Seismic Resisting Performance and Strengthening of Single and Double Corrugated Steel Plate Shear Wall

Abraham Varughese Lalu and Aswathy Ann Mathew

Abstract Corrugated steel plate shear walls (CSPSWs) are most commonly used as a lateral load resisting mechanism in earthquake prone areas. They are used in modular building structures (MBS) and steel structures for its high ductility, and strength. Double corrugated steel plate shear wall (DCSPSW) contains two trapezoidal corrugated steel plates that are connected together either by weld or bolts. It is most often used as an alternative for the conventional steel plate shear walls. Since openings like window and door are unavoidable, the performance of the system with and without openings must be studied. The performance and change of strength of the walls on addition of stiffeners around the openings are to be evaluated. In this paper, the seismic performance of DCSPSW with and without, openings and stiffeners are investigated and compared with that of the ordinary (single) CSPSW.

Keywords Corrugated Steel Plate Shear Wall (CSPSW) · Double-Corrugated Steel Plate Shear Wall (DCPSW) · Seismic performance · Modular building structures

1 Introduction

Steel structures are commonly used in seismic hazard area, for its high strength and malleability. CSPSW are generally used as seismic resisting member principally in MBS and in steel structures in those seismic zones. It includes infill plate (stiffened or unstiffened), with and without openings, with vertical and horizontal structural components. From similar researches, the CSPSW is found to be a cost-effective economical methodology for high rise buildings than typical strategies.

Numerical studies concerning the SPSW was carried out in the past was on flat plates being used as infill plates. The corrugated steel plates are used as replacement

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for their high out-of- plane geometric stability. Due to the high stiffness of corrugated plates despite of its lower thickness than flat plates have been helpful for the construction of light girders [1–3].

The strength of the RBS shear wall could be calculated by a proposed equation, verified on comparison with the value obtained by FE analysis by providing RBS on the beam section to ensure the plastic hinges form on the beam rather on the beam span or on columns [4].

By experimental and numerical means the seismic performance of low and midrise buildings with CSPSW with slits indicated that the shear walls with perforation provided desirable ductility and strength than shear walls without perforation [5]. On application of monotonic loading on CSPSW with and without opening the parameters such as ductility, stiffness, strength and buckling stability were studied to understand the seismic performance by preparing FE models [6].

Predominantly the factor to be considered in the corrugated plates is their low stiffness is the direction perpendicular to the corrugation of the plates and the high strength to arrest the in-plane forces along the direction of the corrugation. The CSPSW in the MBS are commonly a part of the walls incorporated with openings such as doors and windows. The connection of the CSPSW in the normal and MBS make them distinct [7].

In regular structures they are connected on the edges whereas in modular structures they are connected in corners. Since the modules in MBS are connected in corners it helps in the load transfer vertically from column to column. Due to the high stiffness in MBS the CSPSW act as seismic resisting mechanism. On the studies that have been done by other researchers to understand the behavior of the CSPSW, the addition of the openings to the walls impairs the strength and performance of the element [8].

On comparison studies done by the application of pushover and cyclic loading on CSPSW and SPSW on numerous models [9]. Experimental studies on CSPSW with and without openings was carried out and addition of constructional column around the openings to arrest the buckling of the infill plate. The results showed that the initial stiffness of the models with openings are reduced when compared to the model without opening [10].

Since the slit and perforation on the walls are inevitable, small steel strips are used as reinforcement in CSPSW. They are connected, welded in perpendicular to the peak of each corrugation. Since the reinforcement are provided, they enhance the out-of-plane stiffness of the walls. They also enhance the ductility of the plates and also limit the deformation by energy dissipation betwixt the corrugations [11].

A DCSPSW was recently planned by the authors, consist of two corrugated steel plates connected together either by weld or by bolts. The general dimension of the DCSPSW as shown in Fig. 1.

An analytical formula was proposed to predict the ultimate shear strength of DSCSW. Proposal for calculation of the shear yield and the local and global shear elastic buckling were given as three analytical formulas and accuracy was defined

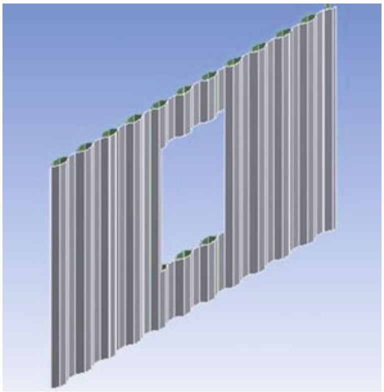


Fig. 1 Geometrical model of double corrugated plate

by experimental means [12]. By the application of monotonic shear loads on finite element models the shear resisting behaviors of the double corrugated walls were investigated [13].

2 Methodology

SCSPSWs and DCSPSWs were modelled and analyzed using ANSYS 16.1 finite element software. Fixed support was provided at the bottom of the columns as a boundary condition for the wall. Monotonic loading was provided in transverse direction.

The load was provided at the top edge of the column in displacement control and in incremental manner. the elements used around the openings for this study is considered from Korean Standard (KS) profiles.

The element type used for the analysis is 20-node solid 186 element, which is higher order 3D element which exhibits quadratic displacement behavior. The 20 nodes of the element have 3 degrees of freedom i.e., translation in nodal x, y, and z direction. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. The meshing used in the model is combined tetra and hexa mesh. The meshing near the opening is not refined.

For the current study, a corrugated wall of a single-story residential building of height 3.1m and length of 4.5m from center to center was considered. The dimensional description of the beams and columns used in the study are provided in Table 1 and material properties of plates, beam and column are shown in Table 2. The material properties of the boundary elements are provided in Table 3 and cross-sectional details are shown in Fig. 2.

CSPSW for the analysis was modelled by changing the corrugation angle with 0°, 45°, 90°. Angle of inclination changed with respect to X axis. The main purpose of changing angle of corrugation for selecting best angle which carrying higher ultimate strength. Some models with different openings, alignment and stiffeners

Table 1 Cross sectional dimensions [4]

	Specimen	Dimension (mm)
Beam	Width of flange (b_f)	398
	Depth	394
	Thickness of web (t_w)	11
	Thickness of flange (t_f)	18
Column	Width of flange (b_f)	432
	Depth	498
	Thickness of web (t_w)	45
	Thickness of flange (t_f)	70

Table 2 Material model behaviour [4]

Type	Young's modulus (MPa)	f_y (MPa)	f_u (MPa)	F_u/F_y
Plate	210,000	341	341	1
Columns and beams	210,000	390	480	1.23

Table 3 Material model behaviour [10]

Type	Young's modulus (MPa)	f_y (MPa)	f_u (MPa)	F_u/F_y
Stiffener elements	192	441	544	1.23

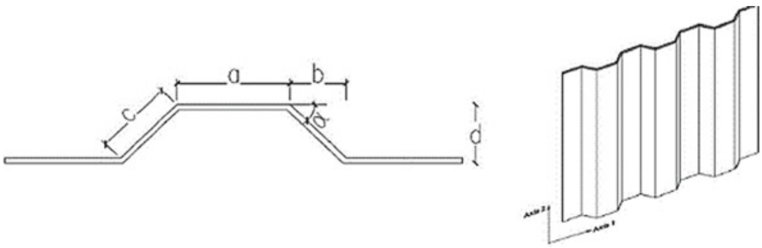
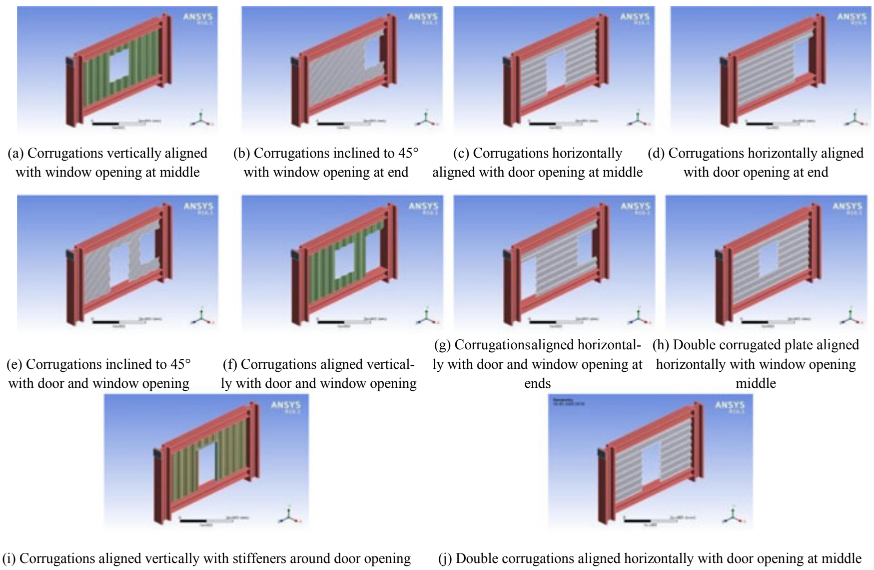


Fig. 2 Geometry of the model [4]

are shown in Fig. 3. The dimensional details of the panel element are given in Table 4.

Study was carried out on the journal of "Alireza Farzampour (Analysis and design recommendations for corrugated steel plate shear wall reduced beam section)" and the results obtained on comparison is less than 0.5% error. Table 5 shows the dimensions of openings used for the study.

Deformation was mostly affected around the door and the window opening provided, therefore to arrest these deformations a small thickness steel element was provided around the opening and thereby improving the strength of the load carrying capacity. The size of the element provided around the opening were



(a) Corrugations vertically aligned with window opening at middle
(b) Corrugations inclined to 45° with window opening at end
(c) Corrugations horizontally aligned with door opening at middle
(d) Corrugations horizontally aligned with door opening at end
(e) Corrugations inclined to 45° with door and window opening
(f) Corrugations aligned vertically with door and window opening
(g) Corrugationsaligned horizontally with door and window opening at ends
(h) Double corrugated plate aligned horizontally with window opening middle
(i) Corrugations aligned vertically with stiffeners around door opening
(j) Double corrugations aligned horizontally with door opening at middle

Fig. 3 Models of CSPSW and DCSPSW

Table 4 Corrugated panel geometry [4]

Specimen	t	a	d	a
Dimension (mm)	1.5	100	50	30

Table 5 Dimensions of opening [10]

Function of opening	Size l × h (mm)
Door	1000 × 2290
Window	1000 × 1600

120 × 60 × 4mm [10]. Steel plate shear walls with boundary elements were one in all of the advanced models.

Therefore, getting more accurate results, frame elements and infill plates were meshed separately by using different element size. The mesh size was kept 150 mm for the frame column and beam and constructional column and 100 mm for the infill plate.

3 Results

In this part, analysis and discussion on the performance of the CSPSW and DCSPSW considering both provision for perforation and without perforations, with different alignment of corrugations were carried out. The ultimate load carrying capacity of each model was different. The ultimate strength of different angle of CSPSW was shown in Tables 6, 7 and 8. The pushover curve and stiffness of the CSPSW under lateral loading are shown in Fig. 4. On incorporation of stiffeners around the window openings, the model with corrugation aligned horizontally was found to be more effective by having better load carrying capacity than other models. But when the door opening was provided with stiffeners the maximum load carrying capacity was found for the model with corrugations aligned vertically. For models with stiffeners for combined door and window opening, the maximum load carrying capacity was obtained for models with corrugations aligned horizontally with a negligible increase in strength than model of corrugation aligned vertically.

For DCSPSW, load carrying capacity of models with corrugations aligned vertically has augmented by 5% to 13% than CSPSW. Likewise, for models with corrugations aligned at 45°, the strength has augmented by 6% to 11% and with corrugations intensified horizontally the strength has increased by 7% to 9%.

As the results signify, the strength of the CSPSW have increased by providing stiffeners around the opening and additionally it can be made more effective by connecting the constructional column from top beam to bottom beam. The strength of the CSPSW have increased much more by making single corrugated plate shear wall to double corrugated shear wall, than the models with stiffeners provided around openings. Among the three-corrugation alignment the maximum load carrying capacity for the DCSPSW was obtained for the model with corrugation aligned vertically.

The addition of stiffeners adds auxiliary strength to the model as for CSPSW, since the openings on the model in real life are unavoidable, the addition of stiffeners to the models are applicable and hence it provides more strength to DCSPSW with openings. The position of the openings, i.e., providing the perforation at the center of the wall and at the end of the walls also affect the strength and stiffness of the models.

For CSPSW models, with corrugations aligned vertically, at 45° and horizontally, with the door and window openings when provided separately, the maximum loads were carried when the placement of the openings were provided at the ends. From the results obtained the maximum loads were carried when the corrugations were aligned horizontally and on the placement of the opening at the end.

On providing both the openings on the shear wall the loads were significantly reduced, and the maximum load were carried on the positioning of the openings on the ends of the plate. On providing both the openings on the same wall, the maximum load was found to be carried by the models with corrugations aligned vertically. Among the models of three configurations, on providing window and door opening separately, the plates aligned horizontally was found to be effective and for models with combined door and window opening the models with plates aligned vertically was found to be more effective under lateral loads.

For DCSPSW models, with corrugations aligned vertically, at 45° and horizontally, with the door and window openings when provided separately, the maximum loads were carried when the placement of the openings were provided at the ends.

Table 6 Results of CSPSW and DCSPSW with corrugation vertically aligned

Opening		Yield deformation (mm)	Yield load (kN)	Stiffness (kN/mm)	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness (kN/mm)	Ductility	Percentage of strength
CSPSW with corrugations vertically aligned									
–	–	146.350	4267.900	29.162	377.770	6209.400	16.437	2.581	1.000
Window	Middle	150.330	4064.700	27.039	341.000	5222.300	15.315	2.268	1.000
	End	140.690	3992.200	28.376	337.500	5300.500	15.705	2.399	1.000
Door	Middle	150.200	4083.900	27.190	412.630	5123.000	12.415	2.747	1.000
	End	137.540	3848.200	27.979	335.760	5214.500	15.530	2.441	1.000
Window and door	Window at end	114.180	3943.000	34.533	380.200	5026.300	13.220	3.330	1.000
	Door at end	143.610	3939.200	27.430	384.030	5033.800	13.108	2.674	1.000
	Window and door at ends	140.450	3681.400	26.211	513.220	5099.200	9.936	3.654	1.000
CSPSW with corrugations vertically aligned with stiffeners									
Window	Middle	138.340	4474.600	32.345	355.840	5494.400	15.441	2.572	5.210
	End	165.650	4991.900	30.135	377.610	5464.200	14.470	2.280	3.088
Door	Middle	120.290	4032.600	33.524	362.200	5313.500	14.670	3.011	3.719
	End	182.530	5007.300	27.433	364.700	5362.400	14.704	1.998	2.836
Window and door	Window at end	123.820	4354.800	35.170	380.750	5350.800	14.053	3.075	6.456
	Door at end	130.310	4412.200	33.859	373.190	5305.600	14.217	2.864	5.399
	Window and door at ends	175.670	4889.000	27.831	399.820	5316.500	13.297	2.276	4.261

(continued)

Table 6 (continued)

Opening		Yield deformation (mm)	Yield load (kN)	Stiffness (kN/mm)	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness (kN/mm)	Ductility	Percentage of strength
DCSPSW with corrugations vertically aligned									
Window	Middle	84.252	4656.200	55.265	305.240	5788.900	18.965	3.623	10.850
	End	115.940	5021.700	43.313	325.210	5924.300	18.217	2.805	11.769
Door	Middle	98.903	4870.900	49.249	293.680	5695.000	19.392	2.969	11.165
	End	102.670	5001.900	48.718	325.290	5893.100	18.116	3.168	13.014
Window and door	Window at end	106.180	4781.900	45.036	341.740	5426.400	15.879	3.218	7.960
	Door at end	96.908	4792.900	49.458	323.990	5426.000	16.747	3.343	7.791
	Window and door at ends	72.544	4124.700	56.858	462.340	5505.000	11.907	6.373	7.958
DCSPSW with corrugations vertically aligned with stiffeners									
Window	Middle	98.058	5180.600	52.832	306.790	6112.100	19.923	3.129	17.038
	End	103.480	4567.000	44.134	346.620	6171.000	17.803	3.350	16.423
Door	Middle	93.369	5354.500	57.348	321.510	6075.300	18.896	3.443	18.589
	End	90.628	4431.600	48.899	322.390	6071.100	18.832	3.557	16.427
Window and door	Window at end	93.259	5005.500	53.673	300.300	5955.600	19.832	3.220	18.489
	Door at end	94.901	4958.800	52.252	324.260	5897.800	18.188	3.417	17.164
	Window and door at ends	99.636	5520.000	55.402	406.410	5931.300	14.594	4.079	16.318

Table 7 Results of CSPSW and DCSPSW with corrugation aligned to 45°

Opening		Yield deformation (mm)	Yield load (kN)	Stiffness (kN/mm)	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness (kN/mm)	Ductility	Percentage of strength
CSPSW with corrugations inclined 45°									
-	-	79.587	4527.100	56.882	330.460	5483.300	16.593	4.152	1.000
Window	Middle	110.920	4388.600	39.565	360.660	5110.000	14.168	3.252	1.000
	End	89.846	4089.300	45.515	359.800	5193.300	14.434	4.005	1.000
Door	Middle	157.440	4050.800	25.729	404.180	5072.700	12.551	2.567	1.000
	End	81.176	4098.400	50.488	366.960	5170.300	14.090	4.521	1.000
Window and door	Window at end	97.561	3927.000	40.252	371.420	4976.700	13.399	3.807	1.000
	Door at end	81.690	3889.900	47.618	366.200	4955.600	13.532	4.483	1.000
	Window and door at ends	164.450	3984.200	24.227	467.330	5062.400	10.833	2.842	1.000
CSPSW with corrugations inclined 45° with stiffeners									
Window	Middle	87.024	4452.200	51.161	353.030	5378.300	15.235	4.057	5.250
	End	112.450	4723.000	42.001	349.640	5359.400	15.328	3.109	3.198
Door	Middle	98.407	4967.900	50.483	397.250	5332.300	13.423	4.037	5.118
	End	132.950	4814.800	36.215	351.580	5284.900	15.032	2.644	2.217
Window and door	Window at end	152.250	4757.200	31.246	331.050	5227.500	15.791	2.174	5.039
	Door at end	119.270	4586.700	38.456	368.940	5245.500	14.218	3.093	5.850
	Window and door at ends	77.475	4088.700	52.774	376.520	5288.200	14.045	4.860	4.460

(continued)

Table 7 (continued)

Opening		Yield deformation (mm)	Yield load (kN)	Stiffness (kN/mm)	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness (kN/mm)	Ductility	Percentage of strength
DCSPSW with corrugations inclined 45°									
Window	Middle	98.624	5023.200	50.933	314.110	5523.300	17.584	3.185	8.088
	End	88.578	4980.900	56.232	288.410	5768.600	20.001	3.256	11.078
Door	Middle	113.050	4967.900	43.944	283.330	5519.100	19.479	2.506	8.800
	End	83.066	4840.000	58.267	244.700	5677.300	23.201	2.946	9.806
Window and door	Window at end	101.450	4751.400	46.835	360.990	5310.800	14.712	3.558	6.713
	Door at end	99.225	4674.200	47.107	343.630	5283.500	15.376	3.463	6.617
	Window and door at ends	85.778	4590.200	53.513	397.910	5421.900	13.626	4.639	7.101
DCSPSW with corrugations inclined 45° with stiffeners									
Window	Middle	174.110	5749.600	33.023	354.390	6071.000	17.131	2.035	18.806
	End	64.888	4537.700	69.931	335.810	6012.800	17.905	5.175	15.780
Door	Middle	60.076	4183.200	69.632	365.590	5980.700	16.359	6.085	17.900
	End	71.325	4636.500	65.005	337.940	5835.800	17.269	4.738	12.872
Window and door	Window at end	94.832	4954.500	52.245	353.320	5803.400	16.425	3.726	16.611
	Door at end	180.750	5471.100	30.269	372.240	5824.600	15.647	2.059	17.536
	Window and door at ends	66.394	4271.500	64.336	378.950	5835.400	15.399	5.708	15.269

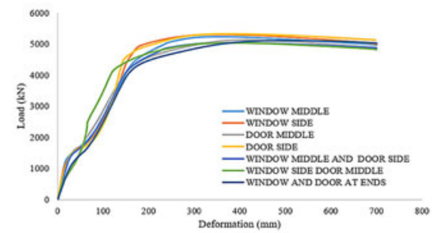
Table 8 Results of CSPSW and DCSPSW with corrugation aligned horizontally

Opening		Yield deformation (mm)	Yield load (kN)	Stiffness	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness	Ductility	Percentage of strength
CSPSW with corrugations horizontally aligned									
–	–	249.950	5209.500	20.842	383.670	6216.800	16.204	1.535	1.000
Window	Middle	198.910	3906.700	19.641	476.600	5198.100	10.907	2.396	1.000
	End	247.600	4234.800	17.103	498.000	5307.200	10.657	2.011	1.000
Door	Middle	217.860	3971.900	18.231	427.630	5144.600	12.411	1.963	1.000
	End	261.740	4081.900	15.595	442.070	5271.200	11.924	1.689	1.000
Window and door	Window at end	255.780	4062.200	15.882	392.880	5008.200	12.747	1.536	1.000
	Door at end	180.180	3995.800	22.177	415.050	5009.600	12.070	2.304	1.000
	Window and door at ends	229.030	3743.200	16.344	453.140	5035.800	11.113	1.979	1.000
CSPSW with corrugations horizontally aligned with stiffeners									
Window	Middle	138.320	3903.600	28.222	409.400	5421.000	13.241	2.960	4.288
	End	111.100	4009.700	36.091	374.990	5507.300	14.687	3.375	3.770
Door	Middle	192.450	4460.900	23.180	472.840	5441.600	11.508	2.457	5.773
	End	163.260	3818.100	23.387	404.760	5355.200	13.231	2.479	1.594
Window and door	Window at end	211.000	4934.000	23.384	392.320	5360.700	13.664	1.859	7.038
	Door at end	92.435	3745.400	40.519	341.000	5290.300	15.514	3.689	5.603
	Window and door at ends	75.714	3381.100	44.656	365.350	5288.500	14.475	4.825	5.018

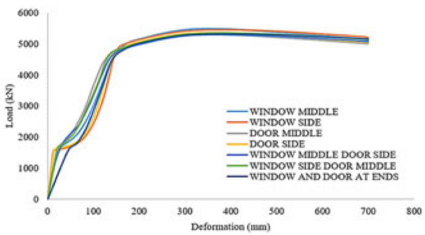
(continued)

Table 8 (continued)

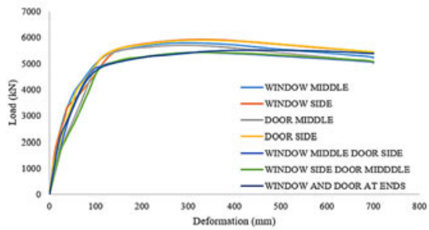
Opening		Yield deformation (mm)	Yield load (kN)	Stiffness	Ultimate deformation (mm)	Ultimate load (kN)	Ultimate stiffness	Ductility	Percentage of strength
DCSPSW with corrugations horizontally aligned									
Window	Middle	99.069	4790.000	48.350	334.490	5669.200	16.949	3.376	9.063
	End	197.690	5179.300	26.199	397.120	5821.900	14.660	2.009	9.698
Door	Middle	126.230	4584.400	36.318	401.680	5591.000	14.494	3.182	8.677
	End	220.240	5087.200	23.098	338.530	5640.800	16.663	1.537	7.012
Window and door	Window at end	124.790	4734.100	37.937	391.880	5441.300	13.885	3.140	8.648
	Door at end	127.050	4764.300	37.499	372.120	5317.100	14.289	2.929	6.138
	Window and door at ends	121.620	4404.700	36.217	482.590	5422.900	11.237	3.968	7.687
DCSPSW with corrugations horizontally aligned with stiffeners									
Window	Middle	74.532	4721.100	63.343	349.210	6112.900	17.505	4.685	17.599
	End	77.054	5121.000	66.459	298.100	6170.800	20.700	3.869	16.272
Door	Middle	73.662	4209.500	57.146	320.460	5921.900	18.479	4.350	15.109
	End	72.181	4294.800	59.500	309.310	6096.500	19.710	4.285	15.657
Window and door	Window at end	49.021	3818.900	77.903	305.230	5891.900	19.303	6.227	17.645
	Door at end	51.657	3860.000	74.723	321.570	5918.400	18.405	6.225	18.141
	Window and door at ends	60.257	4320.000	71.631	343.930	5893.900	17.137	5.708	17.040



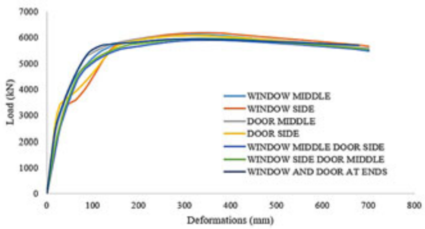
CSPSW vertically aligned



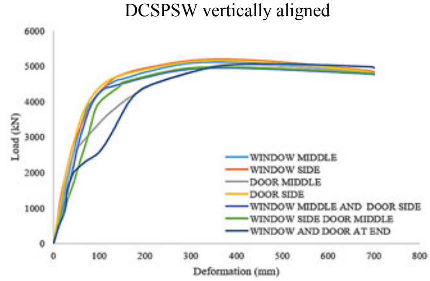
CSPSW with stiffeners vertically aligned



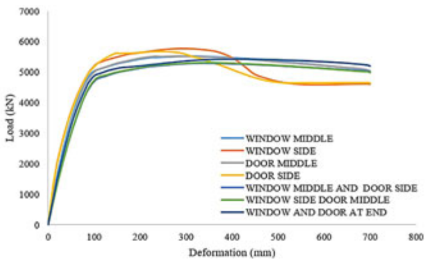
DCSPSW vertically aligned



DCSPSW with stiffeners vertically aligned



CSPSW with corrugation inclined to 45°



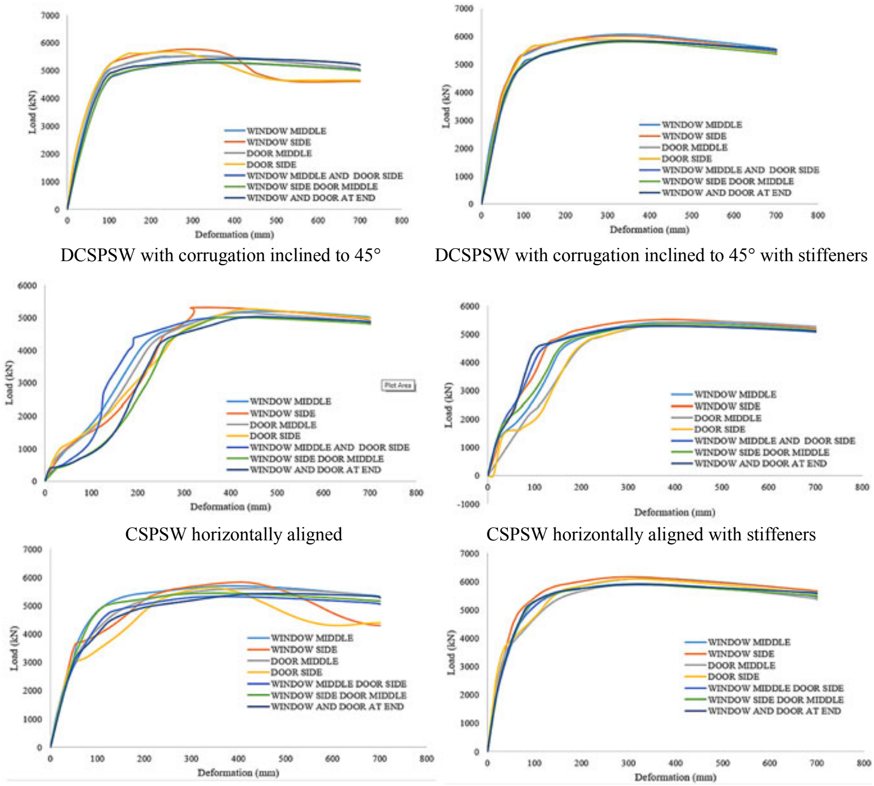
CSPSW with corrugation inclined to 45° with stiffeners

Fig. 4 Load–displacement curves for CSPSW and DCSPSW with and without stiffeners

From the results obtained the maximum loads were carried when the corrugations were aligned vertically and on the placement of the opening at the end. On providing both the openings on the shear wall the loads were significantly reduced as similar to CSPSW, and the maximum load were carried on the positioning of the openings at the ends of the plate. On providing both the openings on the same wall, the maximum load was found to be carried by the models with corrugations aligned vertically.

Among the models of three configurations, on providing window and door opening separately and for models with combined door and window opening the shear wall models with plates aligned vertically was found to be more effective under lateral loads. Addition of stiffeners to the model increases strength to shear wall as in CSPSW.

On providing stiffeners around the opening and throughout the top beam to bottom beam, the lateral out plane bucking of the plates can be arrested. On the model with window opening the maximum load was carried on the positioning of



DCSPSW with corrugation inclined to 45°

DCSPSW with corrugation inclined to 45° with stiffeners

CSPSW horizontally aligned

CSPSW horizontally aligned with stiffeners

DCSPSW horizontally aligned

DCSPSW horizontally aligned with stiffeners

Fig. 4 (continued)

the opening on the end of plate and on models with door opening maximum load was carried by models with openings provided at the ends.

Based on the change in the alignment the maximum load was carried by the models with corrugations vertically aligned and model with combined door and window openings the maximum load was carried by the models with the positioning of the door at the middle and window at the end with the corrugations aligned vertically.

4 Conclusion

By inferring from the results, the study was carried out to identify the performance and change in strength of the models with openings, by changing the position of the opening, i.e., by providing the opening at the end and middle and by the addition of stiffeners around the opening and also providing two infill corrugated plates in CSPSW making it DCSPSW. Similarly, study on different corrugation alignment (horizontal, vertical and aligned 45°) was carried out to identify the best alignment for the shear wall to carry the maximum lateral load.

Addition of the opening to the models reduce the strength of the model and addition of the stiffeners around the opening increase the strength of the model. DCSPSW provides better strength when compared to that of CSPSW without openings and addition of stiffeners to the openings in DCSPSW increases the strength of the model to 15% to 18% than CSPSW with openings. Based on the study of change in the alignment of the corrugations the maximum load was carried by the models with corrugations aligned horizontally for models with door and window opening separately. And for models with combined door and window opening the maximum loads was carried by the models with corrugations aligned vertically.

For DCSPSW models with and without stiffeners the maximum load was carried on the arrangement of corrugations in vertical direction. On the models with door and window opening separately, and on models without stiffeners, the maximum load was carried by the models with perforations at the end of the plate of wall. On the models with stiffeners maximum load was carried by the models with corrugations vertically aligned and the model with combined door and window openings the maximum load was carried by the models with the positioning of the door at the middle and window at the end with the corrugations aligned vertically.

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