The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

DEVELOPMENT OF THE FRICTION-BASED PASSIVE NEGATIVE STIFFNESS DAMPER AND ITS VERIFICATION TESTS USING SHAKING TABLE

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ABSTRACT :

A negative stiffness is regarded as one of the promising control strategies in view of absolute response reduction except that such a control requires, in general, active or semi-active devices. In order to attain the negative stiffness more economically, a new structural control device that realizes a negative stiffness in a passive manner is proposed. The developed device is a typical slide bearing, except that the inverted convex curve is introduced on the sliding plate to generate the negative stiffness. The prototype of the proposed device was assembled, and its performance was investigated by the shaking table test using a girder model with rubber bearings. It was confirmed thorough series of tests that the proposed device generated stable and desired negative stiffness that reduced maximum inertia force of the girder significantly compared to the ordinal friction bearings without considerably increasing the absolute and relative displacement.

KEYWORDS: Negative stiffness damper, Passive damper, Shake table tests

1.INTRODUCTION

The negative stiffness control is one of the structural control methods the characteristics of which is represented by a combination of a “negative” stiffness and a damping element, as shown in Figure 1 (ii). Assuming the control is applied to the structure having “positive stiffness” (Figure 1 (i)), the total force-displacement relation can be represented by Figure 1 (iii). It is obvious from the figure that the structure’s stiffness of *ks* is reduced to *ks* - *k* by means of the negative stiffness of –*k*. Since the reduction of the stiffness elongates a natural period of the structure, the absolute acceleration can be significantly reduced accordingly. In addition, the reduction in structure’s total stiffness restrains the maximum inertia force transmitted to the lower structures, if the displacement response is suppressed by the damping introduced together with the negative stiffness. The advantages of the negative stiffness damper over traditional control devices were examined numerically for a large-scale structure (Iemura, 2007).

In order to realize a negative stiffness, however, the control force that accelerates the deformation should be generated. At present, such a performance is achieved only by using active controlled actuators or semi-active devices with sophisticated controllers and sensors. For the real civil engineering structures, those control systems are not regarded as alternatives of the widely-used passive control devices in view of the long-term robustness as well as the costs for installation and maintenance.

In this research, a new damper realizing a negative stiffness and stable energy dissipation in a passive manner is proposed, and its dynamic performance is investigated through large-scale shaking table tests.

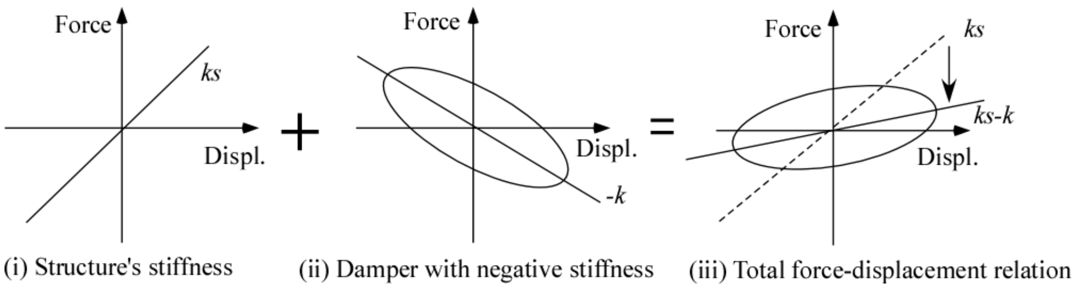


Figure 1 Basic principle of the negative stiffness damper

2. OVERVIEW OF A NEWLY DEVELOPED "PASSIVE NEGATIVE STIFFNESS DAMPER"

Figure 2 shows the overview of the proposed negative stiffness damper, or simply called "NSD". The components of the device are quite similar to the ordinal friction pendulum support or FPS, except that the inverted curve is introduced to the stainless-steel slide plate. Since the vertical weight induced on the unstable convex slide plate accelerates the horizontal deformation due to the gravitational effect, the device's force is negatively proportional to the deformation. It should be noted that the proposed device generates a negative stiffness in a passive manner. The convex plate is supported by a PTFE portion to introduce friction energy dissipation. In order to attain a stable friction behavior while the slide plate moves horizontally, the portion is attached to the pivot support that rotates smoothly.

The mechanism of the damper is shown in Figure 3. The equation of motion with regard to the girder subjected to an earthquake motion is written as follows,

$$\frac{W}{g}\ddot{x} + F(x,\dot{x}) = -\frac{W}{g}\ddot{z} \tag{2.1}$$

$$F(x,\dot{x}) = -N_h + \mu \cdot W \cdot \mathrm{sgn}(\dot{x})\cos\theta \tag{2.2}$$

$$x = R\sin\theta\,. \tag{2.3}$$

Where, W is a vertical weight, x is a horizontal deformation, $\mathrm{sgn}(\dot{x})$ is a sign of the moving velocity, N_h is a horizontal force of the damper, μ is a friction coefficient, θ is a rotating angle and R is a curvature radius of the stainless-steel slide plate. In Eqn. (2.3), a size of a pivot shown in Figure 2 is assumed to be considerably small compared to R.
The horizontal force of the damper can be written by decomposing the vertical weight, namely,

$$N_h = W\sin\theta\cos\theta\,. \tag{2.4}$$

Assuming the horizontal force is proportional to the damper's deformation, Eqn. (2.2) is rewritten as follows.

$$\begin{aligned} F(x,\dot{x}) &= Kx + \mu \cdot W \cdot \mathrm{sgn}(\dot{x})\cos\theta \\ &= -\frac{W}{R}\cos\theta \cdot x + \mu \cdot W \cdot \mathrm{sgn}(\dot{x})\cos\theta \end{aligned} \tag{2.5}$$

Where, It is obvious that the horizontal force of the damper is negatively proportional to the deformation, since W and R are positives. It should be noted that this negative stiffness is generated by a passive manner.

If the rotation angle is considerably small, the Eqn. (2.5) is simplified as,

$$F(x,\dot{x}) = -\frac{W}{R} \cdot x + \mu \cdot W \cdot \mathrm{sgn}(\dot{x})\,. \tag{2.6}$$

This equation indicates that the amount of the negative stiffness is controlled by a vertical load and a curvature radius of a convex slide plate.

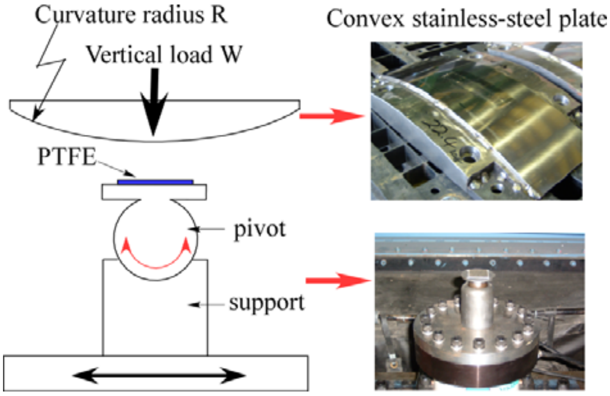


Figure 2 Proposed negative stiffness damper

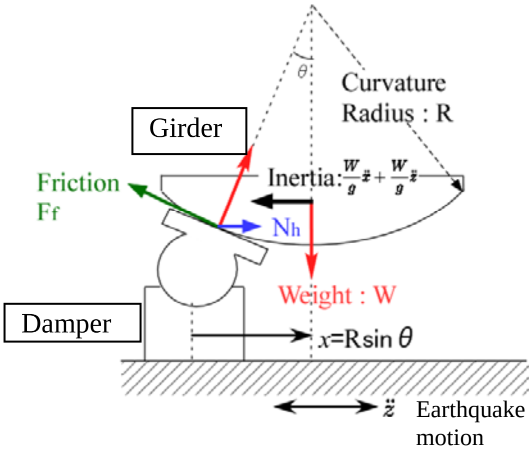


Figure 3 Basic mechanism of the damper

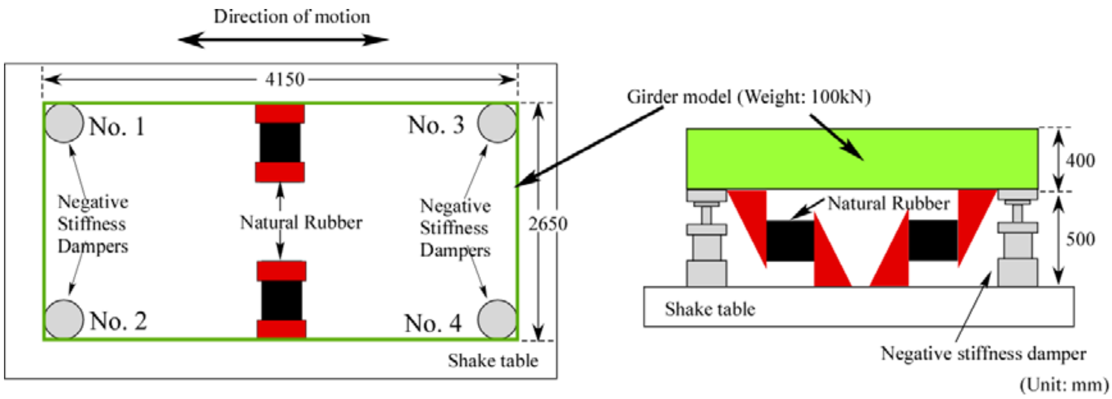
3. VERIFICATION TESTS USING SHAKING TABLE

3.1 Test setup

The dynamic behavior of the proposed negative stiffness damper was assessed by using the large-scale shaking table facility in Disaster Prevention Research Institute of Kyoto University. The shake table has a capability to drive the table (5.0 m×3.0 m) up to 1.0 G in acceleration and 150 kine in velocity with maximum specimen weight of 150 kN. The maximum strokes are 300 mm in longitudinal, 250 mm in transverse, and 200 mm in up-down directions.

As shown in Photo 1, large-scale model of an isolated girder was assembled on the shake table. The model of the girder was a steel-made slab (W4150 mm×D2650 mm×H400 mm), weight of which is approximately 100 kN. The square steel plate (300 mm×300 mm) was welded at each corner of the slab in order to attach the developed negative stiffness damper. Moreover, two cylindrical natural rubber bearings were installed to adjust the natural frequency of the total test system without dampers to approximately 1.25 sec. The total stiffness of these rubber bearings was 254 kN/m, corresponding to the structure's positive stiffness mentioned in Figure 1 (i).

For measuring the behavior of the test system, accelerometers and laser displacement sensors were utilized. The force generated by the developed damper was directly measured by the tri-directional load transducer attached on bottom of each damper. Total test setup is shown in Figure 4 and Photo 1.



(a) Top view (b) Elevation

Figure 4 Schematic view of the test setup

3.2 Input motions for earthquake excitation test

In the series of earthquake loading tests, the shake table was driven by uni-directional accelerations. The east-west component of the strong motion observed at JMA Kobe observatory during the 1995 Hyogoken-Nanbu earthquake was selected as acceleration input. This motion has been commonly used in Japan for seismic desing of a civil engineering structure constructed under a good soil condition. The modified waveform instead of the original records was used for the test, which was fitted to the design spectrum designated in the seismic code for road bridges in Japan. Moreover, maximum acceleration of the wave was scaled down by 0.4 of the original motion due to the stroke limitaions of the girder model and shaking table. The absolute acceleration response spectrum of the motion under 5% damping is shown in Figure 5.

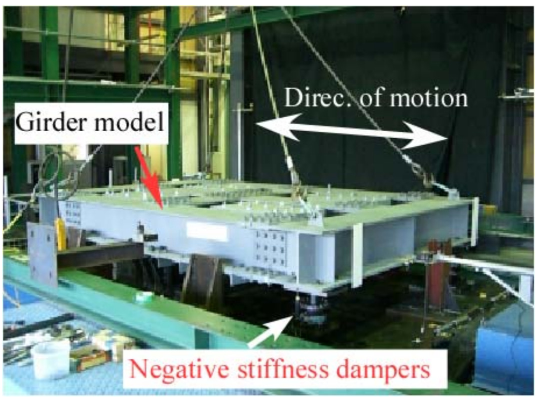


Photo 1 Total test setup

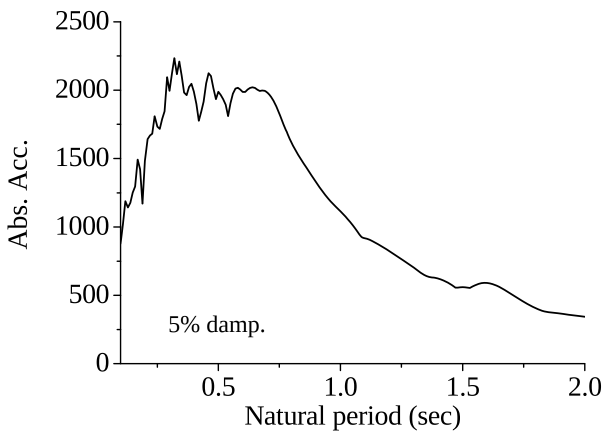


Figure 5 Absolute acceleration response spectrum

3.3 Prototypes of the passive negative stiffness damper

The amount of the negative stiffness given to the prototype dampers was preliminarily determined by a numerical simulation. In this test, the specification of the damper was designed in order to reduce the maximum absolute acceleration of the girder as much as possible. In addition, the maximum relative displacement between the girder and the shake table should be restrained up to 100 mm due to the size of the damper's stainless-steel slide plate. Figure 6 shows the schematic of the simulation model assuming the test structure. The scaled Kobe EW motion aforementioned was used as input acclerelation. For simplicity of simulations, followings were assumed: 1) behaviors of total four dampers depicted in Figure 4 were summed up as expressed in Eqn. (2.6) , 2) the firction coefficient of a PTFE and a stainless-steel plate was 0.1, 3) dependency of friction coefficient on loading velocity was negligible and 4) test structure including rubber supports had no damping. In the simulation, the amount of the negative stiffness was given stepwise from 0 (= flat slide plate) to -200 kN/m, and corresponding maximum relative displacement between the girder and the shake table as well as maximum absolute acceleration of the girder were calculated. See Figure 7 for details.

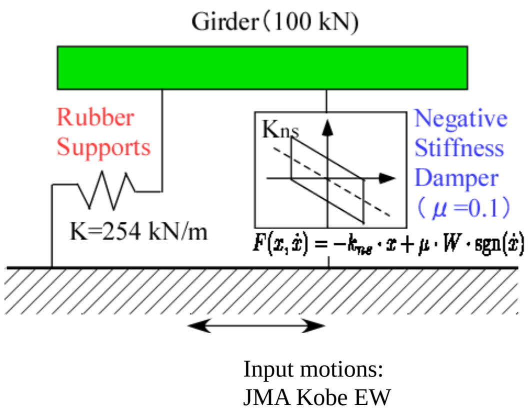


Figure 6 Simulation model of the test system

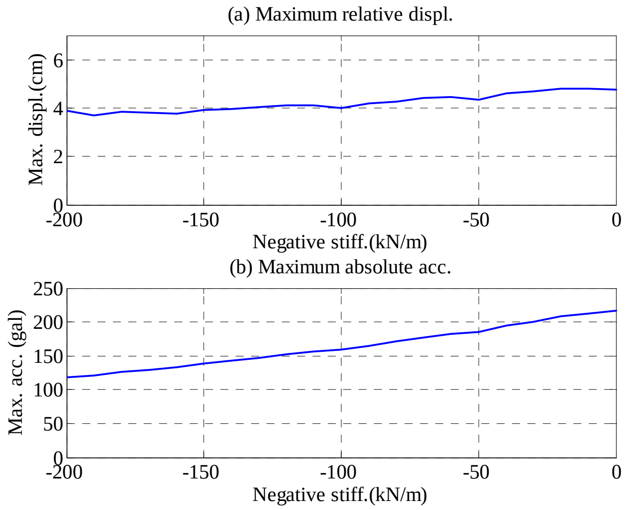


Figure 7 Estimated maximum responses with a NSD

It is estimated from the result that significant reduction in absolute acclerelation is attained by giving a negative stiffness of -200 kN/m to the damper, while meeting the constraint of the relative displacement. Given the design negative stiffness and the vertical weight (25 kN per each device), the curvature radius was obtained from Eqn. (2.6), which was 500 mm. According to the inspection when the specimen was manufactutred, the curvature radius was approximately 497 mm, and the corresponding negative stiffness was -201 kN/m. Moreover, the ordinal friction damper having no stiffness (negative stiffness = 0) was also prepared for comparison, that is denoted as "Flat" in the following figures.

In the shaking table test, planar and vertical positions of the girder model were carefully adjusted so that four dampers support the vertical load almost equally, since the vertical load induced on the damper directly affects the amount of the negative stiffness.

4. TEST RESULTS AND DISCUSSIONS

4.1 Sinusoidal loading tests

The sinusoidal loading tests were conducted in order to comprehend the natural period and damping of the test system. The maximum acceleration of the sinusoidal wave applied to the shake table was 120 gal, and its frequency was varied from 0.5 to 2.0 Hz. In the test, the response of the girder with proposed dampers was compared to that with ordinal friction supports. Figure 8 shows the steady-state response ratio of the maximum acceleration of girder to that of the shake table. It is observed from the figure that the clear peak detected at 1.25 sec in case of using the normal friction supports having no stiffness, was elongated and suppressed by using the proposed negative stiffness damper. It was due to that the stiffness of rubber bearings were apparently declined by means of the negative stiffness introduced by the damper.

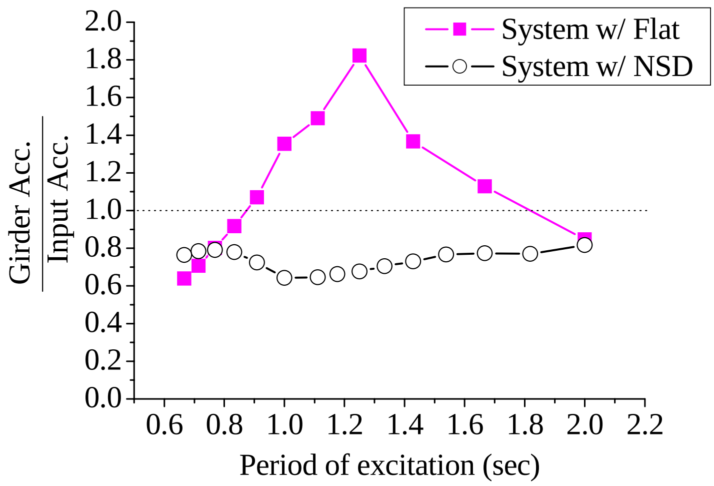


Figure 8 Steady-state acceleration response ratios

4.2 Earthquake loading tests

The earthquake loading tests were carried out to clarify the effect of the proposed damper under strong motion. Figure 9 shows the hysteretic responses of the inertia force of the girder versus relative displacement between girder and the shake table subjected to the Kobe EW motion. This figure is depicted as a comparison with and without the proposed dampers. Figure 10 shows corresponding force, sum of total four NSDs, versus displacement relations. It is clearly observed from Figure 10 that the proposed damper successively generated the force that was negatively proportional to the deformation. It consequently follows that the negative stiffness introduced by the damper declined test system's total stiffness, which dedicated to the significant reduction in the maximum inertia force as shown in Figures 9.

The maximum inertia force, relative and absolute displacements in plus and minus directions as a comparison with and without the proposed damper are summarized in Table 4.1. In this table, minus maximum responses are shown in the bracket. The time histories with regard to the absolute displacement and absolute acceleration with and without the NSD are shown in Figures 11 and 12, respectively. It is found that maximum inertia force of the test system with the NSD was reduced from that with flat friction damper by approximately 40 %. This reduction is clearly observed in Figure 12 as the NSD suppressed absolute acceleration to the small extents. In addition, measured maximum response showed good agreement with that obtained by preliminary simulations, following that the desired negative stiffness was realized in a passive manner by controlling the vertical weight as well as the curvature radius of the damper.

It should be also emphasized that the relative and absolute displacements of the NSD were not significantly magnified compared to those with flat damper. It indicates that the proposed damper is particularly applicable to the structure that both absolute acceleration and displacement affect the damage, such as railway bridges with rail tracks.

Table 4.1 Maximum responses of the girder with and without NSD

Device	Max. Inertia Force (kN)	Max. Relative Displ. (mm)	Max. Absolute Displ. (mm)
Flat friction damper	26.79 (-19.01)	58.46 (-33.81)	45.79 (-50.49)
NSD	16.07 (-14.05)	43.51 (-21.73)	50.39 (-36.41)

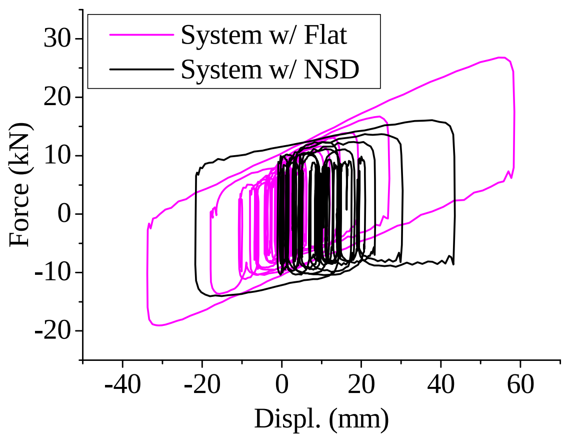


Figure 9 Comparisons of inertial force v.s .relative displacement

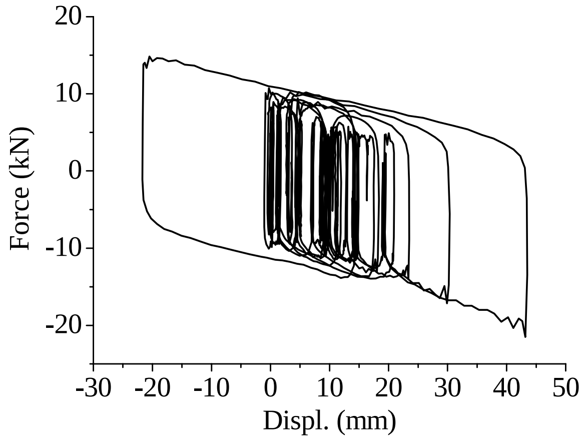


Figure 10 Hysteresis loops of the NSD

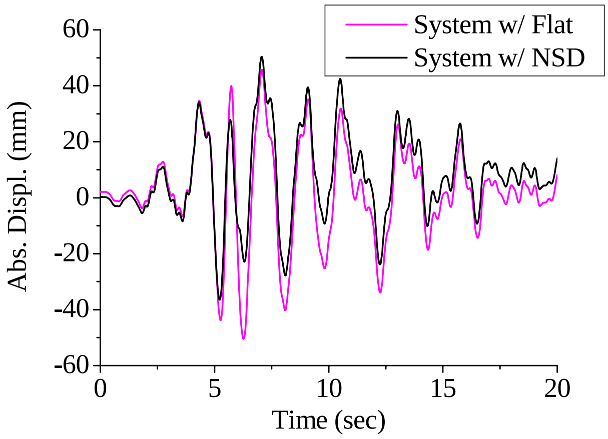


Figure 12 Comparisons of absolute displacements with and without NSD

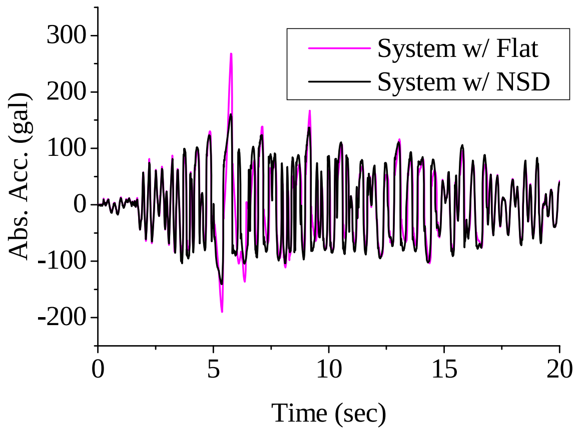


Figure 13 Comparisons of absolute accelerations with and without NSD

5. CONCLUSIONS

In this research, the new device realizing a negative stiffness in a passive manner was developed, and its performance was investigated by the shaking table test using a girder model with rubber bearings. Through sinusoidal tests, it was found that the natural period of the model structure was elongated by means of the negative stiffness introduced by the proposed device that reduced the stiffness of the rubber bearings. It was also clarified that the proposed device successfully generates the stable negative stiffness as well as energy dissipation under both periodical and earthquake motions. It consequently follows that the proposed device significantly reduced absolute acceleration of the girder without considerably increasing the absolute and relative displacement, compared to the ordinal friction bearings.

ACKNOWLEDGEMENT

This research was supported by the Program for Promoting Fundamental Transport Technology Research from the Japan Railway Construction, Transport and Technology Agency (JRTT). The dedication of Mr. Ichikawa (Engineering staff of Kyoto University), Oiles Co., Mr. Tokuoka (alumnus of Kyoto Univ.), Mr. Morimoto (graduate student of Kyoto Univ.), Nomura Jyuuki Ltd., staff and students of structural dynamics laboratory of Kyoto University for carrying out the shaking table tests is fully appreciated.

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