Study on characteristics for steel suspended ceiling with multiple slopes

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Abstract

Ceilings usually used in Japan are made by the construction methods where interior materials such as plaster boards and lightweight steel furring are joined, which are hanged by bolts. Until recently, the method of earthquake resistance of the ceiling had not been promoted. Therefore, when the large earthquakes occurred, many ceilings fell down. Some researchers argue that ceilings should be reinforced by bracings. According to other studies, ceilings with slopes should be separated at slope-changing-parts to avoid excessive stress concentration. On the other hand, ceilings with slopes are adopted in some buildings such as a music hall, and separation in a ceiling surface may be undesirable to prevent sound leakage. Many studies on seismic resistance of ceilings are conducted for flat ceilings, but motion of ceilings formed by multiple slopes has not been detected enough. For example, it is not clear whether the reinforcement method of ceilings with plural slopes is the same as that of ceilings without slope. In addition, we should confirm whether the separation is always required when displacement of the ceilings is sufficiently reinforced by the bracings.

In this paper, we report the loading tests on steel suspended ceilings with two slopes. The size of specimens of suspended ceiling is about 3 m × 1.6 m in horizontal projection. Each specimen is made by the method similar to that of the flat ceiling. Steel furring is joined with screws at slope-changing-part at the center of the ceiling. There are bracings to transmit inertia force of the ceiling surface to a hanging root. A test of the ceiling reinforced in the vertical direction was also carried out. From the results of the tests, we confirm the seismic resistance of the sloped ceilings and discuss whether vertical reinforcement is necessary.

Keywords: Ceiling with steel furring, Seismic resistance, Slopes, Reinforcement

1. Introduction

In the past, people were injured by falling off of non-structural components such as ceilings, and the facilities became in dysfunction through the large earthquakes (for example, reported by NILIM et al., 2016). Through such teachings of the earthquakes, we refer to a suspended ceiling over a certain size as a “specific ceiling” in Ministry of Land, Infrastructure, Transport and Tourism (MLIT) Notification No. 771 (MLIT, 2013). The “*Tokutei tenjou* (specific ceiling)” is defined to avoid the risk of causing enormous person injuries due to fallout — such as of a ceiling covered with large area, hanged on a high position of a room, and composed of heavy materials.

Specific ceilings are classified roughly as "with clearance" or "without clearance" according to the earthquake resistance method (NILIM et al., 2013 and NILIM et al., 2016). In the case of "with clearance", contact between ceilings and surrounding walls is prevented. Inertial force of the ceiling surface is transmitted to a frame by seismic elements such as a brace. In the case of "without clearance", ceilings and surrounding walls are brought into direct contact with each other to directly transmit the inertial force of the ceiling surface, while the brace should not be installed in order to follow the inter-story deformation of the frame. We focus on the type “with clearance” in this paper.

According to the Notification No. 771, when there are steps or gradient changes of the ceiling (hereinafter referred to as "slope-changing-part"), we should especially pay attention to excessive stress concentration to the slope-changing-part, which may cause damage to the ceiling. So that separation at the slope-changing-part has been recommended in the commentary (NILIM et al., 2013). On the other hand, integration of the ceiling surfaces may be required to avoid sound leakage. Yamashita et al. reported that, in some cases, seismic-resistant ceiling with a step can be regarded as having a certain seismic resistance if deformation followability of an integrated ceiling is confirmed to be within an allowable range by experiments (Yamashita et al, 2017).

There is another demand for integration. Among the ceilings corresponding to specific ceilings, some ceilings whose surfaces are sloped for acoustic design, such as a hall. As shown in Photo 1, a part of ceiling of the hall is fallen by recent earthquakes, so we need to take countermeasures. However, technical considerations behind the standards are provided mostly based on a horizontal ceiling, and it is not clear whether the similar earthquake resistance method is also applicable to a suspended ceiling with slope.

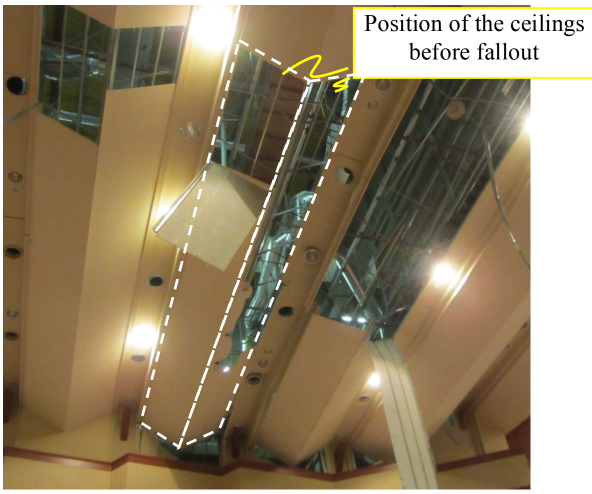


Photo 1: Earthquake damage on the ceiling of a hall with multiple slopes. (NILIM, et al. 2016)

In this paper, in order to clarify the scope of the standards, we report experimental investigation targeted at the suspended ceiling with slope. When earthquake resistance is provided for suspended ceilings with slope, the items to consider are as follows; 1. We confirm a method to integrate it at a slope-changing-part; and 2. When integration is possible, we consider how to transmit inertial force of the ceiling surface.

2. Bending Test of Slope-changing-part of Ceiling

For the item 1, a static monotonic bending test is performed with a specimen from which the slope-changing-part of the ceiling is extracted. And then, out-of-plane bending performance in the slope-changing-part is obtained by calculation.

2.1 Overview

Fig. 1 shows one of the specimens. The specimen is composed of plaster boards and steel furring in accordance with Japanese Industrial Standards (JIS A 6517; 2010), and the specimen is based on a case of a flat ceiling in the past research (Ishihara et al., 2015). At the center of the specimen, the edges of a steel furring and the ceiling surface were cut off once, and C-bars of both edges were fastened with screws. For the specimens Nos. 1, 2, 4 and 5, the number of screws per joint of the slope-changing-part is 2, for the number of screws for Nos. 3 and 6 is 4. The joining angle (the degree of slope-changing-part at the center) is 0° for the specimens Nos. 1 to 3, and ±20° for the specimens Nos. 4 to 6. For the specimens Nos. 1, 3, 4, and 6, steel furring is loaded with facing upward (force is applied in the positive direction), and for Nos. 2 and 5, the ceiling surfaces are loaded with facing upward (force is applied in the negative direction). The tests are conducted for 6 specimens in total. In the test, a steel frame for force application (about 0.29 kN) shown in Fig. 1 was placed on the top of the specimen, and a steel frame was pressed vertically downward by a jack.

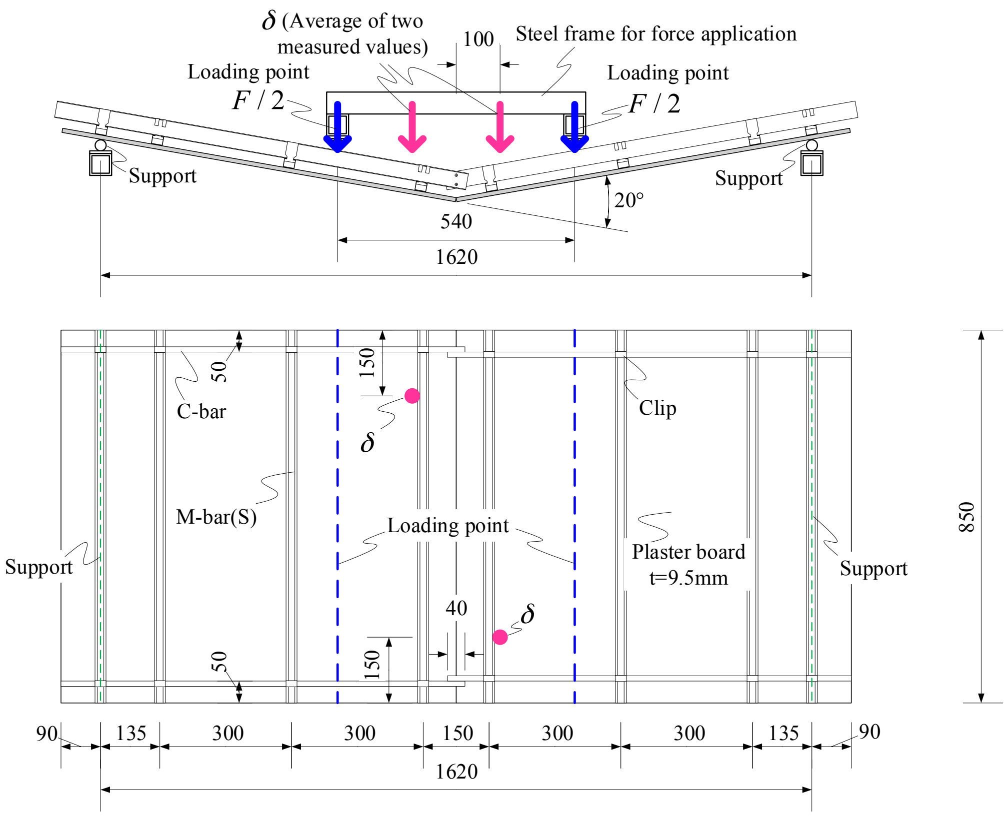


Fig. 1: Specimen, Measurement position. (No. 4).

2.2 Results

Table 1 shows the test results, Fig. 2 shows force-displacement (F-δ) relationship, and Photos 1 to 3 show representative damage conditions. Column "a" in Table 1 indicates F/δ connecting zero-point and the measured value when a steel frame for force application is loaded, the boldfaces in column "b" mean the maximum load, and the italics mean loading with displacement of 50 mm. Table 1 also indicates the results of C1rJJ-P-bj (Ishihara et al., 2015). In Fig. 2, the applied load F is taken as a vertical axis, and the average value δ of the measured vertical displacement is a horizontal axis. As shown in Photo 1, damages were concentrated only at the joint on specimens Nos. 1 and 2 composed of 2 screws. And as shown in Fig. 2, the F-δ relationship of these specimens is lower in strength and stiffness than those of C1rJJ-P-bj in which the C-bar is continuous (Ishihara et al., 2015). In comparison of No. 1 with No. 2, no influence due to difference in applied direction was observed. On the other hand, in specimen No. 3 in which the number of screws at the joint was increased to 4, damage at the joint was suppressed, but a clip near the slope-changing-part opened and the C-bar collapsed (Photo 2). The clip eventually went off (Photo 3). No influence of the difference in the applied force directions was observed in this test. The strength of No. 3 is larger than that of No. 1 and the stiffness of No. 3 is close to the result of C1rJJ-P-bj. For specimens Nos. 4 to 6 with a joining angle of ±20°, the damage type of Nos. 4 and 5 is similar to that of Nos. 1 and 2, and the damage type of No. 3 is similar to that of No. 6, respectively.

Table 1: Test results. Rotation spring stiffness.

No.	Number of screws	Angle of gradient changing part	Loading direction	a	b	c
				F^{ex}/δ (F^{ex}:F per 1m width) kN/m/m	**Maximum strength of F^{ex} (bold)** *strength F^{ex} when δ=50mm (italic)* kN/m	Stiffness of rotation spring k_c kN・m/rad/m
1	2	0°	positive	40.77	*0.55*	0.58
2	2		negative	47.42	*0.72*	0.68
3	4		positive	55.06	**1.35**	0.79
4	2	+20°	positive	15.05	*0.46*	0.21
5	2	-20°	positive	12.47	*0.47*	0.17
6	4	+20°	positive	69.38	**1.35**	1.02
	C1rJJ-P-bj (Reference: Ishihara, 2015)			56.29	**1.11**	0.81

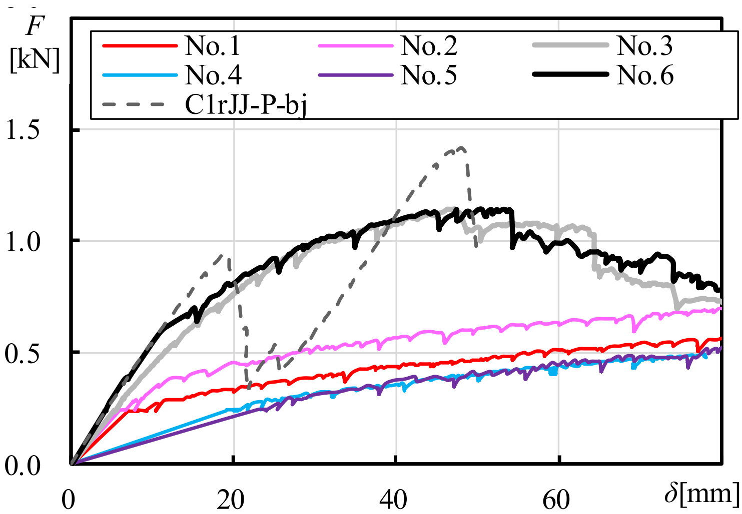


Fig. 2: F-δ relationship.

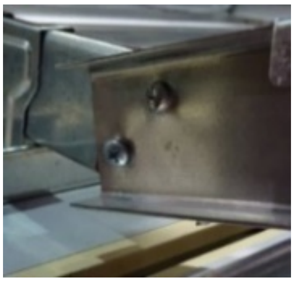


Photo 2: Damage at the joint. (No. 4)

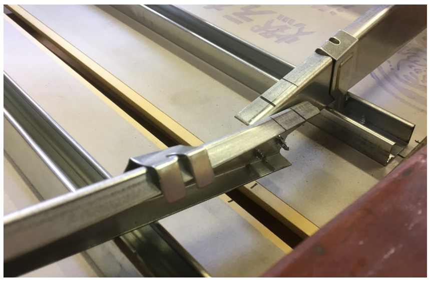


Photo 3: Lateral deformation of C-bar. (No. 6)

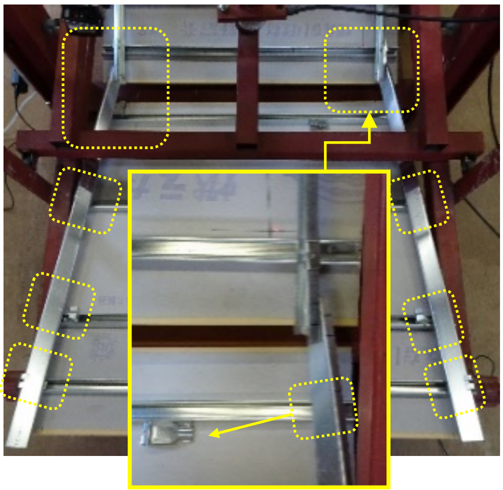


Photo 4: Clip finally disengages. (No. 6)

2.3 Bending stiffness of slope-changing-part

From the experimental results, out-of-plane bending stiffness of a ceiling surface is calculated. As shown in Fig. 3, the ceiling surface is an elastic rod, and the slope-changing-part is a rotation spring. The ceiling has a uniform cross section in x direction, and the formulation is performed as a half model considering symmetry. The load $F/2$ is added at the position of $x = \alpha_F L$ and the displacement δ is measured at $x = \alpha_\delta L$, where α_F, α_δ are $0 < \alpha_F < \alpha_\delta < 1/2$. By rearranging the equation of deflection of the elastic rod, the following equation (1) is obtained:

$$\delta = \frac{F\alpha_F L}{48EI} L^2 \left[3 - 4\alpha_F{}^2 - 12\alpha_\delta{}^2\right] + \frac{\theta_c}{2}\left(\frac{1}{2} - \alpha_\delta\right) L \qquad (1)$$

where θ_c is a rotation angle of the rotation spring with respect to the total length, L. When the bending moment of the central rotation spring is expressed as $M = \alpha_F LF/2 \equiv k_c\theta_c$, the rotation spring stiffness k_c of the joint is expressed by the following equation:

$$k_c = \left(\frac{1}{2} - \alpha_\delta\right) \Big/ \left\{\frac{4}{\alpha_F L^2 (F/\delta)} - \frac{3 - 4\alpha_F{}^2 - 12\alpha_\delta{}^2}{12EI/L}\right\} \qquad (2)$$

where EI is the equivalent bending stiffness of the ceiling surface from the result of the C1JJ-P

(Ishihara et al., 2015). The results obtained by substituting $L = 1620\text{mm}$, $\alpha_F = 1/3$, $\alpha_\delta = 710/1620$, and each value of F/δ in Table 1a are shown in column "c" in Table 1. From the results, k_c in the case of 2 screws is 0.17 to 0.68 kN·m/rad/m, and k_c in the case of 4 screws is 0.79 to 1.02 kN·m/rad/m. For reference, C-bar is continuous, and the rotational spring stiffness of C1rJJ-P-bj (the C-bar is continuous, but the ceiling surface is separated at the center) is calculated to be 0.81 kN·m/rad/m. Therefore, by joining with 4 screws, it can be confirmed that it has the same out-of-plane bending stiffness as when the C-bar is continuous.

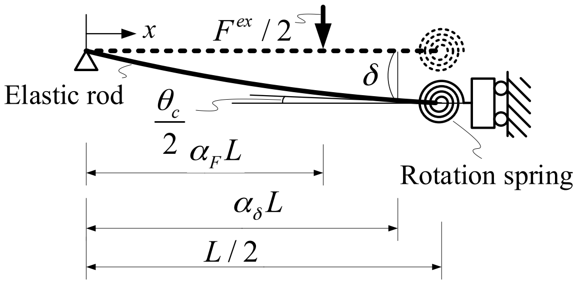


Fig. 3: Modeling for slope-changing-part and ceiling surface (half of the specimen).

3. Horizontal Loading Test of a Suspended Ceiling Integrated with a Slope-changing-part

3.1 Overview

Photo 4 shows the setup of the experiment, and Fig. 4 shows an elevation and a plan view of the specimen. The horizontal projected dimension of the ceiling surface is about 3 m × 1.6 m. The specimen is bent at the center, and the left side is bent at an angle of +30° from the center of the specimen, and the right side is -30° (as shown in Fig. 4). With reference to the discussion in Chapter 2, an intersection of the 2 slopes has 2 joints of C-bar with 4 screws. Four pairs of braces are installed at the positions shown in Fig. 4. The specimen repeatedly applies positive and negative incremental repetitive loads every 5 mm up to about ±15 mm in the direction of arrows in Fig. 4 and then perform positive direction monotonic load until the damaged state becomes clear. The measurement position of the horizontal displacement is point A in Fig 4.

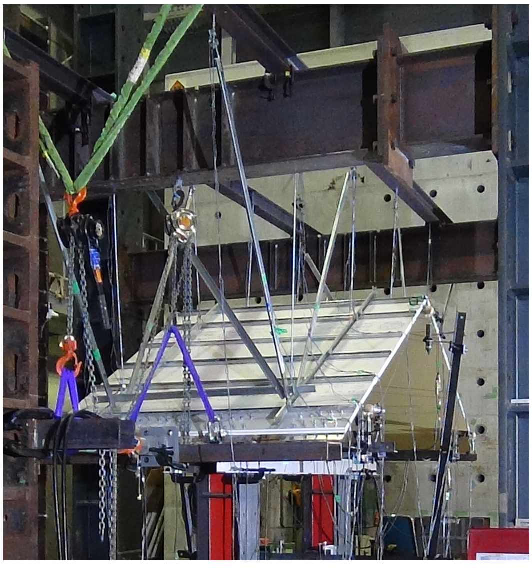
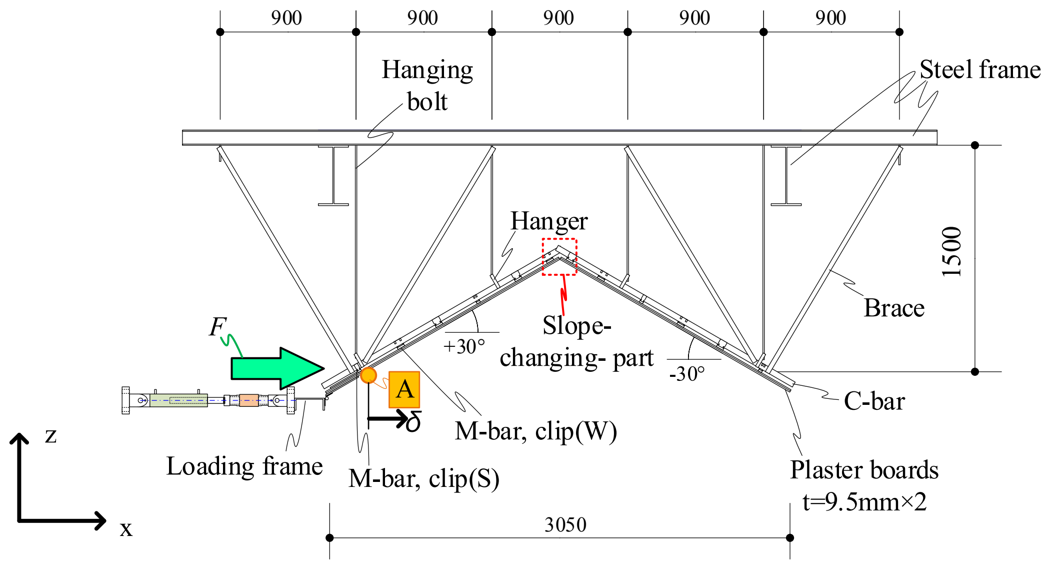
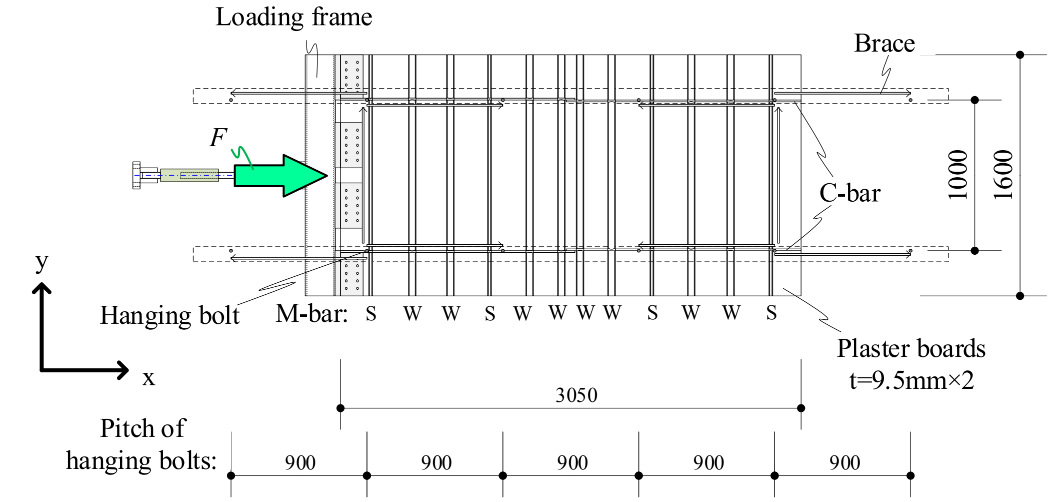


Photo 5: Setup of specimen.



(a) Elevation



(b) Flat plan

Fig. 4: Test specimen of suspended ceiling with slopes.

3.2 Test results and discussion

Fig. 5 shows the load displacement relationship, and Photos 5 to 8 show the main damage status. The vertical axis in Fig. 5 indicates the value F obtained by dividing the load value measured at the applied point by the specimen width 1.6 m, and the horizontal axis indicates the horizontal displacement δ measured at point A. The maximum strength at the time of reaching ±15 mm at repetitive loading is 1.06 kN/m in the positive direction and 0.80 kN/m in the negative direction.

The progress of the experiment is described as follows. After the loading of about -5 mm, there was a misalignment in the clip supporting the ceiling surface which is inclined at +30° close to the applied position during all loading (Photo 5). The clip was joined only by friction with the C-bar in the force direction, so it seems that it was slipping with a small force. When a deviation occurred in the positive direction loading, no decrease in F was observed. On the other hand, at the time of the negative direction loading, F decreased after the deviation occurred, and the deformation proceeded. This phenomenon occurred on at the left side of the ceiling surface, but such a phenomenon was little seen at the right side of the ceiling surface. After that, when the deformation reached about 10 mm, a clearance was observed at the slope-changing-part of the ceiling surface (Photo 6). It means that only a ceiling surface at the left side slipped. During being damaged, no damage was observed at the slope-changing-parts of C-bar. A clip in the vicinity of the applied point opened when loading in the positive direction. Afterwards, due to loading in the negative direction, the opened clip slipped loosely on the C-bar.

After repetition of this damage during repetitive loading, the clip in the vicinity of the applied point disengaged during monotonic loading until the end (Photo 7), bending occurred outside the ceiling surface. When monotonic loading is continuous after that, displacement of the clips of the ceiling surface progressed on the applied point side. Although *F* does not increase while the clip is sliding, when the displacement of the ceiling surface became large, the ceiling surface on the load applied side (left side) climbed the ceiling on the right side (Photo 8), and *F* increased as shown in Fig. 5.

In this study, as with a general flat ceiling, it is thought that a slipping occurred because clips are not fixed with the C-bar, and hangers are not fixed, either. Therefore, when a ceiling with slope is reinforced so that they do not shift, inertial force of the ceiling surface is considered to be transmitted to the frame through the brace. Consideration of the reinforcement method based on the above is a future subject.

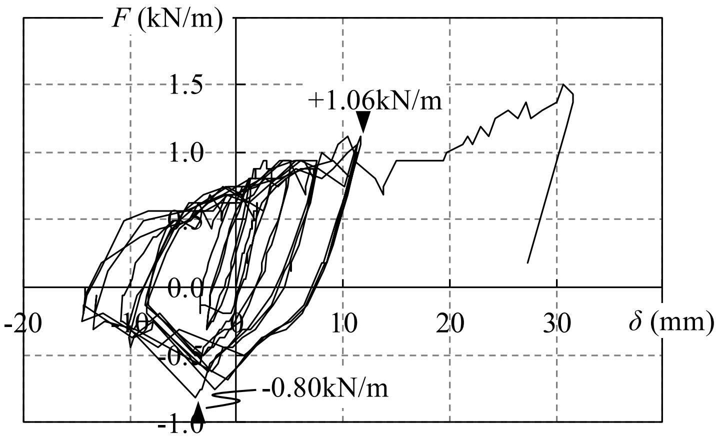


Fig. 5: F (per meter width)-δ relationship.

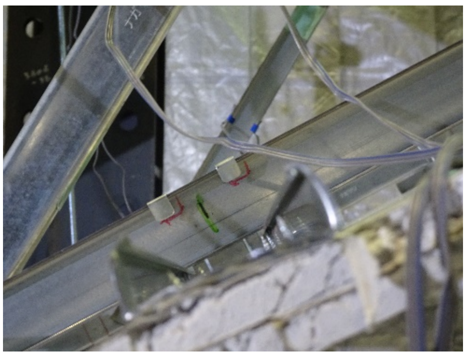


Photo 6: State of δ = -5 mm. The clip was slipped.

Photo 7: State of δ = -5 mm. Gap occurs at slope-changing-part.

Photo 8: Final state. Clip disengages.

Photo 9: Final state. Contact of ceiling surface to steel furring.

4. Conclusion

In this paper, we introduce two studies on mechanical performance of a suspended ceilings with slope, which has fewer studies than flat suspended ceilings. The first study is to confirm the out-of-plane bending characteristic of a slope-changing-part of the ceiling. It is shown that damage can be suppressed by making the number and spacing of screws proper by the bending stiffness of the slope-changing-part obtained from the experimental results. The second study is the horizontal loading test conducted to obtain the points to be noted on the seismic-resistant design of the suspended ceiling with slope integrated at the slope-changing-part. Displacement, detachment, etc. of the clip which is a joining hardware occurred as a damage process. We plan to examine a method of earthquake resistance of a suspended ceiling with slope.

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