17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

EXPERIMENTAL EVALUATION OF OUT-OF-PLANE STRENGTH OF DRY PARTITION WALL WITH LIGHT-GAUGE STEEL

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Abstract

In the Great East Japan Earthquake (2011) and Kumamoto Earthquake (2016), damage to non-structural members such as ceiling and interior and exterior wall led to loss of the building function for a long time. In addition, some buildings were demolished due to numerous damage to non-structural members, in spite of almost no damage to structural members of the buildings. Due to human and physical damage caused by the above earthquakes, the seismic performance of ceiling has been attracting attention, and its research has been advanced vigorously. However, a lot of damage to light-gauge steel dry partition walls (LGS walls) have also been reported. Therefore, it is important to evaluate structural behavior of LGS walls and to establish the damage reduction method.

In present paper, the out-of-plane loading test of LGS walls with various heights were carried out for the purpose of establishing the evaluation method of ultimate strength. Specimens of the experiments are LGS walls consisted of light-gauge steel backing frame and gypsum boards. The light-gauge steel backing frames are composed of tracks (U-67x40x0.8), studs (C-65x45x10x0.8) and reinforcing channels (U-25x10x1.2). And then, reinforced gypsum boards with a thickness of 12.5mm are fastened with screws on the backing frame. The main parameters were selected as follows; (1) height of wall (2,000, 4,000, 6,000, 8,000mm); (2) width of wall (910, 1,820mm); (3) spacing of studs (303, 455mm); (4) clearance between upper track and studs (10, 20, 30mm). These parameters are factors that greatly affect the out-of-plane behavior of LGS wall. In this paper, after clarifying these effects, the evaluation method of the ultimate strength is discussed. In addition to these, (5) pitch of screws, (6) specification of gypsum boards and (7) loading protocol were also selected to the test parameters. In this experiment, a total of 20 specimens were prepared by combining the above test parameters.

Two kinds of failure were observed in the tests, which were local buckling of the stud and slipping-off of the studs from a track. The ultimate strength of LGS wall obtained from the experiments decreased in proportion to wall height. Also, as wall width is wider and the spacing of studs is narrower, the ultimate strength increases. Therefore, the ultimate strength is mostly determined by wall height and the number of studs. Additionally, it has been found that composite effect between gypsum boards and studs is improved according to the number of screws from the other results, and the ultimate strength of LGS wall is increased. On the other hand, LGS wall can be assumed as a simple beam because the deflection curve of LGS wall indicates that the connection between a track and a stud behaves as pin supports. The ultimate strength can be evaluated by plastic analysis with full plastic moment of studs.

Keywords: non-structural member; light-gauge steel dry partition wall; out-of-plane loading test; evaluation of ultimate strength; local buckling

1. Introduction

In the Great East Japan Earthquake (2011) and Kumamoto Earthquake (2016), damage to non-structural members such as ceiling and interior and exterior wall led to loss of the building function for a long time (Fig. 1) [1]. In addition, some buildings have been demolished due to numerous damage to non-structural members, in spite of almost no damage to structural members of the buildings. Due to human and physical damage caused by the above earthquakes, the seismic performance of ceiling has been attracting attention, and its research has been advanced vigorously. However, a lot of damage to dry partition walls with light-gauge steel (LGS walls) have also been reported. For LGS walls, there are specifications written in "Standard Specifications for Public Building Work"[2]. For example, it says that 65 series can only be applied to LGS walls less than 4m in height, and 100 series can be applied to walls less than 5m in height. But these specifications are not determined to be based on structural evidence. Therefore, it is important to clarify and evaluate the structural behavior of LGS walls in order to establish the damage reduction method.

In present paper, out-of-plane loading tests of LGS walls with the various height were carried out for the purpose of grasping the effects of various factors on structural behavior and establishing the evaluation method of ultimate strength of LGS wall.

Fig.1 Damage of LGS wall in Kumamoto earthquake

2. Test Program

2.1 Specimens

Firstly, an outline of LGS wall is shown in Fig. 2. The LGS walls is consisted of light-gauge steel backing frame and gypsum boards screwed to the backing frame. In some case, gypsum boards of double layer are attached on each side of the backing frame, and the second layer board (upper board) is attached to the first layer board (lower board) with adhesive.

Next, an outline of test specimens is illustrated in Fig.3. The test specimen is an LGS wall whose standard size is 4,000 mm in height and 1,820 mm in width (Fig. 3 (a)). For the cross section of light-gauge steel for backing frame, 65 series written in "Standard Specifications for Public Building Work" [2] is used. 65 series are track U-67x40x0.8, stud C-65x45x10x0.8 and reinforcing channel U-25x10x1.2 which are made of galvanized steel sheet (SGCC). The cross section of each member is shown in Fig. 4. For gypsum boards, reinforced gypsum boards of 12.5mm in thickness are used, whose size are 1,820mm in length and 910mm in width or cut from them.

In the backing frame (Fig. 3 (b)), the tracks are fixed to jigs assumed as ceiling and floor with M12 bolt arranged at the interval of 100 mm. The studs are arranged at equal intervals in the track width without connecting to the tracks. The reinforcing channels to connect each stud are generally placed at the interval of 1,200 mm from floor end. But in these experiments, they are arranged at only two positions 1/4 of wall height away from center of wall center to avoid placing loss of stud section at loading point.

The lower boards (Fig. 3 (c)) are attached to the studs at a pitch of 290 mm with M3.5 tapping screws of 22 mm in length. The layout of the lower boards is determined so that joints between adjacent boards does not overlap the loading point.

The upper boards (Fig. 3 (d)) are attached on the lower boards with aqueous emulsion adhesive, and then temporarily fastened with staples at a pitch of about 200 mm and cured for about one day. The layout of the upper boards is arranged so as not to overlap the joint of the lower boards.

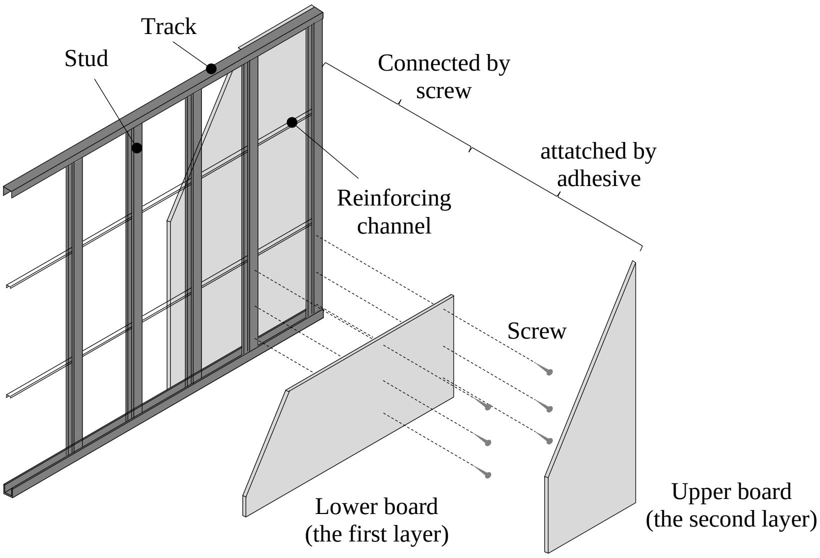


Fig.2 Outline of LGS wall

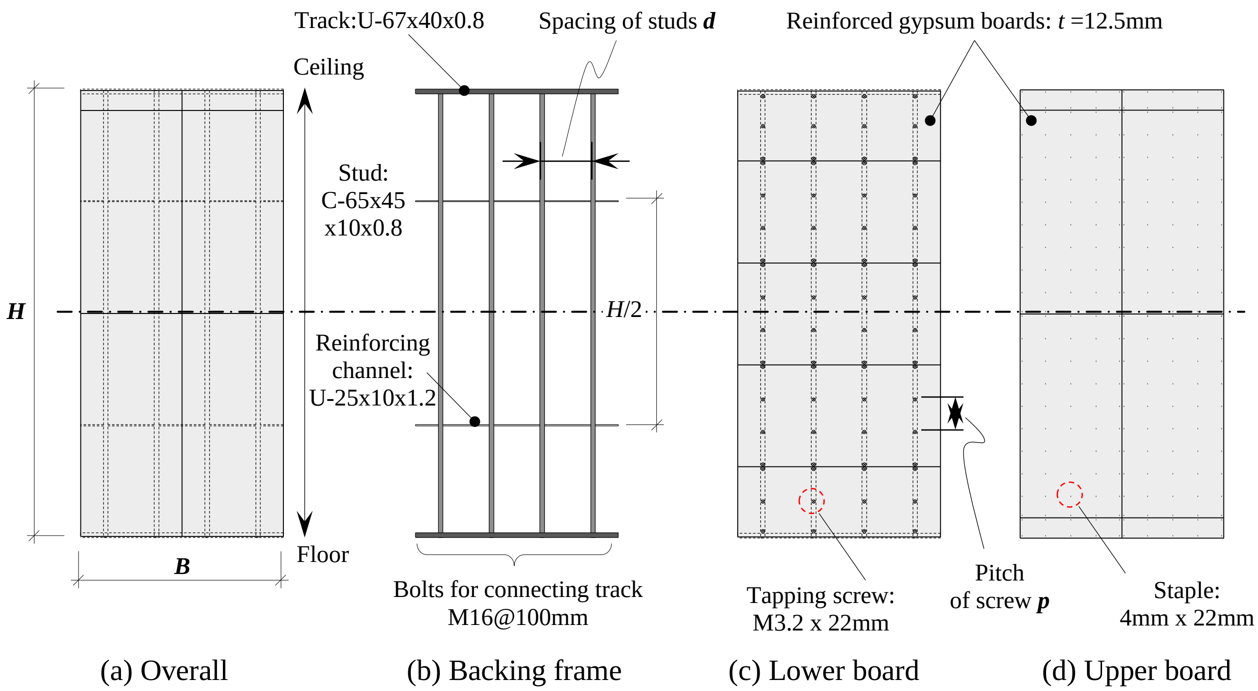


Fig.3 Outline of specimens

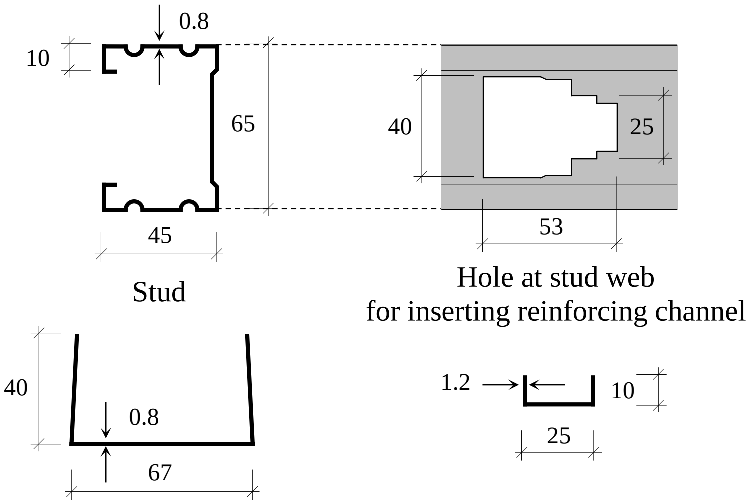
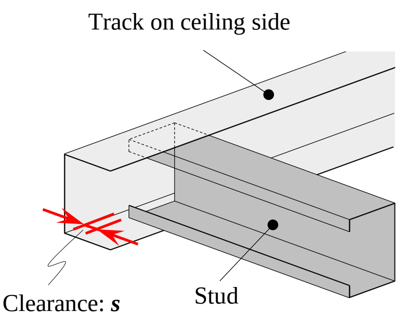


Fig.4 Size of member for backing frame

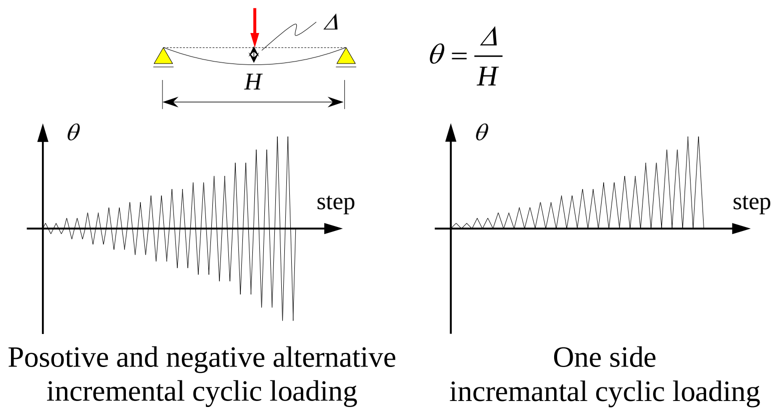
2.2 Test parameters

Test parameters and a list of specimens are shown in Fig. 5 and Table 1, respectively. Basic test parameters are: (1) wall height *H*: 2,000, 4,000, 6,000, 8,000 mm, (2) wall width *B*: 910, 1,820 mm, (3) spacing of studs *d*: 303, 455 mm, (4) clearance *s*: 10, 20, 30 mm. The clearance *s* is defined as a distance between the track on ceiling side and studs (Fig. 5 (a)). The wall height, wall width, and spacing of studs are factors that greatly affect the out-of-plane behavior of LGS wall. In this experiment, after clarifying these effects on the out-of-plane behavior of LGS walls, the evaluation method of the ultimate strength is investigated.

In addition to these parameters, the other parameters are: (5) pitch of screw *p*: 97, 290 mm, (6) specification of gypsum board: single layer or double layer on each side, (7) loading protocol: positive and negative alternating incremental cyclic loading, one side incremental cyclic loading. The pitch of screw *p* (Fig. 3 (c)) is the distance between screws on a stud. For the pitch of screw, 290mm of the standard and 97mm of the narrower pitch are prepared, and the effect of the number of screws on structural behavior is investigated. For the board specifications, double layer on each side are standard, and single layer is also prepared for the purpose of finding the influence of the number of gypsum boards. Finally, two types of loading protocols are prepared to confirm the validity of experimental method (Fig. 5 (b)). In this experiment, a total of 20 specimens were prepared by combining the above test parameters.



(a) Clearance



(b) Loading protocol

Fig.5 Test parameters

Table1 List of specimens

<table>
<tr><th>Specimen No.</th><th>Wall height H [mm]</th><th>Wall width B [mm]</th><th>Spacing of studs d [mm]</th><th>Clearance s [mm]</th><th>The number of gypsum boards on each side</th><th>Pitch of screw p [mm]</th><th>Loading protocol</th></tr>
<tr><td>1</td><td rowspan="5">2000</td><td rowspan="4">1820</td><td>303</td><td rowspan="2">10</td><td rowspan="5">Double</td><td rowspan="6">290</td><td rowspan="8">Posotive and negative alternative incremental cyclic loading</td></tr>
<tr><td>2</td><td rowspan="4">455</td></tr>
<tr><td>3</td><td>20</td></tr>
<tr><td>4</td><td>30</td></tr>
<tr><td>5</td><td>910</td><td>10</td></tr>
<tr><td>6</td><td rowspan="9">4000</td><td rowspan="8">1820</td><td>303</td><td rowspan="4">10</td><td rowspan="4">Double</td></tr>
<tr><td>7</td><td rowspan="8">455</td><td>97</td></tr>
<tr><td>8</td><td rowspan="13">290</td></tr>
<tr><td>9</td><td rowspan="2">One side incremantal cyclic loading</td></tr>
<tr><td>10</td><td rowspan="2">20</td><td>Single</td></tr>
<tr><td>11</td><td rowspan="4">Double</td><td rowspan="10">Posotive and negative alternative incremental cyclic loading</td></tr>
<tr><td>12</td><td rowspan="2">30</td></tr>
<tr><td>13</td></tr>
<tr><td>14</td><td>910</td><td>10</td></tr>
<tr><td>15</td><td rowspan="3">6000</td><td rowspan="2">1820</td><td>303</td><td rowspan="3">10</td><td rowspan="3">Double</td></tr>
<tr><td>16</td><td rowspan="2">455</td></tr>
<tr><td>17</td><td>910</td></tr>
<tr><td>18</td><td rowspan="3">8000</td><td rowspan="2">1820</td><td>303</td><td rowspan="3">10</td><td rowspan="3">Double</td></tr>
<tr><td>19</td><td rowspan="2">455</td></tr>
<tr><td>20</td><td>910</td></tr>
</table>

2.3 Test setup

The standard test setup is shown in Fig. 6. The specimen is set up horizontally by connecting tracks to track connected jigs fixed to reaction beams. A loading frame composed of columns and beams is assembled on the reaction beams, and a hydraulic jack is connected vertically at the top of the frame. Two loading beams are connected to a tip of the hydraulic jack so as to hold the specimen, and the loading beams are connected by PC bars. By adopting the arrangement of the loading beams like this, it enables to carry out positive and negative alternating loading for a wide wall. Although Fig. 6 shows the setup of a specimen with wall height of 4 m, it is possible to install specimens with different wall heights by extending the reaction beams and moving the track connected jigs. The loading frame and the hydraulic jack are provided with lateral bracings.

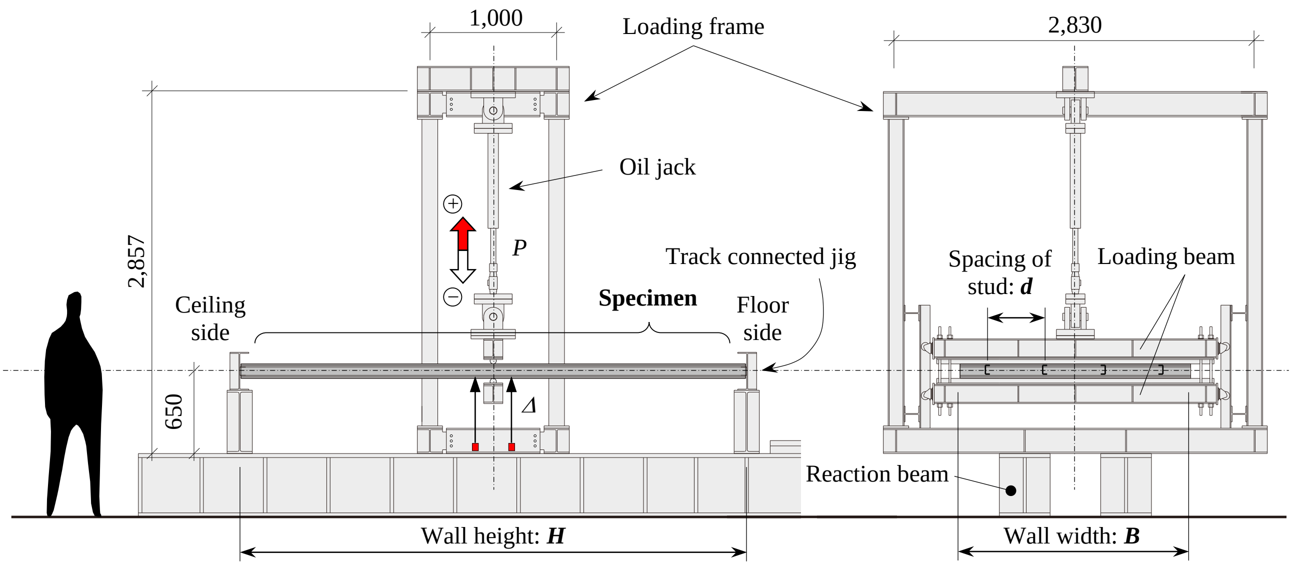


Fig.6 Test setup

2.4 Loading protocol

Loading protocol in this experiment is indicated in Fig. 5 (b). In this experiment, positive and negative alternating cyclic loading were basically carried out, but for some specimens one side cyclic loading of only positive side were also conducted. For control of the experiment, ratio of out-of-plane deformation at center of wall to the wall height (deflection ratio) θ is adopted. Amplitudes of cyclic loading increased by 0.0025 rad until the deflection ratio q reached 0.02 rad, and increased by 0.005 rad after 0.02 rad. The loading was carried out twice per amplitude.

2.5 Measurement program

In this experiment, out-of-plane force P applied at center of LGS wall is measured by a load cell connected to hydraulic jack. And then, outline of measurement for out-of-plane deformation is represented in Fig. 7. Out-of-plane deformations δ of the wall (Fig. 7) are measured by multiple displacement transducers placed along the height of the wall to find distribution shape of the deformation. Especially, out-of-plane deformation Δ which is used to calculate the deflection ratio θ is obtained as average value of the four displacement transducers (Fig. 6) arranged near center of the wall.

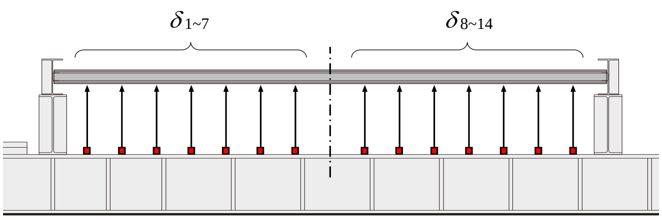


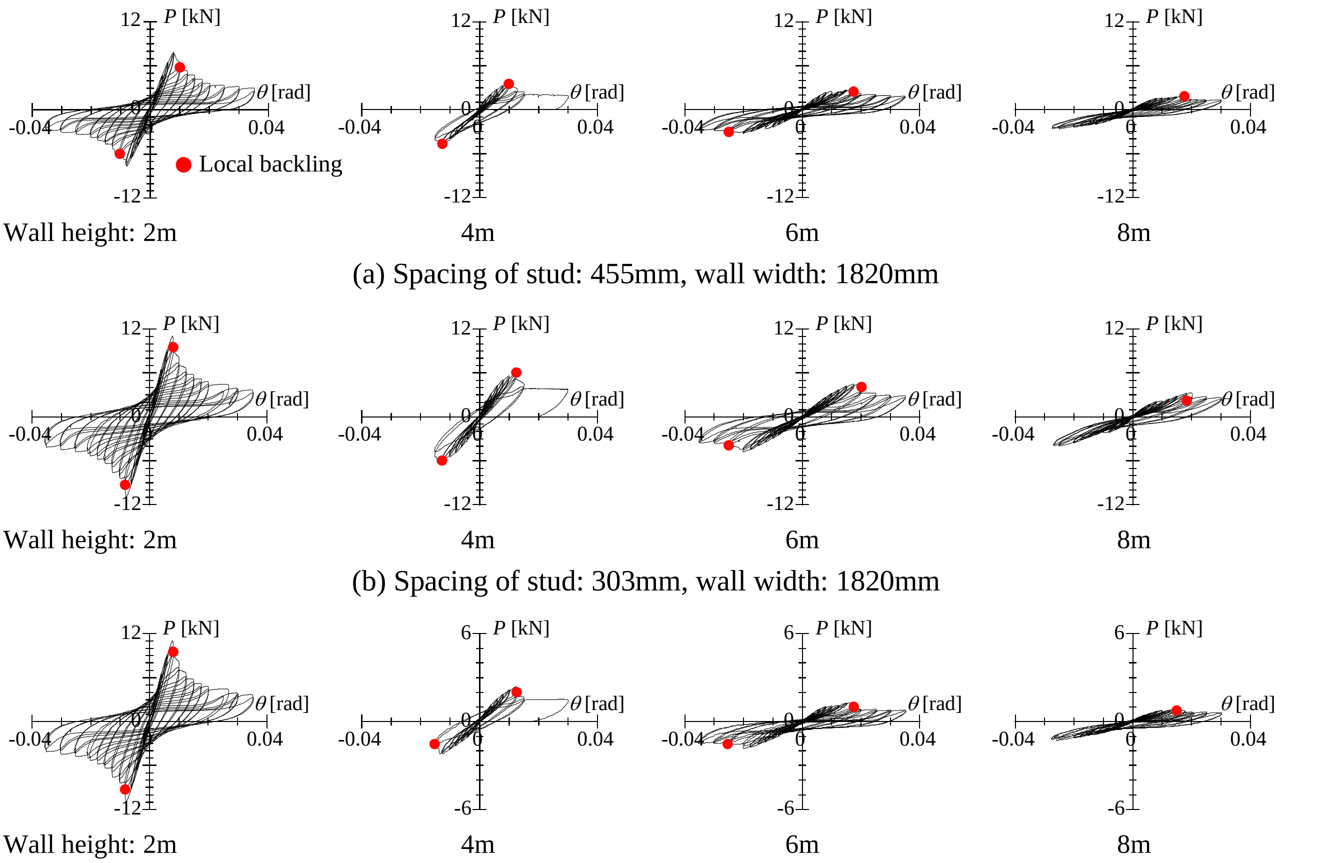
Fig.7 Measurement of out-of-plane deformation

3. Test results and consideration

3.1 Outline of test results

$P-\theta$ relationships obtained from experiments are shown in Fig. 8. The vertical axis represents the force applied at the center of the wall P, and the horizontal axis indicates the deflection ratio θ. In the figure, difference in wall height, spacing of studs and wall width is compared.

Here, common results among all specimens are described. All specimens show almost elastic behavior during an initial loading. As the deformation progresses, slip behavior can be seen due to the gap displacement between studs and boards. At the time of about 0.01 to 0.02 rad of the deflection ratio, local buckling of studs occurred for all specimens as Fig. 9. In Fig. 8, the point at which local buckling of a stud occurred is indicated by a red circle. After that, the strength of LGS wall decreases caused by cracks of studs. But, in almost of all specimens, the strengths aren't completely lost until the deflection ratio reached 0.035 rad.



(a) Spacing of stud: 455mm, wall width: 1820mm

(b) Spacing of stud: 303mm, wall width: 1820mm

(c) Spacing of stud: 455mm, wall width: 910mm

Fig.8 $P-\theta$ relationship

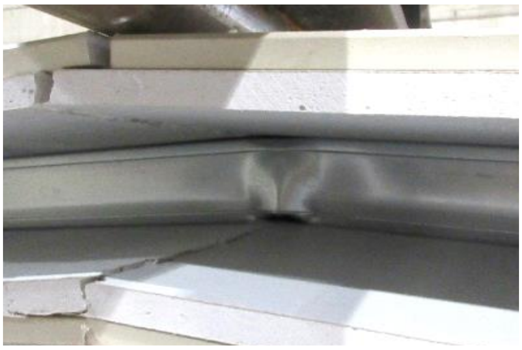


Fig.9 Local buckling of stud at the center of wall

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3.2 Effects of wall height, spacing of studs and wall width

From here, the out-of-plane behaviors of LGS walls are compared by each parameter. First, the difference in wall height *H* is discussed. The results with wall heights of 2, 4, 6, and 8m are shown in Fig. 8. It is confirmed that the ultimate strength decreases according to the wall height. This is because the bending moment applying at the center of the wall increases in proportion to the wall height under the same force. In other words, if the local buckling strength at the same cross section is assumed to be constant, the specimen with higher wall will reach the local buckling strength by smaller force.

Second, the difference in the spacing of studs *d* is verified. For the specimens with the spacing of studs of 303mm (Fig. 8 (b)), the strengths increase compared to those with the spacing of studs of 455mm (Fig. 8 (a)) and the same wall height. This is affected by the number of studs included in the same wall width. The differences in the ultimate strengths due to the spacing of studs are 1.4 times for the wall height of 2m, 1.56 times for 4m, 1.70 times for 6m, and 1.74 times for 8m, and these values correspond to 1.5 times which is the ratio of the number of studs (6/4). Therefore, most of the out-of-plane force applied on the LGS wall is resisted by studs, and it can be said that denser arrangement of the studs is effective to ensure the strength in the same wall width.

Third, the difference in wall width *B* is considered. The specimens with the wall width of 910 mm (Fig. 8 (c)) have smaller strengths than those of with the wall width of 1820mm (Fig. 8 (a)). As well as the effect of difference in the spacing of studs, this is caused by decrease in the number of studs due to the narrower width. The number of studs in the specimens with the wall width of 910 mm is a half of those with the wall width of 1820mm. On the other hand, the ratio of the ultimate strengths are 0.62 times for 2m, 0.45 times for 4m, 0.48 times for 6m and 0.47 times for 8m. Therefore, it can be concluded that the ultimate strength in out-of-plane of LGS walls is greatly affected by the number of studs.

3.3 Effects of clearance between stud and track

Next, effect of clearance *s* between the stud and the track on the out-of-plane behavior are considered. Fig. 10 represents envelope curves of $P - \theta$ relationships of specimens with different clearance. In Fig. 10, the differences in three types of clearances are distinguished by using different colors.

For these specimens, the local buckling of studs occurred for all specimens when the deflection ratio reached about 0.01 rad. However, in case of a specimen with clearance of 30mm – which means the studs are inserted into a track of ceiling side to only 10mm –, the studs slipped off the track as Fig. 11, and the strength was suddenly lost. In Fig. 10, the point at which local buckling of the stud occurred is indicated by a filled circle, and the point at which slip-off of the studs happened is shown by an open circle. In elemental tests of previous research [4], it is described that presence of gypsum board has a large influence on strength of the slipping-off. In this experiment, after the studs slipped off track, deformation of the gypsum boards and pull-out of the screws were observed as well as the previous research. In the future, it is necessary to establish an evaluation method of the strength of the slipping-off.

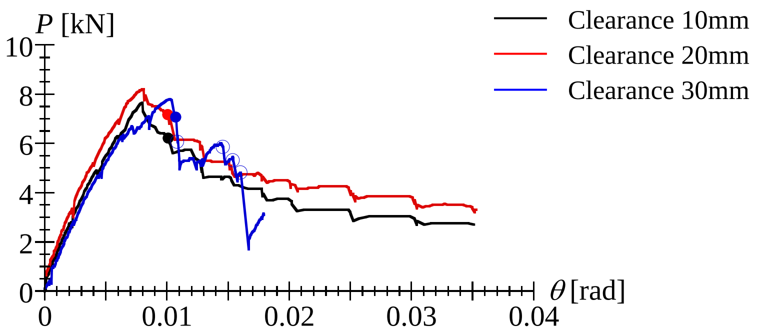


Fig.10 Effect of different clearance on envelope curve of P - θ relationship (wall height 2m)

Fig.11 Slip-off of studs from the track of ceiling side

3.4 Effects of specification of gypsum board

Here, effects of specification of gypsum board are discussed. Envelope curves of $P - \theta$ relationships of specimens with different board specifications is shown in Fig. 12. In the figure, the differences in three types of specifications are distinguished by using three colors.

First, the difference in the number of boards is compared. By reducing the number of boards from two to one, the ultimate strength decreases by about 0.5 kN. This value is equivalent to 12.8% of the ultimate strength of a specimen with double boards. Thus, it can be said that the number of gypsum boards don't greatly affect out-of-plane strength of LGS walls.

Next, the difference in pitch of screws is considered. For a specimen with pitch of screws narrowed from standard 290 mm to 97 mm, the ultimate strength increased by 0.5 kN than that of the specimen with standard pitch due to increase in the number of screws. This value is equivalent to 10% of the ultimate strength of the specimen with standard pitch. In the specimen with the narrower pitch of screws, finally the gypsum boards broke and then studs slipped off a track as Fig.13, leading to a loss of strength. The reason why the gypsum boards were broken is that deformation of the gypsum boards was restrained by the screws arranged densely. In Fig. 12, the point at which the gypsum boards were broken is indicated by a red circle.

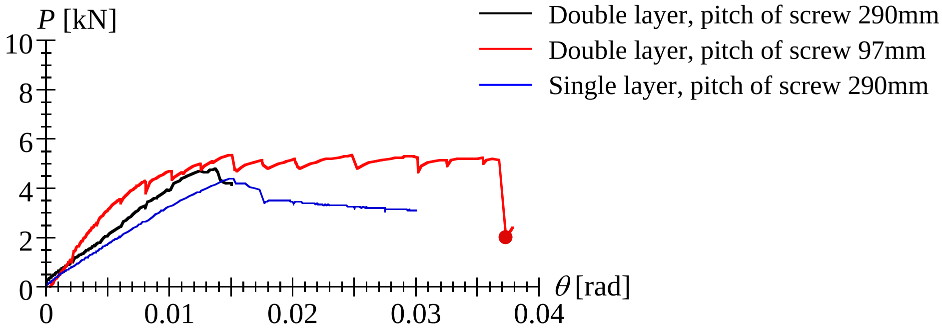


Fig.12 Effect on envelope curve of force-deformation relationship of specification of gypsum board

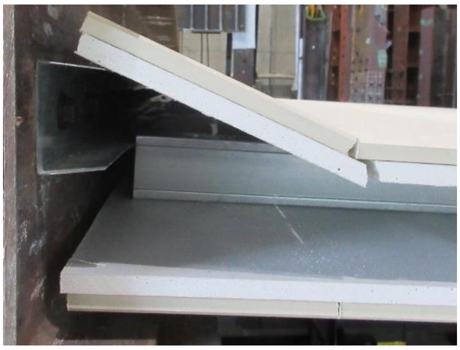


Fig.13 Broken gypsum board

3.5 Deflection curve

The deflection curves obtained from displacement transducers at the time of ± 0.01 rad of deflection ratio are illustrated in Fig. 14. The vertical axis represents the out-of-plane deformation of a specimen at the time of ± 0.01 rad of deflection ratio, and the horizontal axis shows the measurement position along wall height. The left end of a graph is the ceiling and the right end is the floor, and a clearance of 10 mm is provided only at the connection between a track and studs on the ceiling side. However, the deflection curves of each wall height are symmetrical, and it can be said that there is no effect of the clearance. In addition, since no inflection point can be found on the deflection curve, it is considered that the boundary condition at the connection between a track and studs is almost simple support.

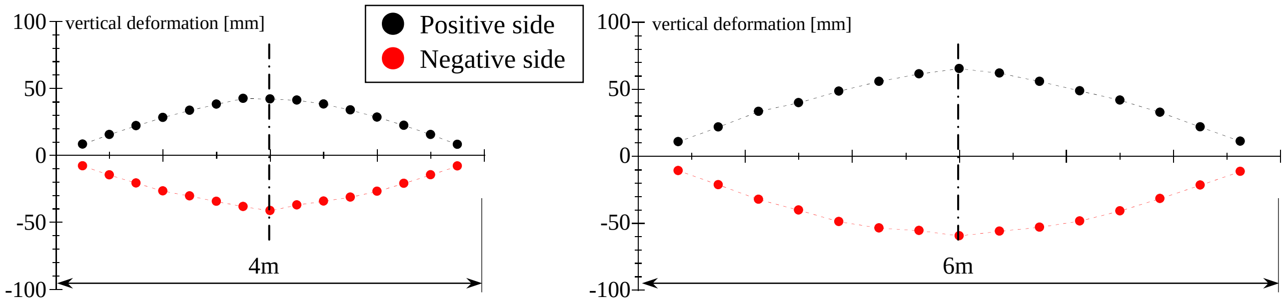


Fig.14 Deflection curve at the time of ±0.01rad

4. Evaluation of and ultimate strength

4.1 Evaluation model of ultimate strength

In this section, the evaluation method of ultimate strength is discussed. The evaluation model of ultimate strength is shown in Fig. 15. Based on the consideration of the deflection curve, the model of an LGS wall can be assumed as a simple beam under a concentrated force in the center. Thus, the ultimate strength P_u determined by the local buckling can be obtained by the following equation.

$$P_u = \frac{4M_p}{H} \quad \cdots (1)$$

Here, M is the full plastic moment M_p of a stud, H is the wall height. M_p can be calculated as the product of the plastic section modulus Z_p of the cross section shown in Fig. 15 and the actual yield stress (296 N/mm^2).

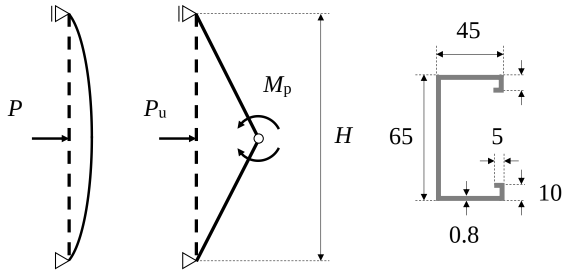


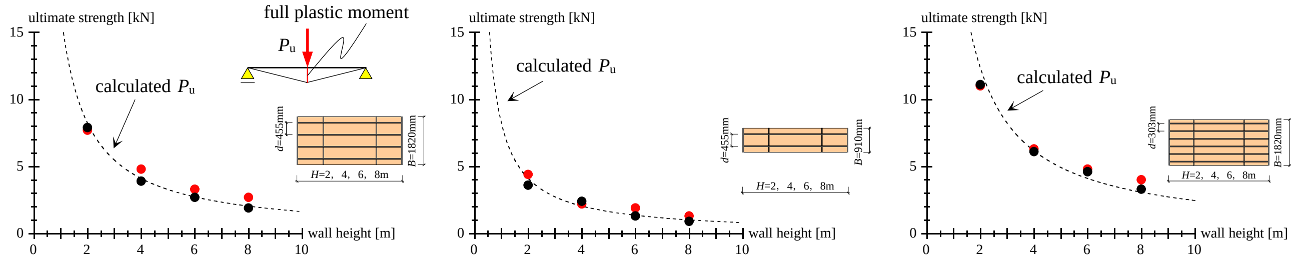
Fig.15 Evaluation model of ultimate strength

4.2 Comparison between test results and evaluation values of the ultimate strength

Comparisons between test results and evaluated values of the ultimate strength are shown in Fig. 16. The vertical axis indicates the ultimate strength, and the horizontal axis represents the wall height. The test results obtained in positive and negative side are illustrated by black and red circles, respectively.

The test results show that the ultimate strengths decrease in proportion to the wall height. This tendency corresponds to equations (1), where the ultimate strength is inversely proportional to the wall height. In addition, the same tendency is obtained even when wall width and spacing of studs are changed as Fig. 16 (b) and (c).

Next, the test results and evaluated values are compared. It can be confirmed that the evaluated values by the mentioned model correspond to the test results for all wall heights. Therefore, it is concluded that the ultimate strength of an LGS wall under out-of-plane force can be evaluated by using the full plastic moment of studs and considering the number of studs included in the wall.



(a) wall width: 1,820mm, pitch of studs: 455mm (b) wall width: **910**mm, pitch of studs: 455mm (c) wall width: 1,820mm, pitch of studs: **303**mm

Fig. 16 Relationship between wall height and ultimate strength

5. Conclusion

In present paper, out-of-plane loading tests of LGS walls with the various height were conducted in order to clarify the effects of the wall height, the wall width, the spacing of studs and so on. Also, an evaluation method of the ultimate strength of LGS wall was investigated.

The test results can be summarized as follows: (1) it was confirmed that out-of-plane deformation of the LGS wall resulted in two types of failure modes of the local buckling of studs and slipping-off of a stud from a track; (2) it was found that the boundary condition of the connection between a track and a stud was an almost simple support because of no inflection point on the deflection curve; (3) the ultimate strength determined by the local buckling of studs is inversely proportional to the wall height, and it is proportional to the number of studs included in the wall; (4) the ultimate strength can be evaluated by the model assuming the LGS wall as a simple beam subject to the concentrated force at the center.

6. Acknowledge

This work was supported by JST Program on Open Innovation Platform with Enterprises, Research Institute and Academia.

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