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Abstract

Steel sheet shear walls with burring holes are employed in low and mid-rise buildings in seismically active regions. A configuration with burrs on the inside enables the thinner wall and omitting the machining of equipment holes. The effects of cross-rails which are generally designed to strengthen the bearing capacities of the studs, on 2.73~4.53m height shear walls were clarified by finite element analysis and experiments. Post-buckling behavior depends on tension fields restrained by the cross-rails. The formulas of the allowable strengths and the indexes of ultimate strengths were developed using the mechanisms.

Introduction

Shear walls containing sheets with vertically aligned burring holes are employed in the low and mid-rise apartments and stores, offices, and warehouses (Fig. 1,2). The walls are panels in which 2.73~4.53-m-long×0.455-m-wide sheets with cold-formed burring holes are fastened to cold-formed steel studs and tracks. Burring holes were created by cold pressing a sheet with small-radius holes.

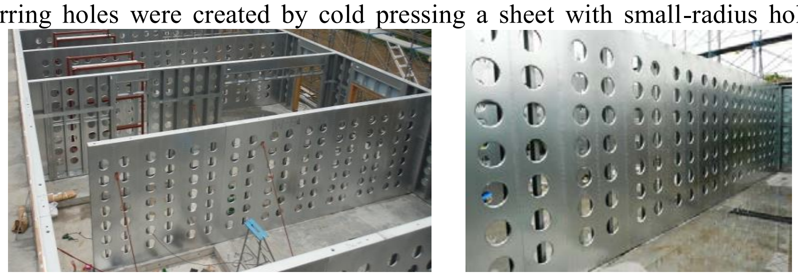

Figure 1: Standard shear walls with burring holes in mid-rise apartments

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A configuration with burrs on the inside and smooth on the outside enables the construction of thinner walls and simplified attachments of finishings (Fig. 2). The machining of holes for equipment can be omitted. The mechanisms for standard and wide walls were investigated [1,2,3]. In contrast, steel shapes with burring holes for joists and beams were developed [4] and used for many kind of structures. This study aimed to clarify the resistance mechanisms of the shear walls with cross-rails and to develop the allowable and ultimate design formula.

Figure 2: High-panelized shear walls with burring holes and devices in holes

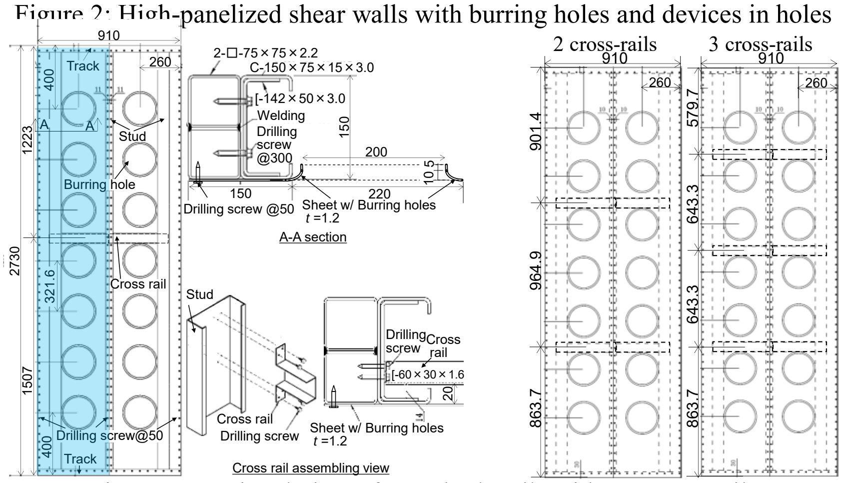


Figure 3: Sectional view of standard walls with 1~3cross-rails

Specifications of shear walls with burring holes and cross-rails

The schematic of 2.73m height standard walls with zero~three cross-rails and 3.53~4.53m height high-panelized walls with an almost same pitch of cross-rails are shown in Figs. 3,4. The sheet containing vertically aligned holes (dia.: 200mm) with a pitch of 320~322mm is hot-dip zinc–alumi–magnesium alloy-coated steel (nominal yield stress: 295N/mm^2, thickness: 1.2mm). The edges of the sheet are connected to studs and tracks using drilling screw (dia.: 4.8mm). A burring hole contains rib (curvature radius: 10mm) and cylinder. The end studs are built-up members (□−75×75×2.2: two members + C−150×75×15×3.0 (+

[−142×50×3.0: for standard walls)) and connected to anchor bolts via tension load connectors. The center stud is C−150×44.5×12×2.2. The cross-rails are [−60×30×1.6 for the standard walls and [−110×50×2.2 for the high-panelized walls and connected to studs to be designed to strengthen the bearing capacities.

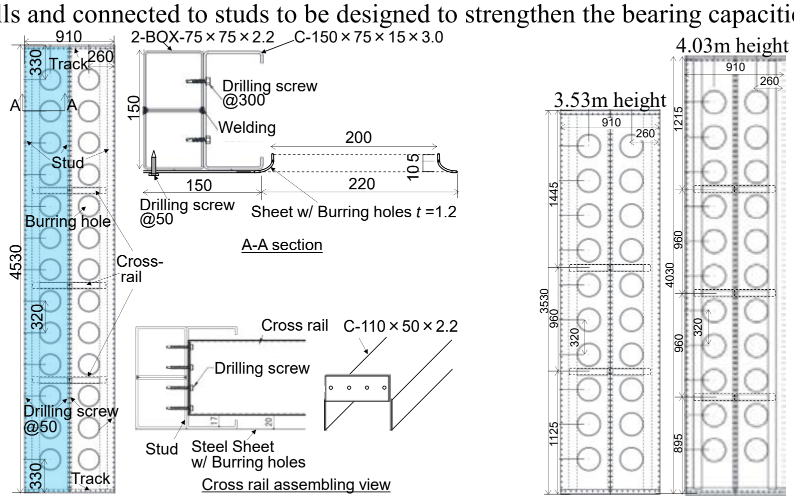


Figure 4: Sectional view of high-panelized walls with cross-rails

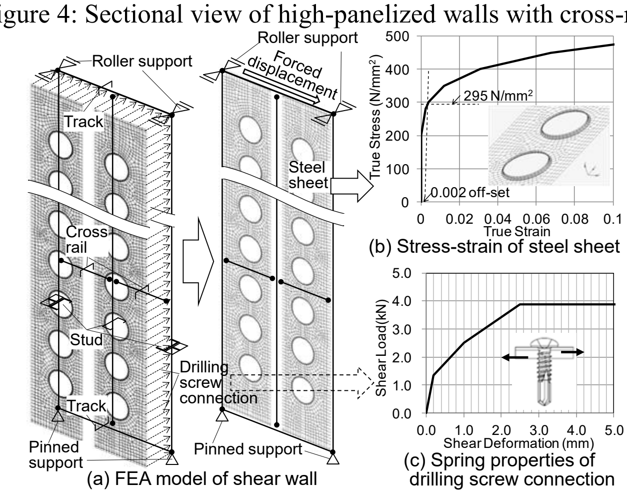


Figure 5: Finite element analysis (FEA) model of shear wall

Shear Resistance Mechanisms of Walls with Burring Holes by FEA

The seismic resistance behavior of the walls was investigated via FEA (MSC. MARC 2014) based on the effects of cross-rails. The sheets with burring holes were modeled using shell elements (Fig. 5a) and the mechanical properties were modeled as stress–strain curves (Fig. 5b). The drilling screw connections were modeled using shear springs based on the experimental results (Fig. 5c) [5,6]. The studs, tacks and cross-rails were modeled by elastic members. The cross-rails had 1/1000 deflection spline curves representing the eccentricity of the end joints. One-way forced displacement was placed on the top of the wall, and pin support connections were placed at the bottom of the wall.

Behavior of standard walls with burring holes and cross-rails (FEA)

The standard walls with variable number of cross-rails show almost same behavior in the elastic region until around 1/300 story angle (Fig. 6). The walls change from the elastic to plastic region and maintain stable strength. The larger the number of cross-rails in a shear wall, the stronger the wall is at 1/100 story angle and over. Contour figures of the von Mises stresses and 1/1 magnification deformation figures from inclined underneath views of lower left corner of the walls in Fig. 3 are shown in Fig. 7. The walls at 1/300 story angle have stress concentrations at the intervals between the holes. The walls at 1/100 story angle experience out-of-plane deformation at the all intervals simultaneously. The deformations are limited in the intervals and a large out-of-plane waveform in a sheet is effectively prevented owing to the ring-shaped ribs of the holes. The deformations at the intervals of the wall with zero cross-rails are larger than that of the wall with three cross-rails. Principal stress flow figures at the interval between second and third hole from the left bottom of the walls are shown in Fig. 8a. The stress directions are indicated by arrows on tangent lines diagonally connects the rib of the vertically lined holes. The wall with three cross rails has the stress flow in order, while that with zero cross-rails has that in disorder. The mean values of horizontal shear forces at four drilling screw connections at the same height of a sheet are shown in Fig. 8b. The wall with three cross-rails exhibits larger horizontal shear force than that with zero cross-rails. The forces at drilling screw points add tension in the intervals. Cross-rails develop tension fields at the intervals using screw connections and order the stress flows.

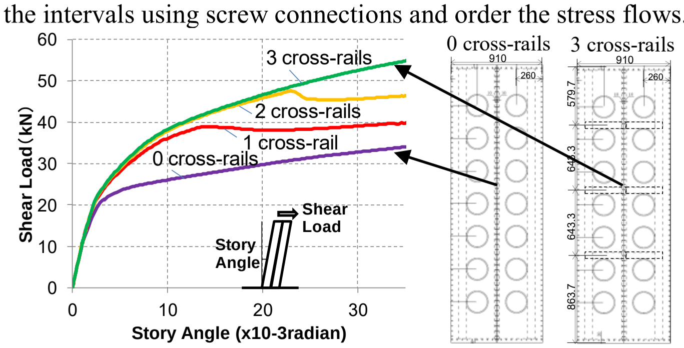


Figure 6: Shear load–story angle relations of walls with 0~3 cross-rails by FEA

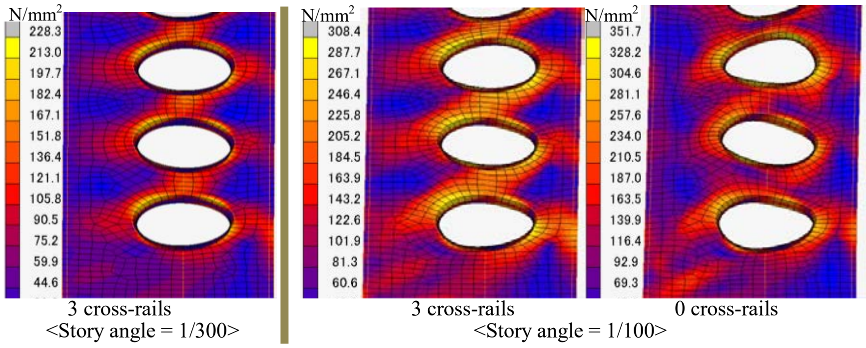
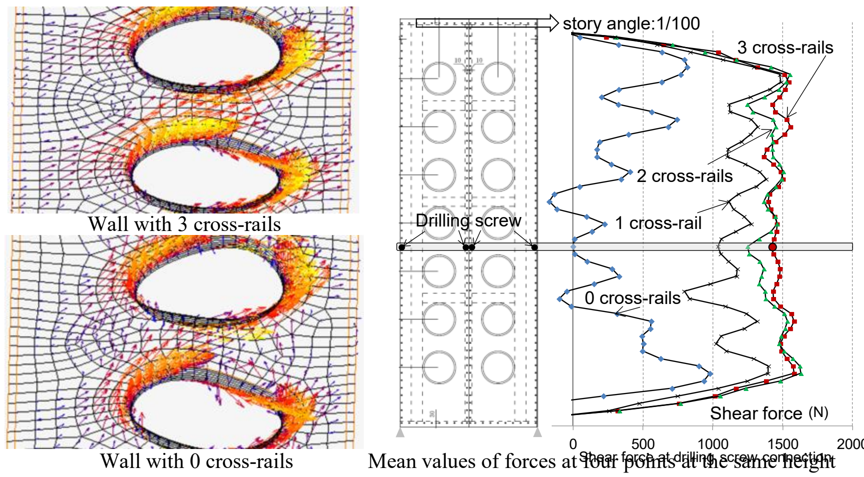


Figure 7: Stress on sheets w/ holes (von Mises stress & deformation (x1.0))



(a) Principal stress flow (b) Horizontal shear force at screw connections

Figure 8: Stress flow on walls w/ and w/o cross-rails at story angle =1/100

Behavior of high-panelized walls with burring holes and cross-rails (FEA)

The walls of variable height with cross-rails show almost same behavior (Fig. 9) and the walls without cross-rails do not show increasing strength in the plastic region. Contour figures of the von Mises stresses and 1/1 deformation figures at the bottom left parts of the walls exhibit stress concentrations at the intervals and experience anti-plane deformation at all intervals at 1/100 story angle (Fig. 10). The effects of wall height are minimal for walls with a same pitch of cross-rails. The shear stresses at the center of the intervals on the vertical section between the holes of points-1~4 in Fig. 10 on the 4.53m high walls with and without cross-rails are compared in Fig. 11a,b. The walls with cross-rails are almost the same from the initial to the ultimate state, while those of the walls without cross-rails decrease after the elastic limit. The wall with cross-rails at 1/100 story angle has ordered stress flow, while the wall without cross-rails has disordered (Fig. 12a,b). Mean horizontal shear forces at drilling screw connections are shown in Fig. 13. The 3.53 and 4.53 m high walls with cross-rails exhibit larger horizontal force than the walls without cross-rails. Owing to the use of the drilling screw connections, cross-rails develop tension fields at the intervals and almost similar behavior as the standard walls.

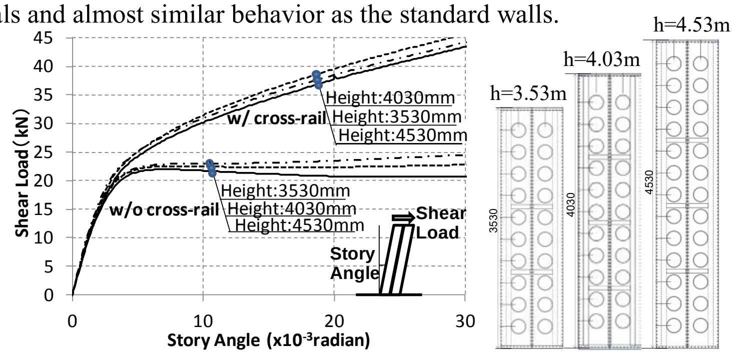
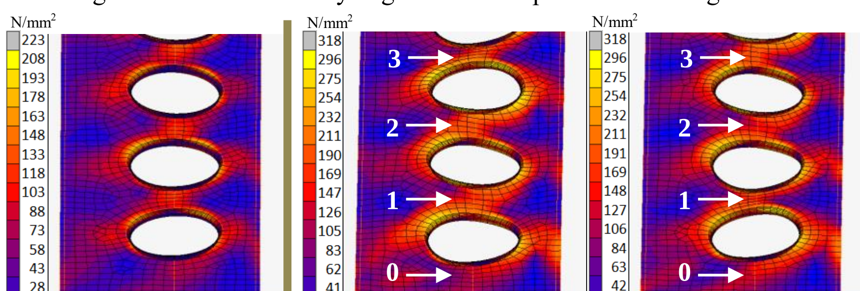
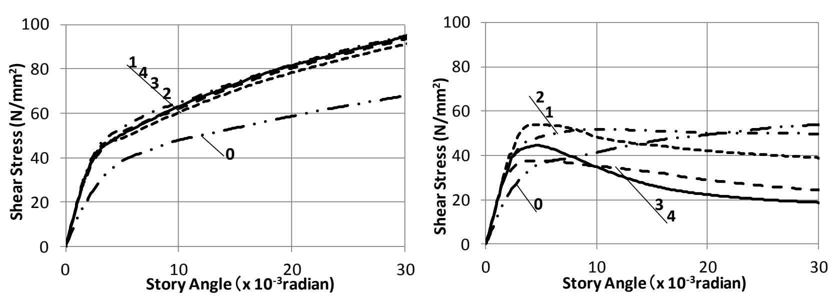


Figure 9: Shear load-story angle relationship of variable height walls



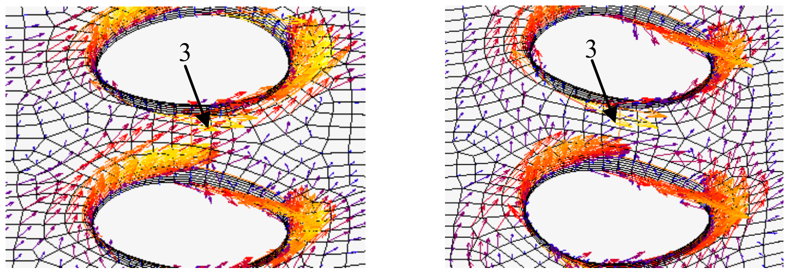
4.53m high wall w/ cross-rails
<Story angle = 1/300>
3.53m high wall w/ cross-rails
4.53m high wall w/ cross-rails
<Story angle = 1/100>

Figure 10: Stress on sheets w/ cross-rails (von Mises stress & 1/1 deformation)



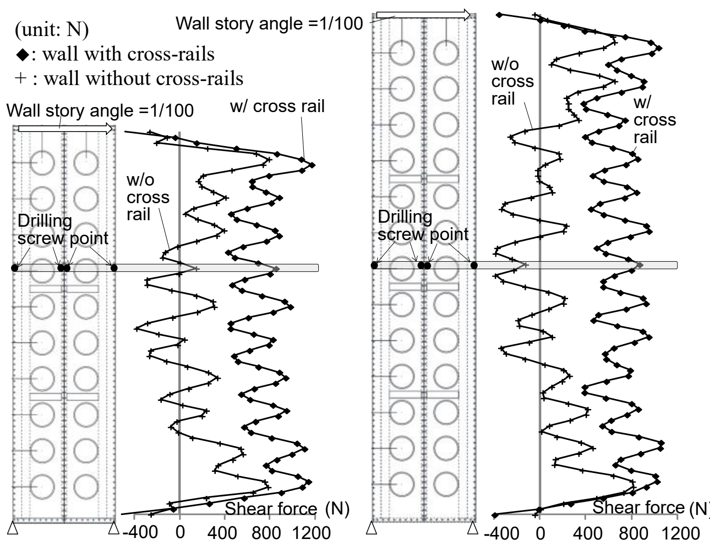
(a) 4.53 m high wall with cross-rails
(b) 4.53 m high wall without cross-rails

Figure 11: Shear stress at the intervals hole between the burring holes



(a) 4.53 m high wall with cross-rails (b) 4.53 m high wall without cross-rails

Figure 12: Principal stress flow at wall story angle= 1/100



Wall height = 3.53 m, story angle = 1/100 Wall height = 4.53 m, story angle = 1/100

Figure 13: Mean horizontal shear forces at drilling screw connections

Allowable design strength formula for shear wall with burring holes

Based on the mechanism of shear resistance, the allowable design strength is derived. The wall changes from the elastic to the plastic region because of shear buckling, which occurs simultaneously at all intervals between the holes (Figs. 6,7,9,10). The stress in an interval is non-uniform, but the likeliness of buckling to occur, depends on the rectangular area that includes the interval, whose diagonal constitutes the tangent line on which the buckling waveforms are located (Fig. 14a). The other areas between the holes and the upper or lower edges are extracted (Fig. 14b,c). The allowable design value is obtained by summing the buckling strength of the intervals in the vertical direction (Eq. 1).

$$Q_a = 2\cdot\left[\tau_a \cdot w_a \cdot t(n-1) + \tau_b \cdot w_b \cdot t + \tau_c \cdot w_c \cdot t\right]\cdot (W/H) \tag{1}$$

$$\tau_i = k_{vi}\cdot \pi^2 \cdot E \cdot \left\{ (t/h_i)^2 / \left[12\cdot\left(1-\upsilon^2\right)\right]\right\} \qquad i = a,b,c \tag{2}$$

$$(a_i/h_i) \le 1.0 \quad k_{vi} = 4.0 + 5.34\cdot (h_i/a_i)^2, \quad (a_i/h_i) > 1.0 \quad k_{vi} = 5.34 + 4.0\cdot (h_i/a_i)^2 \tag{3}$$

$$h_a = L_a \cos\theta, \quad a_a = 2r, \quad L_a = 2\sqrt{(r + w_0/2)^2 - r^2} \tag{4}$$

Q_a is the allowable shear strength; τ_a, τ_b, τ_c are shear buckling stresses at the intervals, derived from Eq. 2 [7]; w_a, w_b, w_c are the interval widths; t is the thickness; n is the number of holes; W, H are the wall width and height. E is the modulus of elasticity, v is Poisson's ratio; r is the radius of the holes.

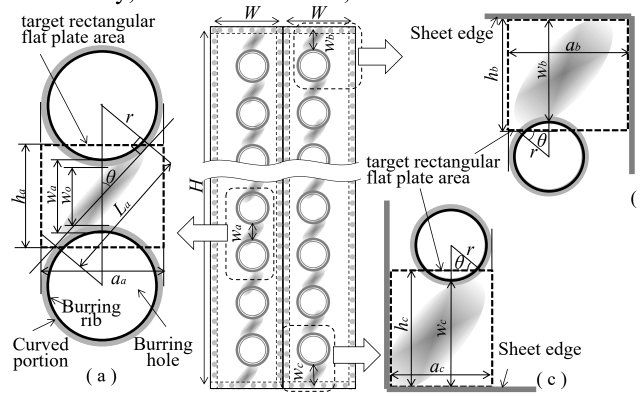


Figure 14: Target rectangular flat plate areas for shear buckling design

Strength index at 1/100 story angle for shear wall with burring holes

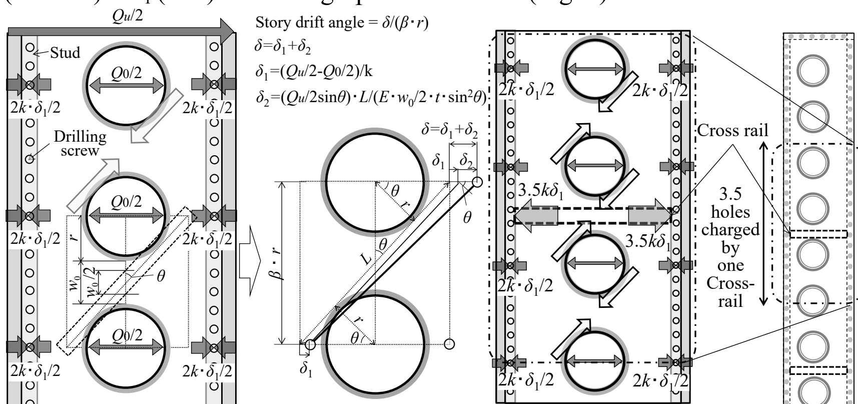
The walls maintain stable strength after shear buckling at the intervals (Figs. 6,9). The wall height has little effect on the strength, and cross-rails increasing the shear strength. The wall strength at 1/100 story angle is used as the index to evaluate the ultimate strength. The tension in an interval balances with the compression of $Q_o/2$ resisted by a burring hole, and the horizontal shear forces at screw connections per a burring hole, $2k\delta_1/2$, derived from the cross-rails (Fig. 15a). $Q_o/2$ is equal to the allowable strength $Q_a/2$.

$$\frac{\delta}{\beta\cdot r} = \frac{\delta_1 + \delta_2}{\beta \cdot r} = \frac{\left(Q_u/2 - Q_a/2\right)/k + Q_u \cdot L/\left(\mathrm{E}\cdot w_0 \cdot t \cdot \sin^3\theta\right)}{\beta\cdot r} = 1/100\cdot \tag{5}$$

$$\because \quad Q_u/2 = Q_a/2 + (2\cdot k)\cdot(\delta_1/2) \qquad \because \quad \delta_2 = \frac{\left(Q_u/2\sin\theta\right)\cdot L}{\mathrm{E}\cdot (w_0/2)\cdot t\cdot \sin^2\theta \cdot t} = \frac{Q_u \cdot L}{\mathrm{E}\cdot w_0 \cdot \sin^3\theta\cdot t} \tag{6}$$

$$\therefore \quad Q_u = 2\cdot\left[\frac{\beta\cdot r/100 + Q_a/2k}{1/k + L/(\mathrm{E}\cdot w_0/2\cdot t\cdot \sin^3\theta)}\right] \tag{7}$$

Q_u is the shear strength of the wall at 1/100 story angle; w_o is the width of the interval between holes without burring ribs; β is the ratio of pitch to radius of the holes; $w_o/2$ is the width of the tension field at the interval. $2k\delta_1/2$ is the horizontal force per burring hole due to screw connections and is derived from cross-rails that charge the compressions between middle points of side-by-side laying cross-rails or tracks (Fig. 15b). A cross-rail charges 3.5 holes for the 3.53 and 4.53 m high walls and 3.0 holes for the 4.03 m high wall. The compression of a cross-rail is 17.5(kN/mm) × δ_1(mm) which is equal to $\Sigma(2k\cdot\delta_1/2)$ for the standard walls (Fig. 3). The compression of a cross-rail is $\Sigma(2k\cdot\delta_1/2)$ = 8.75 (kN/mm) × δ_1 (mm) for the high-panelized walls (Fig. 4).



(a) Force balances of a wall with cross-rails (b) Charged burring holes by a cross-rail

Figure 15: Model of the strength balance of shear wall at 1/100 story angle

In-plane cyclic shear test of steel sheet walls with burring holes

Shearing tests were conducted for the standard walls and high-panelized walls to confirm their seismic resistance mechanism and the applicability of design formulas. The loads were placed on top of the walls (Fig. 16). Three cycles were conducted at the story angles 1/450~1/30 of the wall [9]. The story angles excluded the rotations by the lift of the walls. The specimens were the same as those shown in Figs. 3,4. The mechanical properties and the specifications of the steel sheets, the steel members and connections are summarized in Table 1.

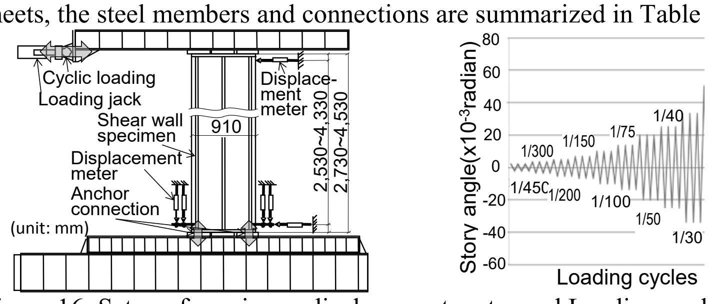


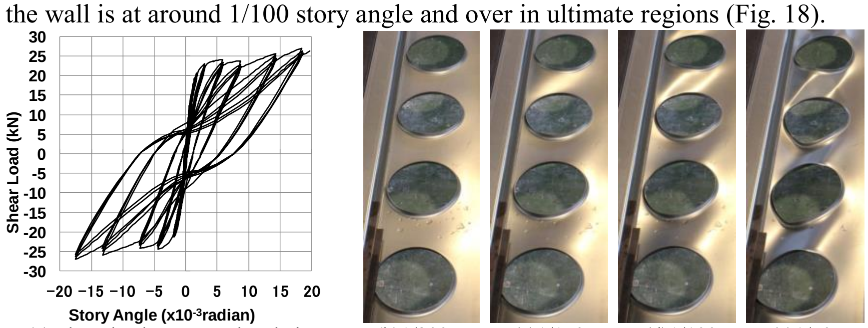
Figure 16: Setup of specimen, displacement meter and Loading cycles

Table 1: Mechanical properties and specifications of members and connections

Member	Standard	Size and mechanical properties
Steel sheet with burring holes	JIS G3323 SGMC400	[for the standard walls] Thickness: 1.23 mm (with coating) and 1.195 mm (without coating) Yield stress: 305 N/mm^2; Tensile strength: 400 N/mm^2; Elongation: 38% [for the high-panelized walls] Thickness: 1.22 mm (with coating) and 1.18 mm (without coating) Yield stress: 332 N/mm^2; Tensile strength: 428 N/mm^2; Elongation: 35%
Studs		Both ends: BOX−75×75×2.2, two members + C−150×75×15×3. (+[−142×50×3.0: only for the standard walls)) Center: C−150×44.5×12×2.2
Tracks		[−155×40×2.2
Cross-rails		[−60×30×1.6 for standard walls, [−110×50×2.2 for high-panelized walls
Drill. screw	JIS B1055	Diameter: 4.8 mm; Length: 19 mm
Anchor bolt	JIS B1180	Diameter: 36 mm; Nominal strength: 880 N/mm^2

Performance of standard walls with cross-rails (Experiment)

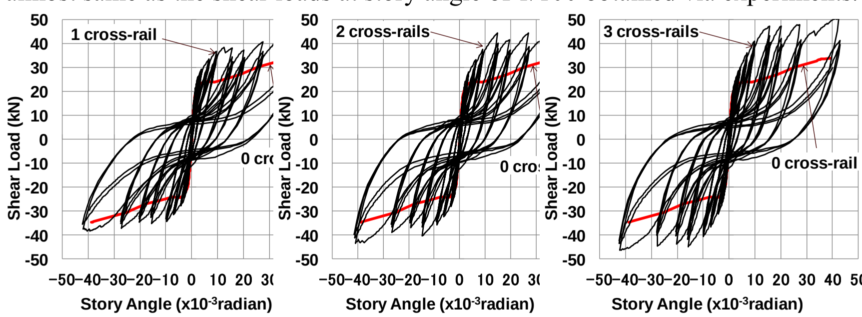
The shear load–story angle curves of a wall with zero cross-rails showed that the stiffness changed from the elastic to plastic regions and maintained the stable strength until the ultimate state (Fig. 17a). Under cyclic loadings, the curves exhibited pinching behavior with stable round loops, which absorb seismic energy. Figs. 17b~e are photos of the lower left corner of the wall in Fig. 3. The wall showed no local deformation at story angle of 1/300. The wall exhibited slight out-of-plane deformation on the intervals between the holes at 1/150 and exhibited shear buckling on the all intervals that deform simultaneously at 1/100. The deformations are limited in the intervals owing to the ring-shaped ribs. The shear buckling waveforms were created on tangents that diagonally connected the vertically aligned holes at 1/50. The deformation figures of Figs. 17b,d are similar to those in Fig. 7 by FEA. The shear load–story angle curves of walls with cross-rails are compared with an envelope curve of that with zero cross-rails, which demonstrated that the larger the number of cross-rails, the stronger the wall is at around 1/100 story angle and over in ultimate regions (Fig. 18).



(a) Shear load–story angle relation (b)1/300 (c)1/150 (d)1/100 (e)1/50

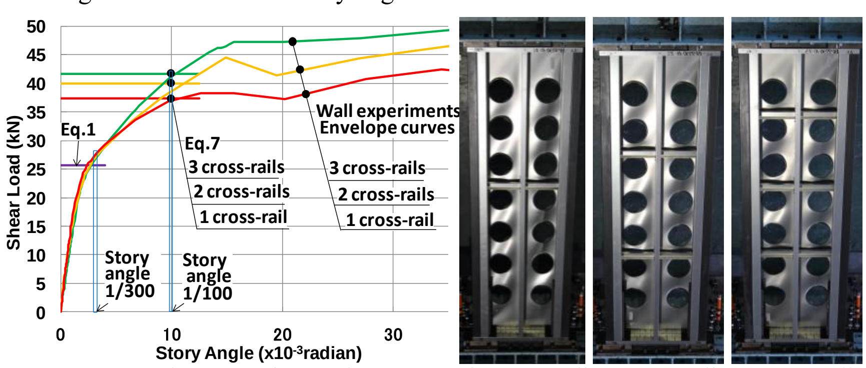
Figure 17: Load–angle relation and behavior at each story angles (0 cross-rails)

Figs. 19b~d are photos of the wall with one~three cross-rails at story angle of 1/100 and exhibited shear buckling on the all intervals that deform simultaneously. The deformations are limited in the intervals owing to the ring-shaped ribs. The envelope curves of shear walls are compared in Fig. 19a. The initial elastic strengths until the serviceability limit of 1/300 story angle for all the walls are almost the same regardless of the number of cross-rails. The allowable shear strengths of the walls derived from Eq. 1 are compared with the experimental results and are a little bit smaller than the shear loads at story angle of 1/300 obtained via experiments (Fig. 19, Table 2). The index strengths of the wall derived from Eq. 7 are compared with the experimental results and are almost same as the shear loads at story angle of 1/100 obtained via experiments.



(a) 1 cross-rail (b) 2 cross rails (c) 3 cross rails

Figure 18: shear load–story angle relation for walls with 1–3 cross-rails



(a) Envelope curves by experiments (b) 1 cross-rail (c) 2 cross rails (c) 3 cross rails

Figure 19: Comparison of the experimental results and design formula Eq. 1, 7

Table 2: Design formula Eq.1,7 compared w/ experimental shear load

Shear wall	Eq.1 [kN]	Shear load at story angle of 1/300 obtained via an experiment [kN]	Eq.7 [kN]	Shear load at story angle of 1/100 obtained via an experiment [kN]
1 cross rail	25.7	27.4	37.3	37.0
2 cross rails	25.7	27.6	39.9	38.6
3 cross rails	25.7	28.1	41.7	41.2

Performance of high-panelized walls with cross-rails (Experiment)

The photos of 3.53, 4.03, 4.53m high walls used in the experiment indicate almost the same behavior (Fig. 20). The walls at story angles of 1/300 and 1/200 showed no local deformations and slight out of plane deformations on the all intervals between the holes at 1/100. The shear buckling waveforms were created on the tangent lines that diagonally connect the vertical holes at story angle of 1/50. The deformation areas were limited in the intervals owing to the ring-shaped ribs of the holes. The figures showing deformation in Fig. 20 are very similar to those in Fig. 10 obtained by FEA.

h = 3.53 m h = 4.03 m h = 4.53 m

(a) Story angle = 1/300

h = 3.53 m h = 4.03 m h = 4.53 m

(b) Story angle = 1/200

h = 3.53 m h = 4.03 m h = 4.53 m

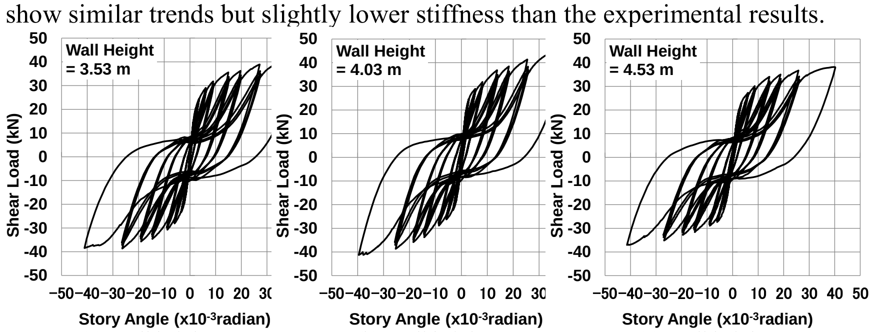
(c) Story angle = 1/100

h = 3.53 m h = 4.03 m h = 4.53 m

(d) Story angle = 1/50

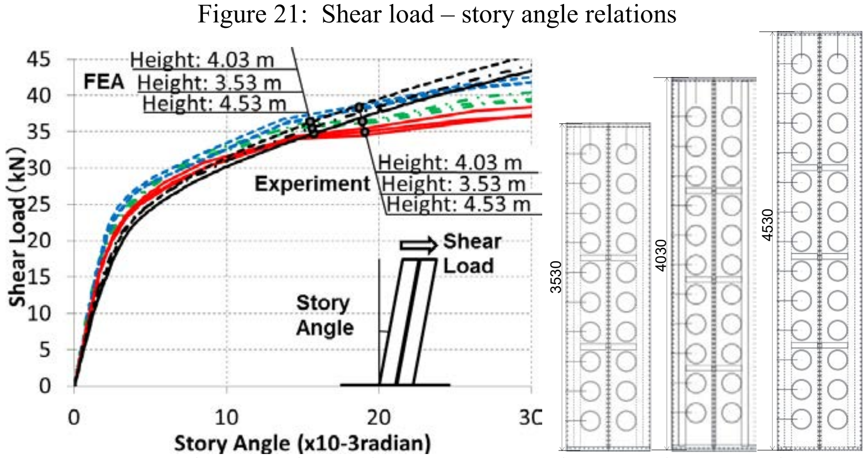
Figure 20: Photos of walls at story angles of 1/300~1/50 by shear experiments

The shear load and story angle relations of the walls are showed in Fig. 21. The 3.53, 4.03, 4.53m high walls showed almost same behavior in the elastic regions. The stiffness changed from the elastic to plastic regions. The walls maintained stable strength until the ultimate state. Under cyclic loading, the walls exhibited pinching behavior with stable round loops, which absorb seismic energy. The shear load at the second cycle at the same story angle decreased slightly, while the shear load at the third cycle did not decrease furthermore. The shear load–story angle relations of the walls are compared using envelope curves (Fig. 22). Three specimens of the same height, i.e., total nine, were taken. The 4.03m high walls were slightly stronger at the story angle 1/100, than the 3.53, 4.53 m high walls. The effect of cross-rails was significant and the charging of burring holes by cross-rails determined the strength for the wall (Fig. 15). A cross-rail charges 3 holes for the 4.03m high wall, and 3.5 holes for the 3.53 and 4.53m high walls. The dispersion of three specimens of the same height is small. The FEA results show similar trends but slightly lower stiffness than the experimental results.



(a) Wall height = 3.53 m (b) Wall height = 4.03 m (c) Wall height = 4.53 m

Figure 21: Shear load – story angle relations



Envelope curves by experiments h = 3.53m h = 4.03m h= 4.53m

Figure 22: Comparison of the experimental results and FEA

The allowable design strengths of the walls as derived from Eq. 1 are the values between the shear load at wall story angles 1/300 and 1/200 (Table 3). The index strengths for the ultimate state of the wall as derived from Eq. 7 are almost the same as the shear loads at story angle 1/100 obtained via experiments (Table 4).

Table 3: Design strength from Eq. 1 and shear load through experiment

Height (m)	Eq. 1 (kN)	Shear load at story angle1/300 obtained through experiment (kN)	Shear load at story angle 1/200 obtained through experiment (kN)
3.53	26.6	23.9 24.0 24.4	27.4 27.2 27.8
4.03	25.1	25.0 25.8 25.1	28.0 28.5 27.9
4.53	26.3	23.1 22.8 23.3	26.2 25.9 26.7

Table 4: Strength index from Eq. 7 and shear load through experiment

Height (m)	Eq. 7 (kN)	Shear load at story angle:1/100 obtained through experiment (kN)		
3.53	33.3	32.7	32.4	33.0
4.03	33.0	32.6	33.5	32.7
4.53	33.0	31.2	31.1	31.6

Conclusions

The seismic performance of steel sheet walls with burring holes aligned vertically, and the effects of cross-rails and wall height on the shear walls were investigated via finite element analyses and experiments. From these investigations, the following conclusions can be drawn:

- The walls exhibited significant stiffness in the initial elastic region, whereas they maintained stable strength under large story angles. Furthermore, the walls showed stable seismic energy absorption capability, as demonstrated by the round loops of the shear load-story angle curves.
- The walls that experienced in-plane shear forces allowed shear stress to concentrate intervals between the aligned burring holes. Stress concentration finally led to the ultimate state because of simultaneous shear buckling at all intervals between the holes, and the buckling areas in the intervals were restricted by the use of ring-shaped ribs of the burring holes.
- The initial elastic strengths until the serviceability limit of the wall story angle of 1/300 and 1/200 for all walls were almost the same, regardless of the number of cross-rails and the wall height.
- The post-buckling behavior depends on the tension fields on the intervals between the holes, which are restrained by cross-rails. The effect of cross-rails maintained wall strength stable in inelastic region and the number of burring holes charged by a cross-rail determines the ultimate strength of the wall.
- Based on analytical and experimental findings, the allowable strength design formula of the wall was developed. The design value was obtained by

summing the shear buckling strength of the intervals between the holes in the vertical direction of the wall. The allowable strength design values obtained using the formula lie almost the same values at wall story angle between 1/300 and 1/200 obtained through experiments.

- The index strength for ultimate state of the wall was determined. The tension in an interval was balanced with the compression resisted by burring holes and horizontal shear forces at screw connections. The index values were almost same as the shear load values of 1/100 story angle obtained via experiments.
- The R-value for the evaluation of seismic performance of shear walls will be discussed in a subsequent report.

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