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Numerical analysis of suspended ceiling considering pounding behavior between ceiling surface and walls

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Abstract. In the previous study, we executed a full-scale shaking table experiment with a suspended ceiling, which is one of the standard styles in China. In this experiment, the perimeter beams corresponding to the actual walls were installed around the ceiling surface. However, the ceiling surface was not firmly connected to the beam, and according to one of the standard styles of suspended ceilings in China, a gap of approximately 13 mm was artificially set between the ceiling surface and the beam. Due to the presence of the gap, a pounding phenomenon occurred between the ceiling surface and the perimeter beam, and the pounding force at the time of the pounding generated a large acceleration, causing damage to the ceiling surface during the shaking test. Measurement items such as displacement and acceleration at some points and strain of some steel parts were sufficient to macroscopically grasp the dynamic behavior of the current style ceiling, but unfortunately, those measurement items were too few to deeply understand the influence of the pounding force on the dynamic behavior of suspended ceiling. Whereupon in this paper, we first propose a numerical model that can simulate the pounding phenomenon between the ceiling surface and the surrounding beams. On this basis, we show the verification of the model by comparing the numerical analysis results with the experimental results. Even though the present numerical models and calculation methods are very simple, they can simulate pounding phenomena with high accuracy at variable performance. Following accuracy confirmation, we will clarify the effect of the pounding on the axial force of the ceiling steel member and the reason why the ceiling was damaged through the numerical results.

Keywords: Suspended ceiling, Shaking table test, Numerical model, Pounding phenomenon

1. INTRODUCTION

CHN-US style suspended ceilings are developed from US-style ceilings which consist of three kinds of T-shape galvanized steel beams provided in three lengths: 3600mm,1200mm and 600mm, which are called main tees, cross tees, sub cross tees and L-bar which is called wall angle in this paper (as shown in Fig.1). The differences between two types of ceiling are as follows: [1] in US-style ceilings, hanging wires are principal method to hanging ceiling grid, while in the CHN-US style ceilings, hanging bolts are main current, and [2] US-style ceilings are classified as perimeter-fixed, with one or more sides of grid member connected to the wall by setting two screws in the seismic clip which constrained grid element to the boundary, (as shown in Fig.2). However, CHN-US style ceilings are mainly adopted floating systems which keep free boundary condition on both sides, only one screw placed in the slot of the clip, allowing the grid member to slide along its longitudinal direction (as shown in Fig.3). Due to the presence of gap between grid member and adjacent wall angle within the clip, a pounding phenomenon occurred between the ceiling surface and the perimeter beam is inevitable which have highly possible cause serious injury. In fact, during the Lushan earthquake in 2013, damages to the CHN-US style ceiling such as falling of ceiling boards and failure of grid members were reported as shown in Photo.1[1]. These damages have led to the severance of the functionality of facilities and have endangered the safety of people.

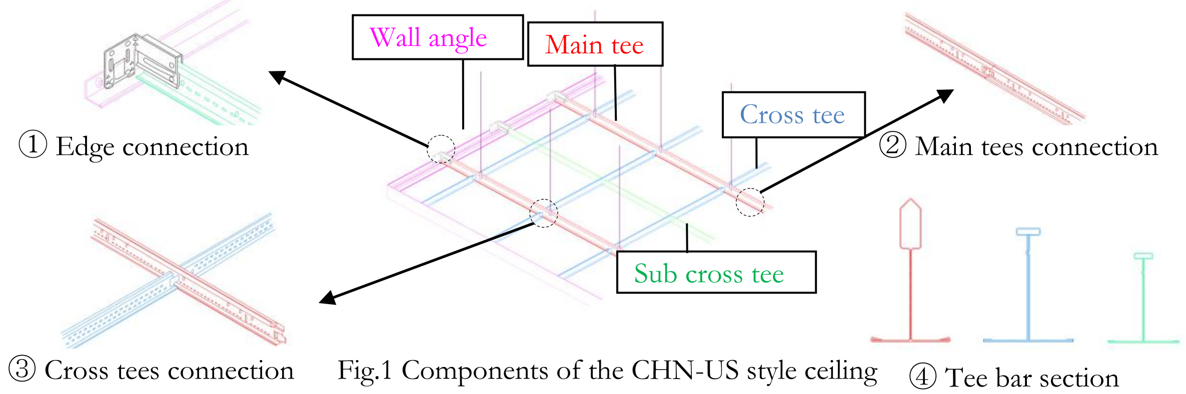


Fig.1 Components of the CHN-US style ceiling

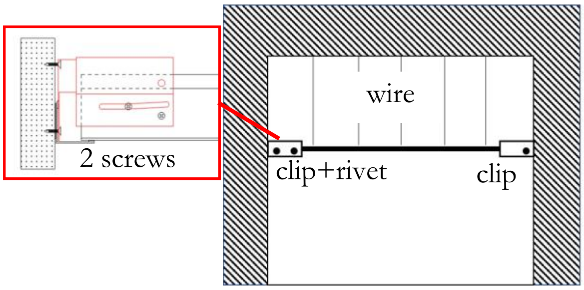


Fig.2 US-style ceiling

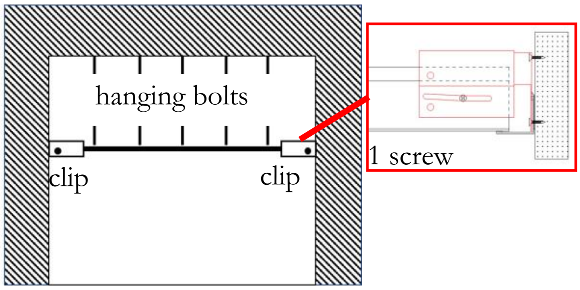


Fig.3 CHN-US style ceiling

Photo.1 Damage of ceiling during Lushan earthquake in 2013

In past, there were some studies on simple methods of appraising axial force based on peak floor acceleration by shaking table tests of perimeter-fixes type suspended ceilings [2] [R.P. Dhakal et al., 2015], the performance of US-style ceiling components such as ceiling joint [3] [Siavash et al., 2015]. However, CHN-US style ceilings are different from US-style ceilings for the ceiling surface can slide along its longitudinal direction freely on both sides. Due to the presence of the gap between the ceiling surface and the wall angle, a pounding phenomenon occurred and it's complicated to simulate by numerical analysis. Therefore, the investigation of the numerical study to simulate the pounding phenomenon still be necessary. To study the analytical method of simulating the essential pounding phenomenon, Motoyui Lab conducted various pounding experiments on gypsum board to simulate pounding (as shown in Photo.2 and Fig.4). By comparing the experimental result with the Hertz model with non-linear damper (which is called Hertzdamp model in this paper) analysis' result and the Voigt model's result, the use of the Hertzdamp model has high accuracy in modeling pounding [4] (as shown in Fig.5~Fig.8), but CHN-US style ceiling surface have different properties from gypsum board, so it's still unclear that the Hertzdamp model could simulate the pounding phenomenon of CHN-US style ceilings. In this study, the pounding occurrence mechanism is clarified by using numerical analysis based on the shaking table test for the CHN-US style ceiling. This paper shows the design and outline of the shaking table test, the characteristic of the test results, and a discussion on how pounding affects the axial force of grid members.

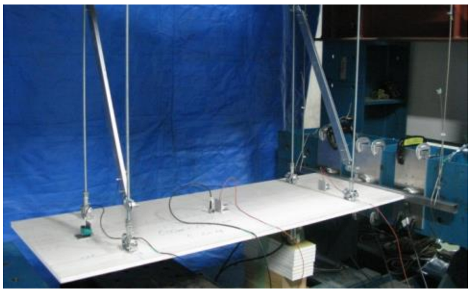


Photo.2 Experiment of the gypsum board pounding behavior

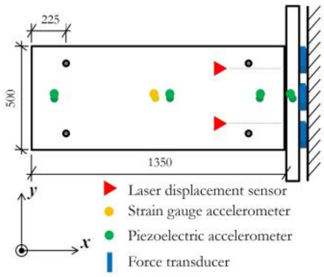


Fig.4 outline of pounding test

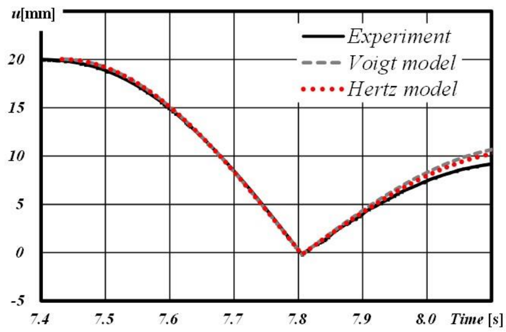


Fig.5 Comparison of displacement

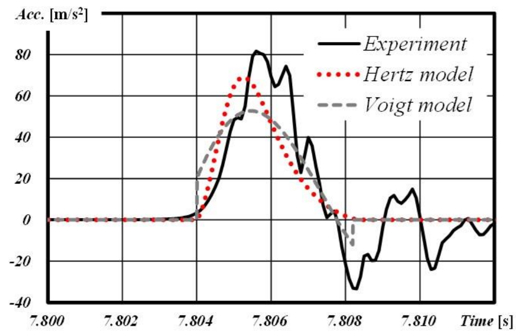


Fig.6 Comparison of acceleration

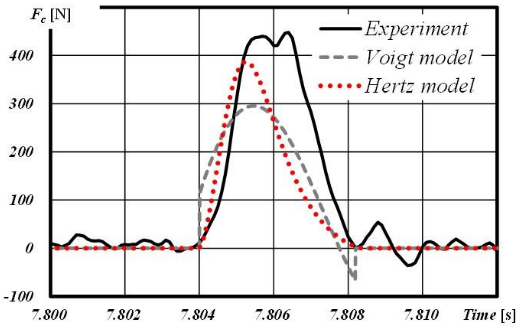


Fig.7 Comparison of pounding force

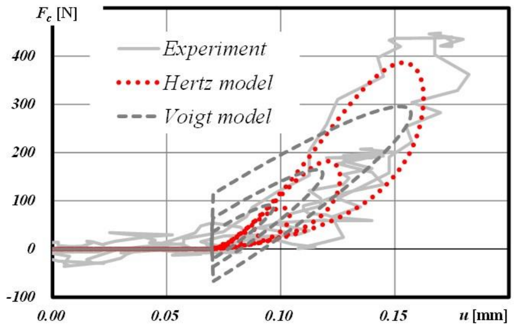


Fig.8 Comparison of displacement-force

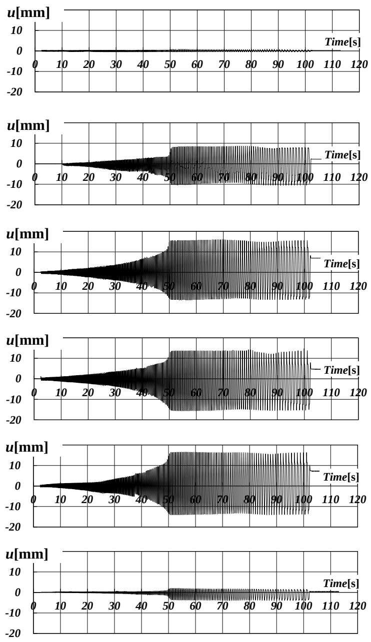
2. OUTLINE OF EXPERIMENT

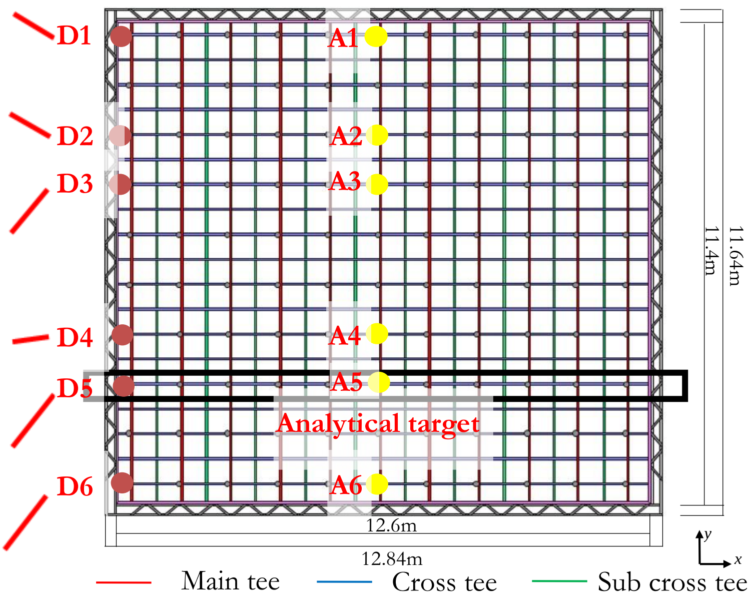
Photo.3 shows the arrangement of the shaking table test [5]. Fig.9 shows the outline of the experiment. The shaking table used in the test assemble with steel platform dimensions of 12840mm×11640m. In order to simulate the boundary condition of the specimen, the perimeter beams were fastened on the platform to represent the surrounding walls (as shown in Photo.4)[5]. The size of the specimen was 12600mm×11400mm (360 lay-in panels of 600mm×600mm with a thickness of 16mm), Φ8 threaded rods of length 1000mm were used for hanging the CHN-US style ceiling (as shown in Photo.5)[5] at an interval of 1200mm. The 3600mm main tees are laid aside parallel to each other at an interval of 1200mm along the Y direction. The cross tees with a length of 1200mm are placed orthogonal to the main tees, sub cross tees were assembled parallel to the main tees(as shown in Fig.9). All sides define the boundary conditions of the ceiling with clips on the wall angles which are called boundary clip in this paper. The grid ends with a nominal gap from the wall angle designed to be able to slide freely within the middle slot of the boundary clip along the longitudinal direction. The total weight of the ceiling was 500kg. The input acceleration applied in the test were sweep waves from 6Hz to 0.8Hz with the acceleration amplitude as the test parameter to explore the failure mechanism of the specimen. The shaking duration was set as 100 seconds. The list of input motions is shown in Table.1.

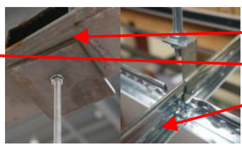
Photo.3 Arrangement of experiment

No.	Wave	Duration	Acceleration	Impact occurred or not	Failure condition
1	Sweep6-0.8Hz	100s	50gal		
2	Sweep6-0.8Hz	100s	150gal	occurred	
3	Sweep6-0.8Hz	100s	250gal	occurred	Buckling of latches
4	Sweep6-0.8Hz	100s	350gal	occurred	Falling of panel
5	Sweep6-0.8Hz	100s	500gal	occurred	Complete collapse of ceiling

Table.1 The list of input motions







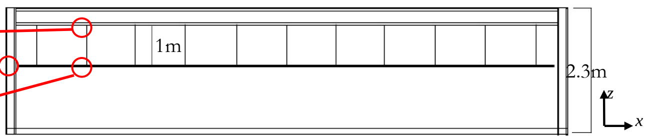


Photo.4 Boundary detail Photo.5 hanging bolt detail Fig.9 Outline of specimen

As shown in the table.1, there was less damage happened but the pounding phenomenon occurred during the sweep of 150gal, so the test result during 150gal will be the investigated target in this paper. Fig.9 also shows the displacement time history from D1 to D6 during the sweep 150gal[6)]. The vertical axis is the value of displacement which refers to the relative displacement between the cross tee and perimeter beam. The test result shows that D1 and D6 are significantly less than other displacement results due to being adjacent to the restraint boundary, so there is no pounding phenomenon that occurred in these two rows that are not applicable in this analysis research. Moreover, the characteristic of symmetry can be found in the test result which is from D2 to D5 even though the gap between the grid end and wall angle in each row of the cross tee has an uneven width. Therefore, we only chose the D5 row of the cross tee (as shown in Fig.9) as the analytical target. Fig.10 and Fig.11 show the left end displacement time history D5 and acceleration time history of the middle of the ceiling A5[6)]. Two characteristic phases were confirmed from the result of the test. First, the relative displacement between the end of the cross tee and perimeter beam becomes greater gradually but smaller than the gap between the grid end and wall angle where the inertia acting on the grid members is larger than the friction force at the boundary clip on both sides. The acceleration amplification of the middle of the ceiling surface relative to the platform is small since no pounding behavior occurs between the grid end and the wall angle. In the second phase, when the relative displacement between the end of the cross tee and perimeter beam increases to approximate 13.3mm which is the maximum range of the gap between the grid end and wall angle but is limited by perimeter beams, (the maximum of displacement time history D5 exceeds 15mm for the elastic deformation of the ceiling itself) the pounding behavior occurred and the acceleration response of the middle of the grid increases rapidly to $15m/s^2$ approximately. Even though the measurement data supplies the fundamental properties of the pounding behavior, it's still insufficient to deeply comprehend the influence of the pounding force on the dynamic behavior of the CHN-US style ceiling.

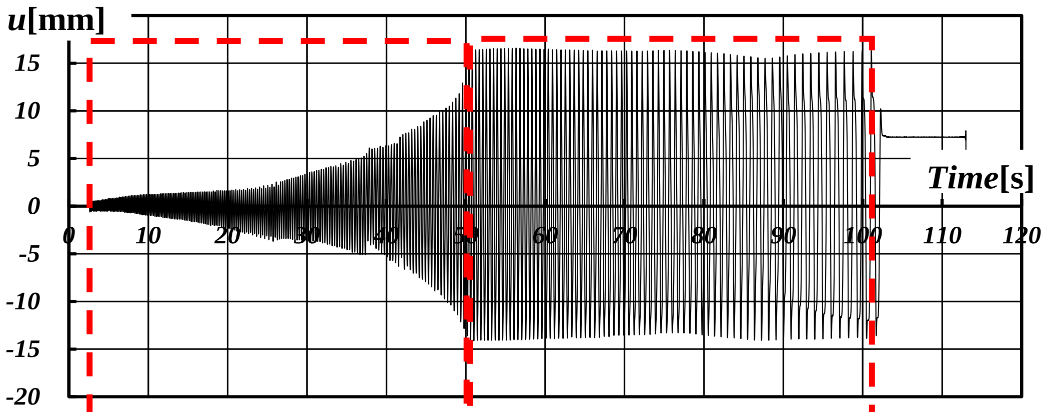


Fig.10 Displacement time history (D5)

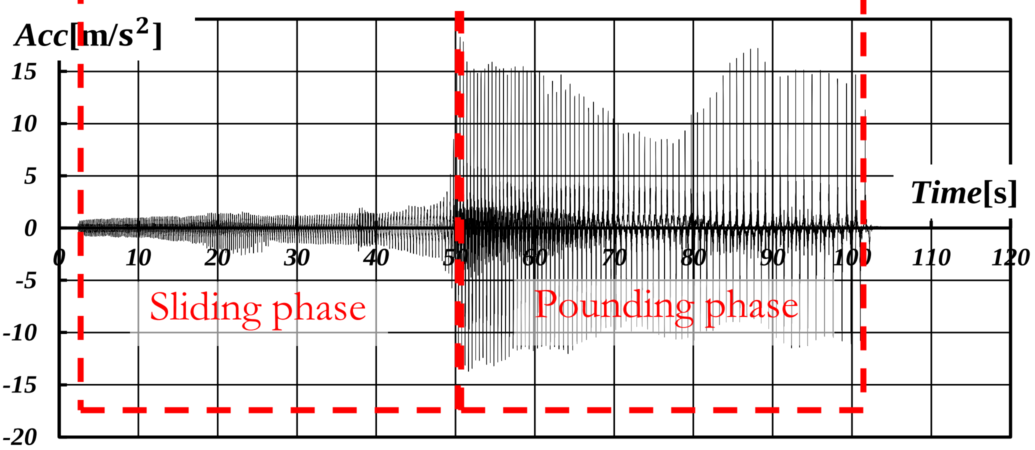


Fig.11 Acceleration time history(A5)

3.SIMULATION BY NUMERICAL MODEL

3.1 OUTLINE OF NUMERICAL MODEL

A simple numerical model was built to simulate the response of the specimen in the shaking table test. In this analysis, 1 row of the cross tee has been chosen as the analytical target (as shown in Fig.12). Fig.13 shows the outline of the numerical model. The total mass of 25kg is allocated to 23 mass points(m_c).

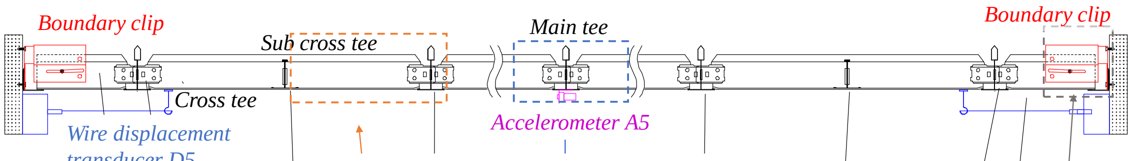


Fig.12 Details of analytical target

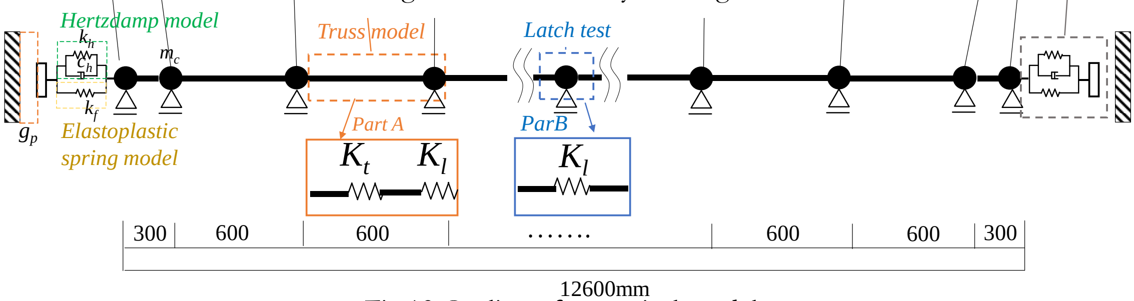


Fig.13 Outline of numerical model

Firstly, a simple truss model was conducted for the cross tee to express the axial stiffness of grid members. Considering that the latch contributed to integral rigidity, the axial rigidity K was calculated as the sum of the rigidity of grid K_t and rigidity of the latch connection K_l (as shown in part A in Fig.13). A tension test of the cross tee and a cyclic test of the latch were designed to evaluate the K_t and K_l. (as shown in Fig.14 and Fig.16). Fig.15 and Fig.17 show the relationship between tension force F_t and strain, the backbone curve of the force F_r-displacement [7].

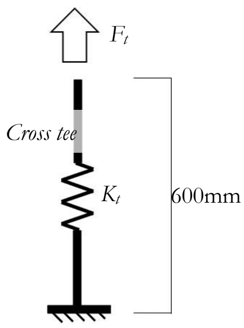


Fig.14 Tension test

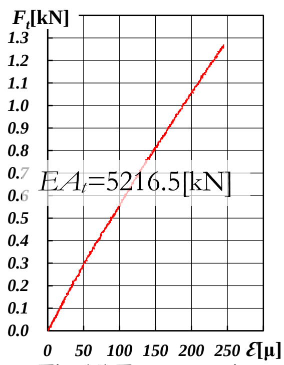


Fig.15 Force-strain

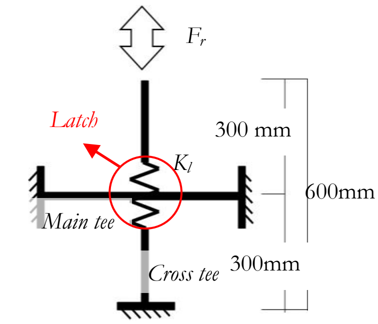


Fig.16 Outline of latch test

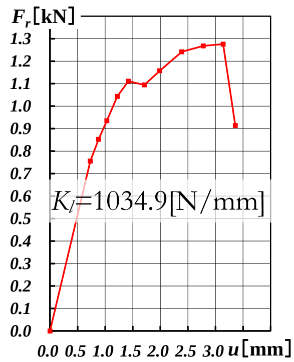


Fig.17 Force-displacement

From the above, the stiffness EA can be defined as follows:

$$\delta = F/K = F(1/K_t + 1/K_l) \quad \text{where } EA_t = 5216.5[\text{kN}],\ K_t = EA_t/H = 8694.2[\text{kN/mm}] \qquad (1)$$

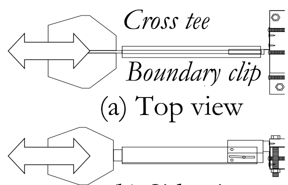
$$EA = KH = 1034.9 \times 600 = 6.2 \times 10^5[\text{N}] \qquad (2)$$

where H is the length of the specimen, for K_t is significantly greater than K_l, K can be considered as K_l

Next, the mechanical properties in the sliding phase need to be clarified, and it can be considered that mechanical properties at the boundary clip are the most significant, so we conducted a mechanical test (as shown in Fig.18) for ensuring their validation of them. From the test result, the mechanical property at the boundary clip can be assumed to be an elastoplastic spring model with slight hardening (as shown in Fig.20(a)). However, results that are obtained by using the parameter values from the test are not close to testing results (as shown in Fig.21(a)) for the stiffness of hanging bolts were not considered in this model, so we also conduct an experiment of hanging bolt test to acquire the stiffness of hanging bolt (as shown in Fig.19). From the test result (as shown in Fig.20(b)), the stiffness K_{bolt} can be defined as follows:

$$K_{bolt}=\frac{12EI}{L^3}+\frac{mg}{L} \tag{3}$$

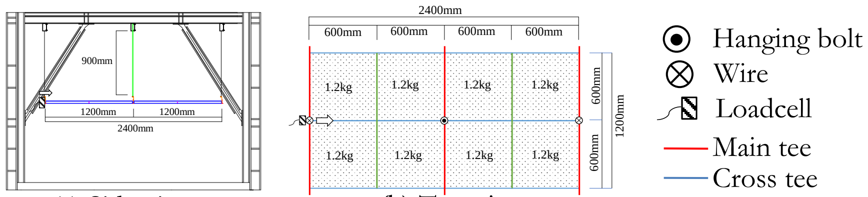
where E is Young modulus, I is 2nd-moment inertia, and L is the nominal Length of the hanging bolt. Therefore we parallel two elastic spring models at both ends of the ceiling to represent the friction at the boundary clip and stiffness of hanging bolts (as shown in Fig.20(c)). By comparing the numerical and experimental results, the value of K_{bolt} has to be set to 0.67-1.07N/mm (as shown in Fig.21).



(a) Top view

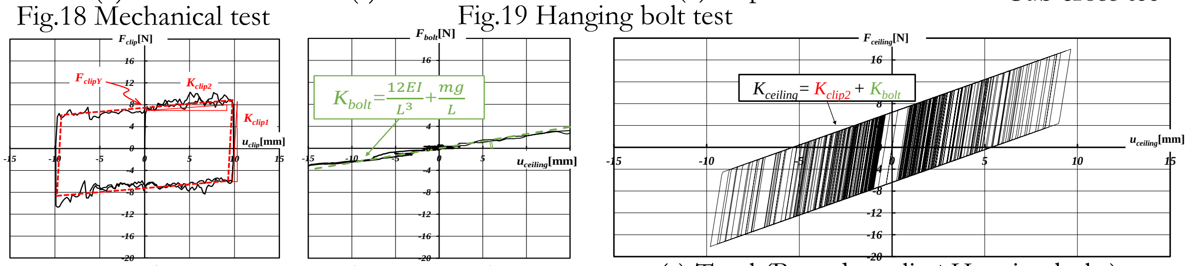
(b) Side view

Fig.18 Mechanical test



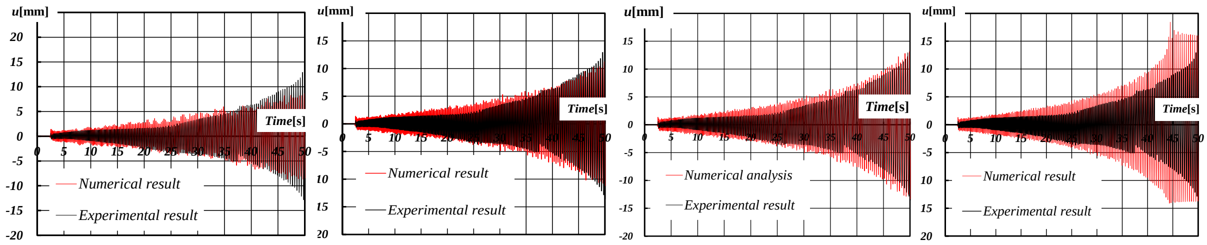
(a) Side view (b) Top view

Fig.19 Hanging bolt test



(a) Boundary clip (b) Hanging bolt (c) Total (Boundary clip+Hanging bolts)

Fig.20 Elastoplastic spring model



(a) Only clip (b) K_{bolt}=0.67N/mm (c) K_{bolt}=1.07N/mm (d) K_{bolt}=1.77N/mm

Fig.21 Comparison between the numerical and experimental result

Finally, a Hertzdamp model was created to simulate the mechanical properties in the pounding phase. Pounding force F_c representation is:

$$F_c = k_h\delta^{\frac{3}{2}} + c_h\dot{\delta} \quad , \qquad c_h = \frac{8}{5}\frac{k_h(1-e)}{e\dot{\delta}_0}\delta^{\frac{3}{2}} \tag{4}$$

where k_h is the pounding stiffness parameter which depends on the material properties of the colliding structures and the attributes of the contact surface. e is the coefficient of restitution which depends on the materials of colliding structures. Comparing the numerical results with different values of stiffness (as shown in Fig.22), k_h should be set to at least 200N/mm$^{3/2}$. The value of the parameters is shown in Fig.23.

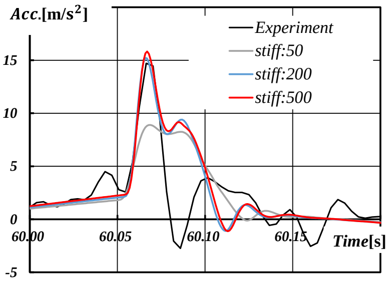


Fig.22 Comparison with different stiffness

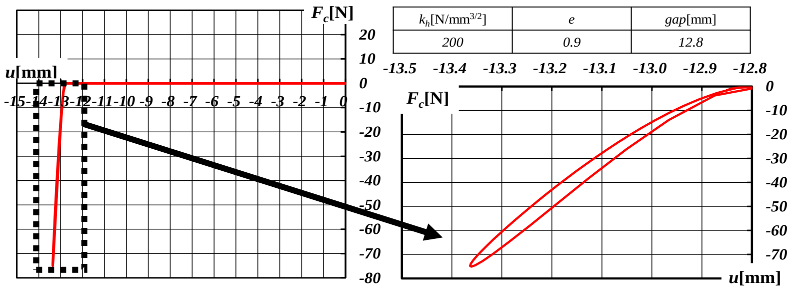


Fig.23 Hertz model with non-linear damper

3.2 VALIDITY OF THE NUMERICAL MODEL

Fig.24~Fig.27 show the response displacement (D4 and D5) of the end of the grid and acceleration of the center of the ceiling (A4 and A5) during the sweep 150gal. By comparing the numerical analysis result (red line) and experiment result (black line), it is confirmed that the numerical analysis result closely matches the experiment result.

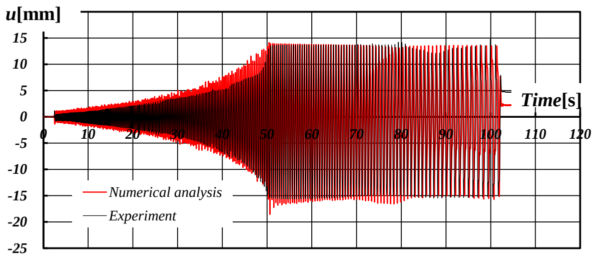


Fig.24 Displacement time history (D4)

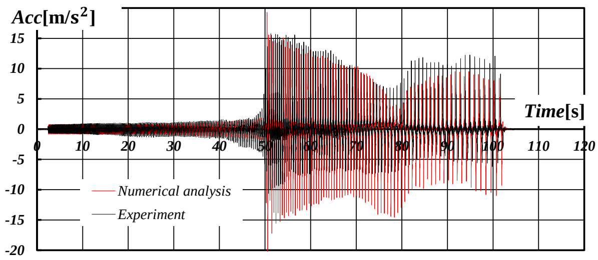


Fig.25 Acceleration time history (A4)

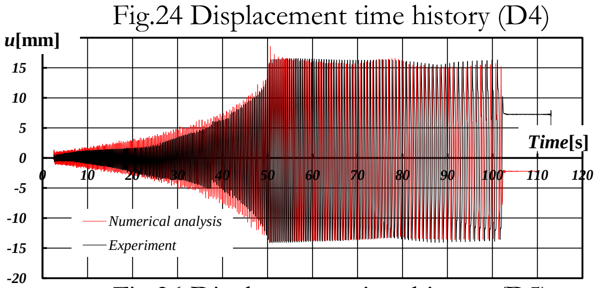


Fig.26 Displacement time history (D5)

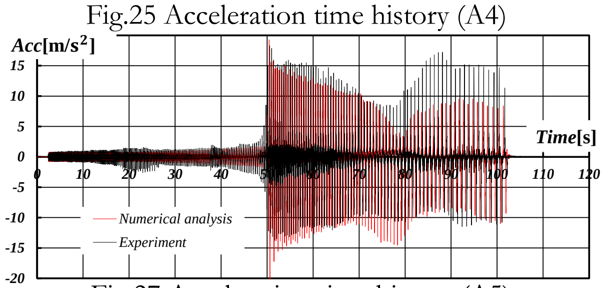
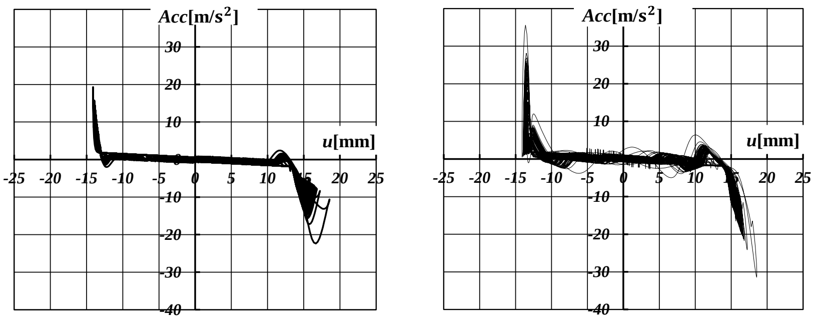


Fig.27 Acceleration time history (A5)

4. EFFECT OF POUNDING ON THE AXIAL FORCE

4.1 RELATIONSHIP BETWEEN THE ACCELERATION AND DISPLACEMENT

Fig.28 shows the acceleration -displacement from numerical analysis results. The vertical axis of Fig.28(a) is the value of the acceleration of the middle of the ceiling, and the horizontal axis is the horizontal in-plane displacement of the ceiling in the shaking direction which is calculated by the relative displacement between grid end and perimeter beam, and the vertical axis of Fig.28(b) is the value of the acceleration of the left end of the grid. Comparing the median acceleration and end acceleration, we figure that the end acceleration is 1.5 times larger than the median acceleration when the pounding phenomenon occurred, so the effect of the excessive acceleration caused by pounding on the axial force of the grid needs to be investigated by numerical studies.



(a)Mid point of the ceiling (b)Left end of the ceiling

Fig.28 Acceleration-displacement

4.2 CHARACTERISTIC OF THE DISTRIBUTION OF IN-PLANE AXIAL FORCE

The research on the effect of pounding on the axial force will be investigated in the analysis result. Fig.29 shows the distribution of inertial force in the ceiling face when a slide occurs. The horizontal axis is the longitudinal direction of the analytical target. From Fig.29, the distribution of the inertial force shows the linear characteristic and the largest inertial force is equal to the predicted inertial force which is calculated as the product of mass and peak acceleration as follows:

$$F_{\text{inertial}} = m \times a_{max} = 25\text{kg} \times 1.5\text{m/s}^2 = 37.5[\text{N}] \quad (5)$$

Fig.31 and Fig.33 show the distribution of in-plane axial force and the acceleration response in the ceiling face before and after the pounding occurs. The horizontal axis is the longitudinal direction of the analytical target. The largest acceleration response at the end of the grid appeared when the pounding happened (red line in Fig.33), but the in-plane axial force is still small at the same time (red line in Fig.31). On the other hand, the largest in-plane axial force appeared and shows the linear characteristic of distribution when the acceleration response at the middle of the ceiling face become the largest after the pounding occurred (blue line in Fig.30 and Fig.32). Therefore, the largest in-plane axial force is not led by the excessive acceleration at the end of the ceiling where the pounding occurred, but by the average maximum in-plane acceleration response.

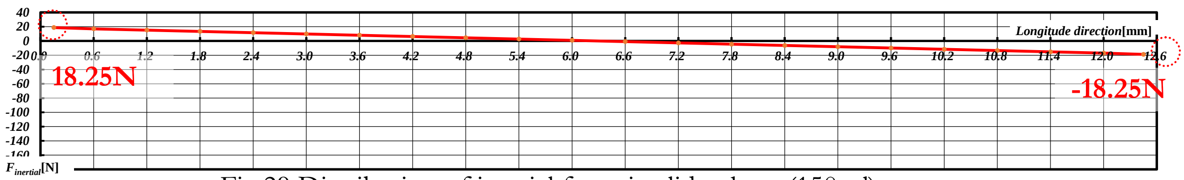


Fig.29 Distribution of inertial force in slide phase (150gal)

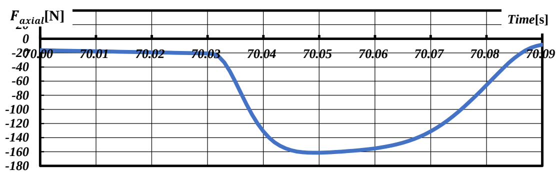


Fig.30 Axial force time history(150gal)

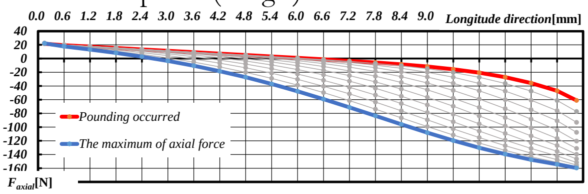


Fig.31 Distribution of axial force(150gal)

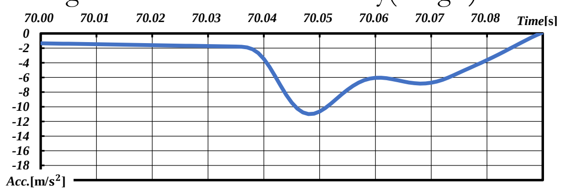


Fig.32 Acceleration time history (150gal)

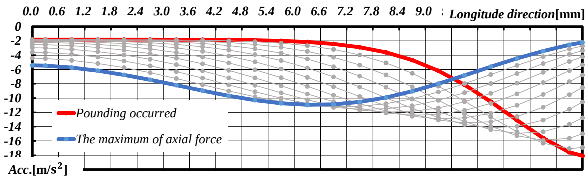


Fig.33 Distribution of acceleration response (150gal)

CONCLUSION

This study aims to investigate the effect of the pounding on the in-plane axial force of the CHN-US style ceiling by using numerical analysis based on the shaking table test. In this research, the validity of the Hertz damp model was confirmed, and the excessive acceleration response on the grid end when the pounding occurred has also been clarified. We figure out the propagation mechanism of both acceleration and in-plane axial force from the numerical result of the acceleration response and in-plane axial force during the pounding that occurred. Through the experiment and numerical analysis, we also find that the kinematic hardening model has high accuracy in modeling the mechanism of the boundary clip, and the influence on the horizontal stiffness from the hanging bolts cannot be ignored in the numerical study.

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