EFFECT OF IN-PLANE SHEAR STIFFNESS ON DYNAMIC CHARACTERISTICS OF FULL-SCALE CEILING SYSTEM

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Abstract

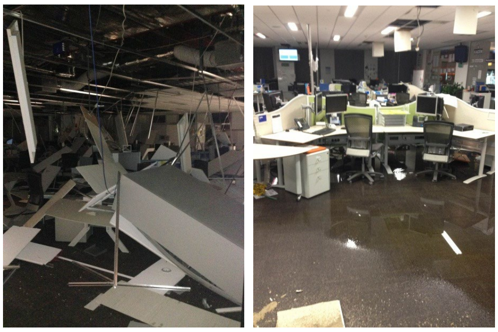
Due to its simplicity of construction and easy installation process of facility equipment, the JPN-US ceiling (ceiling system developed in the United States and customized to Japanese style) is being widely used in office buildings in Japan. However, JPN-US ceilings still have many unclear points about its seismic performance and been excluded from the specified ceiling seismic design until now. In the previous study, the investigation of the in-plane shear deformation of the JPN-US ceiling, and simulate the damage of ceiling falls have been studied using a shaking table test. Based on the test result, in-plane shear stiffness and shear force of the ceiling have been figured. The force transmission and damage occurrence have also been clarified. The equivalent brace model for the numerical analysis of the JPN-US ceiling was proposed and validated with the results of the shaking table test. However, there are still some problems remain. In Japan, one of the methods to reinforce the ceiling system is to install the braces. Since gypsum boards are not fixed with the tees, in-plane shear stiffness will be much smaller than the conventional Japanese-Style ceilings, in which the gypsum board is attached to the steel members by screws. Therefore, braces should be carefully arranged to make it function efficiently. According to the current idea of the Rock Wool Association Japan, placing braces for every main tee is recommended, but as far as the authors know, there is no mechanical study has been conducted whether this arrangement is insufficient or excessive.

The purpose of this paper is to confirm the influence of brace arrangement on the seismic performance of a full-scale JPN-US ceiling by using the shaking table test. The 12.8m×11.6m frame is supporting the ceiling specimen. Two types of 4.8m×12m ceiling specimens, which density of braces and eccentricity at the installation position of braces considered as parameters, are installed on the frame, with a clearance (>200mm) is designed around the perimeter of ceiling surface, so as not to interfere with surrounding elements even after vibration. Two shaking tables of 35ton-4m×6m owned by Tongji University are used subjected to uni-/bi-directional horizontal excitation. As an example of the test results, it is confirmed that when input acceleration is small, the relative displacement of the ceiling surface is also small since the ceiling panels are stuck with tee bar by friction, and rigidly moving together. Yet, when the greater acceleration is input, the panels start to move linearly, causing the ceiling surface becomes bumpy due to the effect of braces pitch. The displacement distribution of the ceiling surface obtained from the experimental study corresponds with numerical modal analysis. Finally, the influence of density of braces and eccentricity at the installation position of braces of full-scale ceiling system on the seismic performance of ceilings are clarified.

Keywords: JPN-US suspended ceiling; In-plane shear stiffness; Numerical analysis model; Shaking table test

1. Introduction

In recent years, non-structural members have been frequently damaged by earthquakes due to large earthquakes. There have been many reports of damage from the ceiling caused by the earthquake in Japan and abroad. **Photo 1** shows an example of damage to the ceiling in previous earthquakes **[1], [2]**. In addition to the danger of human injury, the collapse of the ceiling has a significant social impact from the perspective of business continuity, including the loss of indoor functionality and the time required for restoration. Therefore, it is an urgent task to secure the safety and function of the room for post-earthquake. The JPN-US ceiling (ceiling system developed in the United States and customized to Japanese style) recently also widely used in Japan, as shown in **Fig.1**, especially for high-rise buildings due to its simplicity of construction and easy installation process of facility equipment.



(a) Wellington earthquake in 2013
(courtesy of Dhakal et al., 2016)

(b) Kumamoto earthquake in 2016
(courtesy of Prof. Mizutani, Tokyo Polytechnic University)

Photo 1 Damages of the ceiling system in previous earthquakes

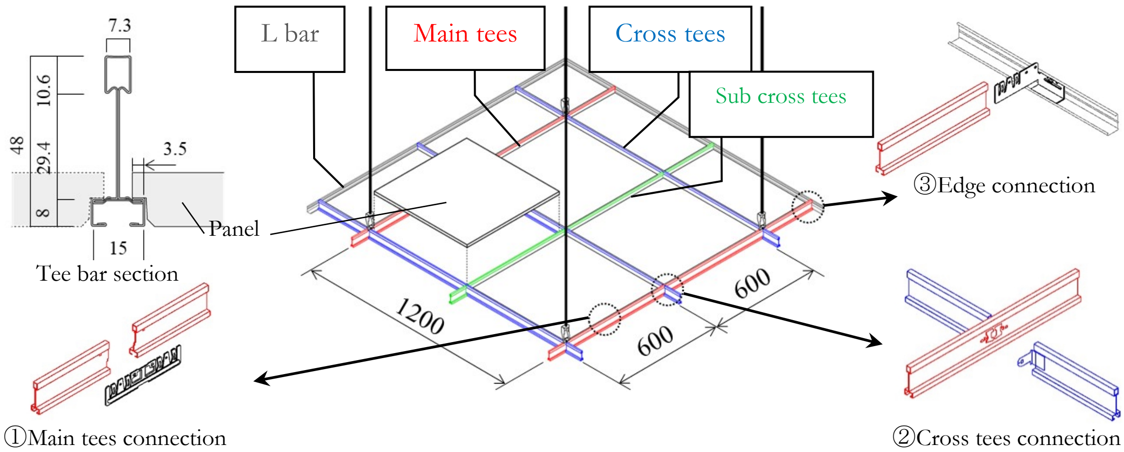


Fig. 1 Component configuration of the JPN-US ceiling

In Japan, according to MLIT Notification No.771 **[3]**, a suspended ceiling that containing over area 200m², and ceiling surface exceeds the height of 6m with mass per unit area is more than 2kg, is considered as Specified Ceiling. Its seismic design should be taken following the technical standards set by MLIT. However, this notification is applicable only for the conventional Japanese style ceiling system. JPN-US suspended ceiling has not yet been targeted in this notification due to its uncleared failure mechanisms and dynamic characteristics, mainly due to its non-rigid ceiling system which in-plane shear stiffness is smaller than the rigidity of the conventional Japanese ceiling, in which the gypsum board is attached to the steel members by screws. Thus, the seismic design method of the JPN-US suspended ceiling has not been established at present in Japan.

Also, the notification states a method of installing a brace for lateral restraints, including clearance around the ceiling perimeter, is adopted as a seismic design method for a system ceiling. This is the main difference between the ceiling of this study and the typical US-style suspended ceiling system, which has been the subject of past experimental studies outside Japan. Suspended ceiling systems in the US or NZ **[4]** uses steel stud or compression posts, sway wire braces for lateral restraints with no clearance around ceiling perimeter instead of suspension bolt, C channel braces with clearance. The in-plane shear stiffness has a significant effect during vibration in this study.

According to the current idea of the Rock Wool Association Japan **[5]**, placing braces for every main tee is recommended, but no research has been conducted to verify the properness of this arrangement from a mechanical point of view. Naturally, for the braces to function efficiently, the layout should be planned with an understanding of the characteristics of the entire ceiling system. Previous studies on system ceilings include static loading tests **[1][6]**, shaking table tests, and numerical analysis models **[7]**, all of which have been obtained for experiments using small specimens. Yet, it is unclear whether the results indicate the characteristics of full-scale ceilings. Since the ceiling system having a larger ceiling area is more vulnerable than a smaller area system **[8]**.

Therefore, the purpose of this study is to verify the validity of the previous experimental results and to clarify the mechanical characteristics of the system ceiling by using shaking table test with the full-scale ceiling specimen, as well as to reduce the functional degradation of the room by suppressing damage during earthquakes.

2. Shaking Table Test with the Large Test Specimen

2.1 Outline of the Experiment

This experiment is designed to confirm the effect of brace arrangement on the seismic performance of the ceiling system, in particular, focus on the influence of eccentricity of the brace mounting position, and the evaluation of the ceiling-in-plane shear stiffness shown in the past studies **[7]**. Testing was conducted by using two of the 4m x 6m bi-axial shaking table at Earthquake Engineering Hall of Tongji University in Shanghai, China (**Photo 2**). The frame supporting the ceiling specimen and the outline of the specimen is shown in **Fig.2**. The test specimens have two ceilings of the same size, which plane dimensions are 4.8m ×12m (160 ceiling panels of 600mm x 600mm). To observe a completely stable state of the ceiling system, a clearance around 200mm is provided around the ceiling surface so that it does not interfere with the steel beam for measurement even after vibration.

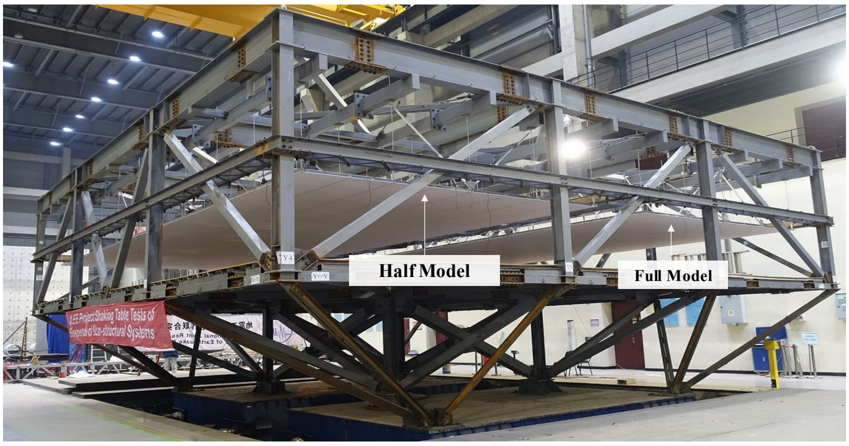


Photo 2 Overall view of the test specimen and supporting frame

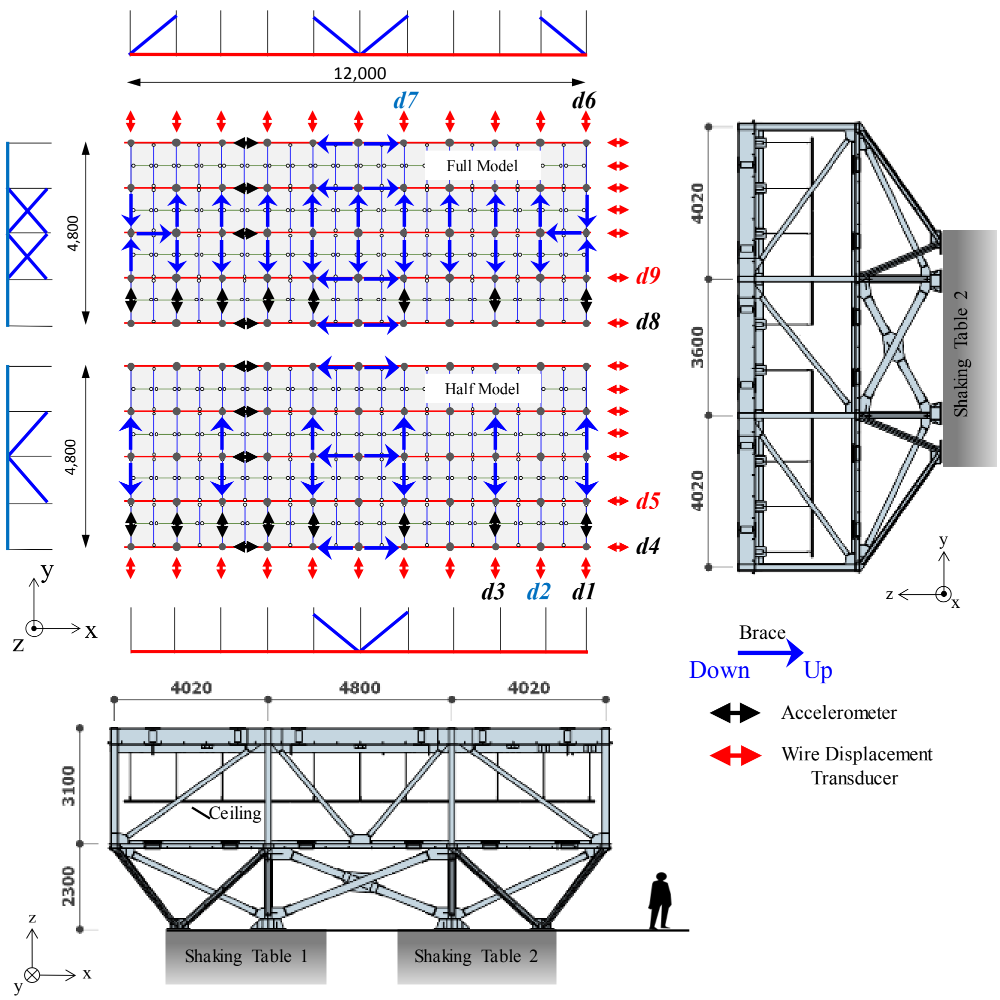


Fig. 2 Shaking Table Test Outline

The suspension length is 1200 mm, and ϕ9, ϕ7 suspension bolts are arranged at 1200mm intervals. The ceiling panel uses a rock wool sound-absorbing board consisting of two 12mm-thick panels. The reason for the two is that the weight per the averaged unit area in the actual system ceiling (include the weight of MEP equipment) is also taken into account, which makes inertial force at the time of massive earthquake is also increased. However, in this study, the ceiling panel greatly affects the in-plane shear stiffness of the ceiling surface, in the actual experiment, the additional panel has details that do not interfere with the T-bar (see **Fig.3**). The differences between the two specimens are the number of braces and the amount of eccentricity from the position where the suspension bolts of the brace are installed to the suspension base (**see Fig. 2, 4**).

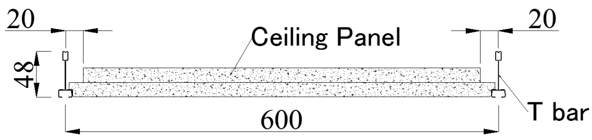


Fig.3 Sectional view of the panel

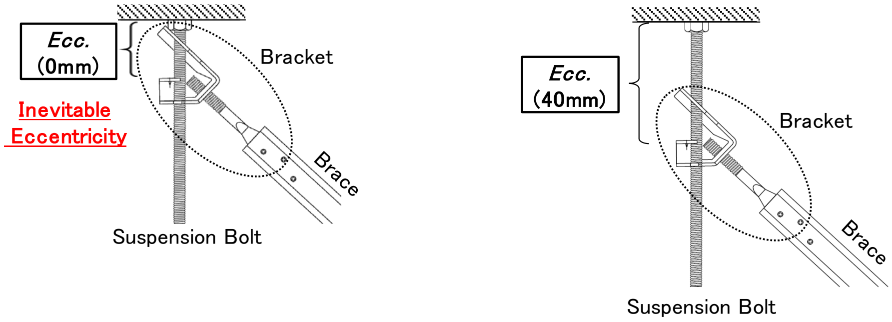


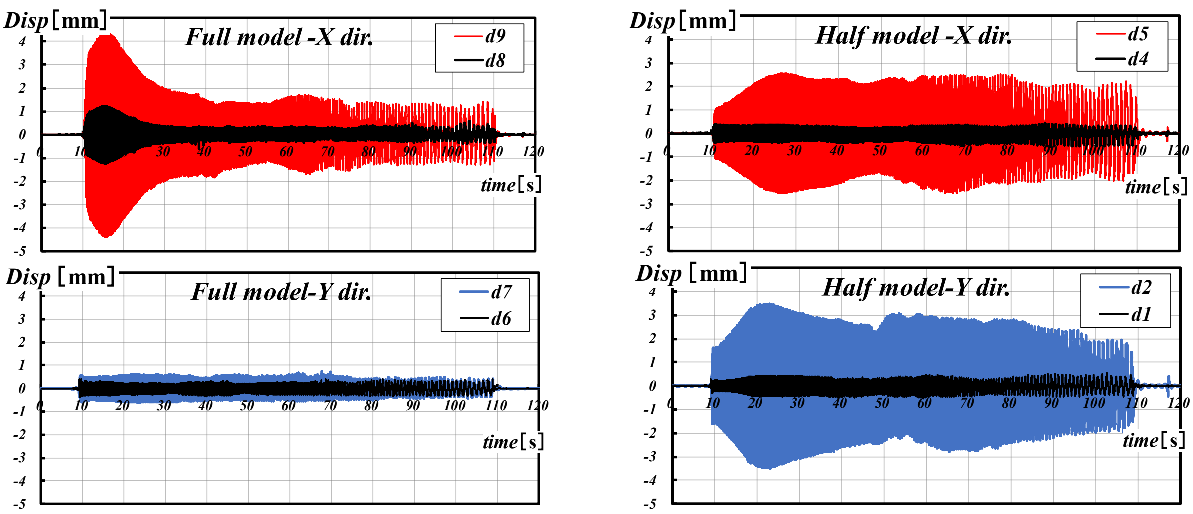
Fig.4 Eccentricity of mounted brace

For ceiling model A (hereinafter referred to as the full model), the braces are arranged at 1200 mm intervals in both the X and Y directions (total of 32), and for ceiling model B, the braces are arranged at 2400 mm intervals in the X and Y directions. A total of 18 are placed, making it about half of the full model, thus ceiling B hereinafter referred to as the half model. On the other hand, the eccentricity is 40 mm for the full model and 0 mm for the half model. The brace section is C-25×19×5 for both models. The total weight of both ceilings, including the base material, is respectively 560kg and 550kg.

2.2 Result of the experiment

2.2.1 Behavior of the stable state

Fig.5 shows stable state results in the relative displacement time history of the ceiling surface when uniaxial Sweep150gal-6~0.6 Hz is input. In the full model, the response displacement of the inner part ceiling surface was relatively large irrespective of the arrangement of the brace due to a large amount of eccentricity in the brace mounting portion. Further, in the half model, since the brace interval is large, the displacement at the intermediate position of the brace is increased, and it is cleared that the ceiling surface does not behave as a rigid body and is deformed with irregularities.



(a) Full model in X, Y direction (b) Half model in X, Y direction

Fig.5 Time history of relative response displacement during input Sweep 150gal

2.2.2 Behavior leading up to the damaged state

When larger motion is input at Sweep 250gal in X-direction, in the full model, the inertial force in longitudinal Y-direction was collected by main T-bar from a middle tributary area of 1200mm and transmitted to the middle braces. Premature failure of suspension bolts occurred at suspension base due to low-cycle fatigue failure causing by the high amount of eccentricity. This failure results in large displacement and creates a greater inertial force to neighbor restraint braces, and as a result, suspension bolt fractures one after another, causing ceiling system losing its lateral restrained and collapsed by collided with the surrounding beams. However, the half model is still undamaged due to the small amount of eccentricity.

Fig. 6, 7, and **8** show the displacement time history, shear force-relative displacement of the outermost panel, and Y-direction displacement distribution at the d3 position (where the brace is installed at the 9.6m position in Figure 8) of the half model. First, in stage ①, the displacement at the place where the brace is installed gradually increases, and the mounting bracket attached to one of the V-shaped braces breaks, causing a transition to stage ②. After that, the mounting bracket of the other brace is also broken, and the process moves to stage ③. In stage ③, due to the disappearance of the bracing effect, the inertial force concentrates on the remaining brace that has not yet broken, so that the panels near the remaining brace fall and the displacement further increases. Later, the ceiling surface collided with the surrounding beams, and the ceiling surface was almost completely collapsed. **Photo 3** shows the situation of the panel falling, the breaking of the suspension bolt in full model, and breaking of the mounting bracket in half model.

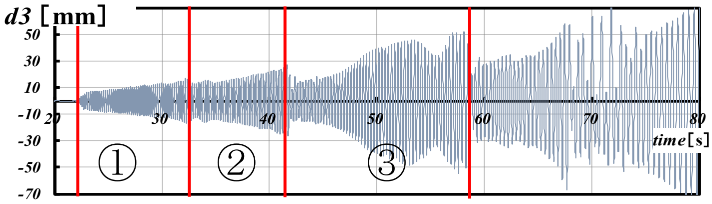
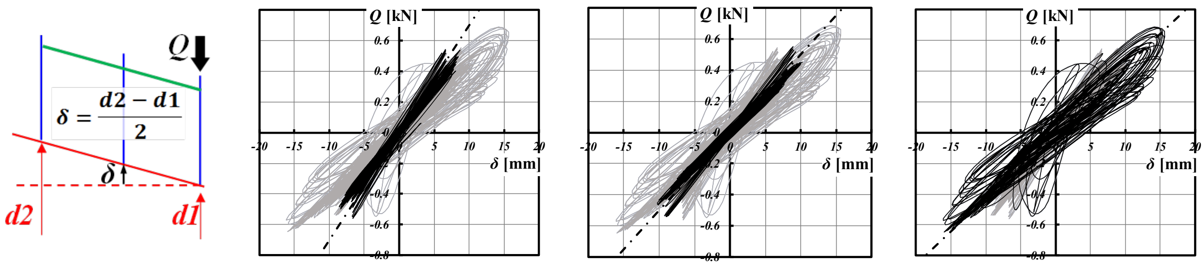


Fig.6 Displacement distribution at the *d3* position



(a) Concept of shear force and deformation

(b) ① Stage

(c) ② Stage

(d) ③ Stage

Fig.7 In-plane shear force and deformation per panel during Sweep 500gal

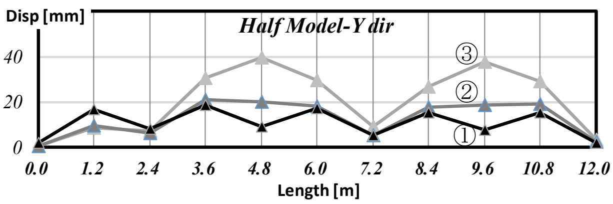


Fig.8 Distribution of displacement in Y direction during Sweep 500gal

(a) The situation of the panel falling

(b) Early fracture due to low cycle fatigue of suspension bolt

(c) Failure of brace mounting bracket

Photo3 Failure mechanisms confirmed by experiment

3. Numerical Analysis Model of Shaking Table Test

To consider the in-plane deformation of the ceiling surface in the analysis model, a specific analysis was performed using the wire model with the brace replacement of the ceiling panel proposed in the previous study **[7]** is shown in **Fig.9**. Besides, **Fig.10** shows details of an upper part and a lower part of a brace attachment and an analysis model.

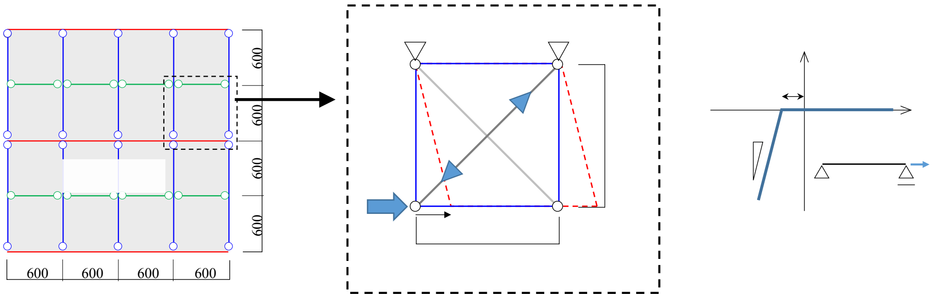


Fig.9 Analysis model of the ceiling panel

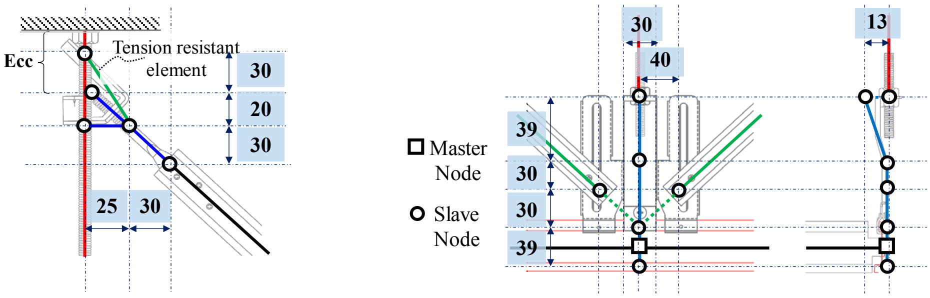
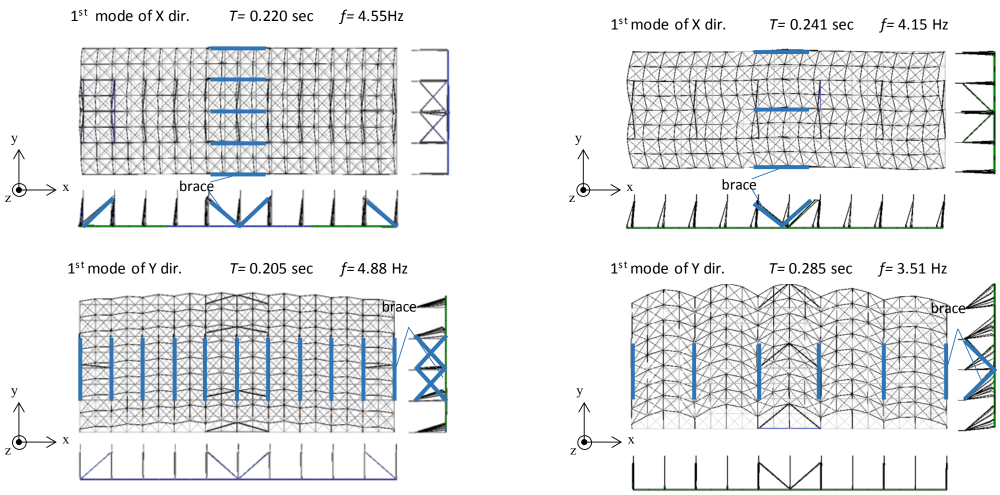


Fig.10 Analysis model for braces connection

Fig.11 shows the remarkable modal analysis results in the X and Y directions. Here, *T* indicates a natural period, and *f* indicates a natural frequency. The bold blue line represents the remarkable arrangement of the brace in each direction. Clearly, from the eigenmode, the ceiling surface did not move as a rigid body the same in the shaking table test result, and it is found that the wider the brace pitch, the larger the bumpy deformation. In **Fig. 12** also shows the displacement distribution of the ceiling specimen obtained from the location where the amplitude in the X and Y directions of the Sweep 150gal input of the shaking table experiment is large, and compared to the eigenmodes; it is confirmed that both results are similar.



(a) Full model, ***Ecc.* 40mm** (b) Half model, ***Ecc.* 0mm**

Fig.11 Modal analysis result of the Full model and Half model

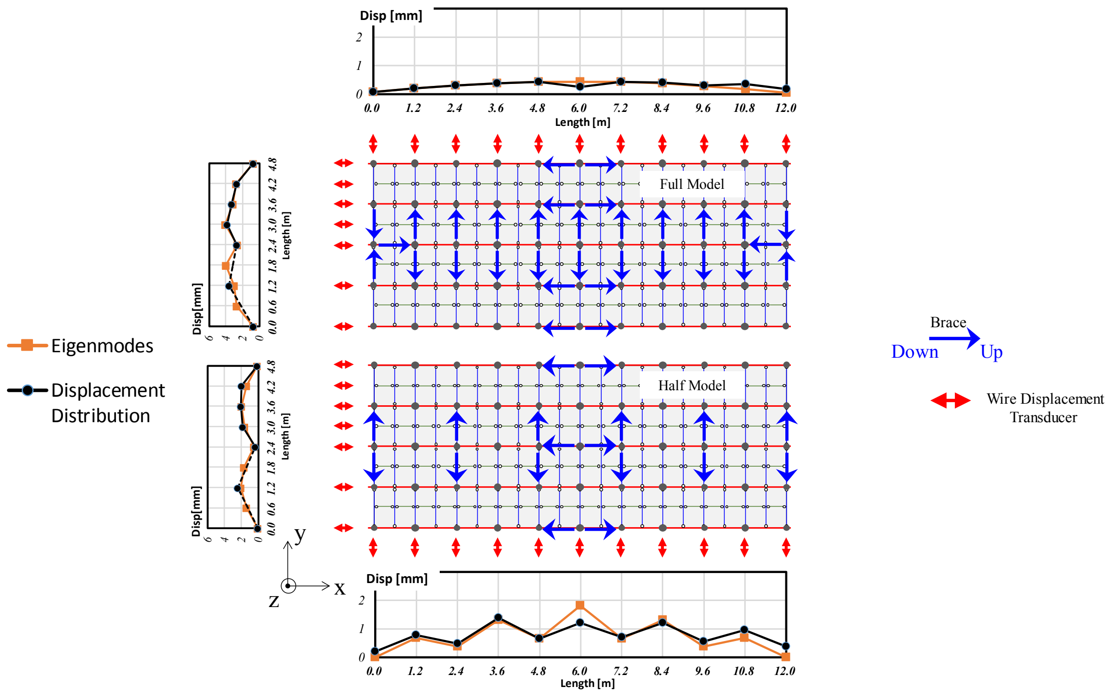


Fig.12 Comparison of Eigenmodes and Displacement Distribution during Sweep 150gal

4. Cyclic Bending Experiment of Suspension Bolt

In section 2, as the leading cause of the ceiling system collapsed, it is conceivable due to low-cycle fatigue failure of suspension bolt by bending, which generated by a lateral force acting from the brace. In this section, to understand the fatigue characteristic of the suspension bolt, a cyclic bending test is conducted to investigate the relationship between the angle of deflection and the number of cycles to failure. **Fig. 13** shows the loading apparatus and test specimen. The test specimen contains a hanging bolt outer diameter of ϕ9 (effective diameter ϕ7.35) and ϕ7 (effective diameter ϕ5.27) which the test specimen interval is

40mm. The loading method is monotonic loading and cyclic loading. The load is the value of the load cell built in the fatigue tester, the deflection δ and the deflection angle θ are determined using the absolute displacement values of high-sensitive displacement transducer, which measuring four places of the test specimen.

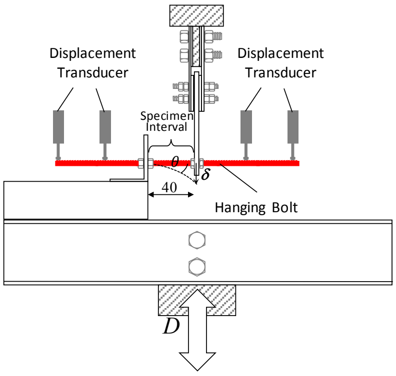


Fig.13 Loading Apparatus and Test Specimen

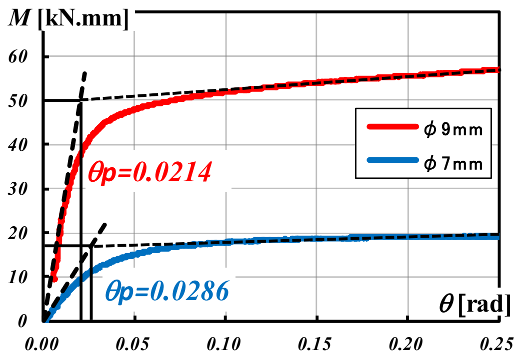
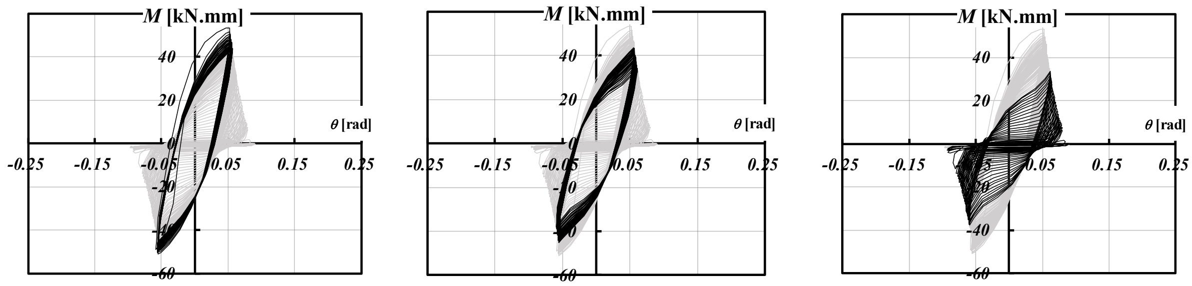


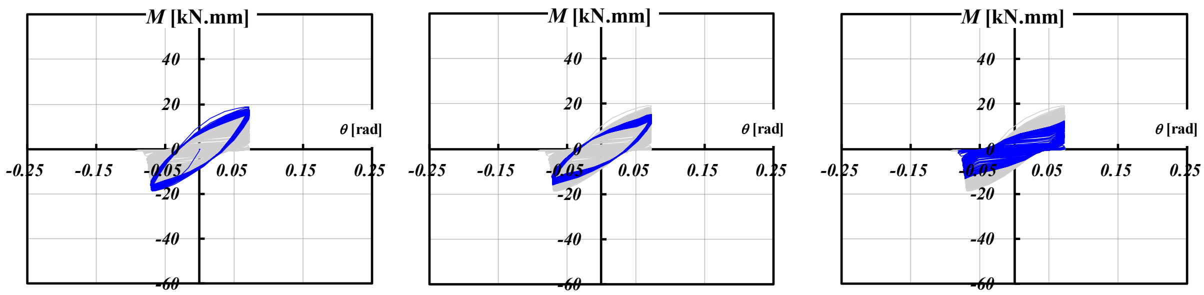
Fig.14 *M*-θ relationship

First, a monotonic test is performed to investigate the elastic deflection angle θp for the full plastic bending strength. The relationship between moment and deflection angle in the monotonic test is shown in **Fig.14**. From these results, for ϕ9 bolt, values of θp=0.02rad, full plastic moment *Mp*=48kNmm, and for ϕ7 bolt, values of θp=0.024rad, full plastic moment *Mp*=18kNmm were obtained. Yield stress of both bolts σy=700N/mm2 (The value of the yield stress is obtained from the full plastic moment by calculating the plastic section modulus *Zp* from the effective diameter). Next, the cyclic bending test is performed with different types of displacement amplitude regarding θ_p.



(a) No. of cycles: 1~30 (b) No. of ycles: 30~N_{cr}=60 (c) No. of cycles: N_{cr}=60~ N_f=90

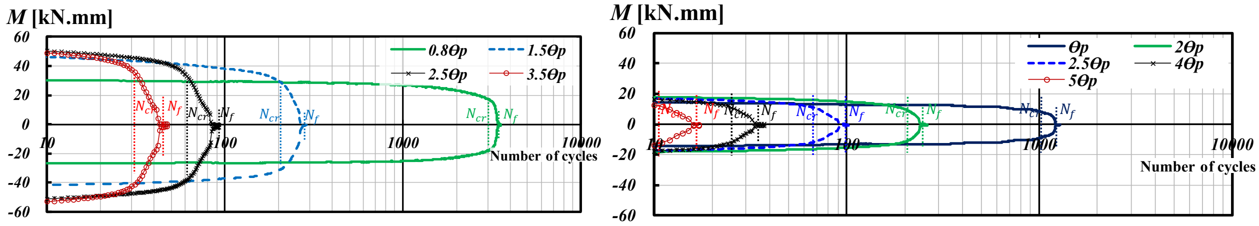
Fig.15 *M*-θ Relationship when θ=3θ_p (ϕ9)



(a) No. of cycles: 1~35 (b) No. of ycles: 35~N_{cr}=65 (c) No. of cycles: N_{cr}=65~ N_f=95

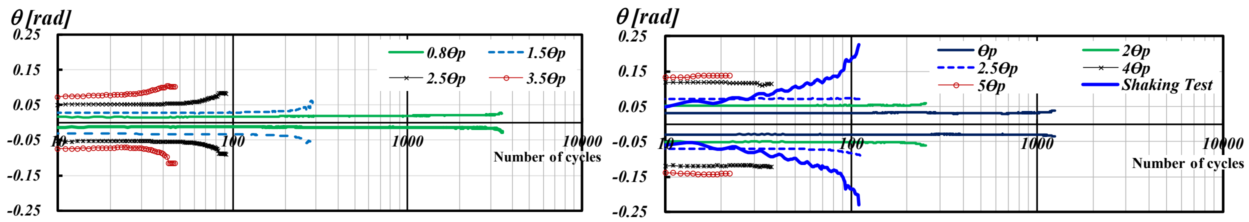
Fig.16 *M*-θ Relationship when θ=3θ_p (ϕ7)

Fig.15, 16 shows as an example of the relationship between the moment and the deflection angle when the displacement amplitude is $3\theta_p$ of both suspension bolts, respectively. Here, N_{cr} is the number of cycles where the small crack occurs, N_f indicates the number to failure of the suspension bolt. The strength of the suspension bolt is gradually reduced, but when N_{cr} is exceeded, it suddenly drops to N_f and breaks down, also shown in **Fig. 17.** The results of extracting the relationship between the maximum and minimum bending moment, deflection angle, and the number of cycles from such results are shown in **Fig.17** and **Fig.18.** Also, from **Fig.18(b)**, early fracture due to low cycle fatigue of suspension bolt which occurred in full model during the shaking table test, can be evaluated.



(a) Suspension Bolt ϕ9 (b) Suspension Bolt ϕ7

Fig. 17 Relationship of max. & min. Moment and Number of cycles



(a) Suspension Bolt ϕ9 (b) Suspension Bolt ϕ7

Fig. 18 Relationship of max. & min. Deflection angle and Number of cycles

Fig.19 shows the relationship between the deflection angle amplitude and the number of cycles to failure N_f. It can be seen that the larger the acting bending moment or deflection angle, the easier the early rupture due to low cycle fatigue failure, and the relationship is expressed by the equation in the figure.

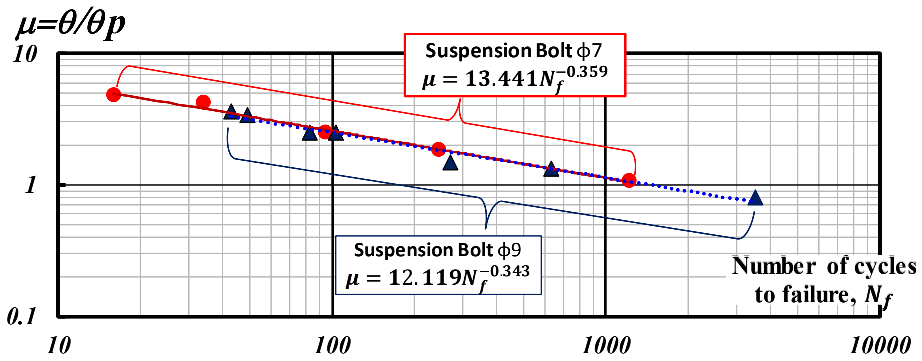


Fig. 19 Relationship of Deflection angle and N_f

5. Conclusion

In this paper, a shaking table test is conducted using a full-scale test specimen to understand the mechanical characteristics of the JPN-US suspended system ceiling (ceiling system developed in the United States and customized to Japanese style) and clarified the characteristics in a stable state and the process leading to falling damage. For the future work, a nonlinear numerical analysis model that can reproduce from a stable state to a damaged state will be proposed, and verify its validity using the experimental results.

6. Acknowledgments

This work was supported by JST Program on Open Innovation Platform with Enterprises (JPMJOP1723), Research Institute and Academia, and JSPS KAKENHI Grant Number JP 16H02375. Finally, the authors acknowledge the support of former graduate student, Mr. Tea Kimcheng, during the entire project.

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