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Theoretical study and development of new base-isolation systems for power equipment

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ABSTRACT: This paper deals with shaking table tests for scale models of base-isolation systems; simplified dynamic analyses; and newly developed base-isolation devices. At first, data of responses are obtained on the shaking table for two kinds of base isolation methods. For the purpose of simplifying analyses in practical design use, "equivalent linear method" is used to be verified in its accuracy based on results of the shaking table tests. As for new devices, ferrite-mixed high damping laminated rubber and temperature-independent viscous devices are concerned. As a result, simplified analytical method is confirmed in its availability, and the devices with sufficient enough characteristics for both ferrite-mixed rubber and the temperature-independent viscous systems are obtained.

1 INTRODUCTION

In order to aim at realizing more rational countermeasures for power equipment, we have been studying on responses of base isolation systems theoretically and have developed new base isolation devices (Suzuki et al., 1987, 1988). From the theoretical study, we have obtained optimal characteristics for various ground and structural conditions; and we have already developed new devices using frictional and viscous methods. Also, a ferrite-mixed laminated rubber device was successfully developed which enables built-in type isolators working as both isolator and energy absorber (Suzuki, 1991).

In this paper, we will report on developing process of those devices and analytical simulations which are verified using data of shaking table tests.

2 SHAKING TABLE TESTS

Major parts of the testing apparatus for the shaking table tests are as shown in Figure 1. This figure shows a band-fixed iron ingot weighing 13.3 tons, supporting system including base isolation devices, and instrumentations. The model is built to act as one mass model dynamically. Similarity law for this scale model is shown in Table 1, in which vertical loading pressure for the rubber bearing (isolator) is concerned to satisfy the same conditions as an assumed prototype model. The characteristics of the laminated rubber bearing are as shown in Table 2. Four devices of modeled rubber bearings were used whose horizontal spring constant is determined so as to make the prototype model possess a natural period of $T_2 = 2.0$ seconds.

The sectional view of viscous damper used in this test is as shown in Figure 2. This device adopts a mechanism which obtains viscous resistant force by means of viscous liquid between an upper disk and a lower pan. The viscous liquid is newly developed hydrocarbon macromolecule which has almost no temperature dependency.

Table 1. Law of similarity

Items	Scale ratio
Length	$L_m = L_p / 3$
Time	$T_m = T_p / \sqrt{3}$
Acceleration	$\alpha_m = \alpha_p$
Vertical Pressure	$\sigma_m = \sigma_p$
Spring Constant	$k_m = k_p / 3$

Table 2. Outline of rubber bearing

Diameter	:	ϕ = 100 mm
Rubber	:	2.5 mm thick x 14
Steel plate	:	1.2 mm thick×13

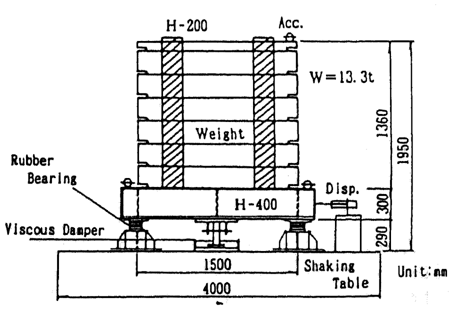


Figure 1. Apparatus on shaking table

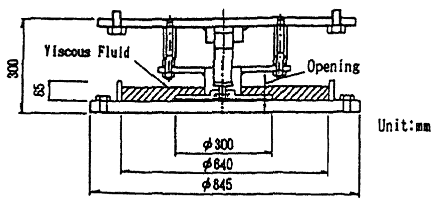


Figure 2. Sectional view of viscous damper

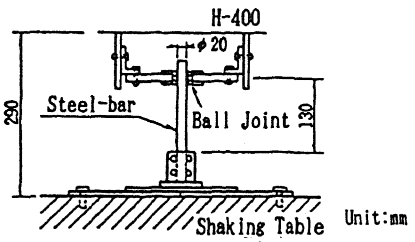
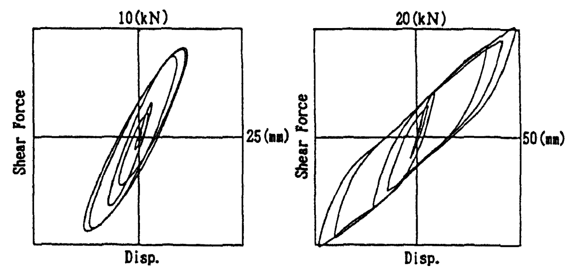


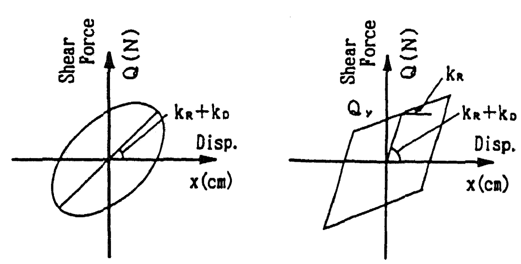
Figure 3. Schematic view of steel bar damper



(a) Rubber bearing with viscous damper(d = 3.5 mm)

(b) Rubber bearing with steel damper(one bar:l=13 cm)

Figure 4. Hysteresis curve of force vs. displacement



(a) Viscous

(b) Elasto-plastic

Figure 5. Restoring characteristics used for analytical model of isolation device

Figure 3 shows a schematic view of the steel bar damper. The lower end of the bar is fixed on the floor plate and the upper end is designed to be movable in vertical direction and free from end moment by the ball joint.

Characteristics of the modeled base isolation devices are determined by the past study for optimal design to make minimum response acceleration of the upper structures. Some examples of free vibration tests are as shown in Figures 4, in which representative hysteresis curves are included for the steel bar damper and the viscous damper. In the case of viscous damper, the hysteresis shows smooth configuration, while in the case of steel bar damper, it shows bilinear like curves.

The characteristics of the models are obtained as shown in Table 3. Other than free vibration tests, random wave tests were carried out, which will be discussed later comparing analytical results.

3 ANALYTICAL SIMULATION

After obtaining responses of the shaking table tests, analytical study was executed to verify its accuracy. Mainly hereafter, "equivalent linear analysis" is discussed, because simplicity of this analytical method is regarded to have considerable advantages for practical design use. The analytical model is selected to be a lumped-one-mass model connected on the base isolation devices installed on the shaking table. According to the results of the tests, the one-mass-model of the upper structure has neither damping nor spring component. Restoring characteristics used for the analysis are as shown in Figures 5 (a) and (b).

3.1 Viscous damper with isolator

Rigorously speaking, the viscous damper acts as visco-elastic manner, and its restoring force might be dependent on frequency of input motion. In this study, elastic component included in the viscous damper is presumed to be constant after the free vibration tests. And the restoring force is expressed by "equivalent viscous coefficient (C_D)" which is a function of maximum velocity v_{max}, as shown in Figure 6, and expressed in Equation (1).

$$m\ddot{x} + [C_R + C_D(v_{max})]\dot{x} + (k_R + k_D)x = -m\ddot{y} \quad (1)$$

Where x, y ; horizontal displacements of the mass and ground, C_R, k_R ; damping coefficient and spring constant for the isolator, $C_D(v_{max})$, k_D ; equivalent viscous coefficient and spring constant for the viscous damper. Results of analysis are as shown in the left column of Figure 7, together with experimental results, in which quite similar wave patterns can be obtained by the analysis compared with the shaking table tests.

3.2 Steel bar damper with isolator

The restoring force is simplified using a bilinear model, as shown in Figure 5(b) based upon the free vibration test. Furthermore, an equivalent linear model was determined by the iteration method. The characteristics for the equivalent model are equivalent spring, k_{eq}, and equivalent damping, h_{eq}. The equivalent characteristics

Table 3. Characteristics of viscous and steel bar damper with isolator

	Viscous Damper with Isolator	Steel Bar Damper with Isolator	
Mass [m]	13.3	13.3	(t)
First inclination [k_1]	–	16.4	(kN/cm)
Second inclination [k_2]	5.78	3.53	(ditto)
Non dimensional shear force [q_y^*]	–	0.39	(–)
Damping factor of rubber in isolator [h_R]	3.5	3.5	(%)

*) q_y : (Yielding force) / (Weight of lumped mass)

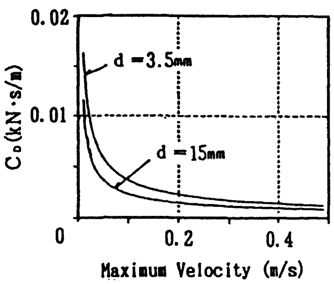


Figure 6. Property of viscous damper

and equation of motion are expressed as follows:

$$h_{eq} = \frac{2}{\pi} \frac{1-k_2/k_1}{1+(k_2/k_1)(\mu-1)} \frac{\mu-1}{\mu} \quad (2)$$

$$k_{eq} = \frac{k_1+k_2(\mu-1)}{\mu} \quad (3)$$

where $\mu = x_{max} / x_y$, $C_{eq} = 2h_{eq}\sqrt{mk_{eq}}$

x_{max} : *maximum response displacement*

x_y : *yield displacement of bar*

$$m\ddot{x} + C_{eq}\dot{x} + k_{eq}x = -m\ddot{y} \quad (4)$$

Results of the analyses are as shown in the right column in Figure 7, in which simulated waves by the equivalent linear methods of both acceleration and displacement around the maximum responses; i.e., in the duration from beginning to about 4 seconds, shows good accordance with the experimental results. As for the latter duration of the shaking with less amplitudes, the analytical results can not simulate fine tremor with high frequency in the acceleration. As a result, this simplified method is regarded to be useful for estimation of maximum responses in practical design use.

4 DEVELOPMENT OF NEW BASE ISOLATION DEVICE

In order to prepare variety of basic methods for adoption of the base isolation systems for power equipment, available development for actual devices are essential in the study. We have developed two kinds of new base isolation devices; namely the high damping ferrite

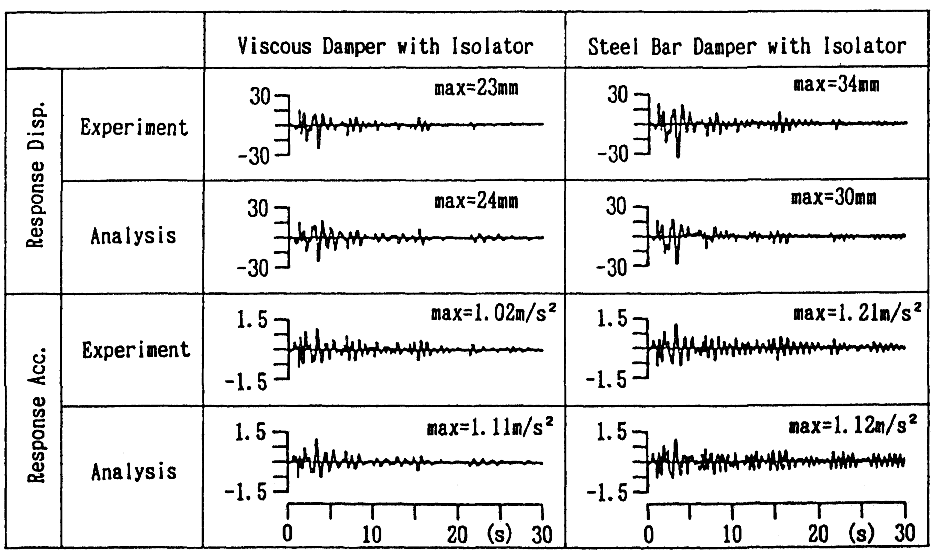


Figure 7. Comparison of experimental results and analytical results

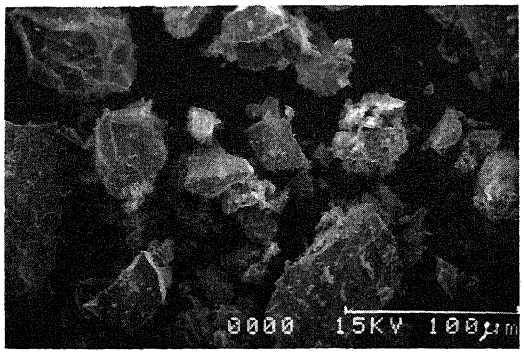


Figure 8. Electron microscope photo of the ferrite

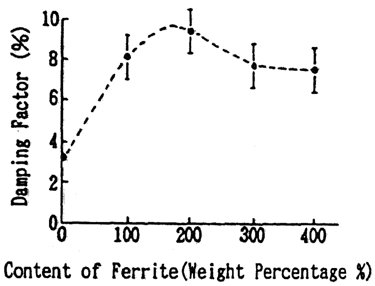
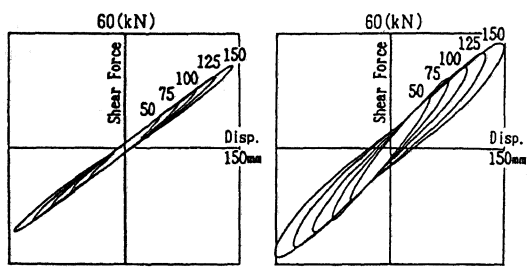


Figure 9. Relation between damping factor vs. content of ferrite



(a) Natural rubber (b) Ferrite rubber

Figure 10. Hysteresis curves of laminated rubber

rubber bearing and the viscous damper.

4.1 High damping ferrite rubber bearing

Usual laminated rubber has only slight damping in its rubber material, which needs any energy absorber outside. With use of byproduct of ferrite, high damping factor, h over 10 % can be obtained, and the ferrite-mixed rubber can be manufactured for laminated rubber. Figure 8 is a photograph of grain of the ferrite.

A result for the optimum mix proportion test is as in Figure 9, showing optimum content exists with h over 10 %. The demonstrative specimen for ferrite-mixed

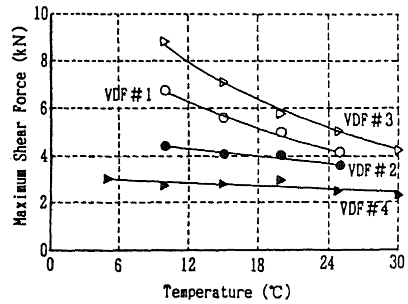


Figure 11. Relation between temperature and maximum shear force (v = 6.3 cm/s, d = 5 mm, ϕ = 30 cm, T = 5 to 30 °C)

laminated rubber is designed to bear 30 tons vertical load with allowable horizontal displacement of ±150 mm. Comparison of hysteresis curves for the conventional natural rubber and the newly developed ferrite-mixed laminated rubber is shown in Figure 10. In this figure, the difference of damping is appeared in their area of loops; as for damping factor, h, 3.5 % for natural rubber, and 12 % for ferrite rubber, respectively.

Other than described in this paper, durability tests were also carried out. This new material of ferrite rubber is confirmed to have sufficient enough creep characteristics.

4.2 Viscous damper

One of lineups of base isolation devices, viscous dampers with damping characteristics without temperature dependency are required for severe conditions for actual use. Figure 11 shows relation between temperature and maximum shear force by an actuator test using sinusoidal displacement load. From the variation of the actual hydrocarbon macromolecule materials, material with sufficient enough characteristics of less temperature-dependent can be selected, and sufficient devices can be also manufactured.

5 CONCLUSIONS

Major conclusions of this study are as described below:

[a] After the analytical study, the equivalent linear method is verified to offer sufficient maximum response estimations for both viscous and elasto-plastic systems based on the results of the shaking table tests. Using this simple methods, practical design is regarded to be expected to carry out.

[b] As for the new base isolation devices, in addition to the past frictional, elasto-plastic and viscous method devices, we have successfully accomplished the high damping ferrite rubber isolator, which shows over 10 % of damping factor; and high viscous material in which the behavior is almost independent of temperature change.

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