STUDY ON SHEAR RESISTANCE OF COLD-FORMED STEEL STUD WALLS IN RESIDENTIAL STRUCTURE

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Abstract

In this paper, tests and finite element analysis are used to study the shear resistance of cold-formed steel stud walls in low-rise residential structures. Firstly, the shear resistance of cold-formed steel stud walls under monotonic loading is tested. The test models, including walls with single-sided gypsum sheathing, walls with single-sided oriented strand board sheathing, and walls with gypsum sheathing on the back and oriented strand board on the face are made in full scale of engineering project. The test apparatus and test method and the failure process of specimens are introduced in detail. Then, the finite element analysis model of cold-formed steel stud walls considering geometric large deformation and materials nonlinear is presented to study their shear resistance. Walls were simulated as shell elements. The studs and tracks are simply connected. The screws connecting the sheathings to the frame are modeled by coupling methods. The solution method of equations is selected by ANSYS program automatically. Finite element analysis results in this paper are close to that of experiment. The results of test and finite element analysis show that sheathing materials influences the wall's shear resistance more greatly. The strength of steel has a less influence on the shear resistance of walls. As the decrease of stud spacing, height of wall and screw spacing at the perimeter, the walls' load ability increases obviously.

Keywords: cold-formed steel, assembled walls, shear resistance, experimental study, finite element analysis

1. Introduction

Assembled walls are the main load-bearing members of cold-formed steel residential buildings, and cold-formed steel stud walls are assembled by C-shaped steel studs (channel with lip flanges), U-shaped tracks (channel without lip flanges), gypsum board and oriented strand board (hereinafter OSB), which are connected by self-piercing or self-drilling screws(North American Steel Framing Alliance, 2000).

The shear resistance of cold-formed steel stud walls is associated with many factors, such as materials of studs and sheathing, screw spacing, height-width ration of wall, stud spacing and so on, so it is difficult to determine walls' shear resistance by theoretical calculation, but mainly by test method (American Iron and Steel Institute, 1998; Serrette and Ogunfunmi, 1996; Serrette et al., 1997). However, tests cannot totally reflect the influence of all the factors on the shear resistance of walls. Finite element analysis certified correct by test is an effective method to study the shear resistance of cold-formed steel stud walls (Xia et al., 2004; Emad et al., 1999). Many scholars at home and abroad only have studied the shear resistance for a certain kind of cold-formed steel stud walls because of a series of complex factors listed above. In order to provide design guidelines' tests and finite element analysis are presented to study the shear resistance of cold-formed steel stud walls in residential structures, and many factors influencing shear resistance are also analyzed in this paper.

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Table 1. Specimens of shear wall tests.

Denotation of wall specimens	Cold-formed steel member	Sheathing	Self-drilling fastener	Fastener interval
SSG	C89×44.5×12×1.0 studs (lipped channel section with web height 89mm, flange width 44.5mm, lip width 12mm and thickness 1mm), Spaced 600mm on center U92×40×1.0 tracks (channel section with web height 91mm, flange width 40mm and thickness 1mm) 50mm×1.0mm strap	gypsum sheathing on one side, with dimension 1.2m×3m and thickness 12 mm	ST4.2	150mm at the perimeter and 300mm in the middle field of board
SSO		OSB sheathing on one side ,with dimension 1.2m×2.44m and thickness 9 mm	ST4.8	
DSGO		gypsum sheathing with thickness 12 mm on one side and OSB sheathing with thickness 9 mm on the other side	ST4.2 and ST4.8	

2. Test Program

2.1. *Specimen Design*

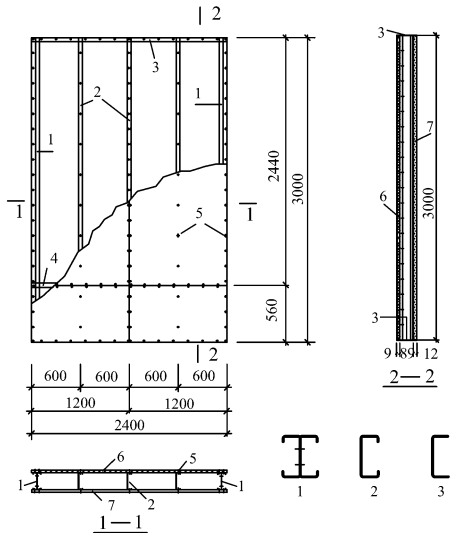
The configurations of specimens are described in Table 1, and the walls with size of 3 m × 2.4 m (height by width) and 1.0 mm thick steel framing were sheathed with gypsum or OSB sheathing. But there was a vertical connecting seam on wall because every board only was half the width of wall, and there was a horizontal connecting seam on wall sheathed with OSB because the length of OSB sheathing was shorter than the length of wall, so a steel strap with 50 mm width and 1.0 mm thickness was fixed along the horizontal connecting seam to strengthen the wall. The studs in the middle of wall were single C-shaped cold-formed steel members, and the studs at both ends of the wall were two back-to-back C-shaped members connected by two lines of self-drilling screws. The 16 mm diameter uplift anchors were used to connect the walls to the test beam at the corner of wall, and the top and bottom tracks of the wall were fixed to the test beam by 12 mm diameter shear anchors. The yield strength of steel f_y was 320 N/mm^2, the tensile strength f_u was 379 N/mm^2, and the extension percentage of steel was 34%. Configuration of DSGO wall is illustrated in Figure 1.

2.2. *Test Apparatus*

The test apparatus is shown in Figure 2. Horizontal load was applied to wall through electro- hydraulic servo actuator, and lateral braces were also provided to limit out-of-plane movement of the test wall. The test process was operated by M2801 servo-control mechanism and computer. All the test dates were collected by a 7V08 date collector.

2.3. *Load Process and Failure Characteristics of Specimens*

Specimens were loaded to yield period by controlling 5∼7 loading steps. After being yield, specimens were loaded to failure by controlling displacement steps. Each loading stage stayed for about



1. Back-to-back stud; 2. C-shaped stud; 3. Track; 4. Strap;
5. Self-drilling fastener; 6. Gypsum sheathing; 7. OSB sheathing

Fig. 1. Configuration of DSGO wall.

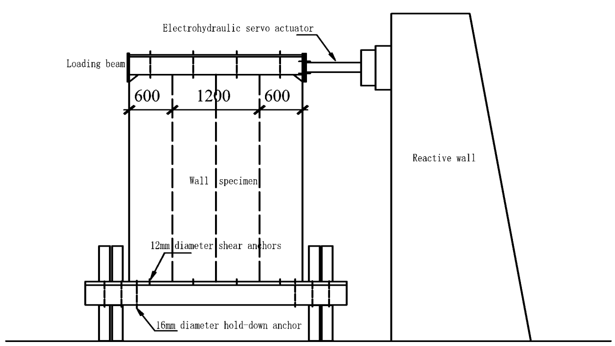


Fig. 2. Test apparatus.

(a) Gypsum sheathing tearing at corner of wall
(b) Buckling of strap
(c) Slip of four panels of OSB sheathing
(d) Local buckling of studs

Fig. 3. Failure modes of specimens.

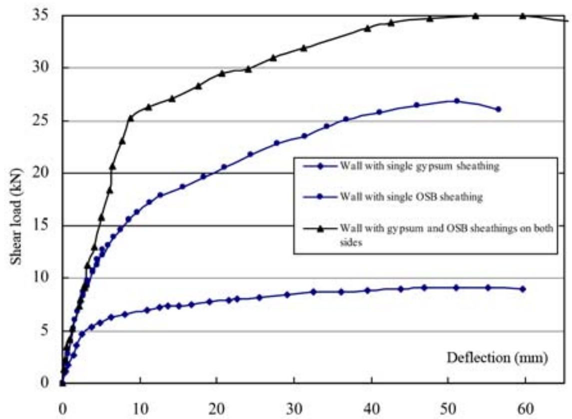


Fig. 4. Load-displacement curves for specimens.

3 minutes. The shear resistance and stiffness of SSG Specimen were lower. As a result, relative rotation was taken place between the two panels of gypsum sheathings, and their vertical connecting seam offset. The gypsum sheathing was tore at the corner of wall perimeter (shown in Figure 3a). The shear resistance strength and ductility of SSO wall were better than that of SSG wall, but the horizontal connecting seam in SSO wall influenced its bearing capacity and stiffness. With the load increasing, the steel strap buckled apparently (shown in Figure 3b), and the slip of the four panels of OSB sheathing was relatively great (shown in Figure 3c), which made the shear stiffness of wall reduced. The integrity, strength and stiffness of DSGO wall excelled that of SSG wall and SSO wall. The failure modes of three kinds of wall were similar. In general, when the failure of all wall specimens was occurred under shear load, most of the screw connecting sheathing and steel members around the wall were failed, and the stud on the end of wall usually locally buckled (shown in Figure 3d). But the gypsum sheathing or OSB sheathing did not drop off integrally due to the less damage of the screw connections in the middle field of wall, so we could conclude that the screws at the perimeter bore higher shear load than those in the middle field.

2.4. *Analysis of Test Results*

The shear load-displacement ($P - \Delta$) curves of all wall specimens are shown in Figure 4. Yield load of all walls could not been easily found from these curves, so all the characteristic loads including yield load were determined by the method prescribed in the Chinese *Specification of Testing Methods for Earthquake Resistant Building* (JGJ 101-96, 1996). The method for determining the characteristic loads of wall is illustrated in Figure 5. The horizontal line AB was drawn form the point A defining maximum load $P_{\max}$, then the secant OD was drawn intersecting line AB and curve OA at point D and C, respectively, when the area $ADCA$ was equal to the area $CFOC$. A vertical line was drawn form point D intersecting curve OA at point E. The shear load and the corresponding displacement of point E were the yield load P_y and the yield displacement Δ_y of wall respectively. With the displacement increasing, the load descend; when the load descend to $0.85P_{\max}$, the corresponding load and displacement were defined as the failure load P_u and the failure displacement Δ_u. The test results determined by the method described above are presented in Table 2.

The yield load P_y, maximum load $P_{\max}$ and failure load P_u of SSO wall were approximately 2.87, 2.94, 2.94 times those of SSG wall under the monotonic loading test. In other words, the load capacity of the wall with single-sided gypsum sheathing was 34∼34.8 % that of wall with single-sided OSB sheathing.

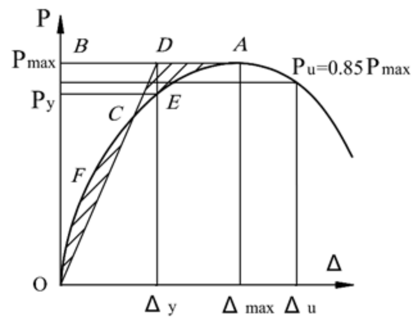


Fig. 5. Determination for special load point of specimens.

Table 2. Experimental results.

Wall type	P_y (kN)	Δ_y (mm)	$P_{\max}$ (kN)	$\Delta_{\max}$ (mm)	P_u (kN)	Δ_u (mm)	Shear resistance (kN/m)
SSG	7.48	13.5	9.12	48	7.75	74.8	3.8
SSO	21.5	23.9	26.84	51.21	22.81	68	11.18
DSGO	29.12	19.6	34.99	59.62	29.72	74	14.58

The sum of yield load SSG wall and SSO wall was 28.98 kN, and the sum of maximum load of those two walls was 35.96 kN, the sum of failure load was 30.56 kN, which are close to the yield load 29.12 kN, the maximum load 34.99 kN and failure load 29.72 kN of DSGO wall respectively. Thus it can be seen that the total load capacity of two kinds of single-sided walls was close to that of double-faced walls with two corresponding kinds of sheathings.

3. Finite Element Analysis

3.1. Finite Element Analysis Model

Finite element analysis model was a mathematic representation of the practical structure, and the model and method of analysis should reflect the main performance of every member. The balanced equation of wall was listed as follows

$$[\mathbf{K}]\{\boldsymbol{\delta}\} = [\mathbf{P}], \tag{1}$$

where $[\mathbf{K}]$ is the stiffness matrix of structure ($[\mathbf{K}] = \int_V [\mathbf{B}]^T [\mathbf{D}][\mathbf{B}]\,\mathrm{d}V$), $[\mathbf{B}]$ stands for the geometric matrix, $[\mathbf{D}]$ stands for the material constitutive matrix, and V stands for the structure volume, $\{\boldsymbol{\delta}\}$ is the joint displacement vector and $[\mathbf{P}]$ is the load vector.

$$\{\boldsymbol{\sigma}\} = [\mathbf{D}]\{\boldsymbol{\varepsilon}\}, \tag{2}$$

$$\{\boldsymbol{\varepsilon}\} = [\mathbf{B}]\{\boldsymbol{\delta}\}, \tag{3}$$

where $\{\boldsymbol{\sigma}\}$ is the stress matrix and $\{\boldsymbol{\varepsilon}\}$ is the stain matrix.

The stiffness matrix of structure $[\mathbf{K}]$ was not constant because the balanced equation considered the geometric and materials nonlinearity. Both the matrices $[\mathbf{D}]$ and $[\mathbf{B}]$ were related to the stress or strain.

Table 3. Material properties of specimen.

Material	Young's modulus (N/mm^2)	Tensile strength (N/mm^2)	Poisson's ratio
Gypsum	1124.7	0.66	0.23
OSB	3500	7.86	0.3
Steel	2.06e5	320	0.3

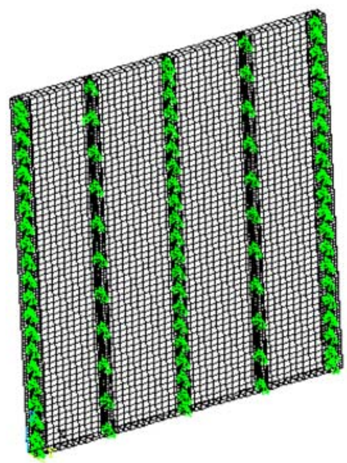
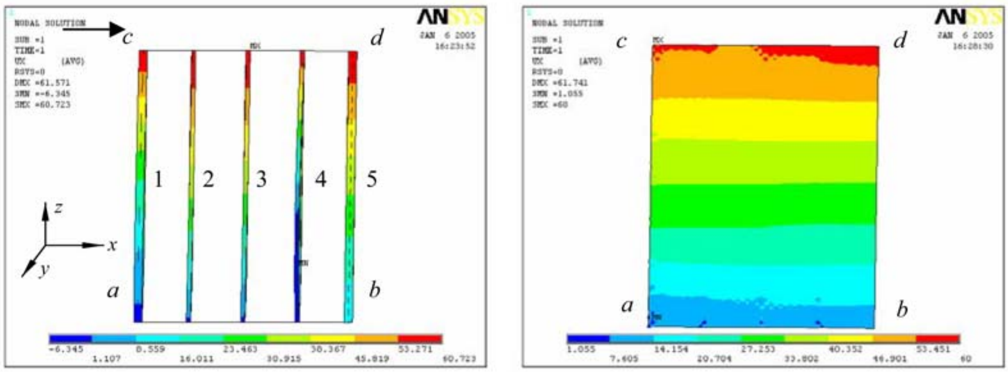


Fig. 6. Finite element models of wall.

The finite element analysis program ANSYS was used to analysis the wall specimens under the monotonic load. The plastic shell elements "shell 181" were used to simulate the cold-formed steel members and sheathing panels. The material properties referring to Kasal et al. (1992), Thomas (2002) and Zhou et al. (2004) are listed in Table 3. The screw connections were handled by coupling method, and the screws were assumed to have free rotations but no displacement along the X, Y and Z-directions without considering the slip between sheathing and steel members. The studs and tracks were simply connected. The displacements along the X, Y and Z-directions and rotations along Y and Z-directions of bottom track were restrained, which means $U_x = 0$, $U_y = 0$, $U_z = 0$, $\theta_y = 0$ and $\theta_z = 0$. And the top track was assumed to have no displacement and rotation along the Y and Z-directions, or $U_y = 0$, $U_z = 0$, $\theta_y = 0$ and $\theta_z = 0$. The finite element model is illustrated in Figure 6. The nodes of top track were coupled in X-directions, and the displacement corresponding to the maximum load was applied on the coupled node. The loading process was controlled by displacement load.

3.2. *Analysis of Specimens*

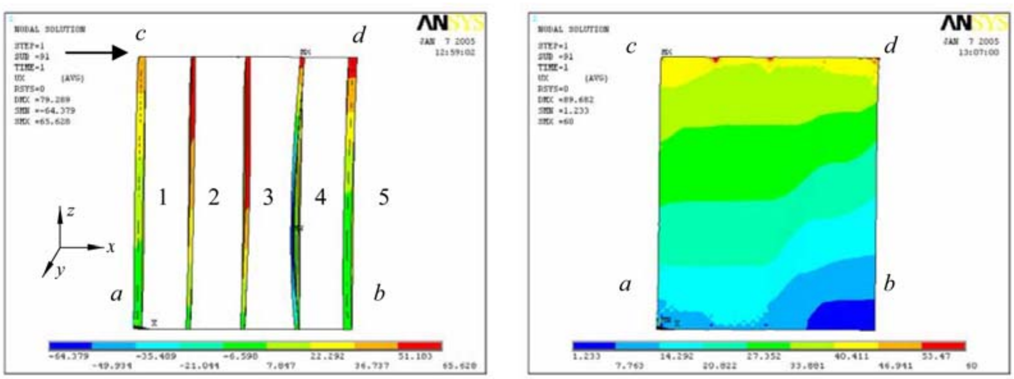
The SSG, SSO and SSGO walls were analyzed through the methods described above, and the finite element analysis results are illustrated from Figures 7 to 9. When the horizontal monotonic load was applied to the walls on point c, the side ac of walls was in tension, the side bd was in compression, and the walls sloped. The sheathing was mainly damaged in the screw connections at the top and bottom of walls, the compressed back-to-back studs locally buckled, and Stud No. 4. overall buckled. The double-faced sheathing could constrain steel frame more effectively than single-sided sheathing, so the studs had lighter distortion in double-faced wall than in single-sided wall.



(a) Displacement along X-direction of steel framing

(b) Displacement along X-direction of gypsum sheathing

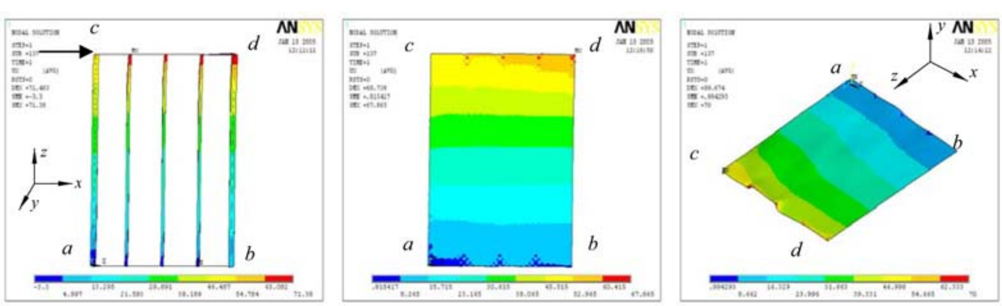
Fig. 7. Displacement of wall with single-sided gypsum.



(a) Displacement along X-direction of steel framing

(b) Displacement along X-direction of OSB

Fig. 8. Displacement of wall with single-sided OSB.



(a) Displacement along X-direction of steel framing

(b) Displacement along X-direction of gypsum sheathing

(c) Displacement along X-direction of OSB

Fig. 9. Displacement of wall with gypsum sheathing on the back and OSB sheathing on the face.

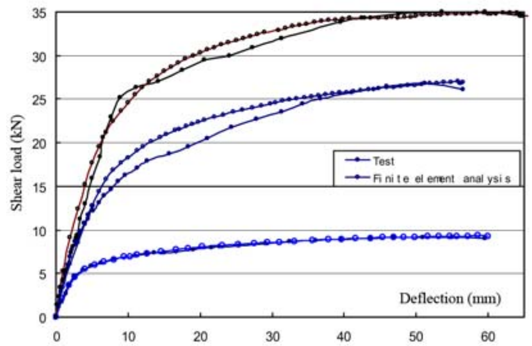


Fig. 10. Comparison of results between test and finite element analysis.

Table 4. The results of test and finite element analysis.

Wall type	Items	P_y (kN)	Δ_y (mm)	P_{max} (kN)	Δ_{max} (mm)	Shear resistance (kN/m)
SSG	test	7.48	13.5	9.12	48	3.8
	finite element analysis	7.71	16.59	9.29	59.79	3.87
SSO	test	21.5	23.9	26.84	51.21	11.18
	finite element analysis	22.46	20.33	26.98	55.15	11.24
DSGO	test	29.12	19.6	34.99	59.62	14.58
	finite element analysis	29.73	17.92	34.86	60.11	14.52

The finite element analysis results were close to those of tests (as shown in Figure 10). There were no obvious yield points in load-displacement curves in Figure 10. The characteristic points of curves were determined by the methods suggested in Chinese *Specification of Testing Methods for Earthquake Resistant Building* (JGJ 101-96, 1996). The comparisons of results between test and finite element analysis were listed in Table 4.

There was a clear error between walls' displacements at yield points or maximal load point measured through test and that calculated by finite element analysis, and the maximum error was 24.56%. But the errors on shear resistance of the SSG wall, SSO wall and DSGO wall were only 0.34% to 1.84%, and the errors on yield load of these three kinds of walls were only 2.1% to 6.03%. The finite element analysis results were close to those of the test. The shear resistance of SSO calculated by finite element analysis was 11.24 kN/m, which was only 3.1% lower than that of wall with the same configuration listed in Japan Iron and Steel Federation (2002). So the method of finite element analysis used in this paper was proved to be correct.

3.3. *Calculation Parameter Analysis of Cold-Formed Steel Stud Walls*

Based on the finite element analysis on the SSG wall, SSO wall and DSGO wall, a series of parameter analysis were done to study the influence of the steel strength, stud spacing, stud height, and screw spacing on the shear resistance of walls.

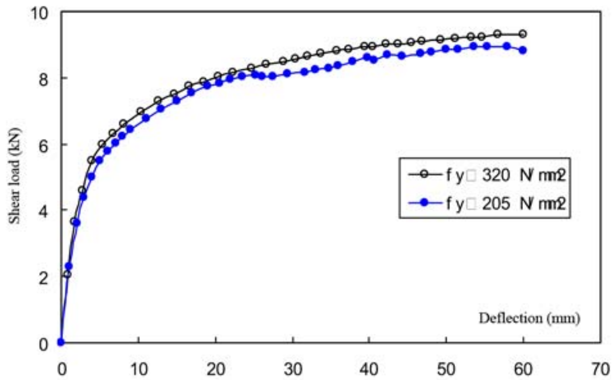


Fig. 11. Load-displacement curves of wall with single-sided gypsum sheathing on the face.

3.3.1. *The Influence of Steel Strength on the Shear Resistance of Walls*

The yield strength of steel of the wall with single-sided gypsum sheathing was 320 N/mm^2, and the maximum resistance of the wall was 9.29 kN. If the steel yield strength of this wall was changed to 205 N/mm^2, the maximum resistance calculated by finite element method was 8.95 kN. The shear resistance of the latter was only 3.65% lower than the former. The load-displacement curves of those two kinds of walls are shown in Figure 11. Obviously, the change of steel strength has little influence on the shear resistance of walls.

3.3.2. *The Influence of Studs Spacing on the Shear Resistance of Walls*

The studs of cold-formed steel stud walls usually spaced 400 mm and 600 mm. However, stud spacing of the test specimens and the finite element analysis models described above was 600 mm. Now the stud spacing of SSG wall, SSO wall and DSGO wall was adjusted to 400 mm, and the finite element analysis results of those walls are described in Table 5, the load-displacement curves are shown in Figure 12. When the stud spacing of SSG wall, SSO wall and DSGO wall was reduced from 600 mm to 400 mm, their shear resistance was increased by 14.47%, 24.11% and 29.96%, respectively. The stud spacing has obvious influence on the shear resistance of cold-formed steel stud walls, and this influence was strengthened with the increase of sheathing restriction.

Table 5. Finite element analysis results of walls.

Wall type	Stud spacing (mm)	P_{max} (kN)	Shear resistance (kN/m)
SSG	400	10.62	4.43
	600	9.29	3.87
SSO	400	33.47	13.95
	600	26.98	11.24
DSGO	400	45.29	18.87
	600	34.84	14.52

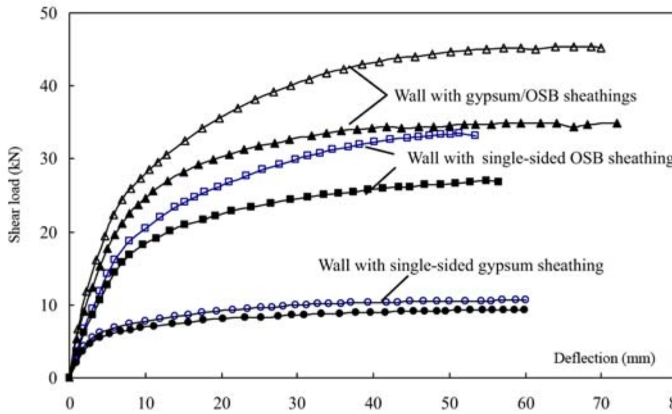


Fig. 12. Load-displacement curves of cold-formed steel stud walls.

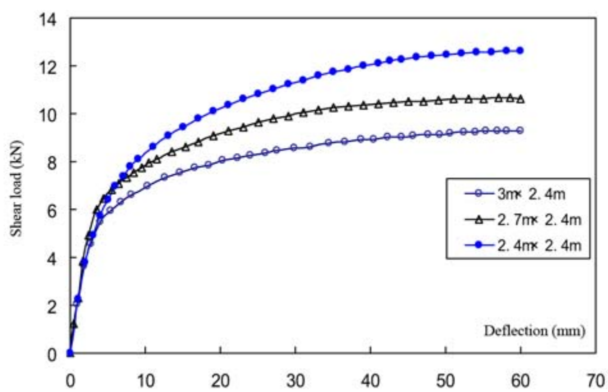


Fig. 13. Load-displacement curves of wall with single-sided gypsum sheathing on the face.

3.3.3. *The Influence of Height of Wall on the Shear Resistance of Walls*

Finite element analysis were presented on three kinds of walls with single-sided gypsum sheathing, whose width were all 2.4 m and the heights were 2.4 m, 2.7 m and 3 m, respectively. The results of finite element analysis are described in Table 6 and load-displacement curves are shown in Figure 13. When the height of walls was increased, the shear resistance of wall with dimension 3 m $\times$ 2.4 m was 12.84% lower than that of wall with dimension 2.7 m $\times$ 2.4 m, whose shear resistance was 15.59% lower than that of wall with dimension 2.4 m $\times$ 2.4 m. So the change of height has more influence on the shear resistance of walls.

3.3.4. *The Influence of Screw Spacing on the Shear Resistance of Walls*

The finite element analysis results of walls with different screw spacing are listed in Table 7. With the narrowing of screw spacing, the shear resistance of walls was increased. When the screw spacing of walls with single-sided gypsum sheathing, or with single-sided OSB sheathing or with gypsum sheathing on the back and OSB on the face, was adjusted form 150/150 (the screw spacing of wallboards was 150 mm at the perimeter and 150mm in the middle field) to 150/300, their shear resistance was improved by 3.36%, 2.85% and 1.93%, respectively. And if changed to 100/300, the shear resistance of walls was respectively improved by 6.98%, 1.33% and 10.54% compared with walls with screw spacing 150/300. So we can conclude that the narrowing of screw spacing in the

Table 6. Finite element analysis results of wall with single-sided gypsum sheathing on the face.

Dimension of walls (height × width)	Height-width ratio	P_{max} (kN)	Shear resistance (kN/m)
2.4 m × 2.4 m	1:1	12.63	5.26
2.7 m × 2.4 m	1.125:1	10.63	4.44
3 m × 2.4 m	1.25:1	9.29	3.87

Table 7. Finite element analysis results of walls.

Wall type	Screw spacing (mm)	P_{max} (kN)	Shear resistance (kN/m)
SSG	@100/300	9.93	4.14
	@150/300	9.29	3.87
	@150/150	9.60	4
SSO	@100/300	27.34	11.39
	@150/300	26.98	11.24
	@150/150	27.74	11.56
DSGO	@100/300	38.52	16.05
	@150/300	34.84	14.52
	@150/150	35.53	14.80

middle field lightly influenced walls' shear resistance when the screw spacing was less than 300 mm, but the walls' shear resistance was strengthened greatly with the decrease of screw spacing at the perimeter. This was in agreement with the phenomenon observed in the test.

3.4. *Design Suggestions*

The shear resistance of many kinds of walls was presented in Table 8 in order to guide actual engineering design. The results were got through the methods of test and finite element analysis introduced in this paper. The steel yield strength was 300 N/mm^2, the studs were C89 × 44.5 × 12 × 1, and the tracks were U92 × 40 × 1.

4. Conclusion

Tests and finite element analysis were presented in this paper to study the shear resistance of cold-formed steel stud walls in residential structures. We can draw the following conclusions:

(1) The material properties of the panel sheathing influence the shear resistance of cold-formed steel stud wall greatly. The shear load capcity of walls with single-sided gypsum sheathing is 34.8% of that of walls with single-sided OSB sheathing, and the total shear resistance of these two kinds of single-sided walls is close to that of wall with gypsum sheathing on one side and OSB sheathing on the other side.

Table 8. The shear resistance of cold-formed steel stud walls.

Dimension of wall (height×width) (m)	Stud spacing (mm)	Screw spacing (mm)	Sheathing	Shear resistance (kN/m)
3×2.4	600	150/300	12mm thick gypsum sheathing on one side	3.87
			9mm thick OSB sheathing on one side	11.24
			12mm thick OSB sheathing on one side	13.48
			12mm thick gypsum sheathing on one side and 9mm thick OSB sheathing with on the other side	14.52
			12mm thick gypsum sheathing on two sides, with thickness 12mm	7.31
			12mm thick OSB sheathing on both sides	25.1
			12mm thick gypsum sheathing on one side and 12mm thick OSB sheathing on the other side	17.11
		100/300	12mm thick gypsum sheathing on one side	4.14
			9mm thick OSB sheathing on one side	12.54
			12mm thick OSB sheathing on one side	15.01
			12mm thick gypsum sheathing on one side and 9mm thick OSB sheathing on the other side	15.89
			12mm thick gypsum sheathing on both sides	7.94
			12mm thick OSB sheathing on both sides	25.12
			12mm thick gypsum sheathing on one side and 12mm thick OSB sheathing on the other side	18.45
	400	150/300	12mm thick gypsum sheathing on one side	4.43
			9mm thick OSB sheathing on one side	13.95
			12mm thick OSB sheathing on one side	21.26
			12mm thick gypsum sheathing on one side and 9mm thick OSB sheathing on the other side	18.87
			12mm thick gypsum sheathing on both sides	8.26
			12mm thick OSB sheathing on both sides	42.72
			12mm thick gypsum sheathing on one side and 12mm thick OSB sheathing on the other side	27.85
		100/300	12mm thick gypsum sheathing on one side	4.82
			9mm thick OSB sheathing on one side	15.75
			12mm thick OSB sheathing on one side	21.98
			12mm thick gypsum sheathing on one side and 9mm thick OSB sheathing on the other side	20.57
			12mm thick gypsum sheathing on both sides	8.32
			12mm thick OSB sheathing on both sides	38.84
			12mm thick gypsum sheathing on one side and 12mm thick OSB sheathing on the other side	27.87
2.7×2.4	600	150/300	12mm thick gypsum sheathing on one side	3.91
			9mm thick OSB sheathing on one side	12.08
			12mm thick OSB sheathing on one side	14.30
		100/300	12mm thick gypsum sheathing on one side	4.24
			9mm thick OSB sheathing on one side	12.92
			12mm thick OSB sheathing on one side	14.67
2.4×2.4	600	150/300	12mm thick gypsum sheathing on one side	4.97
			9mm thick OSB sheathing on one side	13.70
			12mm thick OSB sheathing on one side	16.51
		100/300	12mm thick gypsum sheathing on one side	5.29
			9mm thick OSB sheathing on one side	14.33
			12mm thick OSB sheathing on one side	18.23

(2) The shear resistance of cold-formed steel stud walls is enhanced lightly with the increase of steel strength.
(3) The shear resistance of cold-formed steel stud walls is increased obviously when the stud spacing is reduced from 600 mm to 400 mm.
(4) With the decrease of wall height, the shear resistance of the wall is increased.
(5) With the narrowing of screw spacing at the perimeter, the shear resistance of cold-formed steel stud wall increases greatly.

Acknowledgement

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