Jordan Journal of Civil Engineering, Volume **17**, No. **2**, **2023**
DOI: https://doi.org/10.14525/JJCE.v17i2.04

Experimental and Numerical Study of the Behavior of RC Shear Wall with Opening Using Concealed Stiffeners

Sanjivan Mahadik [1)*], S.R. Bhagat [2)], Pravin D. Gunaware [3)] and Vijay N. Patil [4)]

[1)] Assistant Professor, Department of Civil Engineering, HSBBPVT's College of Engineering, Kashti, India.
* Corresponding Author. E-Mail: sanjivanmahadik@gmail.com
[2)] Professor and Head, Department of Civil Engineering, Dr. Babasaheb Ambedkar Technological University, Lonere, India.
[3)] Assistant Professor, Department of Civil Engineering, HSBBPVT's College of Engineering, Kashti, India.
[4)] Principal, HSBBPVT's College of Engineering, Kashti, India.

ABSTRACT

A shear wall becomes weak when an opening is provided in it. It is important to provide some arrangement in the shear wall having an opening for recovering strength loss due to the opening. It may be recovered by providing some steel profiles around the opening or at weaker sections in the shear wall having an opening. At first, the identification of weaker sections in the shear wall having an opening is important and then, the wall can be made stronger as the shear wall without an opening by strengthening weaker sections. In the present study, the performance of a shear wall having an opening subjected to horizontal cyclic loading along the plane of the shear wall in the presence of concealed stiffeners is investigated. The reduced models of shear walls with openings were tested under axial and lateral load conditions. Load-carrying capacity, deformation behavior and strain behavior of shear walls were studied with experiments and the validation of the results was made with general-purpose finite element software ANSYS. Significant improvements were observed in strength, deformation and strain behavior of a shear wall having a central opening using concealed reinforced concrete (RC) stiffeners and steel tube stiffeners.

KEYWORDS: Shear wall, Strength, Stiffness, Strain, Openings, Stiffeners.

INTRODUCTION

Many buildings worldwide have collapsed during strong earthquakes in the recent past. Even buildings with shear walls had shown different failure modes during such earthquakes. Failure of buildings affects the society and nation due to loss of properties and lives. Failure of buildings may be minimized by providing some practical solutions, like concealed stiffeners in the body of the shear wall.

Due to the provision of openings required in shear walls for utility services or any other purpose, the strength of the wall gets reduced due to reductions in concrete area, as well as stress concentration near the opening or discontinuity of steel. Failure of shear walls due to openings may lead to failure of the building. Some codes have made provisions for an additional reinforcement around an opening in a shear wall, but these provisions do not recover its original strength as a solid wall without an opening. As the size of the opening increases, the reduction in wall strength increases. Openings nearer to the sides of shear walls are more unstable than those at the centre. More precautions are necessary for such situations. To overcome this problem up to a certain extent, the provision of stiffeners around and along the diagonal may prove important. In this regard, a study of the performance of shear walls having openings with the provision of concealed stiffeners is conducted in this research. For the improvement of the behaviour of a shear wall with an opening, the use of reinforcement in different manners around the opening or at the corner was observed in literature, but no evidence of using concealed stiffeners has been found.

Received on 20/7/2022.
Accepted for Publication on 27/10/2022.

Research made on shear walls having openings by previous researchers is summarized in the following paragraphs.

Degradation properties of reinforced-concrete walls having openings using variable reinforcement ratios for static and dynamic loads were studied by Carrillo and Alcocer (2011). It was observed that the resistance of the shear walls depends on the rate of loading, the number of cycles, the strength mechanism behaviour related to failure mode the ductility demand and the energy dissipation. Lin and Kuo (1988) studied the effect of different reinforcement patterns around the opening due to lateral load on a shear wall having an opening. It was found that diagonal reinforcement has more strength than vertical and horizontal arrangements. Different orientations of reinforcement around the opening showed completely different modes of failure. Ductility was found significantly changed due to slight variations in reinforcement patterns around the opening. Shear strength carried by diagonal reinforcement was found to be 40%, while it was 20% with vertical and horizontal arrangements. A study of restoring force nature of reinforced-concrete shear walls having openings using different methods of reinforcing was made by Umemura et al. (2009) by carrying out several tests to know the effect of opening inbox-type shear walls. It was observed that the effective reinforcement around the opening not only increased the shear strength of the shear wall, but also helped improve its overall behavior. The adverse effect due to openings can be reduced by providing additional reinforcement around the openings. Strength of the wall changes with variation in the size of openings and their location. Size and location of openings both affect the strength, stiffness and failure pattern of a shear wall. Three-dimensional effects on openings in pierced shear walls with variable reinforcement ratio were studied by Balkaya and Kalkan (2004). It was observed that the results regarding crack pattern and stress flow using three-dimensional analyses are significantly different from those of two-dimensional analyses.

Due to the non-availability of exact formulae to predict the correct nominal shear strength of shear walls with openings at different locations, shapes or sizes, many researchers used FE software to analyze shear walls with openings or for the validation of experimental results. In this study, the use of steel tube stiffeners and reinforced concrete (RC) stiffeners is adopted to study the improvement in the behavior of shear walls and the results were validated using FE software ANSYS18.2. Similar experiments carried out by Mahadik and Bhagat (2022) on a solid shear wall (without opening) showed a significant improvement in the behavior of the shear wall strengthened with reinforced-concrete stiffeners and steel tube stiffeners in a concealed manner. A significant improvement was observed in the behavior of solid shear walls using concealed stiffeners. An experimental study was carried out by Sivaguru and Rao (2019) for investigating the behavior of shear walls having openings. Results were validated using FE software ANSYS. They used SOLID65 element for concrete and link 8 element for the reinforcement. The use of steel fibre reinforcement in the region of the opening was made to control cracking at the corner of the opening. By using steel fibre in concrete near the opening region of the shear wall, strength and ductility were found to increase. A significant improvement in confinement and cracking resistance was experienced with the shear wall. The mode of failure for the shear wall was found to change from the shearing of the weak plane across the opening to the crushing of both toes of the boundary element. Shear wall having an opening strengthened with FRP laminates was studied by Mohamed et al. (2019) through simulating a model of the shear wall having an opening which was strengthened by carbon fiber-reinforced polymer (CFRP) laminates using FE software ABAQUS. The results were validated with experimental data. It was investigated that strengthening the shear wall having an opening using FRP laminates increases its lateral load strength, ductility, deformation capacity and energy dissipation with substantial amounts. Behavior of CFRP-strengthened shear wall with an opening using a numerical study was investigated by Shirneshan and Behfarnia (2017) through carrying out non-linear finite element analysis with different configurations of CFRP, presenting a bond-slip consecutive model of link element for simulating CFRP strip connections to concrete surface using FE software ABAQUS. Significant improvement was observed using these configurations of CFRP strips in lateral resistance and deformation capacity. Creating an opening in the shear wall of 50% the length and height of the shear wall decreased load capacity and ultimate displacement by

42.10% and 32%, respectively. In the same investigation, it was also observed that the most suitable configuration of FRP strips to increase load capacity and displacement capacity is that of warping around piers. The effect of provision of openings in shear walls was studied by Kankuntla et al. (2016) using FE software SAP. It was observed that due to the opening, the strength of the shear walls decreases. Shape and size of the opening provided affect the rigidity of the shear wall. Lateral stiffness of the shear wall gets affected due to provision of an opening in it. The effect on the lateral stiffness of cantilever shear walls due to provision of openings in them and the related improvement due to strengthening with FRP warp were studied by Fares (2021) using FE software ABAQUS applying monotonic loading. It was observed that the model proposed of CFRP warping significantly improves strength, deformation, energy dissipation capacity and ductility of a shear wall having an opening. The FE software ABACUS was used by Bélaidia et al. (2015) to compare the behaviour of slender reinforced concrete walls using reinforcement in two different manners; namely, the classical method and the band method. The classical method of reinforcement gives better prediction than the method of bands. These two methods of reinforcement are as per Algerian earthquake regulations. Both methods are having nearly the same reinforcement pattern consisting of horizontal reinforcement and vertical reinforcement in two layers and boundary elements at the end. The classical method has larger steel sections in its reinforcement. The classical method offers higher load carrying, less strain and more stability. The method of bands performs better in terms of deformation and displacement and has a lower bearing capacity due to smaller steel sections. Thus, this type of wall is more vulnerable during earthquakes.

Most related previous studies reported in the literature were concerned with strength, stiffness, energy dissipation and failure mode. Lin and Kuo (1988) used different reinforcement layouts and methods for improving the behavior of a shear wall having an opening. It was found that using different layouts and methods of reinforcement can improve the behavior of a shear wall having an opening up to a certain extent. Diagonal reinforcement around the opening was found more beneficial than horizontal and vertical reinforcement arrangement, contributing 20 % more shear strength. Ductility and shear capacity of the shear wall were found affected due to the provision of reinforcement in different arrangements around the opening. In this study, the use of concealed reinforced concrete stiffeners and steel tube stiffeners was tried along the periphery of the opening and the diagonal of the shear wall, thereby expecting improvements in the behavior of a shear wall with opening.

MATERIALS AND METHODS

All specimens were cast with reinforced concrete. Compressive strength of concrete used for casting was observed to be 25 MPa and deformed steel used was having a yield strength of 500 N/mm^2. Four deformed bars of 6-mm diameter were used to form RC stiffeners. Steel tube stiffeners were formed with square steel tube of 40 × 40 mm size and 4 mm thickness. Shear walls were provided with horizontal and vertical reinforcement of 6-mm diameter and boundary element reinforcement was also of 6-mm diameter. Reinforced concrete beams of sizes 300 × 280 mm and 240 × 240 mm were provided at the bottom and the top of the walls for holding the walls in position during loading and to avoid local failure in the shear walls under point loads, respectively. Six models consisting of three series (two of each type) were cast. All six wall models are of 1000 x 1000 mm of size and of 100 mm thickness and have openings at the centre of 400 x 400 mm size. Models PLOP1 and PLOP2 are walls having central openings reinforced with conventional reinforcement as per IS 13920 (2016). According to 10.1.6 of IS 13920: 2016, reinforcement shall be provided in shear walls in the vertical and horizontal directions with suitable spacing and minimum amount as per Table 1 and as per 10.1.7, reinforcement provided shall be in two curtains and with horizontal and vertical bars in each curtain. OPRC1 and OPRC2 are walls with concealed RC stiffeners around the openings and the length connecting the corner of the wall and the corner of the opening in addition to conventional reinforcement. OPT1 and OPT2 are the walls with steel tube stiffeners (40 x 40 x 4 mm size) around openings and lengths connecting the corner of the wall and the corner of the opening in addition to conventional reinforcement. Shear walls with stiffeners are not provided with additional bars along the sides of the openings as per IS 13920 (2016). As per 20.6.2 IS 13920: 2016, additional reinforcement is to be provided along all four edges of the opening of the shear wall and the area of this additional reinforcement shall be equal to that of respective interrupted bars. This additional reinforcement shall be provided with a half on either side of the wall in each direction. Figure 1 shows the reinforcement detailing for the shear wall with an opening by the conventional method and the dimensions of the shear-wall model with an opening, Fig. 2 shows the reinforcement detailing for a shear wall having a central opening and the provision of reinforced concrete stiffeners with the dimensions of the shear wall. Fig. 3 shows the reinforcement detailing for a shear wall having a central opening and the provision of stiffeners made of steel tube and the dimensions of the shear wall. For the wall PLOP, a total of 12 bars of 6-mm diameter equally spaced (160 mm) in two curtains are provided as a horizontal reinforcement. For vertical reinforcement, a total of 16 bars are provided in two curtains equally spaced (160 mm) in the wall stem. Spacing is reduced (70 mm) in an end portion of the wall to form a boundary element. Equally spaced (160 mm) stirrups are provided in the boundary element with reduced spacing (80 mm) in the bottom length. An additional bar of 6 mm is provided on each side of the opening. No additional reinforcement was provided along the sides of the opening for walls OPRC and OPT. The top beam was provided with 8 bars of deformed steel of 12-mm diameter and the beam at the bottom was provided with 8 deformed steel bars of 16-mm diameter as a reinforcement. A mild steel tube of 40 ×40 × 4 mm was used as steel tube stiffeners. Four bars of 6-mm diameter with equally-spaced stirrups were used as RC stiffeners. Table 1 shows reinforcement details, stiffener details and the dimensions of shear-wall models.

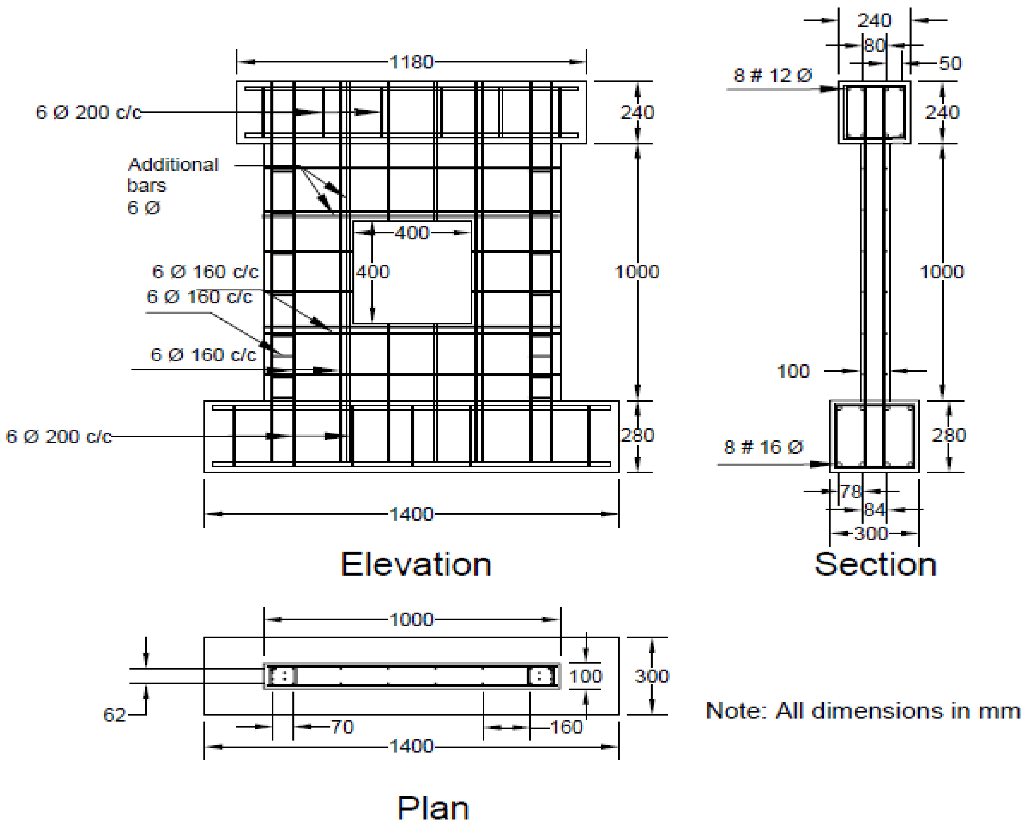


Figure (1): Shear wall with an opening using conventional reinforcement (PLOP)

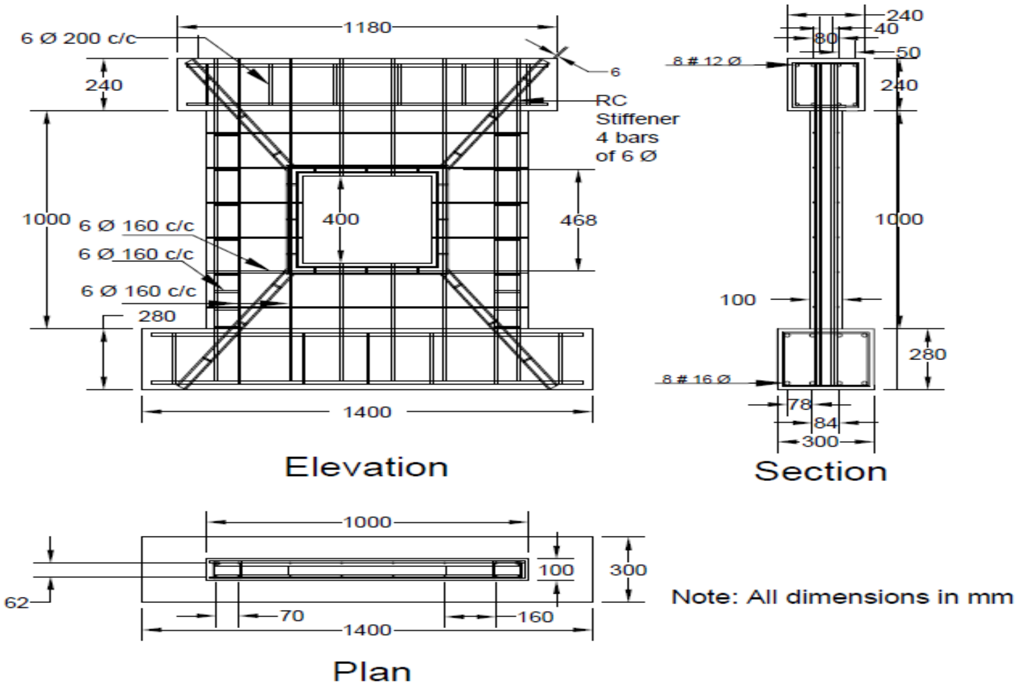


Figure (2): Shear wall with an opening using RC stiffeners (OPRC)

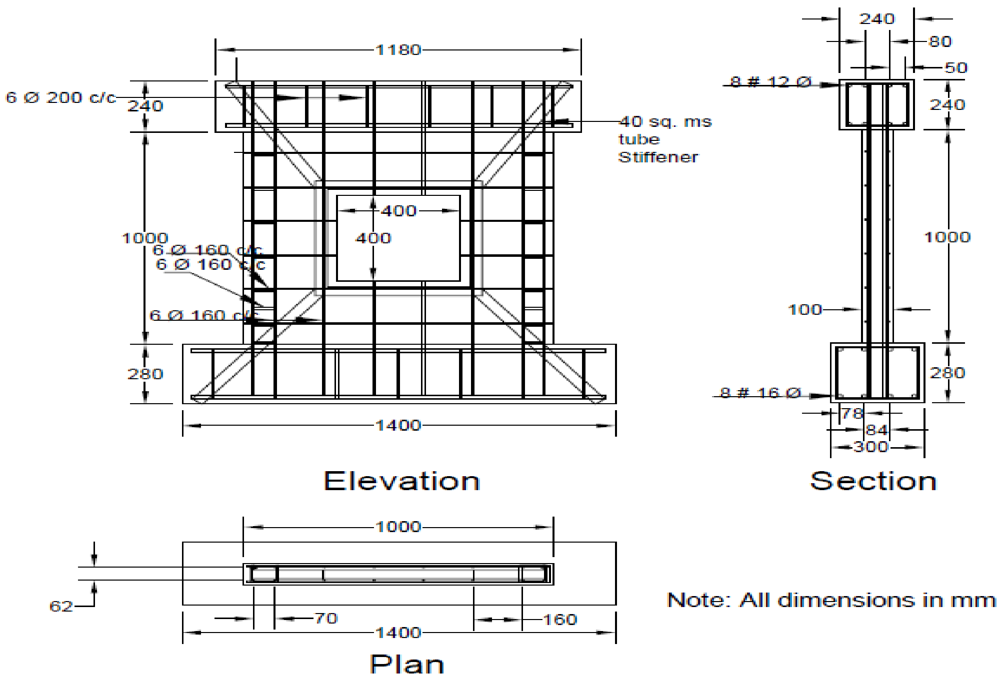


Figure (3): Shear wall having an opening with the provision of steel tube stiffeners (OPT)

Table 1. Details of shear-wall models

Sr. No.	Type of wall/beam	Notation used	Size in mm	Reinforcement in horizontal direction	Reinforcement in vertical direction	Stiffeners
1	Wall with an opening	PLOP	1000 × 1000 × 100 mm with a central opening of size 400 × 400 mm	12 bars of 6-mm diameter placed at 160-mm centre to centre, two additional bars on each side of the opening	16 bars of 6-mm diameter placed at 160-mm c/c, two additional bars on each side of the opening	------
2	Wall with an opening and RC stiffeners	OPRC	1000 ×1000 × 100 mm with a central opening of size 400 × 400 mm	12 bars of 6-mm diameter placed at 160-mm centre to centre	16 bars of 6-mm diameter placed at 160-mm centre to centre	Four bars of 6-mm diameter.
3	Wall having a central opening and steel tube stiffeners	OPT	1000×1000 × 100 mm with a central opening of size 400 × 400 mm	12 bars of 6-mm diameter placed at 160-mm centre to centre	16 bars of 6-mm diameter placed at 160-mm centre to centre	Mild steel tube of size 40 × 40 × 4 mm
4	Boundary element	B E	100 × 100 mm		4 bars of 6-mm diameter with 6-mm diameter stirrups placed at 100-mm centre to centre	--

Loading Frame and Data-acquisition System

Loading frame and data-acquisition system used for testing of shear walls are shown in Fig. 4. Shear walls were tested for cyclic loading with increment of 50-kN load for each cycle using two hydraulic jacks of 500-kN capacity fitted on the loading frame. A constant axial load of seven percent concrete section compressive strength 0.07 $f_c^{'}$ A_c (70 kN) of the shear wall was applied to shear walls during the tests. Loading data and corresponding deformations were obtained with a data-acquisition system and manually with the help of gauges fitted in the loading frame.

Figure (4): Loading frame and data-acquisition system

Strain Measurement

DEMEC gauge was used for the measurement of strain on the surface of the shear wall during testing, as shown in Fig. 5. For the location of the position of gauge measurement, a grid of size 100 × 100 mm was marked on the surface of the shear wall and measurements of strain were taken along the line joining grid points. Initial length of the grid line was observed before load was applied and the final length was obtained when cracks are sufficiently widened prior to failure of the shear wall. After measurements, strain calculations of each grid line and percentage increase or decrease of strain at different locations were obtained. Maximum strains before failure were observed to be 0.0053, 0.0067 and 0.0072 for the wall with conventional reinforcement only, the wall with conventional reinforcement along with RC stiffeners and the wall with conventional reinforcement along with stiffeners of steel tube, respectively. An increase in strain due to provision of RC stiffeners and stiffeners of steel tube in the shear walls having openings is observed to be 26.41% and 35.85%, respectively, as shown in Table 2.

Table 2. Increase in strain on the wall surface in percentage

Sr. No.	Wall type	Maximum strain with DEMEC gauge (experiment)	Maximum strain with FEA	Increase in strain with DEMEC gauge (experiment)	Percentage increase in strain by DEMEC gauge (experiment)
1	PLOP	0.0053	0.0054	--	
2	OPRC	0.0067	0.0067	0.0014	26.41
3	OPT	0.0072	0.0071	0.0019	35.85

Figure (5): Measurement of strain with DMECH gauge

Analysıs of Experımental Results

Table 3 shows the peak loads of each shear wall with an opening and deformations corresponding to these loads. A significant increase was observed in the peak load of shear walls with openings using stiffeners in a concealed manner. Peak load was found to increase by 17.27 % using RC stiffeners and by using steel tube stiffeners, the increase was 27.27 %. Deformation at peak load is more in OPRC than in OPT, which indicates that more deformation capacity is obtained by adding concealed stiffeners in wall cross-sections.

Fig. 6 shows the load-deformation envelope curves (P-Δ curves) obtained through experiments for specimens OP, OPRC and OPT. The load-deformation envelope curves are drawn by joining peak values of load-deformation curves for each loading cycle. It is observed from these curves that the initial stiffness of shear walls OPRC and OPT is greater than that of PLOP (shear wall with conventional reinforcement only) due to the use of stiffeners in shear walls with openings. This may help in controlling drift in buildings. Thus concealed stiffeners are helpful to control drift with additional strength. Both types of stiffeners gave greater strength and stiffness than those of conventional shear wall having an opening as per this study. Shear walls with RC stiffeners behaved better with provided smaller reinforcement area in stiffeners (less steel is required than in the case of steel tube stiffeners) and these are simpler in construction. Reinforcement area used in steel tube stiffeners was $40^2 - 32^2 = 576$ mm^2 and was $\pi/4 \times 4^2 \times 4 = 113.10$ mm^2 for RC stiffeners (4/5th less).

Table 3. Peak loads and corresponding deformations

Sr. No.	Wall type	Peak load for the wall (kN)	Average of peak load for the wall (kN)	Increase in load-carrying capacity (%)	Peak deformation (mm)	Average deformation (mm)	Percentage increase in deformation capacity (%)
1	PLOP 1	112	110	--	4.4	4.3	
2	PLOP 2	108			4.2		
3	OPRC 1	130	129	17.27 %	4.5	4.9	13.95
4	OPRC 2	128			5.3		
5	OPT 1	134	140	27.27 %	6.2	6.5	51.16
6	OPT 2	146			6.8		

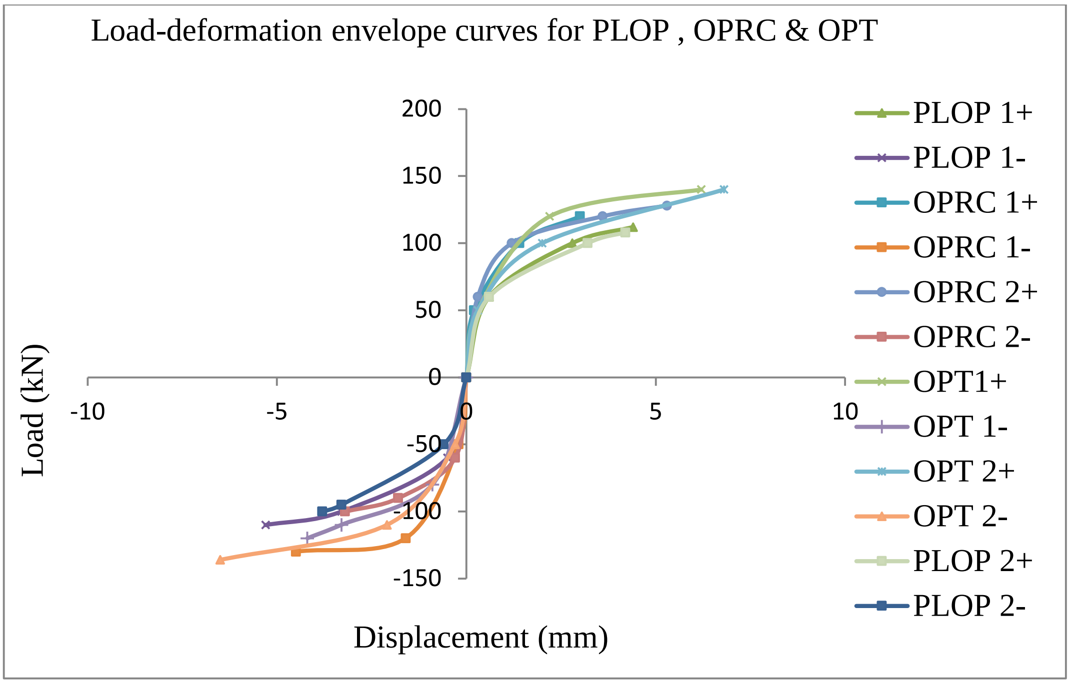


Figure (6): Load-deformation envelop curves for shear walls PLOP, OPRC and OPT

Finite Element Modeling

For the purpose of validation of results, the experimental models were evaluated with FEA software ANSYS 18.2. SOLID65 element was used for concrete and BEAM 188 element was used for the reinforcement for modeling purposes.

Properties of Elements Used

The SOLID65 element used for concrete is an eight-node three-directional isoparametric element. It has three degrees of freedom at each node with translation in three orthogonal directions. BEAM188 element was used for modeling reinforced steel. BEAM 188 was a 2 - node linear or quadratic beam element in 3-D. It has six or seven degrees of freedom at each node and the number of degrees of freedom depends on the value of keyopt (1). BEAM188 supports "restrained warping" analysis by using the seventh degree of freedom at each beam node. By default, BEAM188 element neglects it and assumes that (KEYOPT (1) = 0). It can be activated for warping by KEYOPT (1) = 1. With the warping degree of freedom activated, each node has seven degrees of freedom: UX, UY, UZ, ROTX, ROTY, ROTZ and WARP. Using KEYOPT (1) = 1, bimoment and bicurvature are output.

Loads and Boundary Condition

Load was applied to FE models to evaluate their behavior. Analysis of bottom of walls was restrained in position and direction, whereas top edge and sides were kept free. A load of 70 kN (7 % of concrete compressive strength) was applied to each wall in a constant manner from top while testing. In-plane horizontal load was applied through the top beam till the failure of the wall with a 50 kN load increment.

Material Model

The linear isotropic properties used for concrete element SOLID65 named as Poisson's ratio and modulus of elasticity were taken as 0.2 and 18098 N/mm^2, respectively. To compute multi-linear isotropic stress-strain curve, Eqs. (1) - (3) of Desai and Krishnan (1964) were used.

$$f = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_o} \right)^2} \quad (1)$$

$$\varepsilon_o = \frac{2 f_c'}{E_c} \quad (2)$$

$$E_c = \frac{f}{\varepsilon} \quad (3)$$

f = Concrete stress corresponding to any strain, MPa.
ε = Concrete strain corresponding to f.
ε_o= Concrete strain corresponding to ultimate compressive strength f_c'.

Linear isotropic properties named yield strength and Poisson's ratio of BEAM188 element used for reinforcement are taken as 597.86 N/mm^2 and 0.3, respectively. The value of yield strength for steel was obtained by testing steel used for walls in the laboratory and the Poisson’s ratio was taken as a standard value. The concrete was modelled using the material properties as linear isotropic and multi-linear isotropic materials. The multi-linear isotropic material uses the von Mises failure criterion along with the William-Warnke five-parameter model for defining the failure criterion for concrete. The steel for the FE models was assumed to be an elastic-perfectly plastic material. The bilinear kinematic hardening model has been used. The properties of steel were assumed to be identical in tension and compression. For all the reinforcing bars, the elastic moduli were assumed to be equal to 200 GPa with a value of Poisson's ratio of 0.3.

FEM Plots

Finite element modeling plots for different models of walls including solid bodies, meshing, load-deformation plots and plots for stress and strain plots are tabulated and discussed in the paragraphs following them.

Model of a Wall with an Opening

Table 4 shows FE model plots of meshed concrete structure and reinforcement, deformation plot, stress plot of concrete, stress plot of reinforcement and strain plot of concrete for the shear wall with an opening for an in-plane horizontal maximum load of 110 kN and a vertical constant load of 70 kN. The observed deformation corresponding to the average in-plane horizontal load of 110 kN with the experiment was 4.3 mm. Corresponding deformation and maximum shear stress were observed as 3.61 mm and 1.69 N/mm^2, respectively, with ANSYS for these loads. The maximum stress in steel reinforcement for the corresponding loading was 8.73 N/mm^2. The strain plot corresponding to peak load was obtained. The maximum strain observed was 0.0054.

Wall Having a Central Opening with the Provision of Reinforced Concrete Stiffeners

Table 5 shows meshing of concrete structure, meshing of reinforcement within concrete, deformation plot of concrete structure, stress plot of concrete structure, stress plot of reinforced steel and strain plots of concrete structure for shear walls having central openings with the provision of RC stiffeners. Deformation for a peak load of 129 kN was 4.9 mm using experimentally this model. The deformation plot and stress plot for this model are shown for a peak horizontal load of 129 kN and a constant vertical load of 70 kN. Deformation observed for this model for the peak load was 4.33 mm and shear stress was 1.038 N/mm^2 using ANSYS under this load. For this peak load, the corresponding stress in steel was 197.19 N/mm^2. The strain plot corresponding to the peak load shows the maximum strain to be 0.0067.

Table 4. FE model plots for a conventional shear wall having a central opening at a load of 110 kN

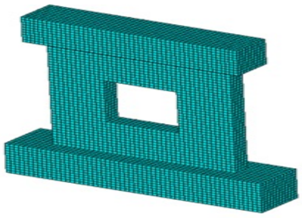
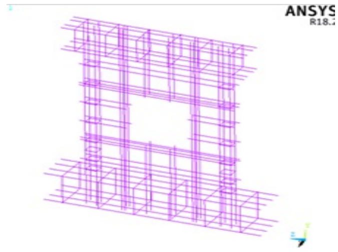
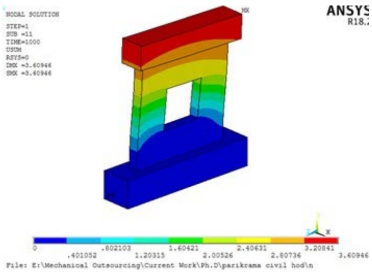
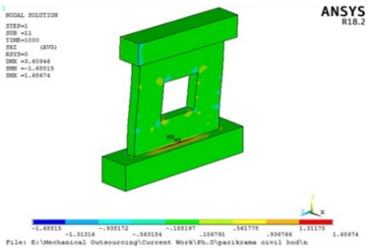
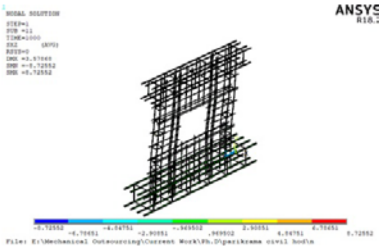
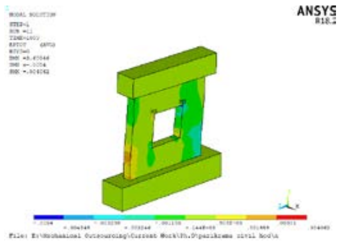
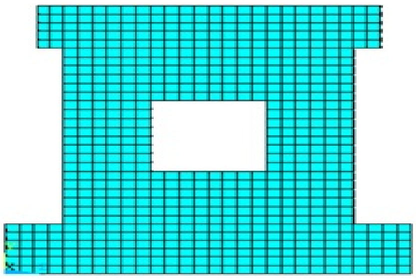
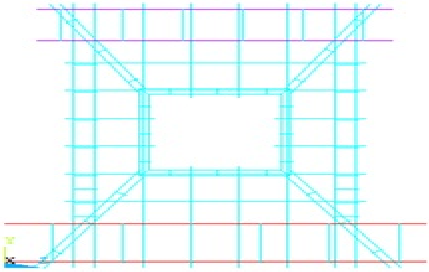
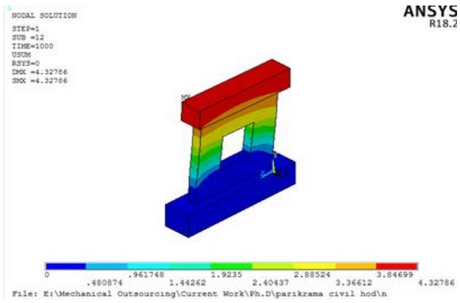
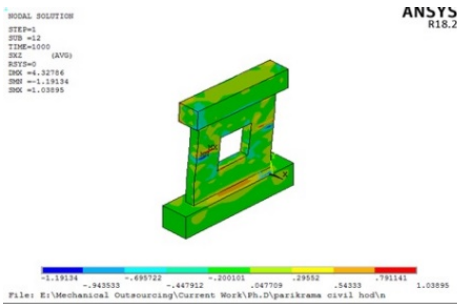
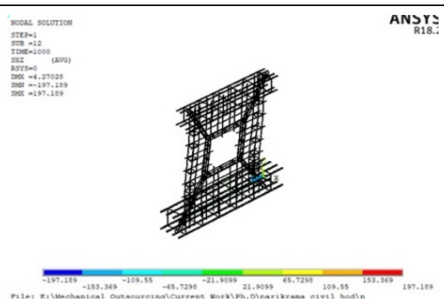
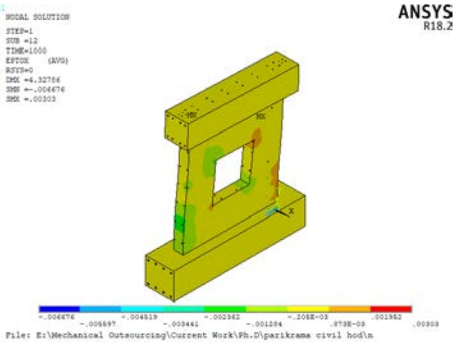
Sr. No.	Item	Finite element outputs
1	Concrete structure meshing	
2	Steel reinforcement meshing	
3	Deformation plot of concrete structure	
4	Stress plot of concrete structure.	
5	Stress plot of reinforced steel	
6	Strain plot of concrete	

Table 5. FE model plots for shear wall having a central opening with the provision of reinforced-concrete stiffeners at 129-kN load

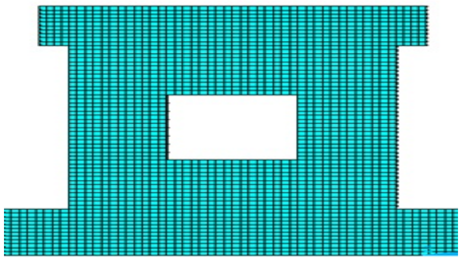
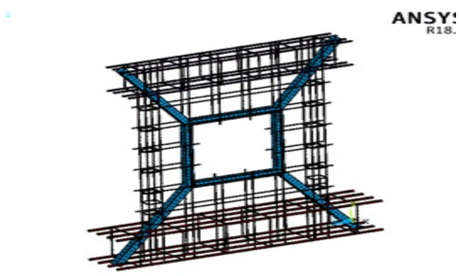
Sr. No.	Item	Finite element outputs
1	Concrete structure meshing	
2	Steel reinforcement meshing	
3	Deformation plot of concrete structure	
4	Stress plot of concrete structure	
5	Stress plot of reinforced steel	

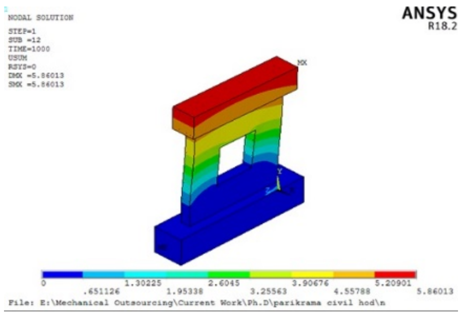
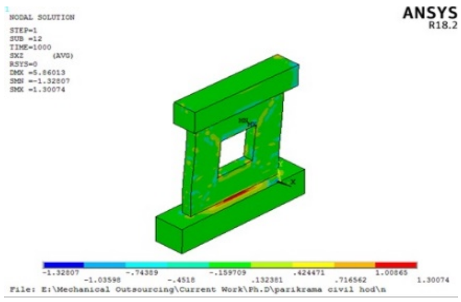
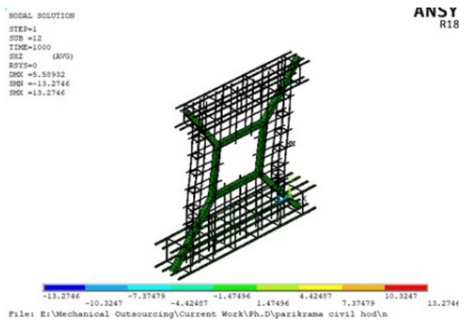
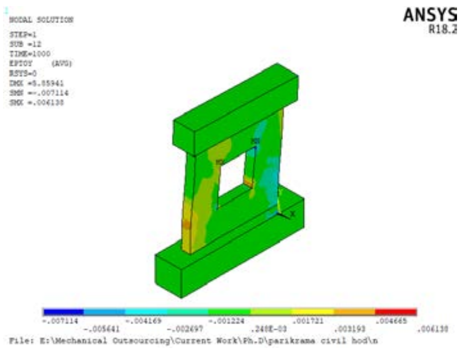
6	Strain plot of concrete	

Wall Having a Central Opening with the Provision of Stiffeners of Steel Tube (OPT)

Table 6 shows meshing of concrete structure, meshing of reinforcement within concrete, deformation plot of concrete structure, stress plot of concrete structure, stress plot of reinforced steel and strain plot of concrete structure for shear walls having central openings with the provision of steel tube stiffeners for a peak horizontal load of 140 kN and a constant axial vertical load of 70 kN in vertical direction. Deformation for this model for a peak load of 140 kN experimentally was 6.5 mm. Maximum deformation was observed to be 5.86 mm and observed maximum shear stress was 1.3 N/mm^2 for the peak load using ANSYS under this load. Stress in reinforced steel at peak load was observed as 13.27 N/mm^2. The maximum value of strain observed at peak load was 0.0071.

Table 6. FE model plots for a shear wall having a central opening with the provision of stiffeners of steel tube at 140-kN load

Sr. No.	Item	Finite element outputs
1	Concrete structure meshing	
2	Steel reinforcement meshing	

3	Deformation plot of concrete structure	
4	Stress plot of concrete structure	
5	Stress plot of reinforced steel	
6	Strain in concrete	

Load-Displacement Curves for Shear Wall (PLOP)

Load-displacement curves for shear walls having central openings and provided which conventional reinforcement are plotted from experimental observations and with FE results for the purpose of comparison and validation, as shown in Fig. 7. With experiments, the peak values for the load were observed as 112 kN and 108 kN for the shear wall PLOP1 and PLOP2 and deformations of these walls for the corresponding peak loads were observed as 4.4 mm and 4.2 mm, respectively, giving an average deformation of 4.3 mm. Deformation observed for the shear walls for an average load of 110 kN was 3.61 mm from the numerical method using ANSYS.

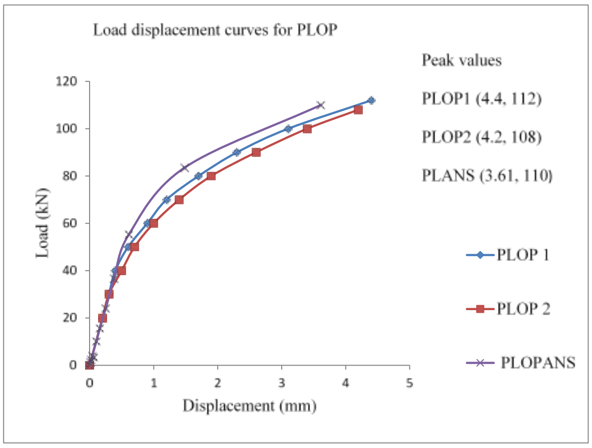


Figure (7): Load-displacement curves for PLOP

Load-Displacement Curves for Shear Wall (OPRC)

Load-displacement curves for shear walls having central openings and provided with conventional reinforcement along with reinforced concrete stiffeners are plotted with experimental observations and with FEA results for the purpose of comparison and validation and are shown in Fig. 8. With experiments, the peak values for the load were observed as 130 kN and 128 kN for the shear wall OPRC1 and OPRC2 and deformations of these walls for the corresponding peak loads were 4.5 mm and 5.3, respectively, giving an average deformation of 4.9 mm. Deformation observed for shear walls for an average peak load of 129 kN was 4.33 mm from the numerical method using ANSYS.

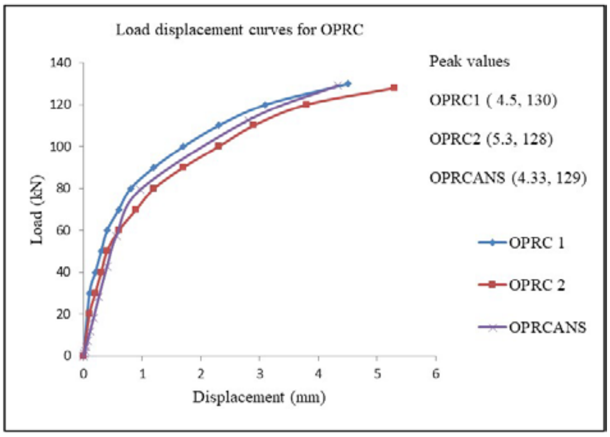


Figure (8): Load-displacement curves for OPRC

Load-Displacement Curves for Shear Wall (PLT)

Load-displacement curves for shear walls having central openings and provided with conventional reinforcement along with stiffeners of steel tube are plotted with experimental observations and with FEA results for the purpose of comparison and validation and are shown in Fig. 9. With experiments, the peak values for the load were observed as 136 kN and 144 kN (average 140 kN) for shear walls OPT1 and OPT2 and deformations of these walls for the corresponding peak loads were observed as 6.2 mm and 6.8, respectively, giving an average deformation as 6.5 mm. Deformation observed for the shear walls for an average load of 140kN was 5.86 mm from the numerical method using ANSYS.

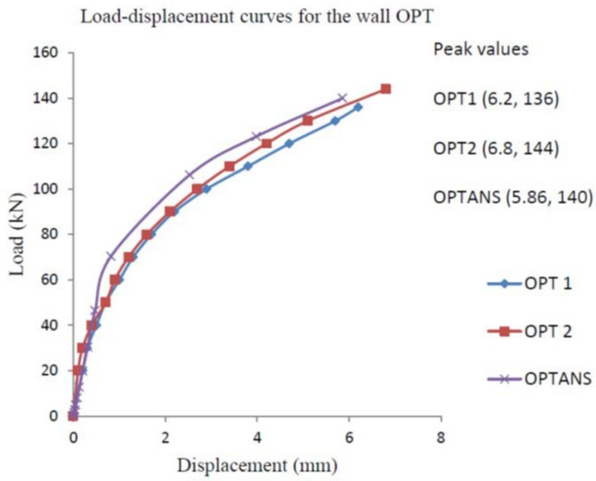


Figure (9): Load displacement curves for OPT

As a shear wall is an important element in structures provided for resisting earthquake forces, care should be taken so that its strength will not be decreased due to the opening. In the present study, experimental and numerical studies were undertaken to identify the weaker sections in the shear wall with an opening and conventional reinforcement subjected to cyclic loading. After identifying weaker sections, strengthening of these type of walls was undertaken using stiffeners of reinforced concrete and steel tube in a concealed manner. After studying the behavior of the improved sections with concealed stiffeners, the addition of concealed stiffeners was proposed in shear walls with openings.

Significant improvements in strength, stiffness, deformation capacity and strain behavior were observed. The results are presented in Table 7, showing the comparative effect of both types of stiffeners in shear walls having openings.

Table 7. Percentage increase in strain at peak load

Sr. No.	Wall type	Average peak load at failure (kN)	Increase in peak load (%)	Average peak deformation (mm)	Increase in peak deformation over PLOP (%)	Strain at peak load	Increase in strain over PLOP (%)
1	PLOP	110	--	4.30	--	0.0053	--
2	OPRC	129	17.27	4.90	13.95	0.0067	26.41
3	OPT	140	27.27	6.50	51.16	0.0072	35.85

CONCLUSIONS

After conducting experimental work and FE analysis of the models of shear walls having central openings using steel reinforcement in the conventional manner and shear walls having openings and concealed stiffeners along with conventional steel reinforcement, the following conclusions are made,

- At a peak load of 110 kN, average deformation was observed to be 4.3 mm experimentally and 3.61 mm using ANSYS for shear walls with openings and reinforced with conventional reinforcement.
- Average deformation for a peak load of 129 kN was observed to be 4.9 mm experimentally for a shear wall with an opening having RC stiffeners and 4.33 mm using ANSYS.
- Average deformation for a peak load of 140 kN was observed to be 6.5mm experimentally for a shear wall with an opening having steel tube concealed stiffeners and 5.86 mm using ANSYS.
- Percentage increase in load-carrying capacity of a shear wall having an opening using concealed stiffeners of reinforced concrete and steel tube was found to be 17.27% and 27.27%, respectively.
- Percentage increase in deformation capacity was found to be 13.95% and 51.16% for shear walls with openings using concealed stiffeners of reinforced concrete and steel tubes, respectively.
- Percentage increase in strain due to provision of concealed stiffeners of reinforced concrete and steel tubes in a shear wall having a central opening is found to be 26.41% and 35.85%, respectively.

Significant improvements were observed in strength, stiffness, ductility, energy dissipation, strain behavior… etc. of shear walls having central openings strengthened with reinforced concrete stiffeners and with steel tube stiffeners as compared to shear walls with openings and reinforced using the conventional method. As the behavior of shear walls with openings using stiffeners increased remarkably, it is recommended to make use of stiffeners in shear walls with openings. Though steel tube stiffeners presented better performance, RC stiffeners also performed well with less quantity of steel. RC stiffeners are also simple in construction. So, it is recommended to use RC stiffeners for strengthening reinforced concrete shear walls having central openings.

Notations

E_c = Modulus of elasticity of concrete.
f = Stress corresponding to any strain, MPa.
ε = Strain corresponding to f.
ε_o = Strain corresponding to ultimate compressive strength f_c'.
f_c' = Compressive strength of concrete.
A_c = Area of concrete section.

REFERENCES

Balkaya, C., and Kalkan, E. (2004). “Three-dimensional effects on openings of laterally loaded pierced shear walls.” Journal of Structural Engineering, ASCE, 130 (10), 1506-1513.

Bélaidia, O., Almansbaa, M., Amrania, D., Taouche-Khelouia, F., Nekmouchea, A., and Hannachia, N. E. (2015). “Comparative study on the behavior of slender RC walls with two methods of reinforcement.” Procedia-Engineerig, 114, December 2015.

Carrillo, J., and Alcocer, S. (2011). “Degradation properties of reinforced-concrete walls with openings.” Dyna, 78 (170), 106-115.

Desai, P., and Krishnan, S. (1964). "Equation for stress-strain curves of concrete." Journal of American Concrete Institute, 61 (3), 345-350.

Fares, A. M. (2021). “The impact of RC shear-wall openings on the lateral stiffness of cantilever shear walls.” Research on Engineering Structures & Materials, 7 (1), 5-63.

IS 13920. (2016). “Ductile design and detailing of reinforced concrete structures subjected to seismic forces.” Bureau of Indian Standards, Manak Bhavan. 9 Bahadur Shah Zafar Marg, New Delhi -110002.

Kankuntla, A., Sangave, P., and Chavan R. (2016). “Effect of openings in shear walls.” IOSR Journal of Mechanical and Civil Engineering, 13 (1), 1-6.

Lin, C.Y., and Kuo, C.L. (1988). “Behavior of shear wall with opening.” Proceedings of Ninth World Conference on Earthquake Engineering, Tokyo, Japan, 4 August, 535-540.

Mahadik, S., and Bhagat, S. R. (2022). “Experimental and numerical study of behavior of RC shear wall using concealed stiffeners.” Jordan Journal of Civil Engineering, 16 (1), 193-210.

Mohamed, H., Ahmed, S.E., and Mohamed, M.H. (2019). “Strengthening of reinforced concrete shear walls with openings using carbon fiber-reinforced polymers.” International Journal of Advanced Structural Engineering, 11 (2), 129-150.

RPA. (2003). “Règlement parasismique algérien”. Printed (1999); Reprinted (2003).

Shirneshan, A., and Behfarnia, K. (2017). “A numerical study on behavior of CFRP-strengthened shear wall with opening.” Computers and Concrete, 19 (2), 179-189.

Sivaguru, V., and Appa Rao, G. (2019). “Behavior of reinforced concrete squat shear walls with utility openings.” 10th International Conference on Fracture Mechanics of Concrete and Concrete Structures, Bayone, France, June 2019, 1-9.

Umemura, H., Aoyama, H., and Hosokawa, Y. (1980). “Restoring force characteristics of RC walls with openings and reinforcing methods.” 7th WCEE, Turkey, 7 January 1980, 209-216.