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Structural Behavior of Bolted Joints in Metal Exterior Wall

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Abstract

In Japan, metal panels are widely used as exterior wall materials for buildings, commercial facilities, etc. because they are applicable for various surface finishes and working. Since there are various types of panels and fastening members, no method has been established for comprehensively designing and constructing them. In particular, it is important to understand the capacity of the exterior wall which is made from metal panels (metal exterior wall), to follow the story drift in order to prevent damage to the walls and to maintain the functionality of buildings after earthquakes. Therefore, in this study, a cyclic loading test of a metal exterior wall was conducted to evaluate the allowable story drift and deformation mechanism of the metal exterior wall.

The metal exterior wall is composed of metal panels and steel components called furring strip and fastener. The joints on the metal exterior wall include a bolted joint between the fastener and furring strip and a screw joint between the furring strip and the panel. At the bolted joints, slotted holes are provided in the fastener in the out-of-plane direction and in the furring strip in the in-plane direction to accommodate construction errors in the structural frame. At the screw joints, slotted holes are also provided in the panel in the in-plane direction to cope with expansion and contraction due to thermal stress.

In addition to the misalignment in the horizontal direction at joints, the horizontal deformation caused by a panel rotation is generated. Moreover, with the deformation of the structural frame, torsion around the material axis of the furring strip occurs.

From this experiment, it is found that the deformation mechanism of the metal exterior wall is mainly realized by (i) slippage at the bolted joint, (ii) misalignment at the screw joint, (iii) deformation due to torsion of the furring strip, (iv) other deformations incidental to torsion of the furring strip. Up to the story drift of 1/100 rad, the specimen is almost elastic. Until then, the ratio of the misalignment at the bolted joint to the total deformation was extremely small because the bolted joint is tightened at 20kN, which is about 60% of the yield strength of M12 stainless steel bolt. If the bolt tension is controlled, the misalignment at the screw joint can precede that of at the bolted joint. Misalignment at the screw joint accounts for 30% and deformation due to the torsion of the furring strip accounts for nearly 60%. It means that the deformation due to the torsion of the furring strip plays a major role as the deformation mechanism of the metal exterior wall.

The rates of deformation at the bolted joint and screw joint have increased since the story drift of 1/67 rad, where the panel cracked and the overall hysteresis behavior becomes nonlinear. On the other hand, the rate of deformation due to torsion of the furring strip, which had maintained the elastic state, decreased and eventually dropped to less than 20% because the damage to the screw joint determines the strength and ultimate state of the metal exterior wall. Finally, the damage progresses at the screw joint and follows the story drift.

Keywords: Metal exterior wall, Cyclic loading test, Bolted joint, Slotted hole

1. Introduction

In Japan, metal panels are widely used as exterior wall materials for buildings, commercial facilities, etc. because they are applicable for various surface finishes and working. Since there are various types of panels and fastening members, no method has been established for comprehensively designing and constructing them. In particular, it is important to understand the capacity of the exterior wall which is made from metal panels as shown in Fig. 1 (metal exterior wall), to follow the story drift in order to prevent damage to the walls and to maintain the functionality of buildings after earthquakes.

In this study, a in-plane cyclic-loading test of a metal exterior wall was conducted to evaluate the allowable story drift and deformation mechanism of the metal exterior wall.

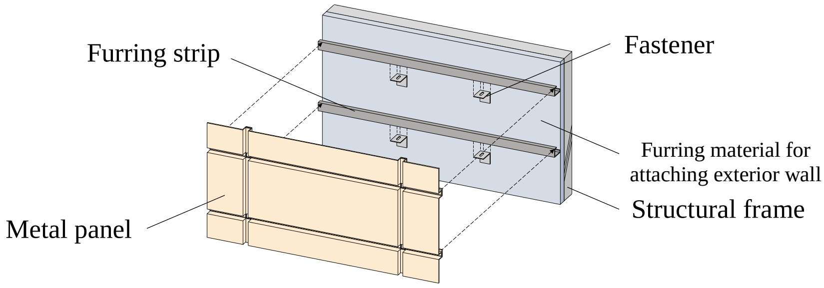


Fig. 1 – Metal exterior wall

2. Construction method of metal exterior wall

The metal exterior wall is composed of metal panels and steel components called furring strip and fastener. The panels are formed by bending the metal plates with a thickness of about 0.8 to 5.0 mm into a box shape, and the height and width can be arbitrarily manufactured. One panel is supported at the upper and lower parts by the furring strips. Fasteners are attached to each furring strip at regular intervals.

The joints on the metal exterior wall include a bolted joint between the fastener and furring strip (Fig. 2) and a screw joint between the furring strip and the panel (Fig. 3). For the bolted joints, the fastener has a slotted hole in the out-of-plane direction and similarly, the furring strip has in-plane slotted holes to accommodate construction errors in the structural frame. In order to prevent the panel from slipping out of the plane after construction, bolted joints were generally fixed by spot welding. However, in recent years, the non-welding method has been promoted due to fire risk[1]. The panel is fixed to the furring strip using drill screws in the order of the upper part of the lower-layer-side panel and then the lower part of the upper-layer-side panel. Specifically, after fixing the upper part of the lower-layer-side panel at only two points, the lower part of the upper-layer-side panel is overlapped there and fixed completely. Each screw joint has slotted holes to cope with expansion and contraction due to thermal stress. Only the lower part of the panel where all screw joints are slotted holes can be moved in the in-plane direction.

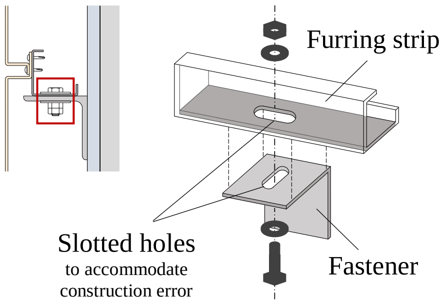


Fig. 2 – Bolted joint

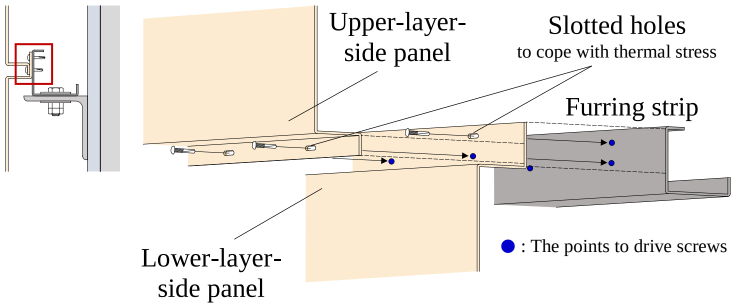


Fig. 3 – Screw joint

3. Experiment outline

3.1 Specimen

The specimen represents a metal exterior wall intended for construction in a middle-rise building. The panel to be tested is an aluminum panel (A1100; F_y=95 N/mm^2) with a height of 838 mm and a width of 1,800 mm (center panel (Fig. 4)). In order to reproduce the actual screw joints, panels to be attached to the upper and lower part of the center panel are partially manufactured and joined together. Fig. 4 shows the dimensions of metal panels. These panels do not include the opening, the outside corner, and the inside corner. Steel components for mounting the panels are two furring strips (Angles with lip: L-60x60x15x15x2.3) and four fasteners (Angle: L-90x90x7). The steel grade for general steel structure (SS400; F_y = 235N/mm^2) is used. The dimensions of these steel components are shown in Fig. 5. Austenitic stainless steel bolts with a nominal diameter of 12 mm (M12, A2-70; F_y = 450N/mm^2) and martensitic stainless steel drill screws with a nominal diameter of 4.2 mm (ST4.2, C1-70; F_y = 410N/mm^2) are used in this test.

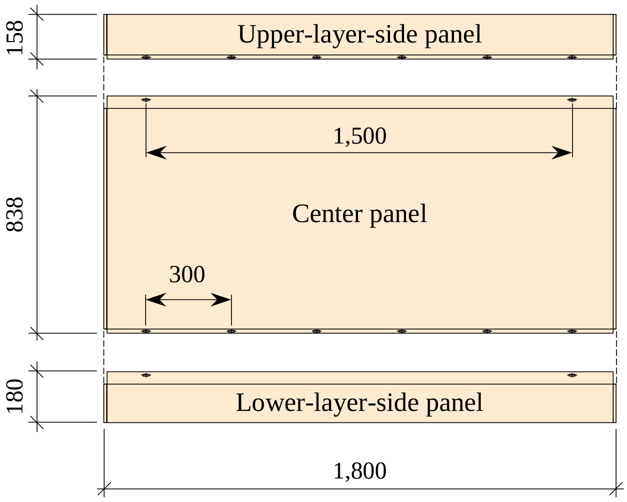


Fig. 4 – Dimensions of metal panels

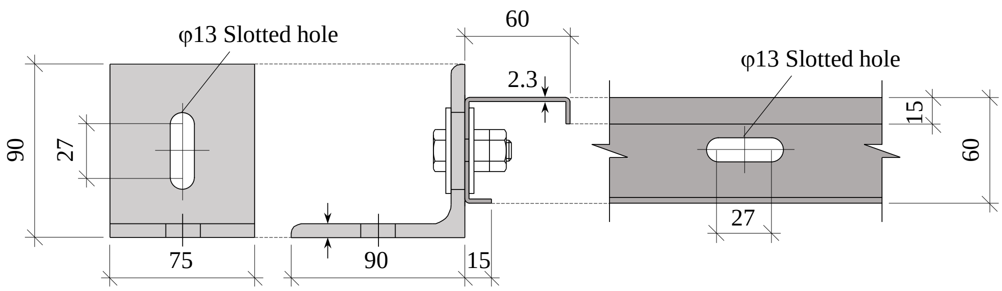


Fig. 5 – Dimensions of steel components

3.2 Setup

The overview of the setup is shown in Fig. 6. First, four fasteners are fixed to a self-balanced type frame jig. Then, two furring strips, which are called the upper-layer-side and the lower-layer-side, are attached horizontally and parallel to the fasteners. One furring strip is bolted to two fasteners. At this time, the bolts are tightened to 20kN, which is about 60% of the yield strength of M12 stainless steel bolt. After attaching the furring strips, the panels are fixed to them with drill screws. The upper-layer-side connection of fasteners is a horizontal roller. In the experiment, the forced displacement is generated by hydraulic jacks connected to the left and right of the rollers via PC steel bars to reproduce the story drift.

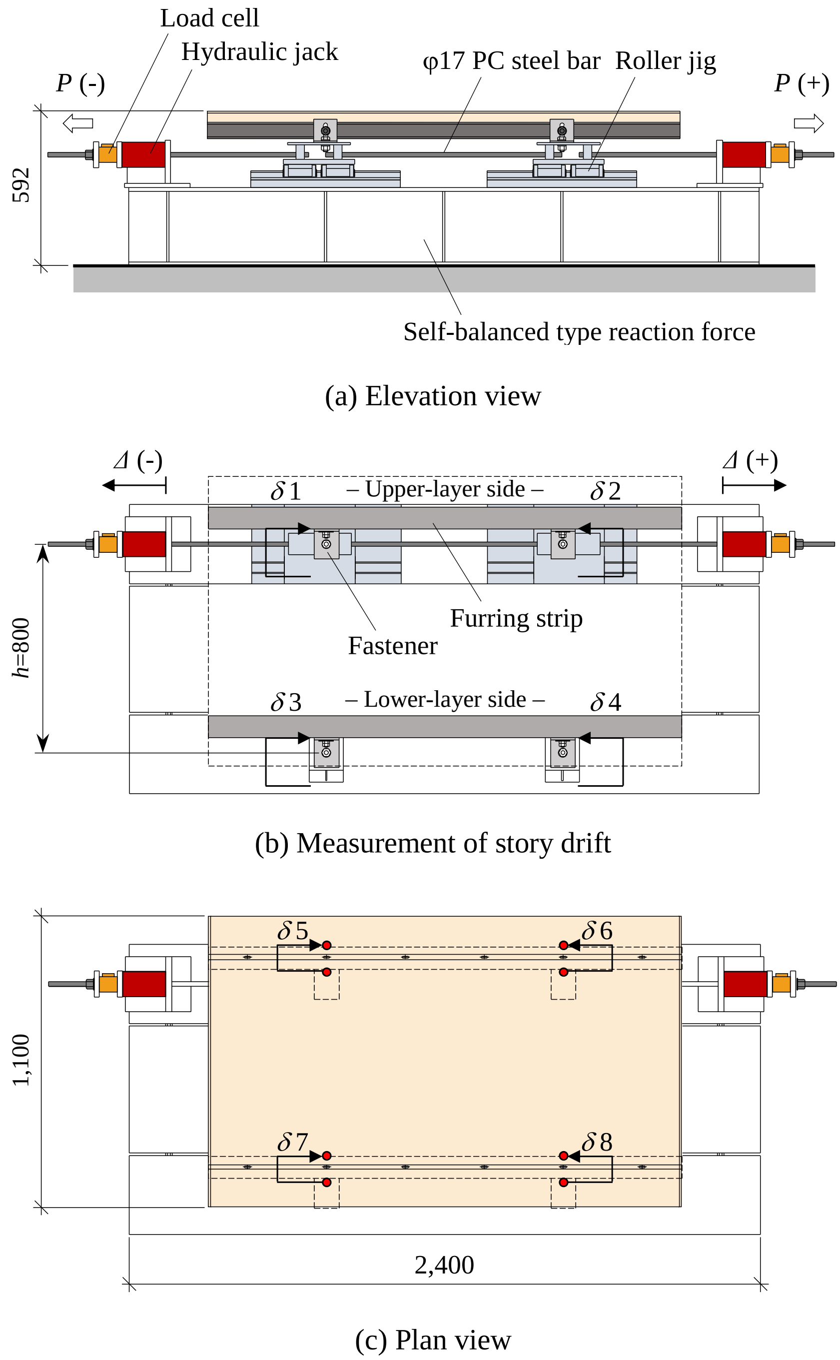


Fig. 6 – Setup

3.3 Measurement plan

Prior to the experiment, the surface roughness of the specimen is measured. In bolted joints on the metal exterior wall, it is known that there is a relationship between the maximum height of roughness (R_z) and the slip coefficient (μ) as shown in Eq. (1)[1].

$$\mu = -1.4 \cdot 10^{-5} R_z^{\,2} + 4.8 \cdot 10^{-3} R_z + 0.131 \tag{1}$$

Using Eq. (1) and surface roughness of this specimen, the slip coefficient can be estimated to be between 0.15 and 0.22 as shown in Fig. 7. Furthermore, slip strength (P_s) can be calculated by the following equation.

$$P_s = \mu \cdot n \cdot m \cdot N_i \tag{2}$$

Where, n: the number of bolt in the stress direction, m: the number of the friction surface, N_i: initial tension of bolt [kN]

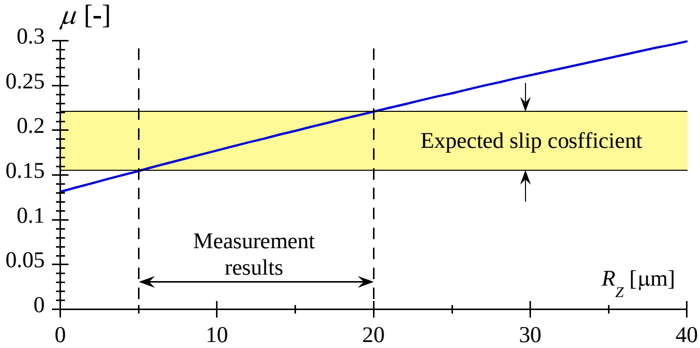


Fig. 7 – Slip coefficient and surface roughness relationship

During the experiment, the in-plane load applied to the metal exterior wall (P) is measured by load cells connected to hydraulic jacks. Story drift (Δ) is the average value of the relative horizontal deformation between the left and right roller jigs and the reaction force jig. In addition, the story drift angle (R) is obtained by dividing Δ by the distance between the upper and lower fasteners (h).

Furthermore, in this experiment, the measurement plan was formed on the assumption that the specimen would follow the story drift due to slippage in the horizontal direction at joints and horizontal deformation caused by a panel rotation. First, the slippage in the horizontal direction at joints is measured as the relative displacement at the bolted joints between the fastener and the furring strip and at the screw joints between the furring strip and the panel. The measurement position is shown in Fig. 6(b) ($\delta 1$~$\delta 4$) and (c) ($\delta 5$~$\delta 8$). Adding the average values of the deformations obtained on the upper-layer side (δ_{bu}, δ_{su}) and the lower-layer side (δ_{bl}, δ_{sl}), slippage at the bolted joint (δ_b) and at the screw joint (δ_s) are obtained. These are divided by the distance between the upper and lower measurement points to convert them into deformation angles, and the sum of them is defined as the misalignment in the horizontal direction at joints (R_j). The deformation angle obtained by subtracting R_j from the story drift angle R is defined as the horizontal deformation caused by a panel rotation (R_r).

3.4 Loading

The loading history in this experiment is shown in Fig. 8. The loading history is a cyclic loading controlled by the amplitude of the story drift angle (R). Until R = 1/100 rad, each cycle (determined according to the performance grade of the curtain wall[2]) is performed for two cycles. Then each amplitude of 1/67 rad, 1/50 rad, and 1/33 rad, which are 1.5 times, 2 times, and 3 times of 1/100 rad, are performed for one cycle in order to confirm the failure condition of the metal exterior wall. Ultimately, the specimen is completely failed by deforming to R = 1/15 rad.

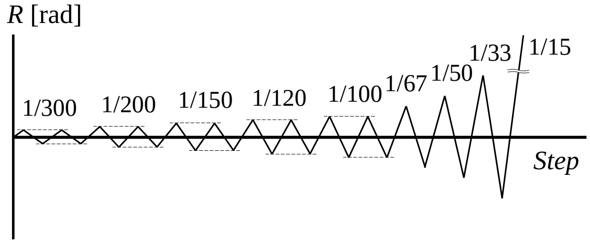
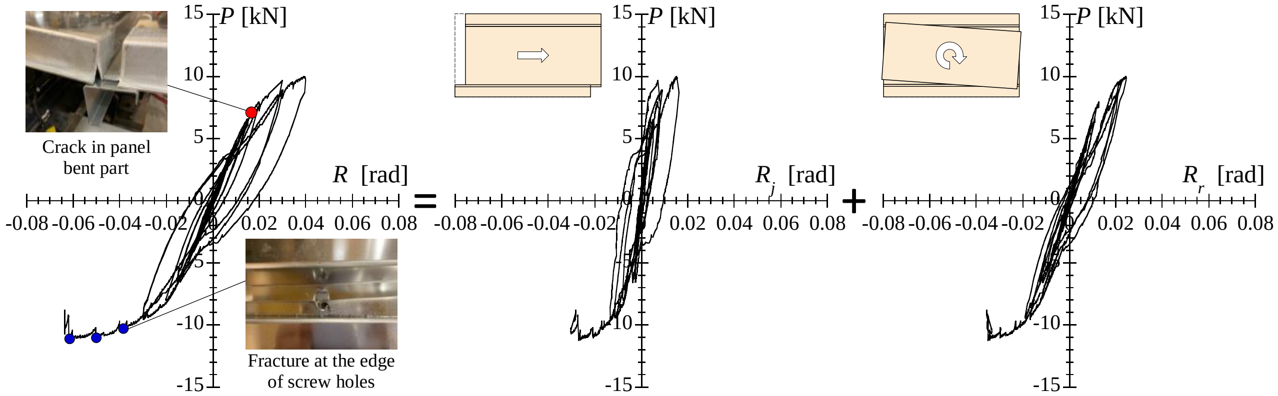


Fig. 8 – Loading history

4. Results and analysis

4.1 Overall behavior

Fig. 9 shows the hysteresis behavior obtained from the experiment. The vertical axis of the figure is the in-plane load applied to the metal exterior wall (P) and the horizontal axis is (a) story drift angle (R), (b) angle of slippage in the horizontal direction at joints (R_j), and (c) angle of horizontal deformation caused by a panel rotation (R_r). Up to story drift angle R = 1/100 rad, there is a roughly linear relationship between the load and story drift angle, indicating that the metal exterior wall almost elastically follows the deformation of the structural frame. On the other hand, when the positive side R = 1/67 rad was loaded, a crack was observed in the bent part of the panel, the stiffness was decreased, and the residual deformation under unloading condition became remarkable. Furthermore, fracture was confirmed at the edge of screw holes at the lower part of the center panel at R = 1/25 rad.

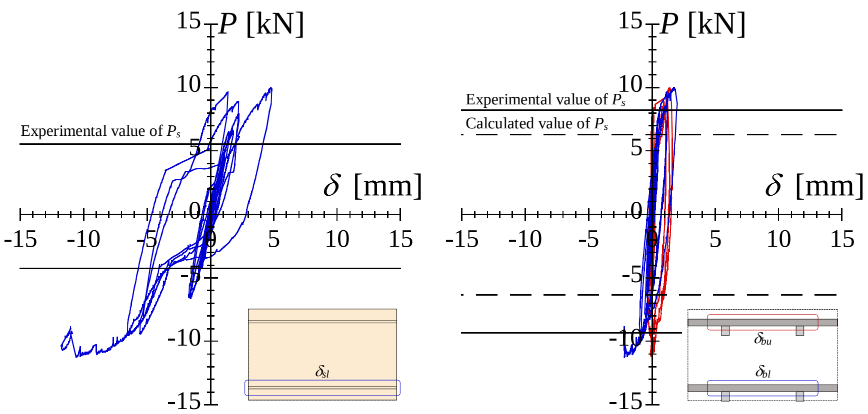


(a) Story drift (b) Slippage at joints (c) Deformation caused by a panel rotation

Fig. 9 – Load-deformation angle relationship

4.2 Slippage in the horizontal direction at joints

The breakdown of the misalignment in the horizontal direction at joints in the overall behavior is discussed in this section. The hysteresis behavior at the screw joint and the bolted joint are shown in Fig. 10. The vertical axis of the figure is the in-plane load (P) and the horizontal axis is the deformation of each joint δ_{sl}, δ_{bu}, and δ_{bl}. At the screw joint, a clear slip behavior is seen at R = 1/50 rad. Meanwhile, at the bolted joint, although the hysteresis curve became slightly nonlinear, and the deformation by about ±1.0 mm was generated, the deformation was smaller than that of the screw joint.



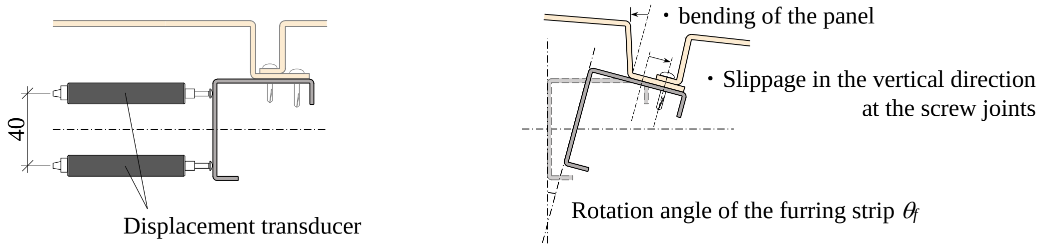
(a) Screw joint (b) Bolted joint

Fig. 10 – Slippage in the horizontal direction at joints (Fig. 9 (b))

Here, it is assumed that most of the initial stiffness of the entire hysteresis curve is due to the stiffness of the furring strip and the fastener. Thus, the evaluation range of the slip strength is defined as the point at which the 0.2 mm offset straight line of the initial stiffness intersects with the hysteresis curve[3]. The calculated values of slip strength are shown by broken lines and the experimental values are shown by solid lines in Fig. 10. From the figure, it can be seen that the deformation did not progress even when the load reached the calculated value of the slip strength. When the slip strength of the screw joint is calculated using the same method, the calculated value of the slip strength is about 4.2kN. Then, by assuming the same slip coefficient as the bolted joint, the initial tension of the drill screw can be calculated which is about 3.4kN. Therefore, it can be concluded that by controlling the tension of the bolted joint during the setup (the bolts are tightened to about 60% of its yield strength in this experiment), it is possible to suppress the deformation of the bolted joint and to force the slip of the screw joint to advance.

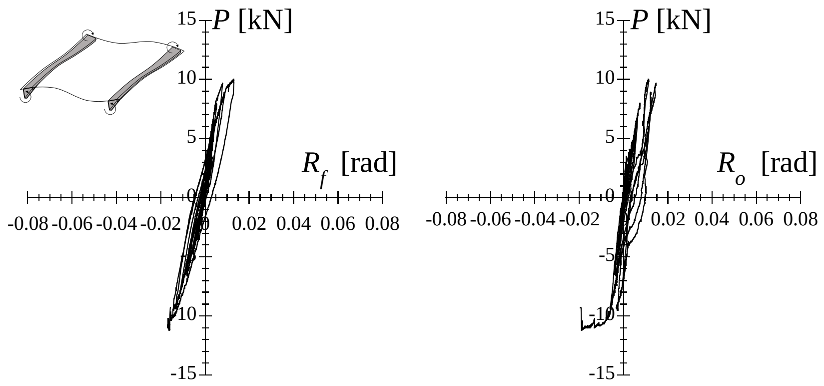
4.3 Horizontal deformation caused by a panel rotation

In this section, the breakdown of the horizontal deformation caused by a panel rotation is described. With the deformation of the structural frame, torsion around the material axis of the furring strip occurs. From the rotation angle of the furring strip (θ_f) obtained by the measurement method shown in Fig. 11, the deformation of the furring strip in the upper and lower direction of the panel can be calculated. The value obtained by dividing this deformation by the distance between the measurement points is defined as the deformation angle due to the torsion of the furring strip (R_f). In addition, the deformation angle obtained by subtracting R_f from the horizontal deformation angle caused by a panel rotation (R_r) is defined as the other deformation angle (R_o). This includes the deformation incidental to the torsion of the furring strip, such as bending of the panel and misalignment in the vertical direction at the screw joints. The respective hysteresis curves are shown in Fig. 12. The vertical axis of the figure is the in-plane load (P) and the horizontal axis is the respective deformation angle R_f and R_o. The deformation due to the torsion of the furring strip is almost elastic. On the other hand, it can be seen that the history of other deformation shows an increase in deformation and a decrease in load due to the fracture at the screw joint.



(a) Measurement points (b) Other deformation incidental to torsion of the furring strip

Fig. 11 – Measurement of torsion of the furring strip



(a) Deformation due to the torsion of the furring strip (b) Other deformation

Fig. 12 – Horizontal deformation caused by panel rotation

4.4 Percentage of each deformation

The deformations described in previous sections are shown in Fig. 13 in percentage at every story drift angle. The vertical axis of the figure is the ratio of each deformation to the overall deformation, and the horizontal axis is the story drift angle (*R*). The deformations are (i) slippage at the bolted joint, (ii) slippage at the screw joint, (iii) deformation due to the torsion of the furring strip, and (iv) other deformations incidental to the torsion of the furring strip. Where, (i) and (ii) are classified into slippage in the horizontal direction at joints, and (iii) and (iv) are classified into horizontal deformation caused by a panel rotation. Similarly, Fig. 14 shows the transition of residual deformation for each story drift angle. The story drift angle at the unloading of the first cycle of each loading amplitude is plotted on the vertical axis. In addition, the ratio of each deformation to the residual deformation angle is shown using the bar graph.

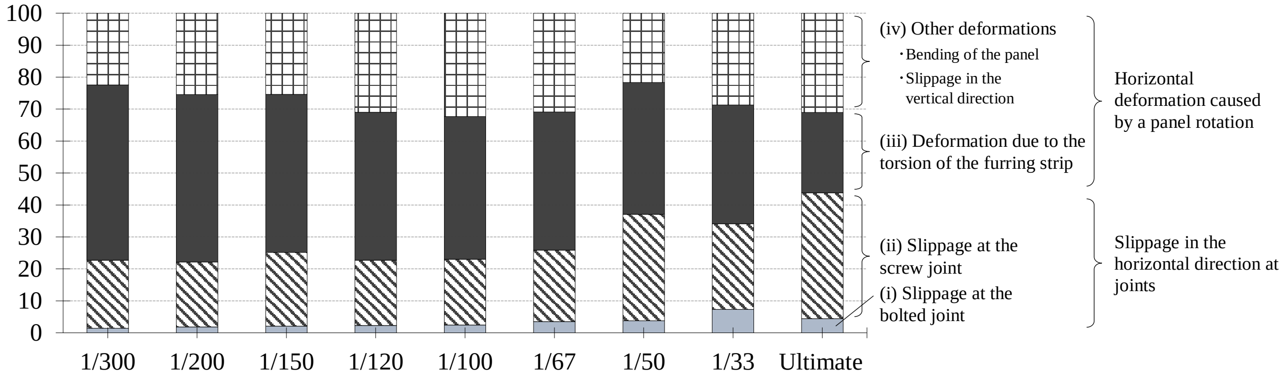


Fig. 13 – Percentage of each deformation at every story drift angle

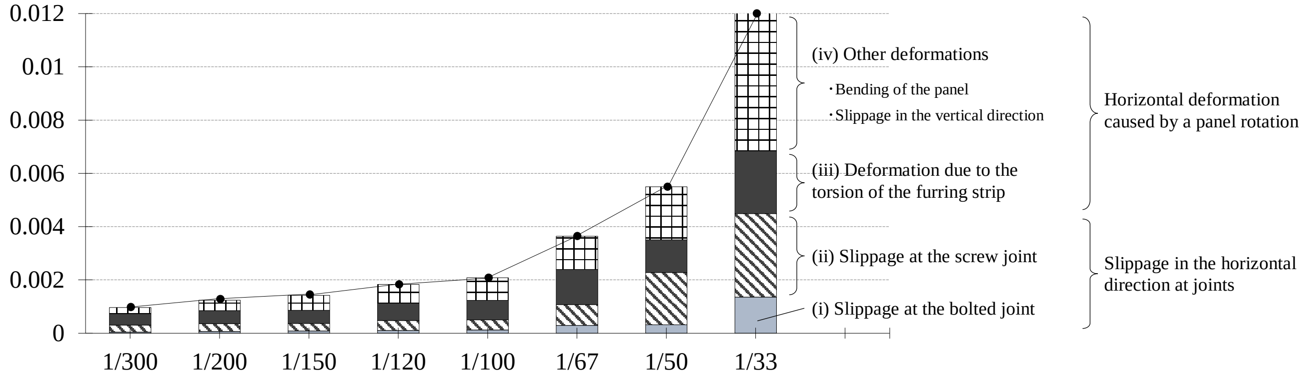


Fig. 14 – Residual deformation and its breakdown

Up to *R* = 1/100 rad, the residual deformation angle is as small as 1/500 rad at most, and the specimen is almost in the elastic range. Until then, the ratio of the slippage at the bolted joint to the total deformation was extremely small. Slippage at the screw joint accounts for 30% and deformation due to the torsion of the furring strip accounts for nearly 60%. It can be seen that the deformation due to the torsion of the furring strip plays a major role as the deformation mechanism of the metal exterior wall.

The percentage of deformation at the bolted joint and screw joint have increased since *R* = 1/67 rad, where the panel cracked. On the other hand, the percentage of deformation due to the torsion of the furring strip, which had maintained the elastic state, decreased and eventually dropped to less than 20%. This is because the damage to the screw joint determines the strength and ultimate state of the metal exterior wall, and eventually, the damage to the screw joint progresses to follow the story drift.

5. Conclusion

In this study, a cyclic-loading test of the metal exterior wall was conducted. The obtained findings are shown below.

1) The deformation mechanism of the metal exterior wall is mainly realized by (i) slippage at the bolted joint, (ii) slippage at the screw joint, (iii) deformation due to torsion of the furring strip, and (iv) other deformations incidental to the torsion of the furring strip.

2) In the elastic region of the metal exterior wall, by controlling the tension of the bolted joint, the deformation mechanism of the metal exterior wall can be controlled to slippage at the screw joint accounts for 30% and deformation due to the torsion of the furring strip accounts for nearly 60% of the total deformation.

3) The strength and ultimate state of the metal exterior wall are determined by the damage to the screw joint.

6. Acknowledgements

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7. References

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