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STUDY ON THE EARTHQUAKE RESPONSE BEHAVIOR OF EXPANSION JOINTS USED FOR SEISMICALLY ISOLATED BUILDINGS

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Abstract

In the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter the Tohoku Earthquake), there was little damage to base-isolated buildings. However, some damages of expansion joints used in those buildings (hereinafter called "Exp. J") were reported. Base-isolated buildings are designed on the assumption that buildings can be used without damage even after a major earthquake. However, if Exp. J are damaged, the function of the building will be impaired. Therefore, Exp. J is required to be highly functional and safe.

According to the results of investigation of Exp. J after the Tohoku Earthquake, many damages of Exp. J were observed. Then, *the Seismic Isolation Expansion Guidelines* was published by the Japan Seismic Isolation Structure Association reflecting the knowledge obtained from the Tohoku Earthquake. In this guideline, the basic concepts and target performance of Exp. J are clearly shown, that have not been shown so far. The experiments using a shaking table are recommended to confirm the performance.

When Exp. J is tested on a shaking table, it is necessary to input the building response waveform where Exp. J is installed. However, when Exp. J is used in a corridor that connects a base-isolated building and a normal building, the behavior of the building on one side can only be reproduced with one shaking table.

Therefore, in this study, we conducted an experiment to verify the safety and performance of Exp. J by arranging two shaking tables side by side, so that the relative movement of two buildings during an earthquake can be reproduced.

In order to select the response waveform as input to the shaking table, we analyzed the natural period of the building, which affect the performance of Exp. J. The natural period of base-isolated buildings was set to 3.00 to 5.00 seconds, and the that of non-base-isolated buildings was 0.01 to 1.00. A time history response waveform was created with a one-mass model using the Newmark β. Then, the difference of the time history response of the created base-isolated building and the non-base-isolated building was recorded, and the spectrum diagram by each period was created.

From the results of analysis, it was found that the response value is greatly affected by the difference in natural period between the two buildings. By reproducing the input waveforms for the two buildings on the shaking table, we were able to confirm the safety and behavior of Exp. J in a more realistic way.

As future research work, we plan to conduct the same verification for other seismic motions and response analysis using multi-mass model, and to conduct vibration experiments using the analyzed waveforms. We will show the validity of this study by comparing experimental results with theoretical values.

Keywords: shaking table test, expansion joints, base-isolated building

1. Introduction

Recently, many earthquakes which seismic intensity over 6 have been occurred in Japan. The seismic measures which mitigate damages are expected to be implemented quickly. One of the best measures to prevent damage of buildings is to use base-isolated building. Now more than 4,500 base-isolated buildings have been built in Japan. In particular, important buildings such as major hospital, government office and evacuation facilities have been tended to build by base-isolated building. Since the 1995 south Hyogo Prefecture earthquake, earthquake observation have made rapid progress, and the obtained data is quickly published in order to improve the seismic technology.

In the 2011 off the Pacific coast of Tohoku Earthquake, seismically isolated buildings were well performed and few damage was observed in the main structure of buildings. However, many damages were found in Exp. J used for seismic isolation building. According to the result of investigation done by the committee in the Japan Seismic Isolation Structure Association, about 30 % of investigated base-isolated buildings showed some damages in Exp. J, not only in the buildings suffered severe quake such as seismic intensity over 6, but also in those that of under 4. Exp. J was expected to work not to transfer the force from one building to another and mitigate the damage of main structure. Therefore some damages have been allowed in Exp. J and damaged one usually be replaced. However, those damages may hinder the continuous operation in the event of a disaster. In this study, we performed a basic experiment to ensure the allowable movement and the safety of Exp. J.

The method of experiment using the shaking table of Exp. J, which recommended by "*Seismic Isolation Expansion Guidelines*", is to install the Exp. J across the shake table and the surrounding jigs. Therefore, the test can be performed the relative movement between the building and the ground. If Exp. J is installed across the base-isolated building and normal one, the relative movement between two buildings must be checked. In this study, two shaking tables are arranged and the movement of two buildings is reproduced to confirm the allowable movement and the safety of Exp. J.

The purpose of this investigation is to establish the performance evaluation method of Exp.J used to the base-isolated building. We propose the method of test using two shaking tables, and examine the selection method of input wave for the shaking table test. Then, we carried out the test by the proposed method, and verified the validity.

2. Experiment

2.1 Shaking tables

In this study, the same two shaking tables are used to confirm the allowable movement and the safety of Exp. J. The two-directional shaking table to reproduce the large horizontal displacement of the base-isolated building, was used. The performance of the shaking table is shown in table 1.

Table 1 ー Performance of the shaking table

	Specification		
Direction of movement	X-direction、Y-direction		
Capacity		X-direction	Y-direction
	Max. Acceleration	2.94 m/s^2	2.94 m/s^2
	Max. Velocity	1 m/s	1 m/s
	Max. Displacement	± 800 mm	± 800 mm
Max. loadable weight	800 kg		
size	1600 mm × 1600 mm		

2.2 Test specimen

Exp. J has different performance and mechanism depending on where it is installed such as roof, cladding, ceiling, floor, and so on. In this study, we chose floor-type Exp. J, because the damage of floor may be hinder the evacuation in the time of disaster. The movement mechanism of specimen is lap joint type in the X-direction, and slide in the rail in Y-direction. Table 2 and Fig. 1 show the performance of the test specimen and the cross-sectional view, respectively. The schematic view of movement of specimen is shown in Fig. 2. This Exp. J consists of three panels (panel 1, 2 and 3), and is installed across building and other structure. The specific assembly procedure is as follows: First, panel 1 which connected to the auxiliary member is placed on the slide rail and receiving base. Then, panel 2 is placed over the panel 1 and fixed on the structure of the slide rail placed. Finally, the panel 3 is placed over the panel 2 and fixed on the structure of the receiving base. The movements of X-direction and Y-direction are achieved by the slide mechanism between panel 1 and slide rail, and lap joint mechanism made of panel 1, 2 and 3, respectively.

Table 2 — Performance of the test specimen

Type		Floor-type Exp.J for base-isolated building
Applied to		Indoor floor
Clearance between structures		950 *mm* (horizontal direction)
Assumed movement		X-direction: 800 *mm*、 Y-direction: 800 *mm*
Allowable residual displacement		50 *mm*
Movment mechanism		X-direction：lap joint type Y-direction：slides on the rail
Material	Panel 1	Galvanized mild steel sheet
	Panel 2	Galvanized stainless steel (SUS304) *
	Panel 3	Galvanized stainless steel (SUS304)*
Planner size		2900 *mm*×1000 *mm*
Assumed max. Loadable weight		350 kg/m^2

* defined in the Japanese Industrial Standards

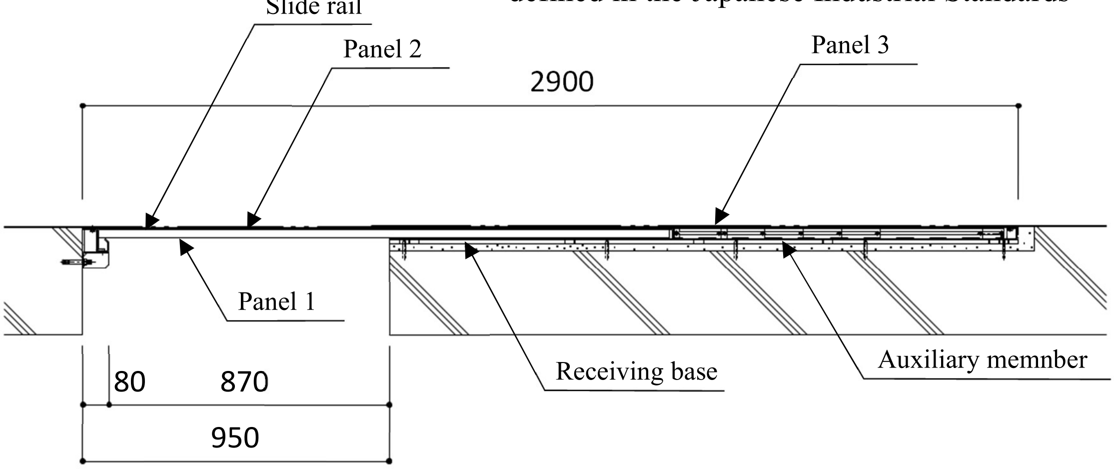

Fig. 1 — Cross-sectional view of specimen

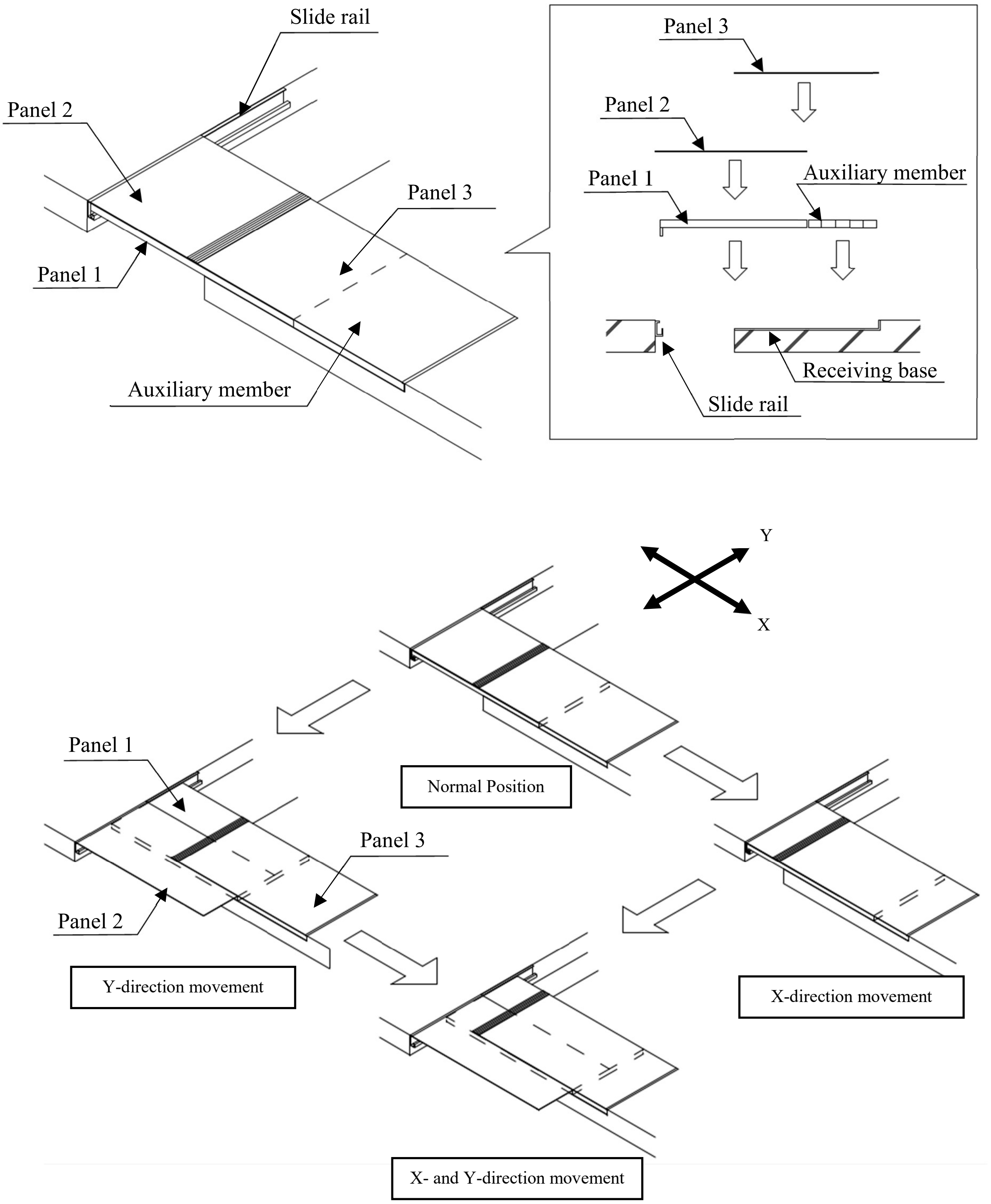

Fig. 2 — Schematic view of movement of specimen

2.3 Input wave

2.3.1 Source wave and building response

Input wave for test is the building response motion made from observation wave. We selected the observation wave obtained from 1995 South Hyogo Prefecture Earthquake. Analysis of building response uses Newmark's β method as shown in Eqs. (1), (2) and (3)

$$x_{n+1} = x_n + \frac{\frac{\dot{x}_n}{\beta \Delta t} + \frac{\ddot{x}_n}{2\beta} - \Delta \ddot{y}_{n+1} + \frac{4h\pi}{T}\left\{\frac{\dot{x}_n}{2\beta} + \left(\frac{1}{4\beta} - 1\right)\Delta t \ddot{x}_n\right\}}{\frac{1}{\beta \Delta t^2} + \frac{2h\pi}{\beta \Delta t T} + \frac{4\pi^2}{T^2}} \quad (1)$$

$$\dot{x}_{n+1} = \dot{x}_n + \frac{\Delta x_{n+1}}{2\beta \Delta t} - \frac{\dot{x}_n}{2\beta} + \left(1 - \frac{1}{4\beta}\right)\Delta t \ddot{x}_n \quad (2)$$

$$\ddot{x}_{n+1} = \ddot{x}_n + \frac{\Delta x_{n+1}}{\beta \Delta t^2} - \frac{\dot{x}_n}{\beta \Delta t} - \frac{\ddot{x}_n}{2\beta} \quad (3)$$

2.3.2 Waves working on Exp. J

If Exp. J install across two buildings, the behavior of Exp.J is affected by both building movements. Figure 3 shows the schematic view of movements of two buildings (building A and B) during an earthquake as one mass model. Z_1 and Z_2 show the distance between two buildings during quake and original position, respectively. x_A and x_B show the horizontal displacement of each building. The relative displacement X can be calculated by Eq. (6). We defined this relative displacement as "*Earthquake harmonic wave*". In the same way, the relative acceleration and velocity can be calculated by Eqs. (4) and (5).

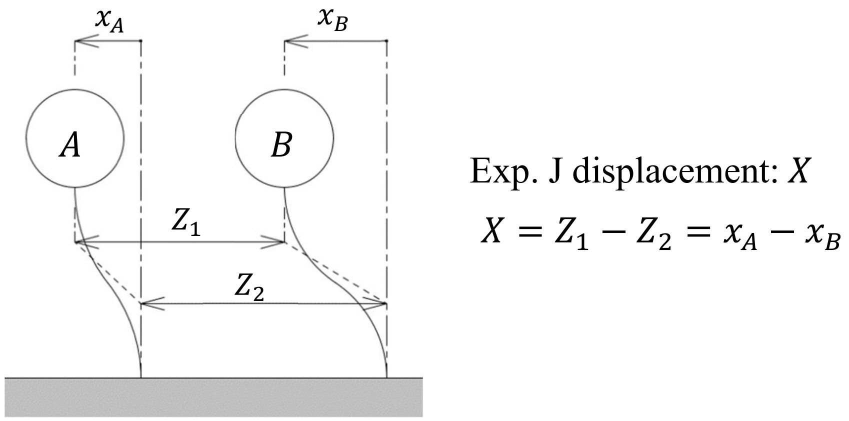

Fig. 3— The movement of Exp. J

$$\ddot{X} = \ddot{x}_A - \ddot{x}_B \quad (4)$$

$$\dot{X} = \dot{x}_A - \dot{x}_B \quad (5)$$

$$X = x_A - x_B \quad (6)$$

2.3.3 Spectrum of "Earthquake harmonic wave"

Generally, the response characteristics of building are represented by a response spectrum diagram according to different natural period. However, in order to confirm the performance of Exp. J installed across two different buildings, it is needed to make the response spectrum of harmonic wave, which calculated from the response of two buildings. The response of each buildings are calculated from Eqs (1), (2) and (3). It is assumed that the natural period of base-isolated building is set to 3.0 ~ 5.0 sec. and that of normal building is 0.02 ~ 1.00 sec. Damping rate is set to 0.03 and β = 0.25. Figures 4 (a), (b) and (c) show the acceleration response, velocity response and displacement response, respectively. In the figure, the *x*-axis indicate the natural period of the normal building, and the *y*-axis is the natural period of the base-isolated building. From these figures, the response value greatly changes depending on the natural period of both buildings.

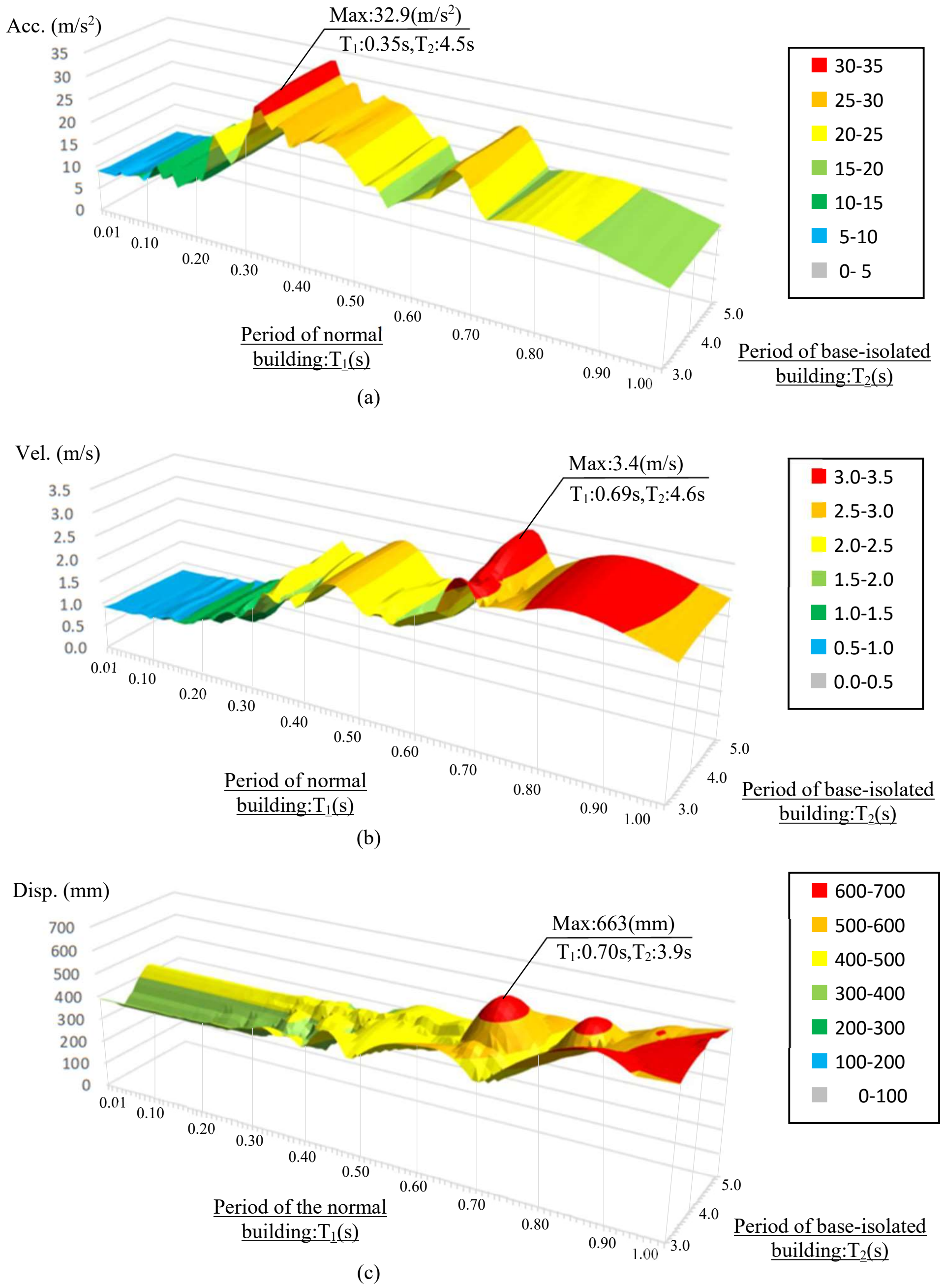

Figure 4 — The response spectrum diagram of "Earthquake harmonic wave"

2.3.4 Selection of waveform for test

From the spectrum diagram in the Fig. 4, the displacement response is most affected according to different natural period. So, we selected the waveform which showed the largest displacement response for shaking table test. Table 3 shows the maximum value when the response displacement is the largest.

Table 3 — The wave which shows the largest displacement

Direction	NS			EW		
	normal building	base-isolated building	Earthquake harmonic wave	normal building	base-isolated building	Earthquake harmonic wave
Natural period(s)	0.70	3.93	-	0.94	3.25	-
Max. Acc. (m/s^2)	25.1	1.0	25.6	15.7	1.8	16.5
Max. Vel. (*m/s*)	2.8	0.9	3.2	2.5	1.0	2.6
Max. Disp. (*mm*)	310	391	663	35.3	475	700

2.3.5 Adjusting the waveform

The selected wave has an acceleration that exceeds the capacity of the shaking table. Therefore, the wave was adjusted as the following procedure: First, the acceleration amplitude of the wave was reduced to the maximum acceleration value of shaking table can perform; Since the displacement amount would be small, the time axis was adjusted to be the same as the original displacement. As a result of this adjustment procedure. the velocity amplitude was decreased. The adjusted waveform is shown in Fig. 5.

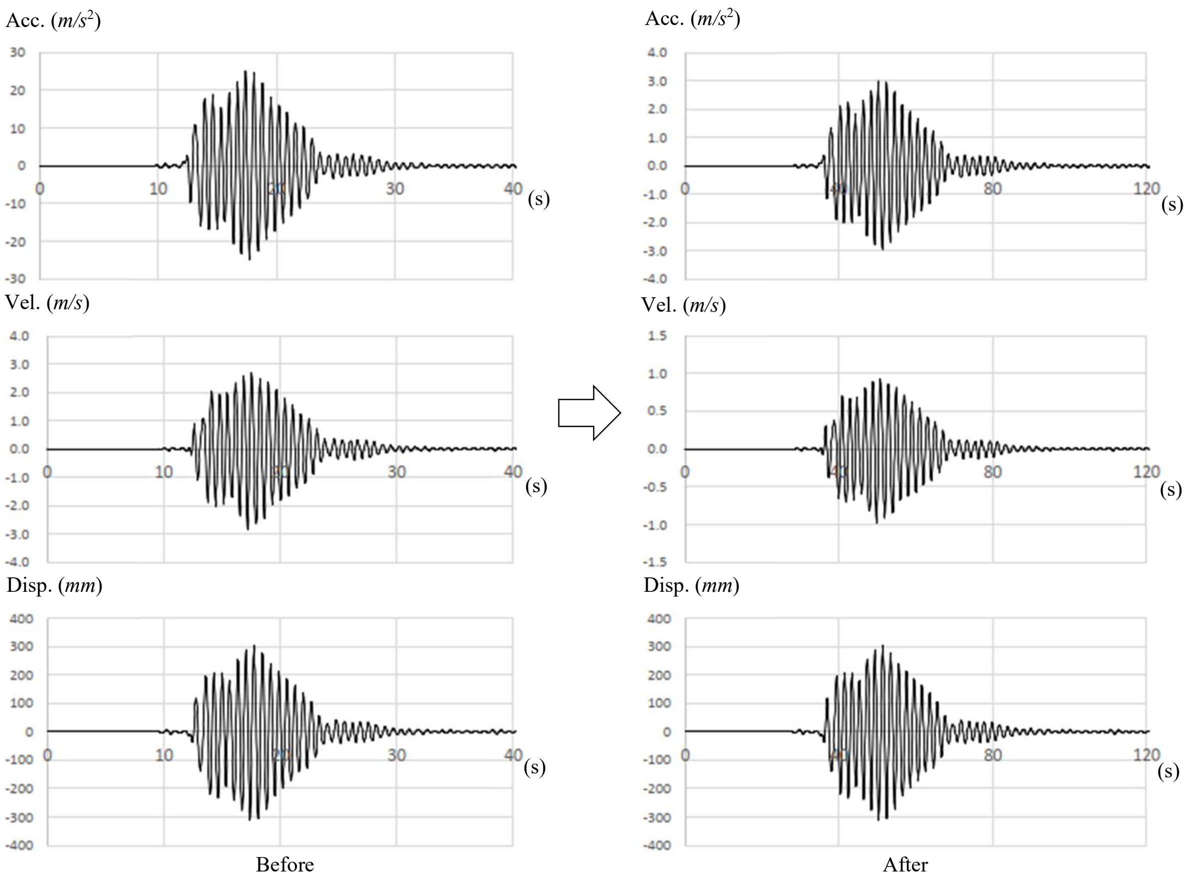

Fig. 5 — The adjusted waveform for test

2.4 Measurement

The acceleration and displacement of *x*- and *y*-direction were measured by the accelerometer and the record of the motor, respectively. The position of the measuring device is shown in Fig. 6.

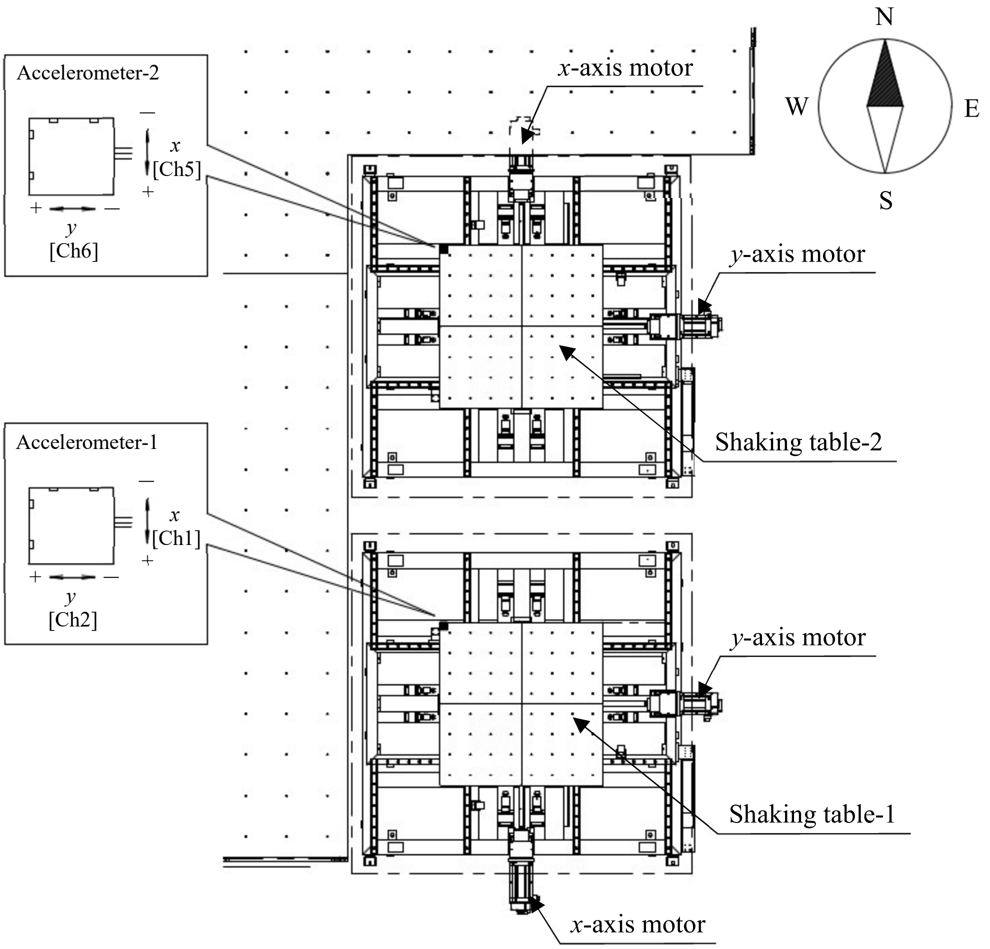

Fig. 6 — The position of the measuring devices

Two kinds of response were calculated by measured data. The one is that the velocity and displacement were calculated from measured acceleration by Eqs. (7) and (8). It is called “response A”. The other is that the velocity and acceleration were calculated from measured displacement by Eqs. (9) and (10). It is called “response B”.

$$\dot{x}_{n+1} = \dot{x}_n + (\ddot{x}_n + \ddot{x}_{n+1})\frac{\Delta t}{2} \tag{7}$$

$$x_{n+1} = x_n + \dot{x}_n \Delta t + \left(\frac{\ddot{x}_n}{3} + \frac{\ddot{x}_{n+1}}{6}\right)(\Delta t)^2 \tag{8}$$

$$\dot{x}_{n+1} = \frac{x_{n+1} - x_n}{\Delta t} \tag{9}$$

$$\ddot{x}_{n+1} = \frac{\dot{x}_{n+1} - \dot{x}_n}{\Delta t} \tag{10}$$

Through this conversion, a Fourier transform was performed, and a high-pass and low-pass filter was applied below 0.03 Hz and above 1.5 Hz.

3. Test results and discussions

A record of the acceleration and displacement measured in the experiment is shown in Fig. 7. Photo 1 ~ 4 show the test rig and specimen set-up.

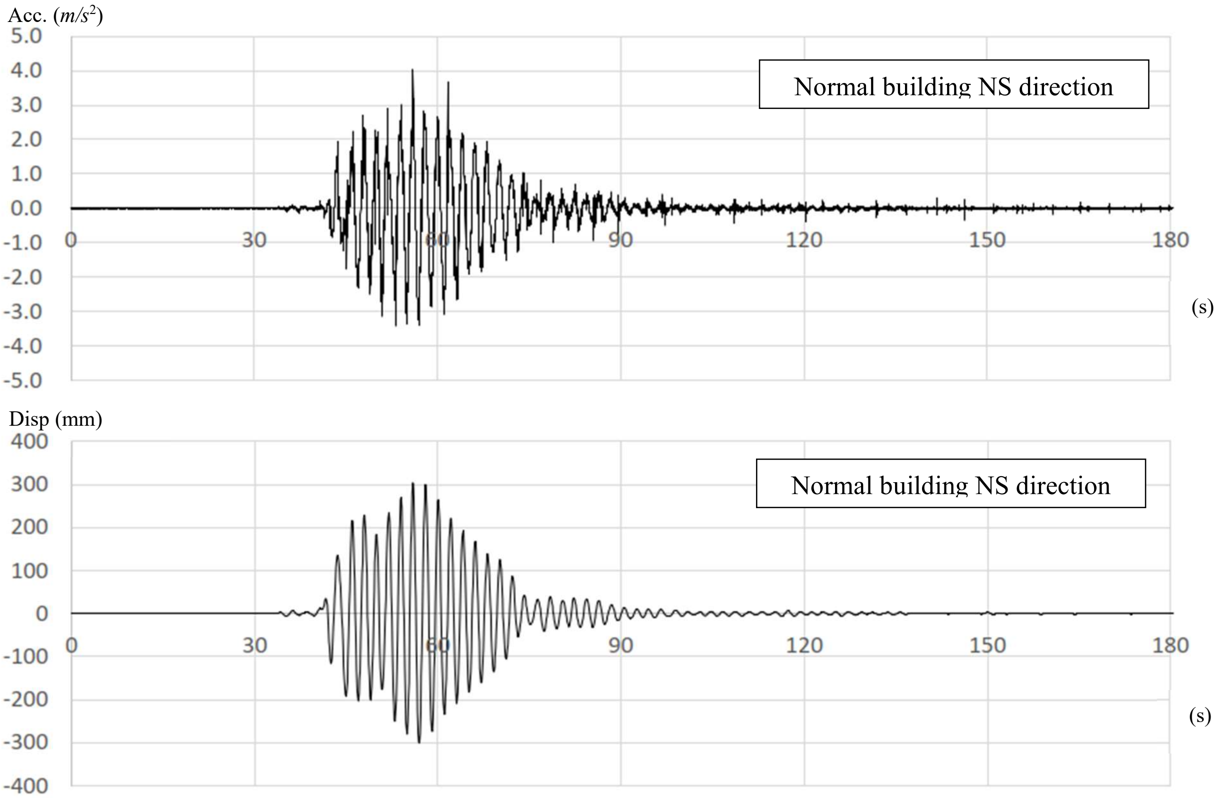

Fig. 7 — A record of the acceleration and displacement

Photo1 - overview of test rig

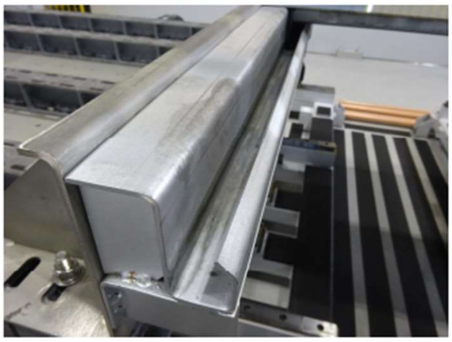

Photo2 - slide rail

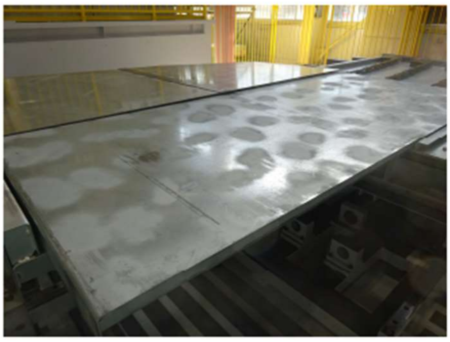

Photo3 –panel 1

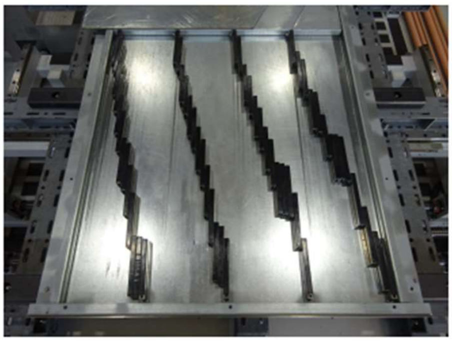

Photo2 - auxiliary member

Figure 8 shows the comparison between the calculated acceleration / velocity / displacement response from measured data and input wave. From this figure, this experiment showed the good reproducibility. it is confirmed that which described in 2.4, the performance of the Exp. J which installed across two different building can be tested by using two shaking tables. There were no noticeable damage to Exp. J after the test in this case. Although it was rubbed and scratched, it did not affect the ability to follow the movement required for this Exp. J.

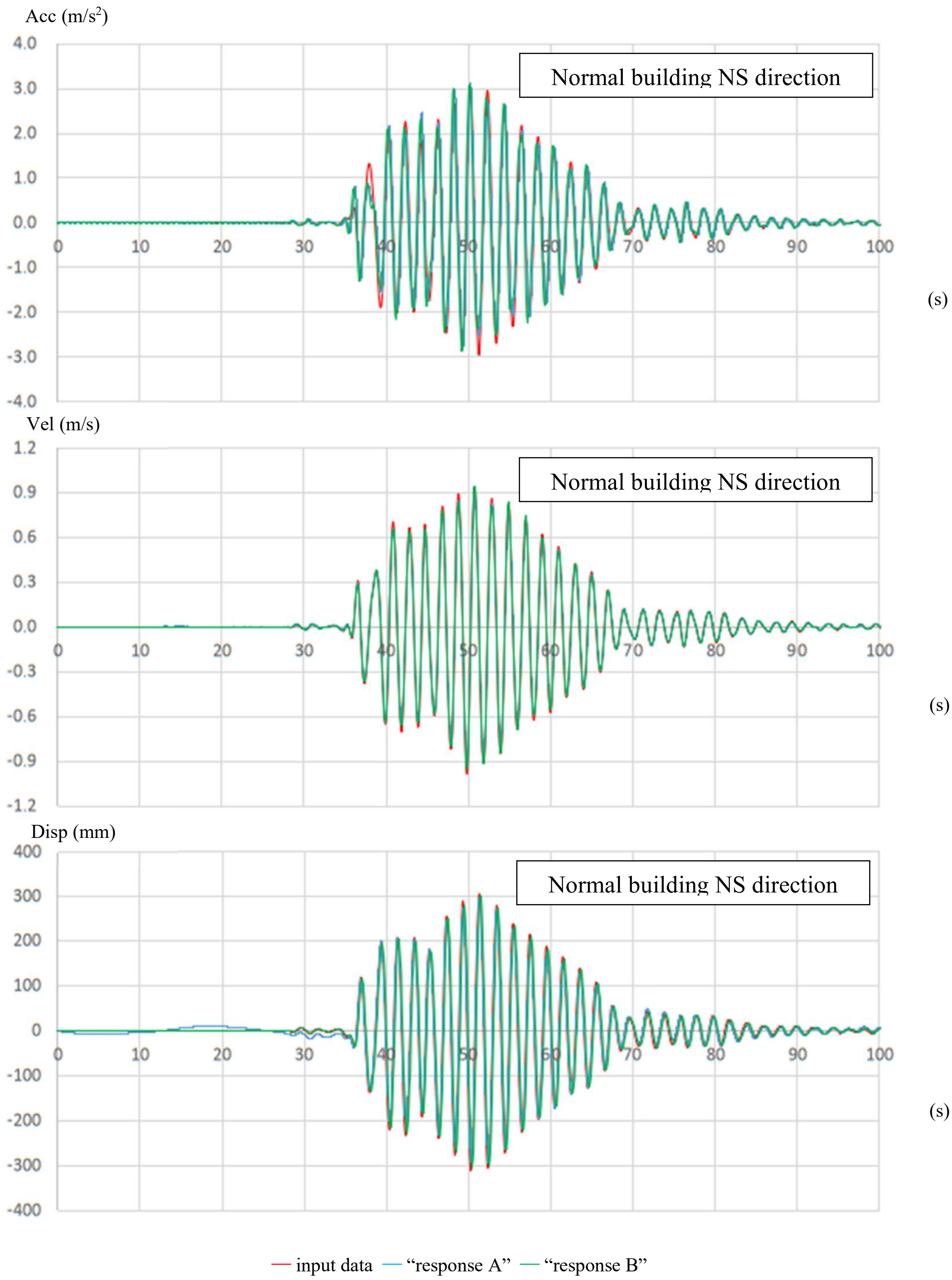

Fig. 8 — Comparison of input and measured data

4. Concluding remarks

We proposed the method for evaluating the performance of Exp.J used in base-isolated buildings. A test method using two shaking tables was proposed, and a method for selecting an input wave for the test was examined. Experiments using the proposed method performed well, and the validity of the test method was confirmed. The safety of Exp.J was confirmed by the experiments, and proved that it could be used continuously after the earthquake.

The following future works remained: It is necessary to conduct an experiment for the case that two base-isolated buildings are connected; Multi-mass analysis is necessary; Experiments on Exp. J for walls and ceilings are required. It is necessary to confirm the vertical movement.

5. References

[1] Japan Society of Seismic Isolation(2013)：Seismic Isolation Expansion Guidelines

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[3] Yorihiko Osaki：New・Introduction to spectral analysis of earthquake motion

