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UNSTABLE BEHAVIOR OF SUSPENDED CEILING DURING EARTHQUAKE

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Abstract

In recent earthquakes, non-structural components such as ceilings were seriously damaged, while most structural frames of such buildings were not. It is no doubt that such ceiling damages should affect daily lives of residents thereof or prevent the use of such facilities for a certain amount of time. For this reason, it has been one of the most urgent issues to deal with. It should also be noted that such ceiling damages have been observed not only in Japan but also in other countries with earthquakes, where different construction methods for suspended ceilings were taken. Although it is clear that falling down of a Japanese-style ceiling is caused by detachment behavior of unique metal connection parts in steel furring, what made those connection parts detached has not been explained obviously yet. The construction methods of earthquake-resistant ceilings in Japan are categorized into two types, either with or without perimeter spacing. In case of a ceiling with spacing, braces are also set in order to prevent the ceiling from swinging, and an inertia force on the ceiling surface in an earthquake is transmitted to a main frame via steel furring and those braces. Due to such concentration of stresses, the connection parts near those braces are easily detached, if the parts do not have enough strength. On the other hand, in case of a ceiling without spacing, it is via points of contact between a ceiling surface and surrounding components like walls that an inertia force is transmitted to a main frame. Therefore, any extraordinary stress is not considered to act on the connection parts. However, some ceilings of this type did fall down due to detachment of connection parts in the past earthquakes. The cause of this detachment is not explained yet, even though many researchers have tried to simulate the failure of such ceilings by shaking table tests.

In our presentation, we focus on dynamic behavior of ceilings without spacing, supposing any unstable behavior of ceilings should cause detachment of metal connection parts. Ceilings suspended by longer hanging bolts are especially discussed here, because in the former shaking table tests, the only test specimen was the standard ceiling with the same pitch and length of hanging bolts, and with the same layout of steel furring. In our numerical method, the Hertz model[2] and the master-slave model are applied in order to simulate the contact and release behavior of a ceiling surface to surrounding components. We present the numerical results showing that a ceiling with longer hanging bolts falls down due to detachment of metal connection parts while a ceiling with shorter ones is not fallen into an unstable condition. The different behaviors of ceilings with shorter and longer hanging bolts agree well with the actual damages done to ceilings in the past earthquakes.

Keywords: suspended ceiling, unstable behavior, seismic performance

1. Introduction

In recent earthquakes, non-structural components such as ceilings were seriously damaged as shown in Photos. 1, while most structural frames of such buildings were not and the maximum acceleration values recorded at the site nearby were also comparatively small. It is no doubt that such failures of ceilings may kill residents and obstruct their daily lives owing to the malfunction of indoor space for a certain amount of time. The social problem was actualized in the Great East Japan Earthquake, in which the social system such as product lines and distribution systems had been shut down by the failure of non-structural components for a long time. Securing indoor space has been one of the most urgent issues to deal with. It should also be noted that such ceiling damages have been observed not only in Japan but also in other countries with earthquakes, where different construction methods for suspended ceilings were taken.

Although it has been clear that falling down of a Japanese-style ceiling is caused by detachment behavior of unique metal connection parts in steel furring of a ceiling, what makes those connection parts detached has not been explained fully yet.

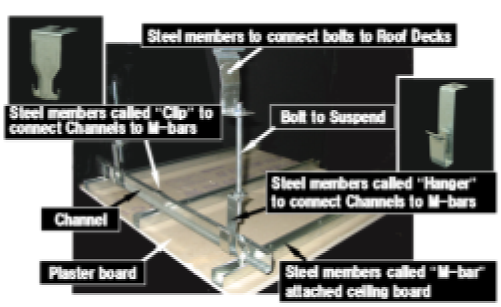
(a) Kushiro Airport Terminal Building
Maximum acceleration at the ground: 0.2G
Tokachi-oki earthquake (2003)

(b) Sendai Indoor Swimming Pool
Maximum acceleration at the ground: 0.2G
Miyagi Prefecture Earthquake (2005)

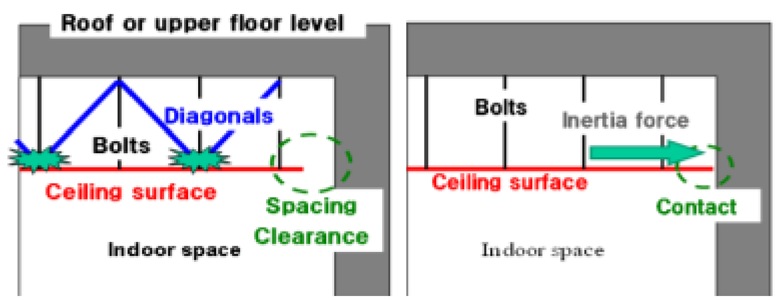
Photos.1 Damage of ceiling in earthquakes

The JPN style ceiling is shown in Photo.2. As a hanging member, a threaded rod (outer diameter: 9mm) is used. The top end of the hanging bolt is anchored to main structural members like slabs or girders, and a channel member, one of steel furring (C-38x12x1.2), is connected to the bottom end by using metal connection parts called ‘hanger’. To that channel, another steel furring called M-bar (M-25x19x0.6) is connected using metal parts called ‘clip’. Onto that, a gypsum board is attached to the M-bar with screws completing Japanese style ceiling. As shown in Photo.2, the JPN style ceiling is quite different from the US one.

The construction methods of earthquake-resistant ceilings in Japan are categorized into two types, either with or without artificial perimeter spacing as shown in Figs.1. The former was recommended in 2001 and was enforced by laws and regulations on ceiling in 2014 by the Ministry of Land, Infrastructure and Transportation in



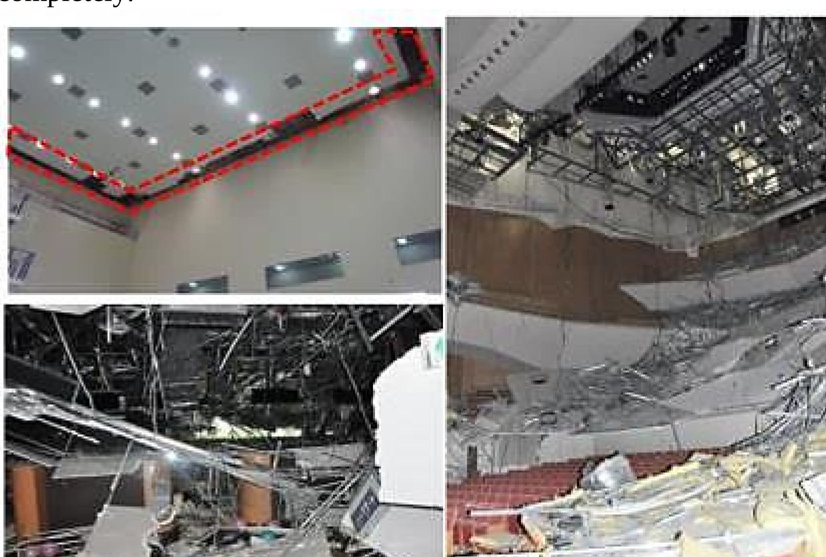
Photos.2 JPN style ceilng



(a)with spacing and braces (b)w/o spacing or braces
Fig.1 JPN style ceiling

Japan. In case of a ceiling with artificial spacing, braces are also required to be set in order to prevent the ceiling from swinging as shown in Fig. 1(a). An inertia force on the ceiling surface in an earthquake is transmitted to a main frame via steel furring and those braces. In this process, the concentration of stresses occurs on the connection parts near those braces and the parts are likely to be detached when they do not have enough strength. We have already found the detachment behavior of connection parts occurred under not only vertical loading but also horizontal loading in Reference [1,2]. In fact, damaged ceiling had been constructed with connection parts which didn't have enough strength. Therefore, it is consistent to consider the concentration of stress and low strength of the connection parts are the reasons why this type of ceiling fell down. On the other hand, in case of a ceiling without spacing, it is via points of contact between a ceiling surface and surrounding components like walls that an inertia force is transmitted to a main frame. See Fig. 1(b). Therefore, any extraordinary stress should not be considered to act on the connection parts. However, in reality, some ceilings of this type did fall down due to detachment of connection parts in the recent earthquakes including the Great East Japan Earthquake.

Photos.3 show the damage examples of ceiling without perimeter spacing in the Great East Japan Earthquake. Based on the technical announcement on ceiling by the ministry in Japan in 2001, pounding of a ceiling to its surrounding walls is supposed to cause the fall of the ceiling. Because of this, the announcement advised that the clearance should be layouted between them. However, it is unlikely that such a great impact force as to make a ceiling fall is caused by the pounding when the ceiling is initially contact to the walls. So, there should be other reasons why the ceiling fell down. The cause of this detachment has not been fully explained yet, even though many researchers have tried to simulate the failure of such ceilings by shaking table tests. Those explanations include too weak perimeter walls (See Photo.2 (b)), complicate shape of ceiling (Photo.2(c)), bad construction and so on. One of the most convincing opinions is the existence of unavoidable spacing in construction. In this paper, to distinguish the unavoidable spacing from the artificial spacing, the former is designated "Gap" and the latter "Clearance". We postulated the ceiling failure was caused by the impact forces which occurred at pounding of the ceiling with gap at such elements like walls. According to our postulation, Ishihara et.al, reported the ceiling with the gap had fallen down as a big block in their shaking table tests [3] though what they considered spacing was not as small as what is normally considered as such. As an example, see Photo.3 (a) which shows the ceiling in a clean room. It is obvious that this ceiling has no spacing, if any, due to the sealability of a clean room. This ceiling did not fall down completely like the examples in Photo.3 (b) and (c). But the most important issue here is not the magnitude of damage but the fact that suffering damage occurred. Once ceilings suffer from any damage, those damages may make progress during an earthquake. It can be said that it's only fortuity that the damage did not progress and the ceiling did not fall completely.



(a) Lab. (Clean room) (b) Sport Entertainment (c) Concert hall
Photos.3 Damage examples of ceilings w/o clearance in the Great East Japan Earthquake

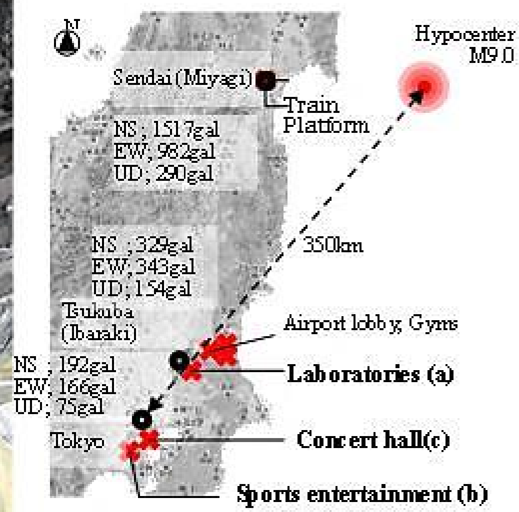


Fig.2 Map of damaged ceiling examples

We focus on dynamic behavior of large-sized ceilings without clearance, supposing any unstable behavior of ceilings should cause detachment of metal connection parts. The ceilings suspended by longer hanging bolts are mainly discussed here, because in the past shaking table tests, the only test specimen was a small-sized standard ceiling with the same pitch and length of hanging bolts, and with the same layout of steel furring. In this paper, it is postulated that an actual ceiling fall-down is caused when any unstable situation occurs in the ceiling system and connection metal falls down, not always with a small-sized ceiling with ordinary specifications. The hypothesis is based on the fact that most existing ceilings do not have such clearance but it is not all of them that did fall down. The hypothesis is verified throughout some numerical results.

2. Preliminary study of ceiling without clearance

In case of ceiling without clearance, an inertial force in an earthquake is transmitted via ceiling surface to its surrounding walls directly. In this chapter, the experimental results to make sure of such transmission mechanism and the numerical results to clarify the buckling behavior of the ceiling surface subject to static uniaxial compression are shown.

2.1 Shaking table test of ceiling without spacing

To examine the transmission of an inertia force on a ceiling surface to a wall via a contact point, we have executed the shaking table test by E-defense using a full-scaled five-story steel building in which a test specimen of ceiling was installed. Photo.4 shows the full-scaled steel building of which the ceiling was installed at the top floor enclosed by red line. The specification of the ceiling is shown in Fig.3. Three load cells on its each edge are set in the space between the ceiling and walls to measure forces transmitted from the ceiling surface to the walls. The location of load cells is shown in Fig.3 and the detail of setting load cells is shown in Photo.5. The input acceleration is 70% of the acceleration recorded at Takatori in the Kobe earthquake.

Experimental results are shown in Figs.4. Fig.4 (a) is the time history of the response acceleration measured on the ceiling surface and the roof slab from which the ceiling is hung. Fig.4 (b) is the inertia force calculated by multiplying the mass of ceiling and the acceleration on the ceiling surface and the sum of forces measured by load cells. From these results, it is understood that the acceleration on the ceiling surface is almost the same as the one on the roof slab, and that the inertia force on the ceiling surface balances the amount of forces by load cells, which is the force transmitted to walls. However, these characteristics are not always observed. It is considered that the former appeared since the natural frequency of the ceiling-walls system belongs to the so-called rigid vibration region owing to the high rigidity of walls in the present test specimen. If the rigidity of walls were not so great, the natural frequency might belong to the so-called damping vibration region and the acceleration on the ceiling surface might be much greater than the one on the slab. Conversely, surrounding walls should be designed as such that the walls have enough stiffness.

Photo.4 Full-scaled 5-story building

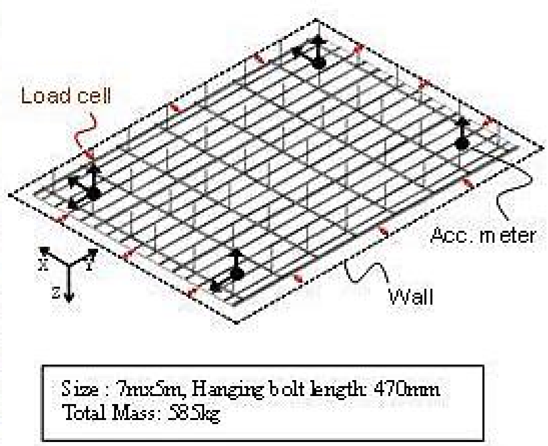


Fig.3 Test specimen of ceiling

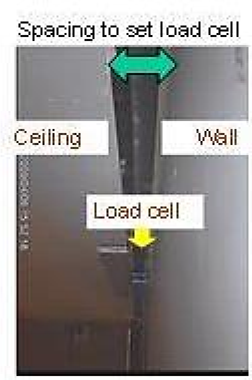


Photo.5 Detail of Load cell

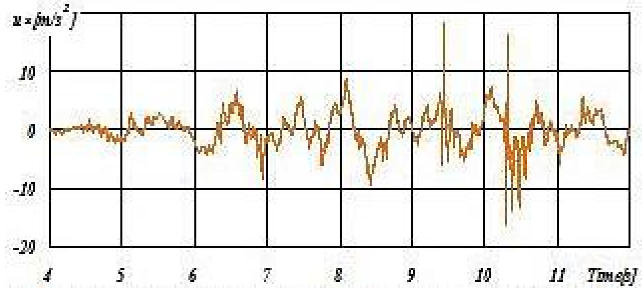


Fig.4(a) Time history of acceleration recorded on roof Slab and ceiling surface

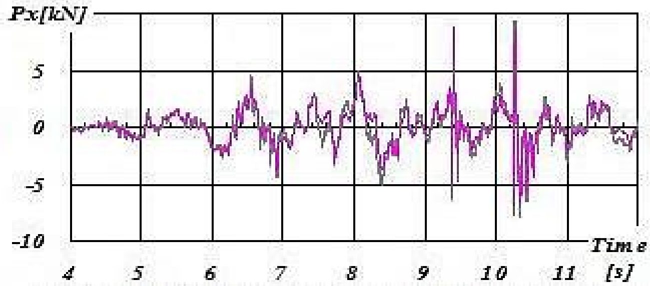


Fig.4(b) Time history of inertia force and One measured by load cell

2.2 Buckling behavior of ceiling surface subject to static compression

Fig.5 shows the test specimen for the static compression experiment. The length of hanging bolts is 1,500mm. Fig.6 shows the relationship between the compression force per unit width and the shortening of ceiling. Both experimental and numerical results are shown in this figure, and the black line is an experimental result and the red line is a numerical results. And Photos.5 show the deformed shapes after the maximum compression strength by experiment and numerical. It is observed that both of the load-displacement curves and deformed shapes agree with each other. This fact means that the present numerical model is appropriate to simulate the

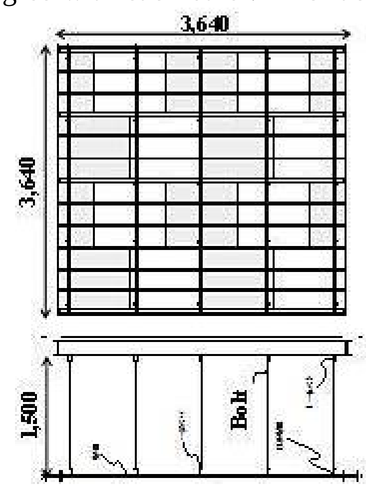


Fig.5 Test specimen of static compression test

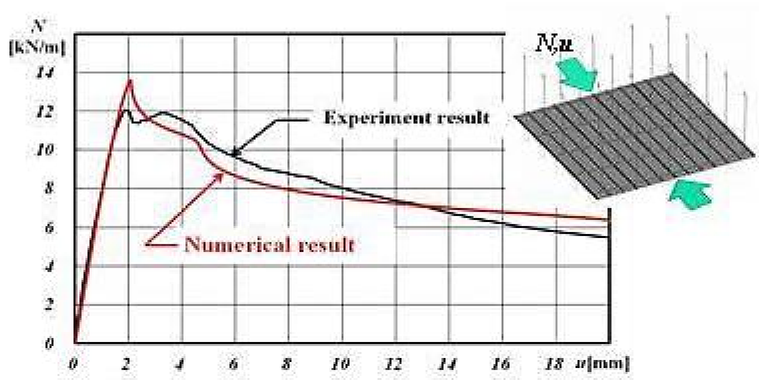
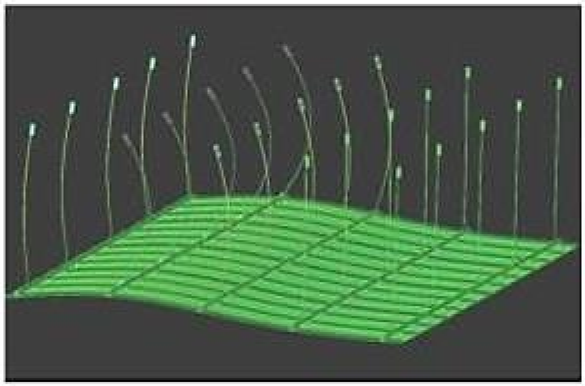


Fig.6 Compression-shortening curve

(a) Experimental result



(b) Numerical result

Photos.5 Deformed shape

collapse behavior of ceilings. Fig.7 (a) shows the compression-shortening curves for various bolt lengths based on the above numerical models and Fig.7 (b) shows the relationship between the maximum compression strength and bolt length. It is understood that the bolt length has the great influence on the maximum compression strength.

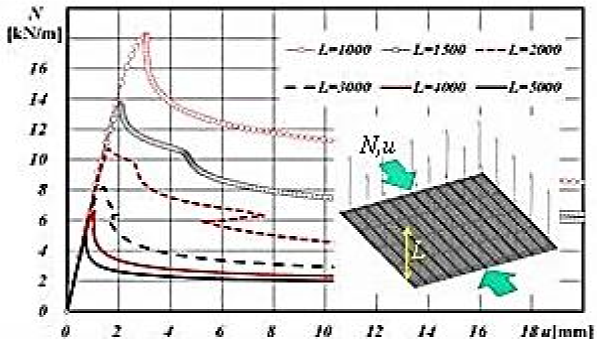


Fig.7 Compression-shortening curve for various bolt length

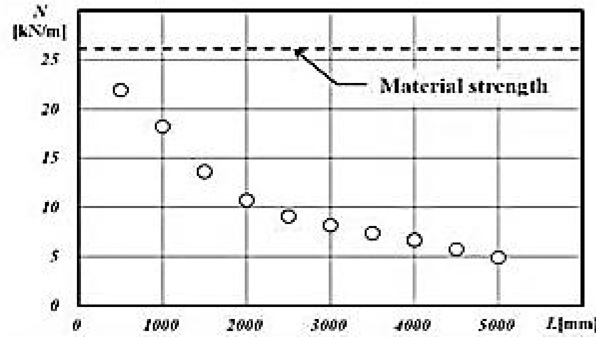


Fig.8 Relationship between Maximum compression strength and bolt length

2.3 Consideration

With an actual damage example, we examine whether it is possible to predict the damage based on the results in section 2.1 and 2.2. Fig.9 is a response acceleration spectrum (damping factor=2%) for an acceleration recorded by K-net at the nearest point from the target building in which a ceiling suffered from damage as shown in Photo.6. The target building is one-story steel one and its natural period measured for a micro tremor is about 0.5 sec. Therefore, the maximum response acceleration is considered to be 15m/sec^2 even if we make high estimate of it. And according to the result in 2.1, the acceleration on the ceiling surface is assumed to be the same as that of the building. The inertia force on the ceiling surface can be calculated by multiplying the acceleration value and the total mass of ceiling (7800kg=26mx30mx10kg/m2) and its value per unit width becomes 4.5kN/m. On the other hand, the maximum compression strength approximately becomes 12kN/m from Fig.8 with 1.8m of bolt length. As a result, the ratio of the maximum force acts on the ceiling surface to the maximum compression strength becomes 1/2.7 and we judge the ceiling has enough strength for the estimated inertia force. However, it contradicts the fact that the ceiling fell down in reality. It is obvious that it is impossible to predict the failure of ceilings based on only the results in section 2.1 and 2.2.

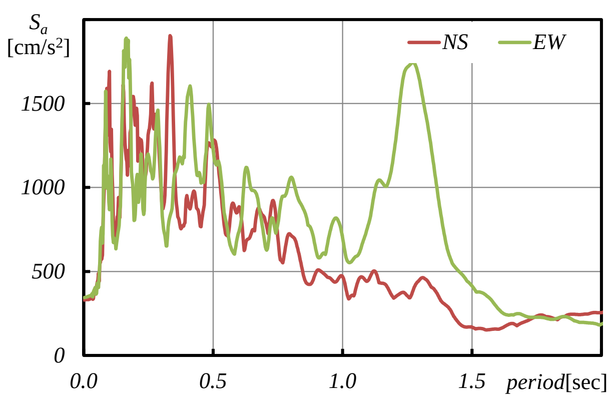


Fig.9 Acceleration response spectrum(h=2%)

Photo.6 Ceiling fall in the target building

The reasons of such contradiction are considered to be the following.

- #1: The acceleration at the site is greater than the recorded one at K-net by the local effect of ground motion.
- #2: The lack of stiffness of walls makes a natural frequency of the ceiling-wall system small and the response acceleration on the ceiling surface becomes greater.
- #3: The gap is not uniform due to bad construction and greater compression acts locally.
- #4: Greater stresses act on metal connection parts by some dynamic unstable phenomena and metal connection parts detach.

All of them are issues to solve urgently. In this paper, we consider Reason #4 and examine it in the following section.

3. Unstable behavior of ceiling subject to dynamic force

The object in this chapter is to show the possibility that the failure is caused by unstable behavior of a ceiling subject to dynamic loads. Here, two-dimensional models are applied for the sake of convenience though three-dimensional models were applied in section 2.2.

3.1 Explanation for unstable behavior under static compression

Here, we explain the unstable behavior under the static compression in detail as shown in section 2.2. Figs.10 show the compression-shortening curve (top) and the transition of axial forces in hanging bolts (bottom) for a ceiling with 3,000mm of bolt length.

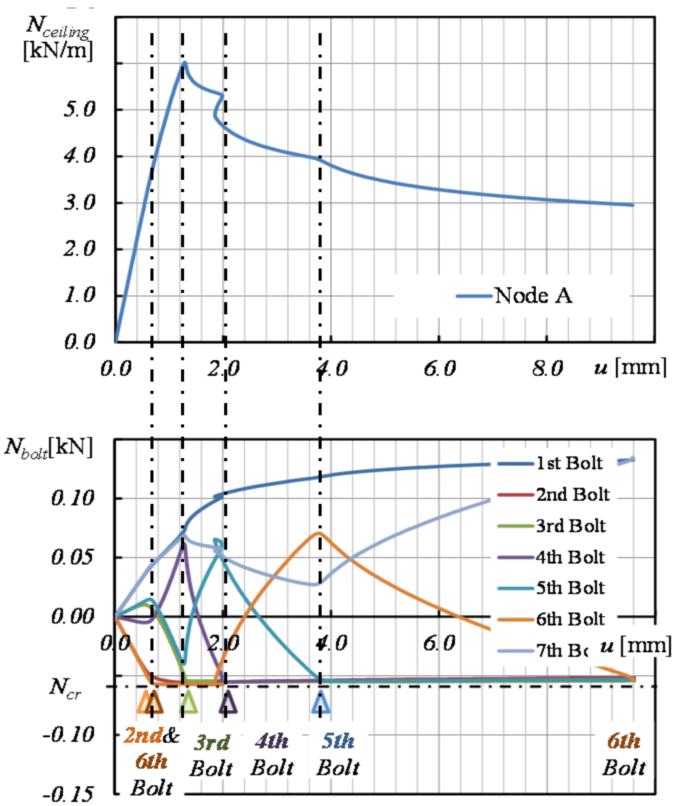


Fig.10 Compression- shortening curve (Top)
And Axial forces in bolts (bottom)

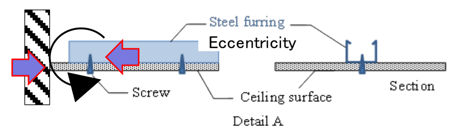


Fig.11 Detail of supproting point at end of ceiling

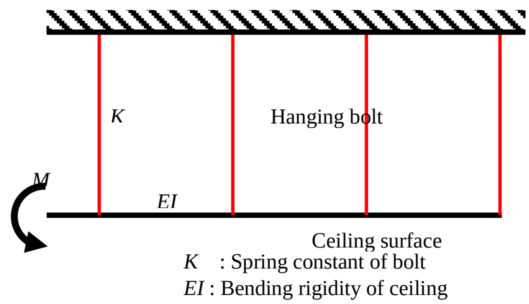


Fig.12 Continuous beam model

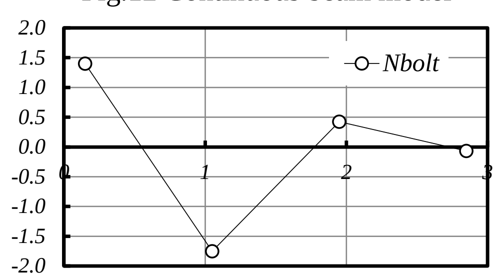


Fig.13 Distribution of axial force in hanging bolt

In Fig.10, the most significant characteristics are as follows.

- #i Axial forces in hanging bolts occur initially.
- #ii Any changes appear in the compression-shortening curve whenever axial forces reach its buckling strength.
- #iii Particularly, the compression strength reaches the maximum value when the axial force of the third hanging bolt reaches the buckling strength.

The reason of characteristic #i is caused by an eccentricity between a centroid of a cross section made of a gypsum board and a steel furring and a supporting point as shown in Fig.11. The supporting point is on a centroid of the gypsum board. Supposing that the Bernoulli-Euler's assumption is hold for the composite cross section, the eccentricity e can be expressed as

$$e = \left\{ 1 + \frac{E_g A_g}{E_s A_s} \right\}^{-1} d \tag{1}$$

where d is a distance between each centroid of a gypsum board and steel furring, and E_g, E_s, A_g and A_s are the Young's modulus and a section area for a gypsum board and steel furring respectively. Substitution of each datum gives 8.0mm as the value of eccentricity. The eccentric moment by this eccentricity can be calculated by multiplying the compression force in ceiling surface and the eccentricity. Now consider a simple continuous beam problem laterally braced by springs (See Fig.12). By making use of the Clapeyron's theorem of three moments, the distribution of axial forces in hanging bolts as shown in Figs.13 can be obtained. This result agrees with the tendency in Fig.10 and the eccentric moment has great influence on axial forces in only two hanging bolts from the end of ceiling in the initial loading state. At this time, the ratio of axial force $N_{bolt\text{-}i}$ in i-th hanging bolt to the compression in ceiling surface N_{ceilig} can be calculated as

$$\frac{N_{bolt-2}}{N_{ceiling}} = 0.0112 \qquad \frac{N_{bolt-3}}{N_{ceiling}} = 0.0141 \qquad \frac{N_{bolt-4}}{N_{ceiling}} = 0.0034 \tag{2}$$

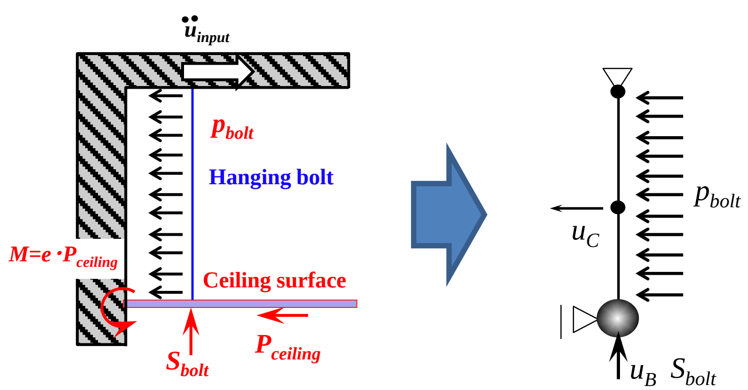
3.2 Dynamic analysis of only hanging bolt

Next, based on the results in the previous section, consider only a hanging bolt extracted from a ceiling system and examine a unstable phenomenun subject to dynamic forces. External forces act on a hanging bolt are 1) an inertia force act on the mass of hanging bolt p_{bolt}, 2) a vertical force generated by the eccentric moment S_{bolt}. The two of forces can be expressed in the form;

$$p_{bolt} = m_{bolt}\ddot{u}_{input} \tag{3}$$

$$S_{bolt} = {}^{s}S_{bolt} + {}^{d}S_{bolt} \qquad {}^{s}S_{bolt} = -{}^{local}M_{ceiling}\, g \qquad {}^{d}S_{bolt} = \alpha\, {}^{total}M_{ceiling}\, \ddot{u}_{input} \tag{4}$$

where ${}^{s}S_{bolt}$, ${}^{d}S_{bolt}$ are a static and dynamic component of S_{bolt}, and m_{bolt}, ${}^{local}M_{ceiling}$ and ${}^{total}M_{ceiling}$ are a mass density per unit length of hanging bolt, a local mass of ceiling corresponding to one hanging bolt and a total mass of ceiling respectively. g and $\ddot{u}_{input}$ are the gravity acceleration and an input acceleration which approximately equals to one on the structural frame that suspends the ceiling supposing walls have enough rigidity. And α is a coefficient and is equal to the ratio of axial force in hanging bolt to compression in ceiling surface as shown in Eq.(2). In the above equatoin, a mass of hanging bolt has little influence on S_{bolt} and is neglected.



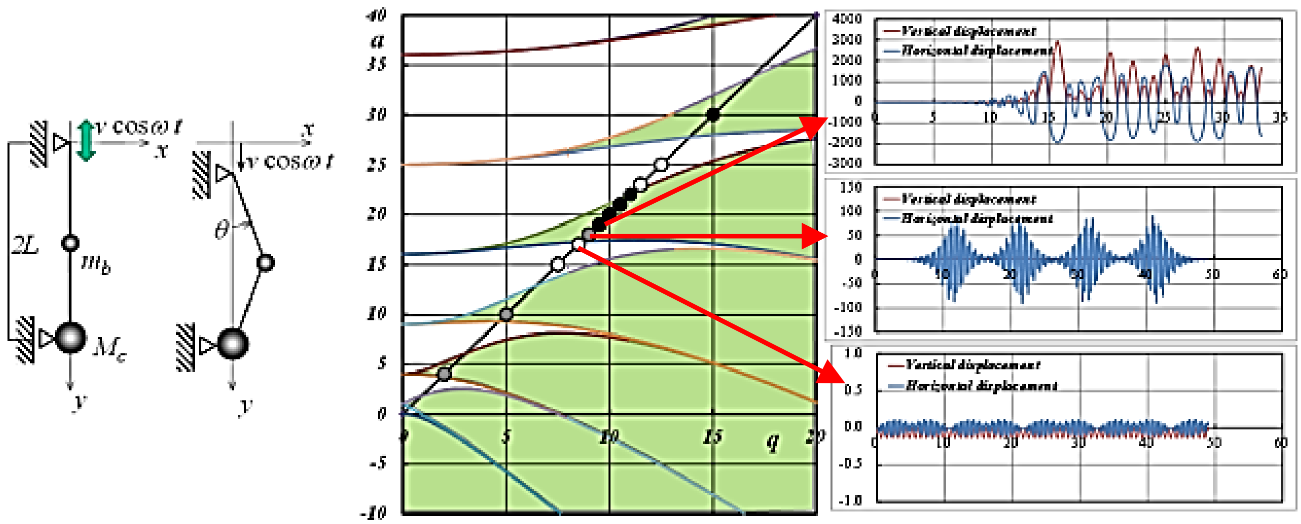
(a)External force act on hanging bolt (b)Analytical model

Fig.14 Extraction of hanging bolt

Now, consider a three hinged model in Fig.15 as a simpler model than one shown in Fig.14 (b). This model means that the bending rigidity of hanging bolt can be neglected under the assumption that the hanging bolt is much longer. Furthermore, p_{bolt} is also neglected though a mass of hanging bolt is taken account. The motion equatoin for the present model becomes to be a well-known Mathieu type equation in the form.

$$\ddot{\theta} + \left(a + 2q\cos 2\tau\right)\theta = 0\,,\qquad a = \frac{4\Omega^2}{\omega^2}\,,\qquad 2q = \frac{\ddot{v}}{g}a\,,\qquad \Omega^2 = \frac{2\,{}^{local}M_{ceiling}\,g}{M_{bolt}L} \tag{5a,b,c,d}$$

where ω and Ω are an angular frequency of input acceleration and a natural angular frequency of the three hinge model. $\ddot{v}$ is an input acceleration in the vertical direction at the top of the model. *Strutt*'s diagram for this model is shown in Fig.15 (b). In this figure, ■ represents an unstable region. A straight line (a=2q) means $\ddot{v}$ is equal to *g*. Refer Eq.(5c). Therefore, the half amplification of input acceleration is greater than the gravity acceleration in the right hand side of this line. ○●● on the line are points actually calculated as examples and colors of them (white, grey, black) mean numeircal results at the points become stable, little unstable or unstable as shown in Fig.15 (c).



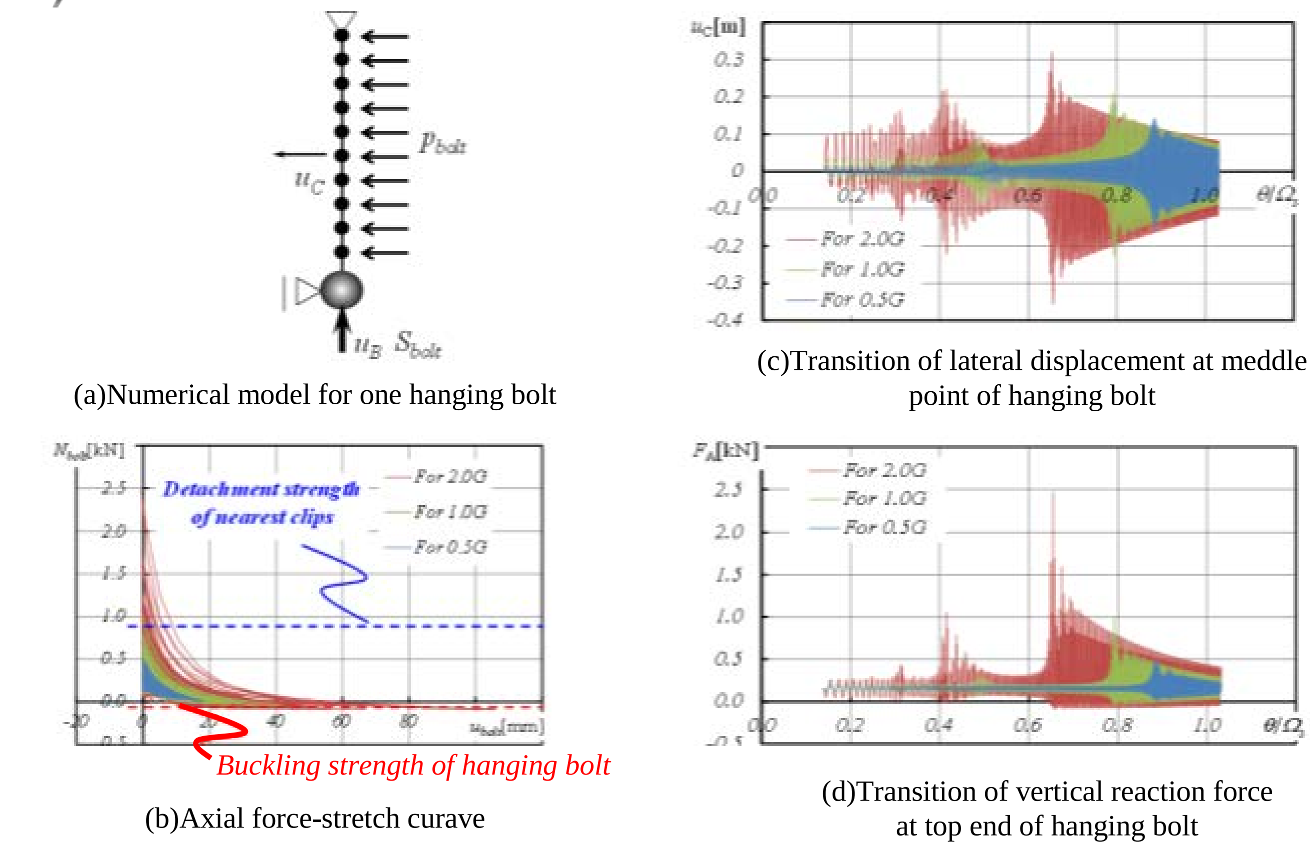
(a)Analytical model (b)Strutt's diagram (c)Examples

Fig.15 Three hinge model

It can be understood from Fig.15 (b) that the unstable area grows wider as *a*/2*q* becomes small. In the hanging bolt, *a*/2*q* can be expressed by making use of Eqs.(4) and (5) as

$$\frac{a}{2q} = \left(\frac{v}{g}\right)^{-1} = \frac{1}{\alpha}\frac{1}{n}\frac{1}{G}\qquad n \cong \frac{{}^{total}M_{ceiling}}{{}^{local}M_{ceiling}}\qquad G = \frac{\ddot{u}_{input}}{g} \tag{6}$$

where *G* is a seismic intensity coefficient and *n* can be approximately equal to the number of hanging bolts in a target ceiling system. From Eq.(6), as the number of hanging bolts increase (in other words, ceiling becomes larger), hanging bolts easily fall into the unstable situation. It should be noted that the unstable area in Fig.15 (b) is obtained by neglecting a damping effect. When taking account of the damping effect, the unstable area shrinks. Furthermore, even if *a/2q*, which means input acceleration is greater than gravity acceleration, is less than 1.0, the three hinge model does not always fall into the unstable situation since the stable area exists in the right hand side of the straight line. Whether the three hinge model becomes unstable depends on the natural frequency of a lateral vibration of the system.



(a)Numerical model for one hanging bolt

(c)Transition of lateral displacement at meddle point of hanging bolt

(b)Axial force-stretch curave

(d)Transition of vertical reaction force at top end of hanging bolt

Fig.16 Dynamic analysis results by standard numerical model

Finally, numerical examples by the model for one hanging bolt in Fig.14(b) are shown. Fig.16(a) is a present numerical model which consists of one hanging bolt divided with 10 corotational beam elements[4] and one concentrated mass at the bottom of the hanging bolt which represents the mass of ceiling surface supported by the hanging bolt. The outer (effective) diameter and length of hanging bolt is 9mm (7.5mm) and 3m respectively. The mass density per unit length of 0.5kg/m is taken account for each beam element. The value of concentrated mass is set to be 16 kg under the assumption that the mass density per unit area of a ceiling surface is 20kg/m2 and hanging bolts are arranged at 0.9m x 0.9m. Now, we consider p_{bolt} and ${}^{d}S_{blot}$ on each nodal mass as inertia forces simultaneously after the static vertical load ${}^{s}S_{bolt}$ act on the bottom of the hanging bolt. The damping proportional to rigidity is assumed and the value is set to be 2% for the first mode. HHT-α method is applied to the time integration and time interval is 0.00125sec. Fig.16(b)-(d) shows numerical results for the model of hanging bolts subject to sweep wave of acceleration with three kinds of constant amplification (0.5G, 1.0G, and 2.0G) and from 0.5Hz to 3.7Hz of frequency respectively. Fig.16 (b) is the relationship between the axial force and shortening of hanging blot. In Fig.16 (b), a red dashed line is the buckling strength and a blue dashed one is the detachment strength of nearest metal connection parts. In Figs.16 (c) and (d), the horizontal axis is the ratio of the frequency for the input acceleration to the natural frequency of this model and the vertical axis in each figure is the horizontal displacement at the middle point of the hanging bolt or the vertical reaction force at the top end. It can be observed that longer hanging bolt oscillates with the larger amplification as shown in Fig.16 (c). However, the magnitude of amplification is not proportional to the magnitude of input acceleration and the frequency at the maximum lateral displacement is different from each other. These facts mean the hanging model behaves as a nonlinear system. Such nonlinear behavior is caused with instability of hanging bolt. As a result, the tensile axial force in hanging bolt becomes too great for a few nearest connection parts to carry it. Consequently, the connection parts detach immediately after the axial force yields the detachment strength of them.

4. Conclusion

In this paper, we suggested that the unstable behavior of a ceiling system without spacing at the perimeter of the ceiling surface subjected to a dynamic disturbance was the reason why such type of ceiling system had fallen down during earthquakes. To make sure of the validation, we conducted several experiments and numerical analyses. The results obtained with them are summarized as followings.

#1 The horizontal acceleration at a ceiling surface without the spacing is close to one at the floor/roof structure where ceiling is suspended if the surrounding wall has enough stiffness.

#2 The ceiling system of which bolt length and surface area are neither so longer nor so wider, is stable under the dynamic disturbance.

#3 Unstable behavior of a hanging bolt has the great influence on the stability of ceiling surface under the compression. And the compressive axial force (vertical force) on a hanging bolt is caused by an eccentricity between a centroid of a ceiling surface and a supporting point even if only the horizontal force acts on the ceiling system.

#4 The dynamic unstable behavior of a hanging bolt may be explained by Mathieu type equation. The fact means the hanging bolt behaves as a nonlinear system. For examples, the axial force or lateral/vertical displacement of hanging bolt are not proportional to the magnitude of input acceleration.

#5 Especially in case of the longer hanging bolt, Such instability of the bolt may easily cause bigger tensile axial force in hanging bolt than the detachment strength of the connection parts near the hanging bolt. So that, it is important to avoid the dynamic unstable behavior of a hanging bolt from the view pint of mitigation of the ceiling failure during earthquakes.

However, we couldn't present the influence of unstable behavior of hanging bolt on the stability of ceiling surface quantitatively. Furthermore, we have not observed the dynamic unstable behavior of a hanging bolt experimentally. These are future works for us.

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