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THE BEHAVIOR OF CEILING WITH STEEL FURRING DURING EARTHQUAKES

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ABSTRACT

In the Great East Japan Earthquake, many ceilings were damaged in the northern Pacific coast area including the Tokyo area and some people were injured and killed by ceiling failures unfortunately. Furthermore, after the shock, it took a long time to restore ceilings. The fact let us know it was a problem of great urgency to reduce such damage of ceilings from the view point of the business continuity plan. We focus on the Japanese style of ceiling with steel furring. The damage patterns of such ceilings are classified into two categories. One is that ceiling surface falls in a great mass and another is that a part of ceiling board falls in the circumference of ceiling. We show that each pattern of damage is caused with a quite different reason.

Introduction

The significant damage of ceiling had been observed in the recent earthquakes of the 2001 Geiyo earthquake, the 2003 Tokachi-oki earthquake, the 2005 Miyagi-ken-oki earthquake and so on. We had experienced that ceiling failure injured or killed persons during an earthquake and impaired functions of buildings after earthquakes. The similar but much greater scale of ceiling failures occurred at the Great East Japan Earthquake happened on 11th of March, 2011 though we had cautioned about such risk through our research. Many engineers had misunderstood that ceiling failures had been caused by the bad construction and they had not examined their consideration had been true or not. After 3.11, the situation changed completely.
The epicenter of the Great East Japan Earthquake was off the coast of Miyagi prefecture and its magnitude was over 9. A lot of ceilings were damaged at wide area in the northern Pacific coast including the Tokyo area far from the epicenter (Fig.1). Such damages revealed the fact that many existing ceilings might fail under not so great earthquake. After then, the Architecture Institute of Japan or the Ministry of Land, Infrastructure, Transport and Tourism begun to tackle the mission to mitigate ceiling failures. Some committees have been set up to make a draft of the seismic code for ceiling. One of authors participates in such committees.
There are two types of ceiling system as the Japan style and the western (US) style. The Japan style one is more popular than the western style. Regarding the extent of damage, the damage of the Japan style one was much severer than the western one quantitatively and qualitatively. Then we have focused on the Japan style of ceiling. We have studied the performance of the ceiling during earthquakes through experimental and numerical results until now. Recently we have found out the reason why ceiling fell down. In Fig.2, the Japan style of ceiling is shown. The Japan style one consists of steel furring and gypsum board. Its standard weight per unit area is approximate 150kN/m^2. The Japan style one is heavier than the western one because a urethane board is used in the western style one instead of a gypsum board in Japan. The heavier weight causes severer damage in the Japan style one. The most important feature of the Japan style is the existence of unique metal joint parts which are called "hanger" and "clip" as shown in Fig.2. Though these metal parts have the enough strength to carry the self-weight of ceiling, it is known that they can be easily detached by horizontal force by an earthquake.

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In this paper, we classify the damage patterns of ceiling into two categories. One is that ceiling surface falls in a great mass and another is that a part of ceiling board falls in the circumference of ceiling. We show that each pattern of damage is caused with a quite different reason.

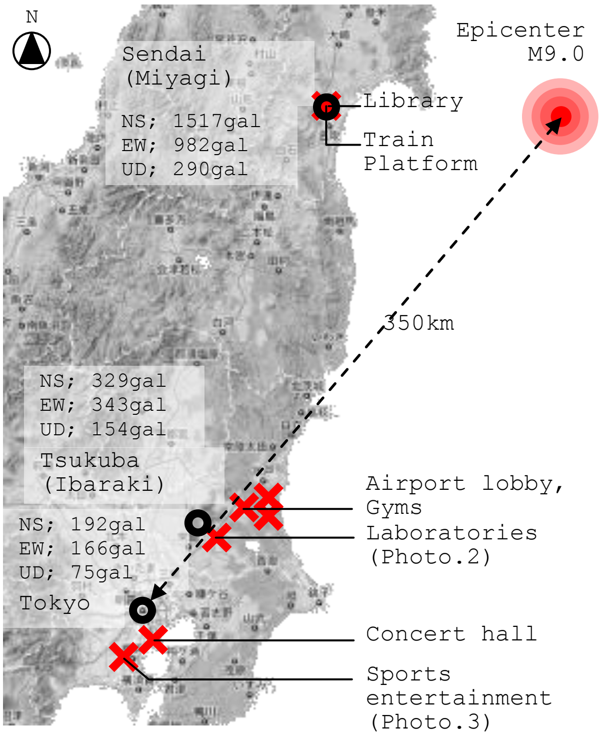


Figure 1 Map of ceiling damages examples by Great East Japan Earthquake

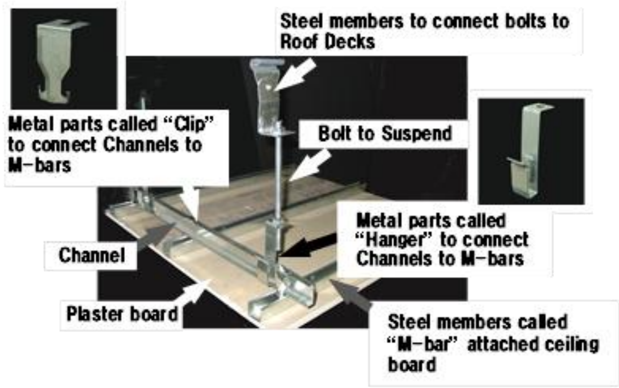
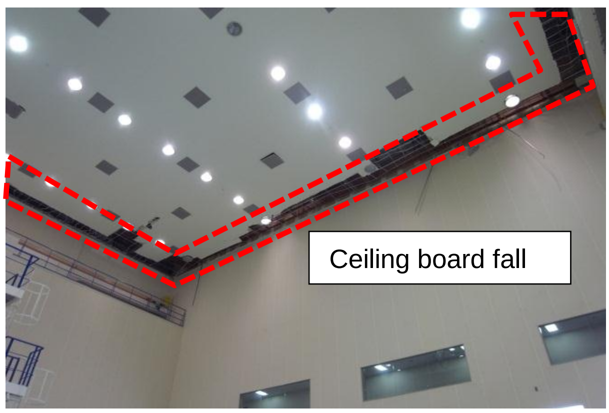


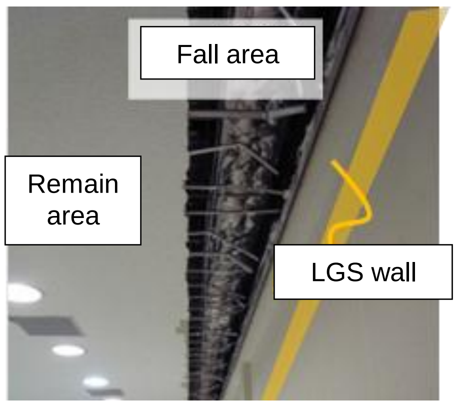
Figure 2 Japan style of ceiling

Damage Patterns of Ceiling in Earthquakes

In this section, two typical damage patterns of ceiling are shown. First one is that a part of ceiling board falls in the circumference of ceiling and another is that ceiling surface falls in a great mass. The occasion for each pattern of damage is quite different. The former is caused by the buckling behavior of ceiling surface while the latter is by the detachment behavior of metal joint parts between steel furring. The reason is obvious from the observation of the damage condition. However, the patterns of damage are not always independent each other. In the most tragic ceiling failure, one pattern of damage transitions into another pattern.
The first example in Photo.1 and 2 is the damage of ceiling boards at the laboratories in Tsukuba. The peak of horizontal ground acceleration was recorded 343cm/sec^2. As shown in Photo.2, only gypsum boards fell down and steel furring remains original position though it have buckled. At the circumference area of ceiling, the membrane compressive stress is greater than one at other area since an inertia force on the ceiling surface accumulates. Then, the ends of ceiling are easy to suffer damage generally.
The second in Photo.3 is the ceiling damage at an airport in Ibaraki. In this case, the ceiling fell down in the

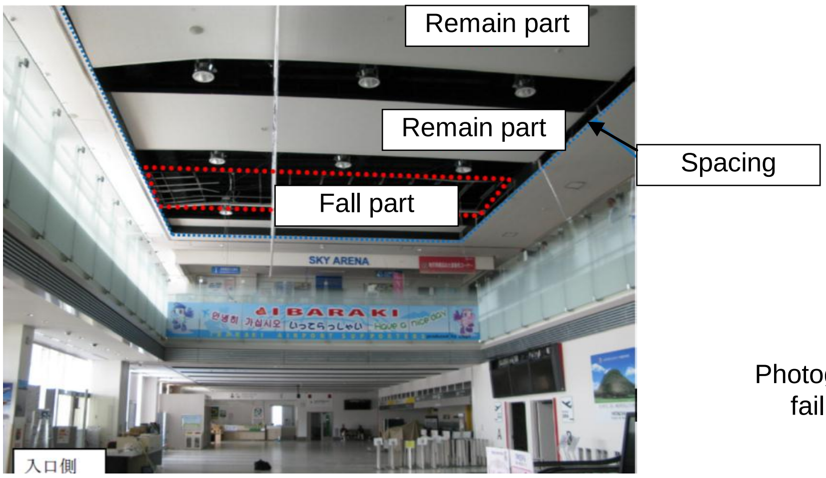


Photograph 1 Pattern 1 of ceiling failure



Photograph 2 Pattern 1 of ceiling failure

great mass and both gypsum board and steel furring fell down. This pattern of damage is caused by the detachment of metal joint part called “Clip”. Once the detachment of “Clip” occurs, the chain of the detachment can easily happen. As a result, ceiling falls in the great mass. The spacing between ceiling and the surrounding component can be seen. And bracing members are set for ceiling not to swing during an earthquake. The method with the spacing and bracing members are recommended by the Ministry of Land, Infrastructure, Transport and Tourism (ML IT).
The last example in Photo.4 is the ceiling damage at the top floor of an eight-story building in Yokohama. A few persons were injured. The peak of horizontal ground acceleration was recorded 165gal. The roof of the building is formed by truss beams that cover over 34m span. In this case, there were not spacing. The surrounding wall also suffered serious damage. I guess that the ceiling which had lost counterparts fell down.



Photograph 3 Pattern 2 of ceiling failure in which is caused by detachment of Clip

Photograph 4 Ceiling failure by combination of Pattern 1 and 2

Structural Characteristics of Ceiling Surface under Static Loading

In the previous section, we showed two typical damage of ceiling. We have already published the characteristics of metal joint parts used at the connection between steel furring and the mechanism/process of damage. Then, we focus on the characteristics of ceiling surface. Especially, consider why/how a ceiling surface buckles.

Compression Test of Ceiling Surface

At first, the compression test of ceiling surface was executed. Fig.3 shows test specimen. The ceiling surface is made of gypsum boards (thickness: 9.5mm) which are attached to M-bars by screws and the steel furring members are suspended with bolts of which outer diameter is 9mm. The spacing of bolts is about 850mm and its length is 1,500mm. As the stress condition on the ceiling surface becomes the uniform uniaxial compression state, the displacement on one edge is controlled by using the H-shaped beam (H-400x400) while another opposite side of edge is fixed by using the same size of H-shaped beam as shown in Photo.5.
Fig.4 shows the relationships between compressive resultant stress and stretch for the respective direction load. The compressive resultant stress means the compressive force by unit length. According to the results, the maximum compressive strength reaches to about 12kN/m. After the maximum strength, the compressive force decreases immediately. The deformation at the post maximum strength shows in Photo.6. It can be understood that both ceiling surface and hanging bolts buckle.

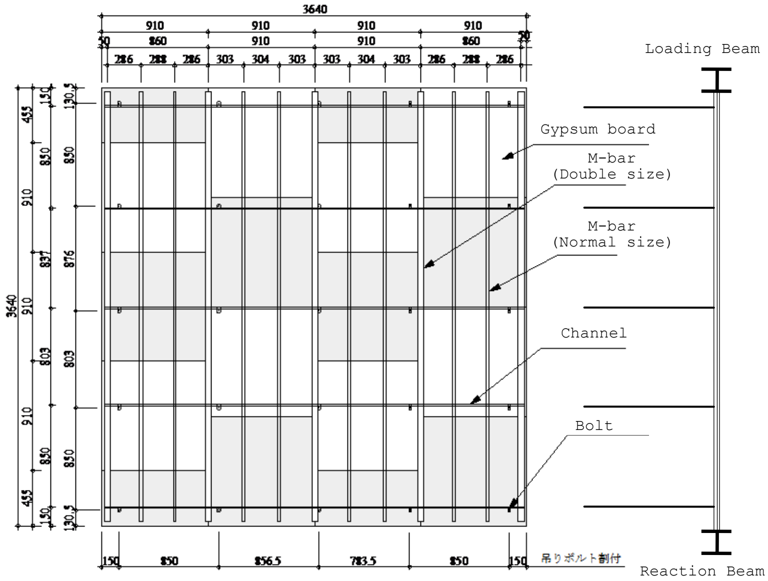


Figure 3 Test specimen

Photograph 5 Loading edge

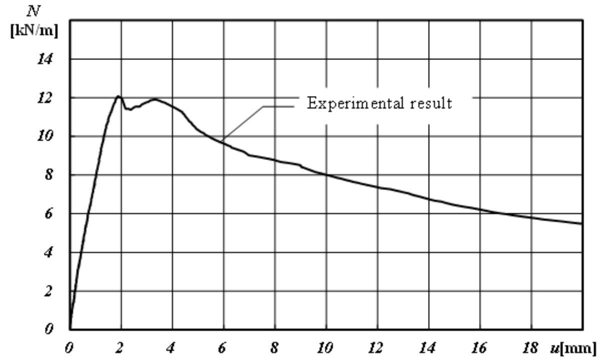


Figure 4 Compression vs. shortening

Photograph 6 Deformation after peak

Unfortunately, the compression test was executed only for one test specimen. So, the process to collapse is not obvious through the test result. Is the maximum compressive strength determined by instability of ceiling surface? Of course, it is right but it should be considered why ceiling surface falls into the unstable condition.

Numerical Analysis for Compression Test of Ceiling Surface

Here, we investigate the unstable behavior of ceiling surface under uniaxial compression force by numerical analysis. To validate a numerical model, we compare the numerical result with the experimental result. See Fig.5 shows the relationship between compressive resultant stress and shortening. The numerical result is close to the experimental one. And the deformation by numerical analysis also agrees with the observed at the experiment (See Photo.6 and Fig.6). Then, the present numerical model can be considered to be appropriate.

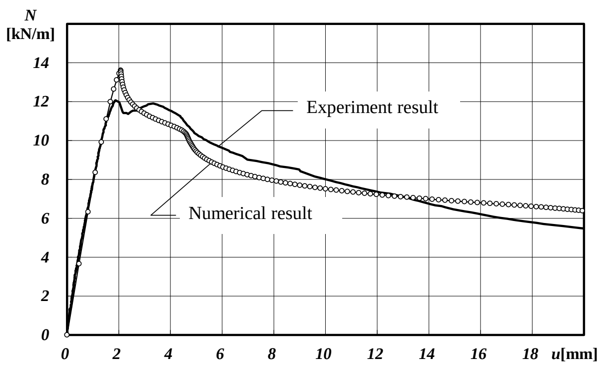


Figure 5 Comparison of numerical and experimental results

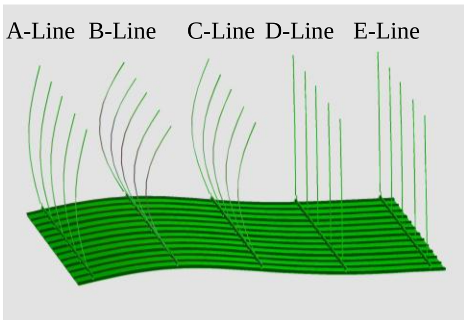


Figure 6 Deformation by numerical

Using the above model, the results obtained by using models with various lengths of bolts are shown in Fig.7. The longer bolts become, the less the compression strengths of ceiling surfaces become. The relationship between compression strength and bolt length is shown in Fig.8. Fig.9 shows the relationship between axial forces on bolts and the shortening of the ceiling surface. By comparing Fig.7 with Fig.9, the maximum compression strengths are determined with the buckling of bolts. Namely, the ceiling surface falls into unstable condition when the bolts buckle. The reason is that the restriction effect of bolts on the out-of-plane deformation of ceiling surface vanishes as soon as bolts buckle. Then, though the longer bolts are sometimes used, a ceiling surface with such bolts is more dangerous than one with the shorter bolts. A lot of engineers think the stress acts on a bolt is tensile and its slenderness ratio is meaningless. However, it is understood that the thought is entirely wrong through the numerical results. The strength of the bolt can be calculated with the formula of Euler's buckling for the pin ended column (Solid line in Fig.10).
The compressive strength of 12kN/m for the bolt length of 1,500mm (See Fig.8) is enough to resist the inertia force by an earthquake. For example, supposing the mass per unit area of ceiling surface [m] and response acceleration on ceiling surface [S_a] are 15kg/m^2 and twice of the gravity (2x9.8m/sec^2), the limit of ceiling length L_{limit} can be calculated as following.

$$mL_{limit}S_a < N_{max} \qquad L_{limit} < \frac{N_{max}}{mS_a} = \frac{12{,}000^{\mathrm{N/m}}}{15^{\mathrm{kg/m^2}} \times 19.6^{\mathrm{m/sec^2}}} \cong 40\,\mathrm{m} \tag{1}$$

If this result is true, why the Japan style of ceiling smaller than L_{limit} fell down in earthquakes as shown in Photos.1 and 2? It is thought that the cause of ceiling failure is the impact force generates when ceiling surface collides with a surrounding component like a wall. In this section, the spacing between ceiling surface and the surrounding components is supposed to be zero. But, it is impossible to set the spacing to zero and there is always some unavoidable spacing by the gap of construction actually. So, we investigate the relationship between the spacing and the impact force in the next section.

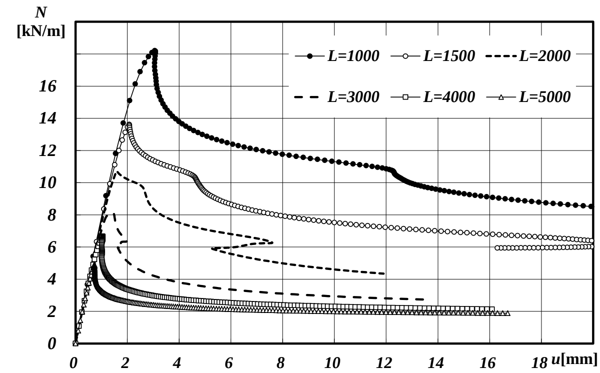


Figure 7 Influence of bolt length

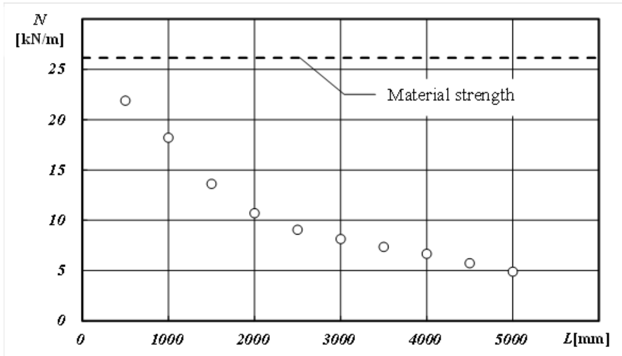


Figure 8 Relationship between compression strength of ceiling surface and bolt length

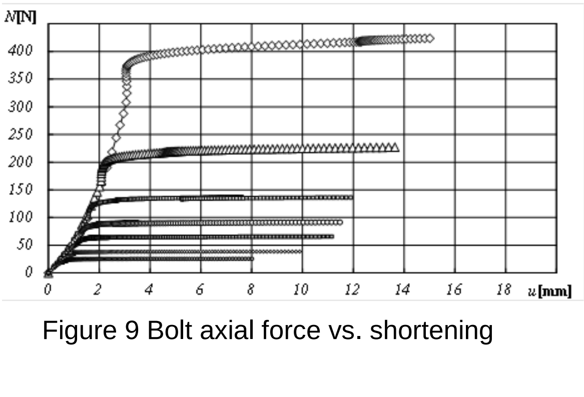


Figure 9 Bolt axial force vs. shortening

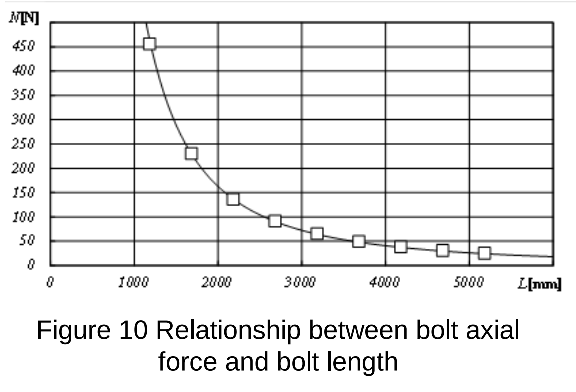


Figure 10 Relationship between bolt axial force and bolt length

Impact Force at the End of Ceiling Surface

Now consider the simple model with one mass and two springs as shown in Fig.11 where M is a mass of a ceiling surface and K is a spring constant which represents a surrounding component. It can be considered that the impact force reaches the maximum value when the situation becomes the stationary vibration condition. Readers can understand the fact is right by imaging an old toy called "Clackers". At the time, the mass repeats pounding and leaving behavior alternately. The assumptions that The natural period of ceiling system is assumed to be infinite because the spring constant as a pendulum is much smaller than one of the surrounding component are introduced for the simplicity. It can be led from this assumption that the time in which the mass keeps in contact state is much shorter than the time in which the mass leave the spring. Similarly, the damping effect to the motion of the mass can be neglected during leaving condition. Then the velocity of the mass during leaving is constant. As a result, the period of the stationary vibration state is determined only with the velocity of the mass.

$$T = 4\frac{d}{v} \tag{2}$$

where T is the period in the stationary condition, d is a spacing and v is a velocity of the mass (See Fig.12). If we can obtain the velocity of the mass, the impact force, F_{impact} can be found by using Eq.(3).

$$F_{impact} = \sqrt{MK}\,v \tag{3}$$

We make use of the balance of momentum before and after collision. Assuming that the value of K is great, the maximum response displacement is nearly equal to the spacing. Then Eq.(2) can be rewritten in the form;

$$T = 4\frac{u_{\max}}{v_{\max}} \qquad T = 4\frac{S_d(T)}{S_v(T)} \tag{4.a,b}$$

where S_d and S_v are the values of displacement and velocity response spectra for target input acceleration.

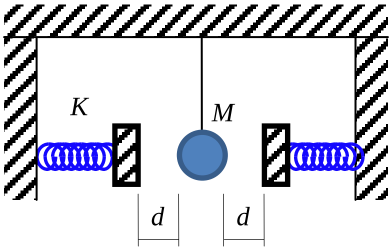


Figure 11 Model

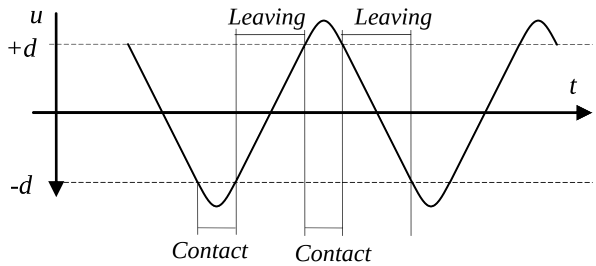


Figure 12 Stationary condition

Strictly speaking, the present problem is not a harmonic oscillator problem. Therefore, Eq.(4.a) is a just approximate expression. However, our objective in this paper is that we show the method which engineers can conveniently estimate the approximate intensity of impact force at the collision. From such view point, the expression of the second equation in Eq.(4) is enough. Though by using Eq.(4.b), we can find the period in the stationary condition, Eq.(4.b) is a nonlinear equation. Here, we suggest the convenient method to find the maximum velocity according to Eq.(4.b). Figs.14 and 15 show the displacement response spectrum and the velocity response spectrum for the target input acceleration as shown in Fig.13. From these response spectra, the relationship between the velocity response and displacement response can be obtained as shown in Fig.16. If the spacing is set to any value, the maximum velocity can be found using Fig.16. For examples, in case that the spacing is 2cm or 10cm, the maximum velocity becomes around 25cm/sec or 62cm/sec respectively. Inserting these values into Eq.(4.b) gives the periods of 0.32sec and 0.65sec. These results are shorter since the displacement response corresponding to these periods is smaller than the spacing. It is inconsistent. Exactly speaking, it is necessary to iteratively process data for eliminating such inconsistence. Therefore, it can be said that the velocities found above, is just approximate. However, it is our objective to suggest the convenient prediction method and the values are adopted. Here, consider the case of M=450kg and K=4,500kN/m. Substituting in Eq.(3) from each value gives impact force;

$$F_{impact} = \sqrt{450 \times 4{,}500{,}000} \times 0.25 = 11.25 \times 10^3\,N \quad \text{for spacing =2cm} \tag{4.a}$$

$$F_{impact} = \sqrt{450 \times 4{,}500{,}000} \times 0.62 = 27.9 \times 10^3\,N \quad \text{for spacing=10cm} \tag{4.b}$$

We calculated numerical examples to validate our prediction method. The values of the mass and spring constant are 450kg and 45,000kN/m and the values of spacing are 2cm and 10cm. The damping effect is neglected. Numerical results are shown in Figs.17 and 18. The values of the maximum velocity and impact force are 29.2cm/sec, 13.2kN for spacing of 2cm and 66.8cm/sec, 29.1kN for spacing of 10cm. These values approximately agree with our prediction ones. The present prediction method is useful to estimate the velocity and impact force approximately though the above mentioned inconsistence is involved.

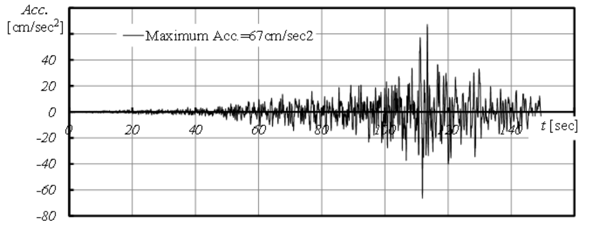


Figure 13 Input acceleration

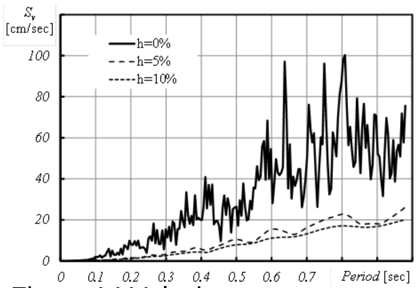


Figure 14 Velocity response spectrum

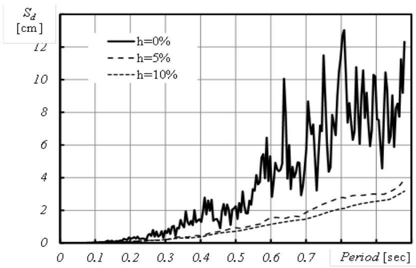


Figure 15 Displacement response spectrum

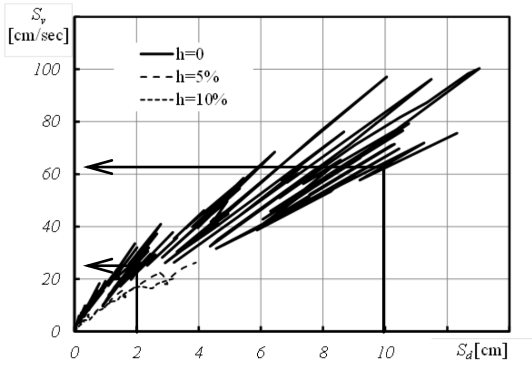
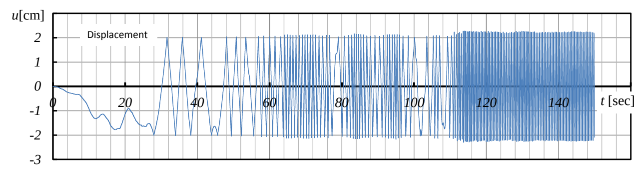
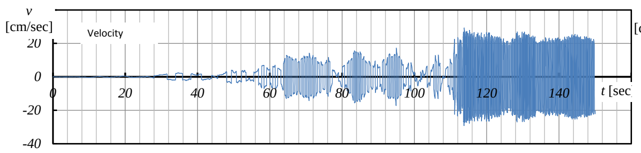


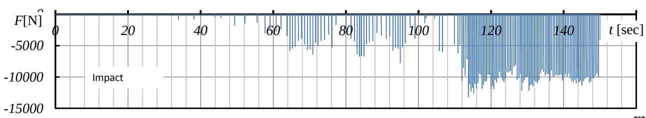
Figure 16 Relationship between Sv and Sd



Time history of displacement

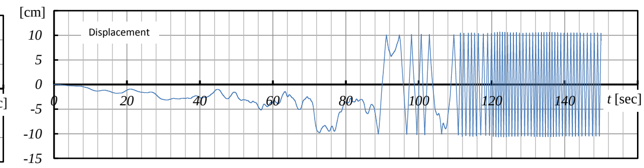


Time history of velocity

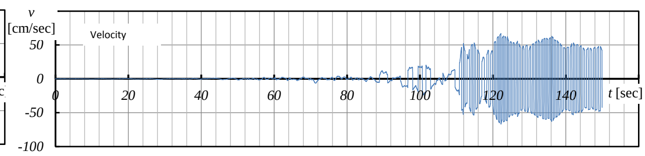


Time history of impact force

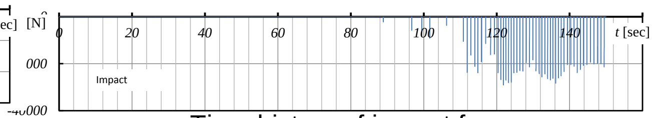
Figure 17 Numerical example spacing=2cm



Time history of displacement



Time history of velocity



Time history of impact force

Figure 18 Numerical example spacing=10cm

It is noted that the maximum velocity can be determined only by the value of spacing and response spectra of input-acceleration while the impact force can not be calculated by using the value of the system like a mass and spring constant.

The maximum values of impact forces become much greater in comparison with the ordinary inertia force. For example, in case of the spacing 2cm, the impact force reaches 13.2kN. The value corresponds to around 3G (because the mass is set to 450kg) though the maximum value of input acceleration is not so much. The reason why such great impact force occurs is to make spring constant great and to neglect the damping effect. Therefore, these values should be appropriately evaluated based on the actual situation when engineers consider the reason of ceiling damage. On the other hand, the fact is useful for engineers to consider the seismic design of ceiling. Namely, they should find the suitable stiffness and damping ratio of the surrounding component to degenerate the impact force.

Conclusions

We investigated the behavior of ceiling with steel furring during an earthquake. Especially, we focused on the ceiling without the spacing between ceiling surface and the surrounding component. The obtained results were summarized as followings.
#1. The static compression strength of ceiling surface is enough great to resist the horizontal force in an earthquake except the ceiling suspended with too long bolts.
#2. The greater the impact force occurs at the collision of the ceiling surface and the surrounding component becomes, the larger the spacing is. The spacing should be as small as possible or apply any special device like a damper.

Acknowledgments

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