located in the left- bottom position (L-B):

As mentioned before, this position of openings is not recommended; the reduction percentage of the shear capacity of the wall reaches 31% to 49% while applying the proposed strengthening configuration has not significantly made a great difference in the behavior of walls; Fig. 63, Fig. 64 and, Table III.

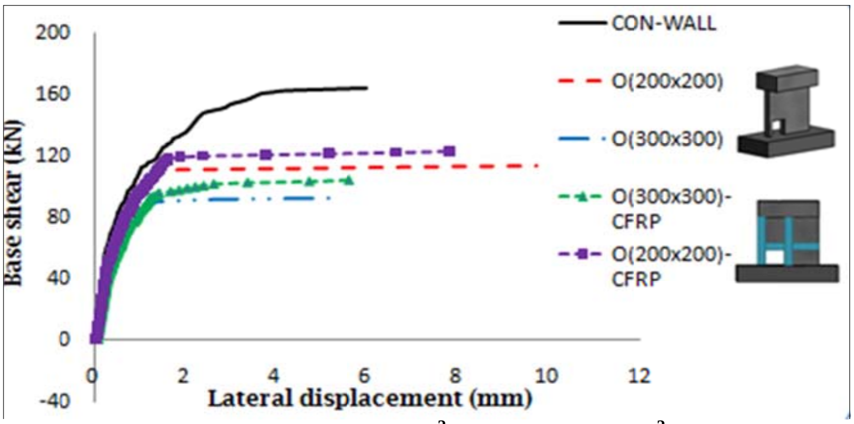


Fig. 63: Openings (200x200mm^2) and (300x300mm^2) - (L-B).

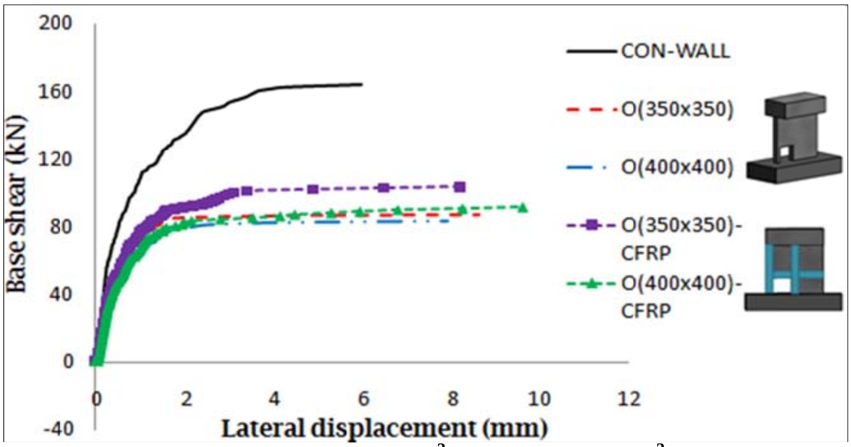


Fig. 64: Openings (350x350mm^2) and (400x400mm^2) - (L-B).

Table III: Summary of the results for the studied cases.

Position	Opening Size (mm)	Opening /wall ratio	Un-strengthened wall: Base shear (kN)	Un-strengthened wall: Reduction in capacity (%)	Strengthened wall: Base shear (kN)	Strengthened wall: Increase in capacity (%)
CON-Wall	-	-	163.9	-	-	-
(C-M)	200x200	4.9	143.7	12.3	156.8	9.1
	300x300	11.1	123.6	24.6	140.7	13.8
	350x350	15.1	106.6	34.9	126.7	18.8
	400x400	19.8	91.5	44.2	109.7	19.9
(C-T)	200x200	4.9	153.0	6.7	178.7	16.8
	300x300	11.1	144.1	12.1	171.6	19.1
	350x350	15.1	127.0	22.5	148.1	16.6
	400x400	19.8	110.8	32.4	129.0	16.4
(C-B)	200x200	4.9	152.2	7.2	162.1	6.5
	300x300	11.1	138.1	15.8	143.0	3.6
	350x350	15.1	116.1	29.2	127.8	10.1
	400x400	19.8	102.1	37.7	110.5	8.2
(R-M)	200x200	4.9	146.7	10.5	160.1	9.1
	300x300	11.1	132.7	19.1	151.1	13.9
	350x350	15.1	130.1	20.6	146.8	12.8
	400x400	19.8	114.0	30.4	139.6	22.5
(R-T)	200x200	4.9	154.1	6.0	176.8	14.7
	300x300	11.1	149.0	9.1	160.5	7.7
	350x350	15.1	146.0	10.9	163.3	11.8
	400x400	19.8	128.2	21.8	151.1	17.9
(R-B)	200x200	4.9	149.8	8.6	186.1	24.2
	300x300	11.1	131.0	20.1	163.9	25.1
	350x350	15.1	126.8	22.6	168.4	32.8
	400x400	19.8	117.6	28.3	132.5	12.7
(L-M)	200x200	4.9	143.2	12.7	173.9	21.5
	300x300	11.1	117.0	28.6	136.7	16.8
	350x350	15.1	106.3	35.2	123.7	16.4
	400x400	19.8	92.4	43.6	107.8	16.6
(L-T)	200x200	4.9	161.0	1.8	174.9	8.6
	300x300	11.1	153.6	6.3	160.0	4.2
	350x350	15.1	130.7	20.3	150.0	14.8
	400x400	19.8	117.8	28.1	139.9	18.7
(L-B)	200x200	4.9	113.1	31.0	122.3	8.1
	300x300	11.1	91.8	44.0	103.8	13.0
	350x350	15.1	87.4	46.7	103.5	18.4
	400x400	19.8	83.6	49.0	91.4	9.4

VI. Conclusions

For achieving architectural and mechanical needs, it becomes inescapable matter in some situations to make openings in RC shear walls. So, it is necessary to study the effect of these openings on the behavior of shear walls. The present study focused on investigating the influence of locations, and dimension of openings on the lateral load carrying capacity of squat RC shear walls under the application of lateral monotonic loads along with the existence of vertical loads. This study also presented a proposed scheme of CFRP strips for retrofitting these shear walls with openings. The current work was based mainly on numerical modeling of the shear walls using the well-known finite element program ANSYS; verification models were conducted for ensuring the accuracy of these numerical models. The obtained conclusions from this study can be summarized as follows:

1- The height-to-length ratio (aspect ratio) of RC shear walls affects mainly the mode in which these walls fail. In case of squat shear walls that have aspect ratio less than 1.5, the nonlinear shear deformation is the reason for the highest percentage of walls' lateral displacement. Paths of compressive stresses (strut) and tensile stresses (tie) appears clearly during the application of lateral monotonic loads on RC walls.

2- For the same opening size, the existence of a square opening in top positions (C-T, R-T and L-T) results in the minimum loss in the load carrying capacity among all the studied locations. For the studied square openings whose area ranges from 4.9% to 19.8% of the total area of the reference wall and located in the position of (L-T), the reduction percentages of the obtained base shear ranges between 1.8% and 28.1% of the base shear obtained from the reference wall. When these openings are located in the position of (R-T), the reduction percentages range between 6% and 21.8%. Constructing these square openings in the position of (C-T) causes a reduction in the shear capacity of percentages of 6.7% to 32.4%.

3- It is not preferred to locate an opening in the position of (L-B) where the maximum compression stresses concentrate; the studied square openings in this position cause the maximum reduction in the wall's shear capacity. When the opening with the smallest size is located in this position, the lateral load carrying capacity decreases by a percentage of 31% of the reference wall's base shear; this percentage increases with increasing the opening size till 49% in case of the largest opening, 400x400mm^2.

4- The proposed configuration of CFRP sheets proves its effectiveness in retrofiring RC shear walls with openings. The greatest improvement in the nonlinear behavior of retrofitted shear wall with opening causes in case of shear walls with right-bottom (R-B) located openings in which the percentage of increasing shear capacity reaches 24% of the obtained shear capacity of un-strengthened walls.

References

[1]. K.Kolozvari, T. A. Tran, K. Orakcal, andJ. W. Wallace, "Modeling of Cyclic Shear-Flexure Interaction in ReinforcedConcrete Structural Walls. II: Experimental Validation,"ASCE, volume 141, issue 5, 2014.

[2]. S. Borra, R. Nanduri and S. Naga, "Design Method of Reinforced Concrete Shear Wall Using EBCS ", American Journal of Engineering Research (AJER) , Volume-4, Issue-3, pp-31-43, 2015.

[3]. M. Marius, "Seismic behaviour of reinforced concrete shear walls withregular and staggered openings after the strong earthquakes between 2009 and 2011," Engineering Failure Analysis, Volume 34, Pages 537-565,2013.

[4]. J. Paterson and D. Mitchell, "Seismic Retrofit of Shear Walls withHeaded Barsand Carbon Fiber Wrap ," ASCE, volume 141, issue 5, 2003.

[5]. N. Mohamed, A. S. Farghaly, B. Benmokrane, and K. W. Neale, "Drift Capacity Design of Shear Walls Reinforced with GlassFiber-Reinforced Polymer Bars,"ACI Structural Journal, Volume 111,2014.

[6]. M.A. Hube, A. Marihuén, J.C. de la Llera, B. Stojadinovic, "Seismic behavior of slender reinforced concrete walls," Engineering Structures,Volume-80, pp-377-388, 2014.

[7]. L. D. Lefas, M. D. Kotsovos, and N. N. Ambraseys, "Behavior of Reinforced Concrete Structural Walls: Strength,Deformation Characteristics, and Failure Mechanism ," ACI Structural Journal, 1990.
A.A. Tasnimi, "Strength and deformation of mid-rise shear walls under loadreversal,"Engineering Structures,volume 22, issue 4, pages 311-322, 1998.

[8]. M. DENG, X. LIANG and K. YANG, "Experimental Study on Seismic Behavior of High Performance Concrete Shear Wall with New Strategy of Transverse Confining Stirrups," The 14thWorld Conference on Earthquake Engineering, 2008.

[9]. W. CAO, J. ZHANG, J. ZHANG, M. WANG,"Experimental study on seismic behavior of mid-rise RC shearwall with concealed truss,"Journal of Beijing University of Technology, 2008.

[10]. J.C.Lombard, "Seismic strengthening and repair of reinforced concrete shear walls using externally bonded carbon fibre tow sheets ," Master Thesis, Carleton university, Canda, 1999.

[11]. Hiotakis, "Repair and Strengtheneing of Reonforced Concrete Shear Walls for Earthquake Resistance Using Externally Bonded Carbon Fibre Sheets and a Noval Anchor System," Master Thesis, Carleton university, Canda, 2004.

[12]. S. Altin, Ö. Anil, Y. Kopraman, M. E. Kara, "Hysteretic Behavior of RC Shear Walls Strengthened with CFRP Strips," Composites: PartB,Volume 44, Issue 1, Pages 321-329, 2013.

[13]. A. Farghaly, B.Benmokrane"Experimental Investigation of Concrete Shear Walls Reinforced with Glass Fiber–Reinforced Bars under Lateral Cyclic Loading," ASCE, volume 18, issue 3,2014.

[14]. C. A. Cruz-Noguez, A. Hassan, D. T. Lau, J. Woods, and I. Shaheen "Seismic Retrofit of Deficient RC Sear Wallswith FRP Tow Sheets," Tenth U.S. National Conference on Earthquake Engineering, 2014.

[15]. W. Leonardo, C. Puentes and D. Palermo"Modeling of RC Shear Walls Retrofitted with Steel Plates or FRP Sheets," ASCE, volume 138, issue 5, 2012.

[16]. W. Leonardo, C. Puentes and D. Palermo"Seismic Behavior of RC Shear Walls with Externally Bonded FRP Sheets: Analytical Studies," ASCE, volume 18, issue 5, 2014.

[17]. D. Mostofinejad, M. M. Anaei“Effect of confining of boundary elements of slender RC shear wall by FRP composites and stirrups: Analytical Studies,” Engineering Structures, 2012.
[18]. A. Ali and J. K. Wight“Rc Structural Walls with Staggered Door Openings,” ASCE, volume 117, issue 5, 1991.
[19]. B. Li,K. Qian, and C. T. N. Tran “Retrofitting Earthquake-Damaged RC Structural Walls withOpenings by Externally BondedFRP Strips and Sheets,” ASCE, volume 17, issue 2, 2013.
[20]. A. S. Mosallam, and A.Nasr“Structural performance of RC shear walls with post-construction openings strengthened with FRP,” Composites Part B, volume 115, pages 488-504, 2016.
[21]. ANSYS engineering simulation software[https://www.ansys.com/]
[22]. G.V.R. Rao, N. Gopalakrishnan, K. P. Jaya, K. Muthumani, G. R. Reddy and Y. M. Parulekar“Studies on Nonlinear Behavior of Shear Walls of Medium Aspect Ratio under Monotonic and Cyclic Loading,” ASCE, volume 30, issue 1, 2014.
[23]. ANSYS help documentation.
[24]. S. Qazi, L. Michel, E. Ferrier“Impact of CFRP partial bonding on the behaviour of short reinforcedconcrete wall under monotonic lateral loading,” Composite Structures , volume 128, pages 251-259, 2015.
[25]. E. Hognestad "A study of combined bending and axial load in reiforced concrete members" University ofIllinois, 1951.
[26]. K. J. Thompson and R. Park " Stress strain model for grade 275 reinforcement steel with cyclic loading" Bulletin of the new zealand national society for earthquake engineering, vol. 11, no. 2, 1978.