Seismic Reinforcement Method for Ceilings in Under-viaduct Stations Combining Noise Abatement Measures

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In stations built beneath low viaducts, the void between the bottom of the viaduct and the suspended ceiling over the station is small, therefore it is difficult to install the usual anti-seismic braces used for reinforcement. In addition, the anti-vibration rubber that is conventionally used for noise abatement, weakens the anti-seismic reinforcement performance of this type of structure. As such, we developed a less costly, more practical seismic reinforcement method, where the ceiling cavity is not obstructed. Structural cyclic loading tests were carried out to evaluate the anti-seismic performance of this method. This method demonstrated strong anti-seismic performance. In addition, acoustic tests were conducted with the new construction method. Results demonstrated the noise reduction effect with the new and the conventional method was the same.

Keywords: anti-seismic ceiling, hanging distance, steel pipe, train noise abatement measures

1. Introduction

For station facilities used by an unspecified number of people, it is critical to ensure not only the seismic safety of the body of the station but also that of the ceiling, which is one of the members making up the station space. The safety of the station ceilings is already considered in the Japanese Building Standards Law and technical advice based on this Law [e.g., 1]. However, for under-viaduct stations beneath low viaducts, ceiling hanging space (ceiling void) is often small, therefore it is difficult to apply ordinary seismic reinforcement methods.

In the case of station ceilings, noise abatement is also important to improve the station environment for users, in addition to ensuring anti-seismic performance. Under-viaduct stations may be exposed to loud train noise when a train is running, and conventionally, noise abatement was achieved with anti-vibration hangers. However, the use of anti-vibration hangers is difficult to combine with ordinary seismic reinforcement methods.

Therefore, we first developed a new seismic reinforcement method for ceilings with small voids. One of the features of the developed method is that it does not create obstructions in the space above the ceiling by not using diagonal material, unlike ordinary seismic reinforcement methods. Next, we studied noise abatement measures which could be combined with this seismic reinforcement method. The developed measures take into account the noise propagation paths of actual stations and can be used together with other seismic reinforcement methods. As such, it is proposed as a seismic reinforcement method for cases where train noise abatement measures need to be taken in ceilings with shallow voids.

2. Seismic reinforcement method for ceilings with shallow voids

Station buildings built under low viaducts often have shallow ceilings voids. At the same time, there needs to be enough space for ducts and other mechanical and electrical equipment, like in ceilings of normal height. When ceiling voids are small it is difficult to use conventional seismic reinforcement methods that rely on diagonal members (i.e. anti-seismic brace, Figure 1 (a)), as described in "Explanation of the Technical Standards for Measures against Falling Ceilings in Buildings” [2] (hereinafter “Ceiling Technical Standards”) (Fig.1 (b)), because they cause too much obstruction in the ceiling void. Another possible method is to construct the ceiling base material, such as hanging bolts, from channel steel or other similar material: however, the problem of this method is that it is difficult to include anchors in the construction for fixing channel steel or other similar material, to the viaduct and adjusting ceiling level is also difficult. Thus, this section first describes the analytical study made of the seismic performance of a ceiling with a small void without seismic reinforcement. Then, it outlines the new seismic reinforcement method developed by RTRI, which is relatively easy to construct, inexpensive, and does not create obstructions in the void. Finally, it reports on results obtained from structural experiments to verify the seismic performance of this new method.

2.1 Seismic performance of ceilings with small voids

Ceilings with small voids have a hanging bolt shear
span that is shorter than in ceilings with normal voids. Therefore, the seismic performance may be satisfied without seismic reinforcement. This section describes an analytical study made of the seismic performance of a ceiling with a small void and without seismic reinforcement.

2.1 Outline of the analysis

Figure 2 shows the model used for analysis, and Table 1 summarizes the specifications for it. The hanging bolts (fixing/supporting the top), ceiling joist receiver, and ceiling joist were all defined as beam elements. The hangers, defined as plate elements with the same cross-section as the plate thickness of the hanger, were placed between hanging bolts and ceiling joist receiver. SGCC materials (allowable stress 270 N/mm²) were used: they were modeled as elastic bodies without considering material nonlinearity. Clips were defined as elastic connecting spring elements that used the average value of the stiffness [3, 4] obtained from the results of a past clip test, and were placed between ceiling joist and joist receiver. The ceiling material (ceiling panel) was not modeled: only its weight was considered. A horizontal load was statically applied to each intersection of the ceiling joist and joist receiver, using the design seismic intensity of 1.47 G for a single-story building in the horizontal seismic intensity method of the Ceiling Technical Standards. The analytical parameters were the hanging distance (5 cases, 250 to 450 mm) and the loading direction (2 cases, ceiling joist and joist receiver).

2.1.2 Results of the analysis

Figure 3 is an example of a deformation diagram for a hanging distance of 450 mm. Deformation differed with loading direction. In the ceiling joist receiver direction, the top and bottom of the hanging bolt were fixed, whereas, in the ceiling joist direction, the bottom was close to the pin, resulting in a large story drift of 45 mm. This may have been caused by the bottom of the hanging bolt resisting in the ceiling joist receiver direction by bending around the strong axis of the ceiling joist receiver, whereas in the ceiling joist direction, the fixation degree of the bottom of the hanging bolt was low because the bottom resisted because of the twisting of the ceiling joist receiver.

Figure 4 shows the results of the analysis of the working bending stress of the hanging bolt that had the largest ratio of working stress to allowable proof stress for each of the respective parts of the ceiling. In the ceiling joist receiver direction, the stress fell below the allowable value at a hanging distance of about 350 mm or less, whereas it exceeded the allowable value at a larger hanging distance or in the ceiling joist direction, where the stiffness at the bottom was smaller. This finding has revealed that even ceilings with small voids require proper seismic reinforcement.

2.2 Specifications for seismic reinforcement of ceilings with small voids

From the study in the previous section, we found that some sort of seismic reinforcement is required even for ceilings with small voids. To improve the seismic performance of ceilings inexpensively without obstructing the void, the surroundings of the hanging bolts should be reinforced using general-purpose material. Thus, we proposed a seismic reinforcement method using steel pipes.

Figure 5 (a) shows the specifications of the proposed seismic reinforcement method. In this method, ordinary small-diameter steel pipes are used as reinforcing members and installed so as to cover the hanging bolt before the bottom of the pipe is tightened with a nut. This should introduce an initial axial force, with the hanging bolt as the reaction force, and makes the viaduct as the hanging base and the steel pipe come into contact with each other, thus making it resist the horizontal force working on the ceiling.
by the bearing force of the steel pipe during an earthquake (Fig. 5(b)). In addition, in order to prevent the joint in the lower hanger from becoming a weak point, the upper part of the hanging bolt, CC-19, made of the same material as the ceiling joist receiver, is reinforced and installed in the direction orthogonal to the relevant member for the sake of both the conventional hanger reinforcement member (bracket RP) used for installing the anti-seismic braces, and the rotational resistance of the joint.

Although all the components of the seismic reinforcement method above are inexpensive and easy to install, they only require the space above the ceiling to be slightly shielded; therefore, it is effective for ceilings with small voids.

2.3 Outline of the test

A structural experiment was conducted to verify the seismic performance of the proposed seismic reinforcement method.

2.3.1 Test pieces

Table 2 lists the test pieces. A total of four test configurations were used, including two hanging heights: 300 and 450 mm, and two directions for applying force: ceiling joist receiver direction and ceiling joist direction. The ceiling specifications shown in Table 3 and Figure 6 were the same for each experiment. The steel pipe used for the reinforcing member was a square pipe measuring 25 mm × t 1.6 mm, with length adapted to the hanging height. As for the hanging bolt, according to the results of our tensile test, the elastic coefficient was 207 kN/mm², and the 0.2% proof strength, or yield resistance, was 490 N/mm². Considering that it is difficult to control the tightening torque of hanging bolts during ceiling construction work, a normal torque value of 15 Nm, which can be achieved with a wrench or similar tool, was used as the experimental control value.

2.3.2 Experimental method

With the force application jig bolted to the ceiling panel, alternated positive and negative forces were applied with an actuator via the force application jig. The following loading schedule was performed with the Ceiling Technical Standards in mind. Each displacement was applied using the following loads: 0.45 kN (horizontal seismic intensity 0.5 G), 0.9 kN (1.0 G), 1.5 kN (1.65 G), 2.0 kN (2.2 G), and 3.0 kN (3.3 G) for three positive and negative cycles, and then it was loaded up to story drift angle of 1/10 to the positive side. The measured parameters were the load, horizontal displacement of the ceiling surface, and the axial strain of the square pipe. For the axial strain measurement of the square pipe, out of a total of nine hanging points, one was affixed to each of the two surfaces perpendicular to the applied force to the two cross-sections on the top of the three hanging points, A, B, and C, as shown in Fig. 6.

Before loading, the square pipe was tightened with a nut up to the control value, and the initial strain was measured. Table 4 lists the average values of the initial strain at each hanging point. There was a variation from about -130 to -250 μ depending on the construction error of the square pipe. The tensile stress of the hanging bolt at this

| Test piece | Ceiling dimensions | Hanging distance | Force application direction |
|------------|--------------------|------------------|----------------------------|
| No. 1      | 2.0 m × 2.0 m      | 300 mm           | Ceiling joist receiver direction |
| No. 2      |                    | 450 mm           | Ceiling joist direction |
| No. 3      |                    |                  | Ceiling joist receiver direction |
| No. 4      |                    |                  | Ceiling joist direction |

Table 2 Test pieces

| No. | Hanger reinforcing member | Force application direction |
|-----|---------------------------|-----------------------------|
| 1   | Bracket RP                | Ceiling joist receiver      |
| 2   | S clip, RP-S clip, RP-S cover | Ceiling joist receiver |
| 3   | S clip, RP-S cover        | Ceiling joist direction     |
| 4   | S clip, RP-S cover        | Ceiling joist direction     |

Table 3 Ceiling specifications (dimensions in mm)

| No. 1 | No. 2 | No. 3 | No. 4 |
|-------|-------|-------|-------|
| -99   | -146  | -154  | -133  |
| -220  | -183  | -255  | -219  |
| -128  | -205  | -70   | -134  |
| -243  | -201  | -257  | -234  |

Table 4 Square pipe initial strain (μ)

| Test piece | Hanging point A | Hanging point B | Hanging point C | Average value |
|------------|-----------------|-----------------|-----------------|---------------|
| No. 1      | -255            | -201            | -257            | -234          |
| No. 2      | -220            | -183            | -255            | -219          |
| No. 3      | -128            | -205            | -70             | -134          |
| No. 4      | -243            | -201            | -257            | -234          |

Fig. 6 Ceiling test piece of force application in the ceiling joist receiver direction

Fig. 7 Relationship between horizontal load and horizontal displacement
time was 120 N/mm² when the compressive strain of the square pipe was -250 μ, which was about a quarter of the yield resistance of the hanging bolt.

2.4 Experimental results

2.4.1 Relationship between load and displacement

Figure 7 (a) shows the relationship between the horizontal load and horizontal displacement for the repeatedly loaded part. Results showed that over 2.0 kN (equivalent to the maximum design horizontal seismic intensity, 2.2 G) and up to 3.0 kN there was no load reduction despite repeated loading. Fig. 7 (b) shows the relationship between the horizontal load and horizontal displacement for the whole. Although the stiffness of each test piece decreased after loading following successive loading, the load continued to increase and no large reduction in load occurred up to the story drift angle of 1/10 (displacement: 50 mm for No. 1 and 2, or 45 mm for No. 3 and 4). In addition, test piece No. 1 displayed a slight decrease in load near a horizontal displacement of 20 mm, and the loading was stopped halfway; however, the load at that time was about 9 kN (equivalent to 10 G), which demonstrated that it had sufficient proof strength.

The experiment suggests that the proposed method has good seismic performance. In addition, comparison of results by force application direction showed that the load in the ceiling joist direction was slightly larger than that in the ceiling joist receiver direction, and the anisotropy seen in Fig. 3 almost disappeared, with no large difference found in the force application direction.

2.4.2 Percentage of story moment burden above/below the hanging bolt

To know the ratio of the story moment burden of the upper to the lower part of the hanging bolt, the axial strain of the upper part of the square pipe was used to obtain the curvature of the upper part of the square pipe and the distance from the top of the square pipe to the inflection point. It was calculated using (1) and (2) below:

\[ \phi_1 = \frac{(e_3 - e_1)}{D}, \quad \phi_2 = \frac{(e_4 - e_2)}{D} \]  

(1)

\[ a = \frac{(100\phi_1 - 25\phi_2)}{(\phi_1 - \phi_2)} \]  

(2)

where \( \phi_1, \phi_2 \): curvature of cross-section 1, 2 of the upper part of the square pipe; \( e_1, e_2, e_3, e_4 \): axial strain of cross-section 1, 2 of the upper part of the square pipe; \( D \): square pipe diameter; and \( a \): distance from the top of the square pipe to the inflection point.

Figure 8 shows the calculated curvature and inflection point distance values for test piece No. 2. Although the relationship between the horizontal load and curvature (Fig. 8 (a)) varied depending on factors such as construction error in each square pipe, overall the curvature tended to increase with load. According to the calculated data, the distance to the inflection point (Fig. 8 (b)) is infinite in the curvature in the smaller-load range, but it is almost a constant value (≈ 200 to 300 mm) in the larger-load range. Among these, the hanging points, where bending due to construction errors and other factors does not occur in the square pipe at a horizontal load of zero (i.e. where the curvature is almost zero), are considered to exhibit average behavior. Their inflection point distances (Table 5) were

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**Table 5** Inflection point distance

| Test piece | Inflection point distance (mm) |
|------------|-------------------------------|
| No. 1      | 300                           |
| No. 2      | 200                           |
| No. 3      | 325                           |
| No. 4      | 280                           |

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**Table 6** Bending moment obtained using experimental results

| Test piece | Hanging distance (mm) | Inflection point distance (mm) | Initial strain (μ) | Results of the cross-sectional analysis |
|------------|-----------------------|-------------------------------|--------------------|----------------------------------------|
| No. 1      | 300                   | 200                           | -130               | 0.029 - 0.20                           |
| No. 2      | 200                   | 200                           | -220               | 0.048 - 0.21                           |
| No. 3      | 325                   | 325                           | -130               | 0.029 - 0.20                           |
| No. 4      | 280                   | 280                           | -220               | 0.048 - 0.21                           |

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**Table 7** Cross-sectional stress distribution

| Test piece | Moment Mf (kNm) |
|------------|-----------------|
| Point C    | 0.26            |
| Point Y    | 0.26            |
| Point U    | 0.26            |

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**Fig. 12** Comparison between the calculated proof strengths at points C, Y, and U and the experimental results
about 0.7 times relative to the hanging distance of either 300 or 450 mm regardless of the test piece. This means that the top of the hanging bolt bears 70% of the story moment thanks to the steel pipe reinforcement, while the bottom of the hanging bolt has a fixation degree that can bear 30% of the story moment regardless of the force application direction. These results reveal that, in addition to that the stiffness and proof strength of the upper part of the hanging bolt being improved thanks to the steel pipe, in particular, those of its lower part in the ceiling joint direction (low in Section 2.1) are also improved, giving the entire ceiling good seismic performance.

2.4.3 Natural period of the ceiling and required clearance to the wall

The natural period of the ceiling was obtained from the minimum value of the secant stiffness at each horizontal load, and the required clearance between the ceiling and wall was calculated using the calculation method in the Ceiling Technical Standards. The “required clearance”, means the separation from the wall or other structure, provided to prevent the ceiling from falling due to collision with the surrounding walls, etc., due to earthquake motion. This clearance is a key parameter for improving the seismic resistance of a suspended ceiling. Figure 9 shows the results of the calculations. The natural period for the maximum design load, 2 kN, was about 0.95 s for a hanging distance of 300 mm or about 0.3 s for a hanging distance of 450 mm, which shows that it has a high stiffness for both as a suspended ceiling. This tells us that the required clearance calculated is about 5 mm for a hanging distance of 300 mm or about 11 mm for a hanging distance of 450 mm and the clearance can be reduced. Being able to reduce the clearance is effective also for taking the train noise abatement measures described later.

2.5 Analytical study of the load resistance mechanism

This section describes an analytical study of the load resistance mechanism for the proposed method.

2.5.1 Analytical study

A cross-sectional analysis was conducted based on the Bernoulli-Euler theory, for the hanging position. For both the hanging bolt and square pipe, the physical properties of the material were set to an elastic coefficient of 200 kN/mm², an yield strength of 400 N/mm², and a yield strain of 2000 μ, and a perfect elasto-plastic model was used. The tensile force of the square pipe was set to zero because it cannot be transmitted to the viaduct at the hanging source. The initial compressive strain of the square pipe was set to -200 μ considering the experimental results.

Figure 10 shows the relationship between the moment and curvature obtained by the analysis. Figure 11 shows the cross-sectional stress distribution. At points O to C, the compressive stress of the square pipe was generated in the entire cross-section, and at point C, the tensile edge stress of the square pipe was zero. At points C to Y, the zero-stress range of the square pipe spread toward the compression edge, and at point Y, the compression edge of the square pipe reached the yield strength. It can be seen that after point Y, the range with the yield strength reached was expanded and the hanging bolt reached the yield strength before reaching the maximum bending moment (point U).

2.5.2 Comparison with experimental results

The story shear capacity of the ceiling test piece at each point was obtained using the bending moments of points -C, -Y, and -U obtained by cross-sectional analysis, and calculated with (3) and (4) below:

\[ M_x = M_0(L - a)/a \]  \hspace{1cm} (3)

\[ Q = 9(M_i + M_j)/L \]  \hspace{1cm} (4)

where \( L \): hanging height; \( M_i \): bending moment at the top; \( M_j \): bending moment at the bottom; and \( Q \): story shear capacity of test piece. \( a \) is given by equation (2). By using the average value of the initial strain obtained by the experiment, \( M_i \) was obtained by cross-sectional analysis. \( a \) was obtained from the square pipe results where the curvature was close to zero when the horizontal load was zero in the relationship between the horizontal load and curvature (Fig. 8), which was calculated from the axial strain of the square pipe in the experiment.

Table 6 lists the bending moment \( M_i \) values at points C, Y, and U. Figure 12 compares the story shear capacity (dotted line in the figure) at points C, Y, and U obtained by the calculation and the experimental results (solid line in the figure). This figure includes the square pipe yield point, where the axial strain at the top of the square pipe calculated from both the inflection point distance and the axial strain of cross-section 1 yielded compressively at all three hanging points. It can be seen that for all the test pieces, the stiffness gradually decreased after point C and almost matched the square pipe yield point. The decrease in stiffness after point Y was gradual, and the shear force tended to increase also after exceeding point U. This may be due to the effect of strain hardening following the yielding because the material performance was modeled as being perfectly elasto-plastic in the analysis. From the contents so far, we can conclude that despite construction errors in the square pipe, the use of this calibration method makes it possible to evaluate the story shear capacity of almost the entire ceiling and analytically clarify the resistance mechanism with the proposed method.

3. Train noise abatement measures for metal ceilings

Under-viaduct stations may be exposed to loud train-induced noise when a train is running, and conventionally, train noise abatement measures have been implemented using anti-vibration hangers equipped with hanging bolts. However, if an anti-seismic braces (conventional seismic reinforcement method) are installed, the noise abatement effect of anti-vibration hangers may be diminished because train vibration propagates to the ceiling through the anti-seismic braces (Fig. 13). In addition, for the seismic reinforcement method proposed in the previous section, this method is not applicable because anti-vibration hangers reduce the seismic performance by decreasing the stiffness of the entire ceiling base. Thus, this section studies the noise propagation path based on measurements taken in actual stations, focusing on metal ceilings with, for exam-
ple, aluminum ceiling panel, which have become common in station building ceiling in recent years. In addition, this section studies noise abatement measures which can be used in combination with the proposed seismic reinforcement method and describes verification of the effectiveness of the method through acoustic experiments.

3.1 Train noise propagation path in under-viaduct stations

Train noise in under-viaduct stations is classified into (1) airborne sound (propagated from stairs, escalators, etc.), and (2) structure borne sound (train vibration generated in tracks propagates and radiates to the underside, walls, and floor of the viaduct slab). In addition, if the underside of viaduct slabs have finishing material like a metal ceiling, structure borne sound can be categorized into (1) noise emitted by train vibrations propagating to the ceiling finishing material via hanging bolts ("ceiling structure borne sound"), (2) noise radiated from the underside of the viaduct slab and then transmitted through the ceiling finishing material ("ceiling transmitted sound"), and (3) noise propagating through gaps in the ceiling finishing material ("ceiling gap propagation sound"). Figure 14 shows the propagation path of each type of sound. Anti-vibration hangers are one of the main measures used to mitigate ceiling structure borne sound.

3.2 Sound insulation performance measurement of a metal ceiling in an actual under-viaduct station

We researched the sound insulation performance of a metal ceiling in an actual under-viaduct station (Station A). Figure 15 outlines the measurement method. Difference in sound pressure level between the concourse and the space above the ceiling was measured while radiating pink noise from the loudspeaker installed in the concourse. Figure 16 shows the comparison between measured results and transmission loss values [5] of the aluminum plate. The figure also shows the results of similar measurements taken in RTRI's full-scale simulated station building, which has ceiling specifications similar to those in Station A. It can be seen that at or above 500 Hz, the sound pressure level difference for the metal ceiling (Station A and simulated station building) is smaller than that for the aluminum plate. One of the possible reasons is that the ceiling gap propagation sound is propagated through the ceiling gap between the fitted parts of the ceiling that is constructed by fitting the ceiling panel.

3.3 Verification of effect of ceiling noise abatement measures

The measurement results in the previous section suggested that noise can be abated by closing the gaps between the ceiling panel fitted parts. Thus, we conducted an acoustic experiment to study the noise abatement effect of a metal ceiling where the gaps in the fitted parts were closed with anti-vibration material (hereinafter "packing"). The experiment was conducted in a reverberation room in the upper and lower stories in accordance with “JIS A 1418 Acoustics -- Measurement of floor impact sound insulation of buildings” (Fig. 17). Table 7 lists the experimental cases. In Case 0, only the RC slab was used without installing any ceiling; in Case 1, only a metal ceiling was used without any noise abatement measures; in Case 2, the conventional reinforcement method was used with anti-vibration hangers; in Case 3, the gap between the ceiling panel fitted parts was closed with packing, without using any anti-vibration hangers. Figure 18 shows the results of measurements when standard heavy impact equipment was used as a sound source.

Case 1 (without noise abatement measures) generated a sound pressure level higher than in Case 0 (RC slab only) at or above 250 Hz. In addition, Cases 2 and 3 (with noise abatement measures) generated lower sound pressure levels than in Case 1, confirming the effectiveness of the measures. Furthermore, Case 3 generated a lower pressure level than in Case 2 at or above 500 Hz, which suggests that the use of packing was effective for abating sound propagated through ceiling gaps. These results indicate that the packing installed in the gaps between the fitted parts of the ceiling panel may have the same noise abatement effect as when conventional anti-vibration hangers are used.

4. Conclusion

In this paper, a seismic reinforcement method using steel pipes was proposed for ceilings with small voids, and the seismic performance was verified through structural experiments. The results demonstrated good seismic performance of the proposed method, without lowering the load relative to the maximum design load. Results also showed that the proposed method makes it possible to reduce the clearance with surrounding walls or similar structures, because of the greater stiffness.
In addition, closing gaps between ceiling panels with packing was shown to be an effective method for abating noise in under-viaduct stations: this was verified through acoustic experiments, demonstrating that it has the same noise abatement effect as conventional anti-vibration hangers.

From the above, for ceilings with small voids, a reinforcement method was proposed that consists of a seismic reinforcement method and noise abatement measures combined (Figure 19). This method has been adopted in actual stations because of its high ease of construction and low cost.

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