Seismic Design for Improvement Construction Method of Ceiling of Existing Stations

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The type of structural supports used for ceilings in stations differ from those used in other buildings. In order to evaluate the seismic performance of station ceilings, it is therefore necessary to understand the function of supporting parts in the structure, and to evaluate loads acting on the ceiling during earthquakes. Shaking table tests and analytical studies of existing suspended station ceilings were conducted, focusing on the function of supporting parts in the structure. Seismic design to be applied to the method of improving the ceiling of the existing stations so as to make it safer during earthquakes is proposed.

Keywords: station ceiling, horizontal ceiling member, double ceiling, design seismic force

1. Introduction

Past earthquakes have often caused suspended ceilings to collapse. Consequently, given that stations are busy places, it is important to ensure the safety of people in stations by preventing ceiling damage during earthquakes. The Building Standards Law in Japan was amended in July 2013 stipulating new measures to prevent the collapse of ceilings in buildings. In October 2013 and July 2016, the Technical Standards Concerning Measures to Prevent the Collapse of Ceilings in Buildings [1, 2] (hereinafter called “Ceilings Technical Standards”) were presented, and an interpretation of the amended Building Standard Law and technical considerations was compiled.

In order to apply the Ceilings Technical Standards to station ceilings, it is necessary to clarify the differences that exist between ceilings used in stations and those in general buildings in terms of type of structural support and use. A method for calculating the loads acting on station ceilings during earthquakes for seismic design is proposed here, based on the Ceilings Technical Standards. The seismic performance of existing ceilings designed and constructed before the revision of the Building Standards Law was verified on the basis Ceilings Technical Standards.

2. Reality of station ceilings

This chapter explains in detail the differences in structural support of ceilings in stations and general buildings, and then summarizes the key points. The general seismic countermeasure for general buildings stipulated in the Ceiling Technical Standards is to use braces, along with the prerequisite that suspended ceilings be hung from major structural members (Fig. 1 (a)). In over-track buildings, there are often cases where the ceiling is hung from roof furring members or horizontal structural members (hereinafter called “horizontal ceiling members”) such as channel

Fig. 1 Hanging base side member of ceiling

steel (Fig. 1 (b)). In under-viaduct stations, there are many cases (hereinafter called “double ceiling”) where the ceiling is hung from the waterproof folded plate preventing water leakage (hereinafter called “waterproof ceiling”) (Fig. 1 (c)).

The suspended ceilings mentioned above are not hung from major structural members. Therefore, it is difficult to apply the method for calculating the design seismic force described in the Ceiling Technical Standards to such ceilings. Shaking table tests and analytical studies of the suspended ceilings in existing stations were conducted to examine the influence of the hanging base on the ceiling response (Chapter 3). The results were used to propose a seismic design method for station ceilings (Chapter 4).

3. Influence of hanging base on ceiling response

The influence of the hanging base on the ceiling response was examined analytically and experimentally for the two types of hanging ceiling used in stations, i.e. ceilings suspended from horizontal ceiling members and those suspended from waterproof ceilings.

3.1 Ceilings suspended from horizontal ceiling members

3.1.1 Analytical study

In order to understand the influence of the difference

in the cross section of the horizontal ceiling member on the ceiling story stiffness, an elastic frame analysis of ceilings was performed. The parameters used for the analysis were the cross sections of the horizontal ceiling members. The composition of the suspended ceiling used for the analysis is shown in Fig. 2. In this model the ceiling was suspended from horizontal ceiling members mounted between beams, and the braces were mounted in the direction of the weak axis of the horizontal ceiling members. Horizontal forces were equally applied to each intersection of the ceiling face and hanging bolts. Horizontal forces were applied in the direction of the weak axis of the horizontal ceiling members.

The results of the analysis are shown in Table 1. It summarizes the ratios of ceiling story stiffness with respect to each horizontal ceiling member to that of the infinite stiffness of the hanging base. As the geometrical moment of inertia of horizontal ceiling members increases, the ceiling story stiffness increases. This is because the horizontal deformation of the horizontal ceiling members to which the braces are attached, is small.

Fig. 2 Analytical model

Table 1 Ceiling story stiffness

Horizontal ceiling member		Ratio of the ceiling story stiffness to infinite stiffness
Section of member, mm	Geometrical moment of inertia of weak axis, cm^4	
Infinite stiffness	—	1.00
L-25x3	0.332	0.015
L-50x6	5.23	0.102
[-75x40x5x7	12.2	0.147
[-100x50x5x7.5	26.0	0.258
C-100x50x20x2.3	19.0	0.180

3.1.2 Shaking table tests

To understand the influence of the cross section and the end support conditions of the horizontal ceiling members on the ceiling response, shaking table tests were conducted. The outline of the tests is shown in Fig. 3. The ceilings were suspended from the horizontal ceiling members mounted between the beams of the support frame on the shaking table. The following test parameters were applied: horizontal ceiling member cross-sections: C-100x50x20x3.2, C-150x75x20x3.2; and the end support was fixed/pinned. Four test parameters were applied in total (C-100 pin, C-150 pin, C-100 fix, C-150 fix). Other components, i.e. hanger bolts, braces and ceiling components, were the same for all of the test specimens. The ceiling specifications are shown in Table 2. The stress acting on each member of the ceiling when the design story shear coefficient was applied was set at less than the allowable stress. Assuming

the ceiling of the 2nd floor of a two-story over-track station, the design base shear coefficient was set at 16.5 m/s^2 based on the Ceiling Technical Standards. In actual metal ceilings, the ceiling area borne by a pair of earthquake resistant braces is about 10 m^2 . However, due to experimental constraints, the ceiling area of the specimens was 6 m^2 . Therefore, an additional mass corresponding to the missing ceiling area was loaded on the ceiling specimens. Three waves with different phases were input as earthquake motion, in accordance with requirements in Notification No. 1461 (2000) from the Ministry of Construction. The three waves were the Kobe wave, the Hachinohe wave and a random wave. Each earthquake motion was input gradually starting with a small acceleration.

The relationship between the maximum acceleration of the ceiling face and the deflection angle of the horizontal ceiling members is shown in Fig. 4. As the maximum acceleration of the ceiling face increases, so does the deflection angle of the horizontal ceiling member. Under the same maximum acceleration of the ceiling face, the larger the cross section of the horizontal ceiling member, the smaller the deflection angle. When the end support was fixed, the deflection angle was small. In the design example of the Ceiling Technical Standards, the limit value of the deflection angle of the horizontal ceiling member at the design story shear coefficient (16.5 m/s^2 in the case of this test)

Fig. 3 Outline of shaking table test

Table 2 Ceiling specifications

Hanging bolt	W3/8@900 mm
Hanging length	1000 mm
Brace	C-40
Ceiling joist seat	CC-19
Ceiling joist	CW-19
Ceiling material	Aluminum spandrel ceiling width 100mm, thickness 0.8 mm
Ceiling area	6 m^2
Joint between horizontal ceiling member and hanging bolt	LG-hook with reinforcing metal

was 1/300 radian. Only the experimental parameter of “C-150 fix” was below this limit value.

From the analytical studies and experimental tests, when ceilings were hung from members with low stiffness, such as horizontal ceiling members, the influence of the hanging base on the ceiling response was significant. Therefore, the seismic force for these ceilings must be calculated using the stiffness of the ceiling story including the horizontal ceiling member.

Fig. 4 Relationship between maximum acceleration and deflection angle

3.2 Ceilings suspended from waterproof ceilings

3.2.1 Analytical study

To understand the seismic response of double ceilings composed of a waterproof ceiling hung from a viaduct and ceiling hung from the waterproof ceiling, a dynamic analytical study was conducted. The analytical model is shown in Fig. 5. This model is the 2-mass system model of the waterproof ceiling and the finishing ceiling. The mass of each waterproof ceiling and finishing ceiling was set as the mass corresponding to 10 m² for each ceiling area. The natural period of the waterproof ceiling was 0.1 s. The natural periods of the finishing ceiling were 0.1, 0.3, 0.5, 1.0, and 2.0 s. The dumping factor was 5 %, and white noise was input to the viaduct (the hanging base).

Fig. 5 Two-mass system model of double ceiling

The transfer function of the waterproof ceiling and the finishing ceiling with respect to the viaduct (the hanging base) is shown in Fig. 6. In the transfer function of the finishing ceiling with respect to the viaduct (Fig. 6 (a)), when the natural periods of the waterproof ceiling and the finishing ceiling are different, the transfer function is large at the natural periods of each ceiling. And when the natural periods of the waterproof ceiling and the finishing ceiling are close, the transfer function is large at the coupled natural period. In the transfer function of the waterproof ceiling with respect to the viaduct (Fig. 6 (b)), when the natural periods of the waterproof ceiling and the finishing ceiling are different, the transfer function is large at the natural

period of waterproof ceiling. And when the natural periods of the waterproof ceiling and the finishing ceiling are close, as is shown in Fig. 6 (a), the transfer function is large at the coupled natural period. This is because the mass of the waterproof ceiling is heavier than that of the finishing ceiling.

Fig. 6 Transfer function of acceleration response

3.2.2 Shaking table tests

To verify the seismic response of the double ceiling, shaking table tests were conducted. The outline of the test is shown in Fig. 7. The double ceilings were suspended from the rigid hanging base side members mounted between the beams of the support frame on the shaking table. The test parameters were the finishing ceiling stiffness varying according to the two following cases: One where the specimen was shaken in the direction of the ceiling joist and the other is a case where the specimen was shaken in the direction of the ceiling joist seat. The components of the waterproof ceiling and the finishing ceiling were the same for the two test specimens. The ceiling area assumed in the experiment was 10 m² (unit weight: finishing ceiling 100 N/m², waterproof ceiling 194 N/m²). Due to

Fig. 7 Outline of shaking table test on double ceiling

experimental constraints, the ceiling area of the specimen was 6 m² as mentioned above. Therefore, an additional mass corresponding to the missing area of each ceiling was loaded onto the waterproof ceiling and the finishing ceiling. The allowable strength of the finishing ceiling was 1700 N (manufacturer's value). By preliminary response analysis, the specifications of each member of the waterproof ceiling were set so that the waterproof ceiling did not yield before the finishing ceiling yield. The specifications of the waterproof ceiling are shown in Table 3. And the detail of the hanging base of the finishing ceiling is shown in Fig. 8. The specifications of the finishing ceiling were the same as those shown in Table 2. And the input earthquake motions was the same as those described in the previous section.

The relationship between the maximum acceleration of the support frame and that of the waterproof ceiling face, and the relationship between that of the support frame and that of the finishing ceiling face are shown in Fig. 9. At the same maximum acceleration of the support frame, although there were variations in the results, the maximum acceleration of the finishing ceiling face was generally larger than that of the waterproof ceiling.

From the analytical studies and experimental tests, the waterproof ceiling and finishing ceiling showed the behavior of a double pendulum. It was confirmed that the response of the finishing ceiling increased. Therefore, it is necessary to take the behavior of a double pendulum into account when calculating the seismic force to be applied to the design of a double ceiling.

4. Method for calculating design seismic force of ceiling in consideration of hanging base conditions

As is described in the previous chapter, not only did two types of suspended station ceiling, i.e. suspended from horizontal ceiling members or suspended from a waterproof ceiling, demonstrate a significant seismic response when hung from hanging base members with low stiffness, they also demonstrated double pendulum behavior. The method for calculating the design seismic force described in the Ceiling Technical Standards is a method for calculating seismic force of a ceiling with a 1-mass system on condition that the ceiling is hanging from major structural parts. Therefore, it is difficult to apply the method for calculating the design seismic force described in the Ceiling Technical Standards to the two kinds of suspended station ceiling mentioned in the previous chapter. Consequently, a method for calculating the design seismic force for these two types of ceiling is proposed.

4.1 Method for calculating design seismic force for ceiling suspended from horizontal ceiling members

In the case of ceilings suspended from horizontal ceiling members, when the stiffness of the finishing ceiling is sufficiently higher than that of the horizontal ceiling members, the seismic response of the whole ceiling can be expressed as having a behavior close to that of a suspended structure, because the stiffness of the horizontal ceiling members is low. The design seismic force for ceilings hanging from horizontal ceiling members is calculated from the

Table 3 Specifications of waterproof ceiling

Hanging bolt	W3/8@900 mm
Hanging length	1000 mm
Brace	C-40
Primary furring member of waterproof	L-50x50x6
Furring member of waterproof	C-100x50x20x2.3
Waterproof folded plate	H-88x t0.6@200
Area of waterproof ceiling	6 m ²

Fig. 8 Detail of hanging base of finishing ceiling

Fig. 9 Maximum acceleration

story shear coefficient using the overall stiffness of a series of springs and the overall mass of the horizontal ceiling members and the finishing ceiling. The design seismic force for the finishing ceiling is calculated by multiplying this coefficient and the finishing ceiling mass, and the design seismic force for the horizontal ceiling members is calculated by multiplying this coefficient and the overall mass. The concrete flow of this calculation method is shown in Fig. 10 and explained below.

Procedure 1: The ceiling hanging from the horizontal ceiling members is replaced with a 1-mass system model having the mass (M) and the stiffness (K). The mass (M) is the sum of the mass of the horizontal ceiling members (M_p) and the mass of the finishing ceiling (M_c). The stiffness (K) is calculated from the overall stiffness of a series of springs using the stiffness of the horizontal ceiling members (K_p) and the stiffness of the finishing ceiling (K_c).

Procedure 2: The story shear coefficient (k_s) is calculated by the response spectrum method described in the Ceiling Technical Standards using the natural period ($T = 2\pi\sqrt{M/K}$) of the substituted 1-mass system model.

Procedure 3: The design seismic forces (Q_p , Q_c) of the horizontal ceiling members and the finishing ceiling are calculated using the coefficient described below:

When the period (T) is less than 0.1 s: It is judged that the horizontal ceiling member and the finishing ceiling

have sufficiently high stiffness. Therefore, the design seismic force (Q_c) is calculated by multiplying the mass of the finishing ceiling (M_c) and the story shear coefficient of the rigid ceiling based on the Ceiling Technical Standards. The threshold standard of the period 0.1 s is set in accordance with the Ceiling Technical Standards.

For cases other than those given above:

$$Q_p = k_h(M_p + M_c) \quad (1)$$

$$Q_c = k_h M_c \quad (2)$$

The maximum story shear force of the finishing ceiling and the deflection angle of the horizontal ceiling members obtained from shaking tests on the ceiling suspended from the horizontal ceiling members were compared with results obtained using the proposed method. The results are shown in Table 4. These show that the proposed method can be used to estimate safe side experimental values.

The prerequisite for this method is that each joint in the ceiling is firmly fixed: if the joints slide easily when exposed to earthquake forces then this method cannot be applied, because it was developed on the premise that a mode analysis can be applied. Consequently, the prerequisite for this method is that the ceiling stiffness be greater than that of the horizontal ceiling members. When the difference in stiffness between the ceiling and the horizontal ceiling members is small, it is necessary to evaluate the ceiling using the following method.

Fig. 10 Flow of calculation method proposed

Table 4 Comparison of values between method proposed and test

	Method proposed	Test result
Def. angle of horizontal ceil. member, rad	1/145	1/317
Max. shear force of finishing ceiling, kN	1.53	1.26

4.2 Method for calculating design seismic force of double ceiling

In cases where the ceiling is hung from a waterproof ceiling, it is necessary to treat the double ceiling as if it were a double pendulum. Strictly speaking, a modal analysis should be performed to calculate design seismic forces, but this is cumbersome. A simple method for calculating the design seismic force is therefore proposed. The design seismic force for the waterproof ceiling is calculated by

multiplying the overall mass of the double ceiling and the story shear coefficient calculated from the 1-mass system having a coupled natural period. The design seismic force for the finishing ceiling in consideration of the amplification originating from the waterproof ceiling is calculated by the vertical distribution coefficient (hereinafter called "Ai distribution coefficient") of the seismic story shear force coefficient as stipulated in Notification No.1793 (1980) of the Ministry of Construction. The concrete flow of this calculation method is shown in Fig. 11 and is explained below.

Procedure 1: The coupled natural period in the primary mode (${}_mT_1$) and that in the secondary mode (${}_mT_2$) are calculated. When the natural period of the waterproof ceiling and that of the finishing ceiling are known, the coupled natural periods are obtained from the following equations.

$${}_mT_1 = \sqrt{p + \sqrt{p^2 - q^2}} \quad (3)$$

$${}_mT_2 = \sqrt{p - \sqrt{p^2 - q^2}} \quad (4)$$

$$p = \frac{(1+b)T_w^2 + T_c^2}{2}, \quad q = T_w T_c, \quad b = \frac{M_c}{M_w} \quad (5)$$

Procedure 2: The story shear coefficients (k_{h1} , k_{h2}) are calculated using the response spectrum method described in the Ceiling Technical Standards using both the coupled natural periods, ${}_mT_1$ and ${}_mT_2$.

Procedure 3: The design seismic forces (Q_w , Q_c) of each story of the double ceiling are calculated as described below:

When the period (${}_mT_1$) is less than 0.1 s and the period (${}_mT_2$) is less than the period (${}_mT_1$): It is deemed that the double ceiling has sufficiently high stiffness. Therefore, the design seismic force is calculated by multiplying the mass of the double ceiling ($M_w + M_c$) and the story shear coefficient of the rigid ceiling according to the Ceiling Technical Standards. The threshold standard of the period 0.1 s is set according to the Ceiling Technical Standards.

For cases other than those given above:

$$Q_w = \max(k_{h1}, k_{h2})(M_w + M_c) \quad (6)$$

$$Q_c = A_c Q_w M_c / (M_w + M_c) \quad (7)$$

The coefficient (A_c) is an Ai distribution coefficient calculated by the 2-mass system model of the waterproof ceiling and the finishing ceiling, and this is calculated as described below.

$$A_c = 1 + (1/\sqrt{\alpha_c} - \alpha_c) 2 {}_mT_1 / (1 + 3 {}_mT_1) \quad (8)$$

$$\alpha_c = M_c / (M_w + M_c) \quad (9)$$

When the design seismic force of the waterproof ceiling is calculated by the modal mass as mentioned above, it is more accurate. However, in the proposed method, it was decided to use the total mass for the purpose of calculating seismic force in consideration of calculation simplicity and the need to produce safe-side calculation results.

The maximum story shear forces of the double ceiling obtained from the results of the shaking test were compared with those obtained with the proposed method. The results are shown in Table 5. The comparison indicates that the proposed method can be used to make safe-side estimates of story shear forces.

The prerequisite for this method is that each joint in the ceiling is firmly fixed: if the joints slide easily when exposed to earthquake forces then this method cannot be ap-

plied, because it was developed on the premise that a mode analysis can be applied.

Fig. 11 Flow of calculation method proposed

Table 5 Comparison of values between method proposed and test

		Method proposed	Test result
Maximum shear force, kN	Waterproof ceiling	3.88	2.01
	Finishing ceiling	1.64	1.13

5. Seismic performance of existing ceiling designed and constructed before revision of Building Standards Law

The previous chapter described a method for calculating loads acting on station ceilings during earthquakes for seismic design. In this chapter, the seismic performance of existing ceilings designed and constructed before the revision of the Building Standards Law was verified based on the Ceilings Technical Standards. In concrete terms, on existing ceilings designed with a story shear coefficient of 9.8 m/s^2 (1.0 G), the relationship between the primary natural period of the buildings and that of the ceiling was calculated, when the story shear coefficient calculated by the simplicity spectrum method described in the Ceiling Technical Standards exceeded 1.0 G.

The results are shown in Fig. 12. In the range below the line shown in the figure, the seismic force for the de-

Fig. 12 Combination of natural period of buildings and that of ceilings when story shear coefficient exceeds 1.0 G

sign of the ceiling is estimated to be less than 1.0 G, so the seismic performance requirements of the existing ceiling are satisfied. In this study, it is a prerequisite that the suspended ceilings be hung from major structural members. In cases where the suspended ceilings are not hung from major structural members, it is necessary to evaluate the ceiling using the method described in chapter 4.

6. Conclusion

A method for calculating the design seismic force for ceilings in cases where the ceilings are not hung from major structural members was proposed in this paper which was verified for calculation accuracy. The combination of the natural period of buildings and that of ceilings when the story shear coefficient exceeds 1.0 G was described for existing ceilings designed and constructed before the revision of the Building Standards Law.

References

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