DEVELOPMENT OF FRICTION DAMPER WITH COUPLING MECHANISM FOR DISPLACEMENT CONTROL OF BASE-ISOLATED SYSTEM

免震層の変位抑制を目的とした 連結機構摩擦ダンパーの開発

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After the 1995 Kobe earthquake, the application of base isolation in detached houses increased in Japan. To date, about 4,000 base-isolated detached houses have been built. However, large base displacement of a base-isolated detached house, beyond the usual design limit, was observed in Sendai when the Great East Japan Earthquake occurred on 11 March 2011.

In this paper, a new device is proposed for controlling seismic displacement of a base-isolated building structure by means of a friction damper with coupling mechanism. Experimental and analytical results show the effectiveness of the proposed device.

1. INTRODUCTION

Construction of base-isolated building structures has substantially increased since the 1995 Hyogo-ken Nanbu (Kobe) earthquake in Japan. A point of concern, however, is that the seismic response displacement in the base-isolation layer might exceed the design limit due to excessively severe ground motion¹⁾⁻³⁾. In fact, when the Great East Japan Earthquake occurred on 11 March 2011, a base-isolated detached house built in Sendai experienced a maximum displacement of 355 mm, which exceeds the usual design limit of 300 mm for such houses⁴⁾.

To avoid or mitigate the damage caused by such excessive displacement, we have developed a new device, the friction damper with coupling (FDC) mechanism, which controls the displacement caused by severe earthquakes. The FDC is a passive damper that is activated to suppress the displacement of the base-isolation system when the deformation of the damper reaches the prescribed length. In case of moderate earthquakes, the FDC is inactivated not to impair the isolation effect by generating large damping force.

The FDC consists of two parts: a friction damper connected to coil springs, and a coupling mechanism that transmits the friction force when the deformation of the device reaches a certain limit.

Although basic analytical and experimental studies^{5),6)} have already

conducted, the specimens used in those studies had a rather short period to represent a base-isolated building. In the present study, we improved the specimen to elongate the period by replacing leaf springs with coil springs.

This paper reports the seismic response characteristics of a base-isolated structure incorporating an FDC, as examined by shaking table tests. A 4-degree-of-freedom (DOF) specimen is used to elucidate the effect on response accelerations of higher modes. Furthermore, the analytical method for this system is validated by comparison with analytical and experimental results.

2. OUTLINE OF FDC

Figures 1 and 2 respectively show a photograph of the FDC specimen and a schematic of the FDC in a neutral position.

As shown in Figure 3, the external damper rod and the friction damper are coupled to transmit friction force after the damper deformation reaches the preset gap length. Coil springs are installed between the friction damper and the piston rod to absorb the shock induced by coupling.

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Figure 1. FDC mechanism

Figure 2. FDC in neutral position

Figure 3. Activated FDC

Figure 4 shows a conceptual diagram of the base-isolated building model incorporating an FDC. As shown in Figure 5, the friction force is not transmitted to the primary structure until the displacement reaches the prescribed length L_s . Once the single directional (rightward in Figure 4) displacement exceeds L_s and the piston rod is coupled with the friction damper, the coupler never detaches the external rod from the internal rod, and the axial force of the damper increases until reaching the maximum friction force.

Figure 4. Conceptual diagram of the system

Figure 5. Restoring force model of the FDC

The gap L_s and the maximum friction force F_c of the FDC can be designed such that an optimal effect is obtained. In this study, the coil springs are designed to have a stiffness of 75 kN/m.

3. SHAKING TABLE TESTS

3.1 Outline of Specimen

Figure 6 shows the schematic of the base-isolated specimen. A three-story frame whose columns are steel leaf springs is mounted on linear bearings. An oil damper as a damping device and an FDC as a displacement control device are incorporated into the specimen.

Table 1 shows masses and stiffnesses of the specimen identified by static loading tests. The damping ratio of the specimen when its base is fixed is identified as approximately 0.1 %.

Figure 7 shows normalized mode shapes of the base-isolated specimen. The mode vectors are normalized such that the maximum displacement equals unity, namely, $\max_i(u_i) = 1$, where ${}_s u_i$ represents s th modal displacement of the i th story.

The maximum friction force of the linear bearing and the damping coefficient of the oil damper were identified as 0.061 kN and 2.1 kNs/m (16.7 % of the critical damping of the whole structure), respectively. Thus, the base-isolated specimen is damped as in normal base-isolation systems.

Figure 6. Elevation of a base Isolated Specimen

Table 1. Mass, stiffness and period of base-isolated specimen

Floor	Mass [t]	Stiffness [kN/m]	Mode	Period [s]
3rd	0.49	262.0	1st	3.22
2nd	0.56	243.0	2nd	0.48
1st	0.62	221.0	3rd	0.23
base	1.50	12.4	4th	0.17

Figure 7. Normalized modes

3.2 Experimental Cases and Input Ground Motions

In the shaking table tests, the specimen was subjected to one directional horizontal excitation. The FDC was installed such that it was activated by

displacement in the positive direction (rightward in Figure 6).

The upper structure has 3-DOFs. By adding the DOF of the specimen base, the DOFs of the whole specimen sum to 4, whereas the specimen is represented as a 1-DOF model by restraining the deformation of the upper structure using braces. Table 2 lists the experimental cases.

Table 2. Experimental cases

	FDC Without Coupling	With FDC, $L_s = 50$ mm	
		$F_c = 0.5$ kN	$F_c = 0.9$ kN
1-DOF	CASE A1	CASE B1-1	CASE B1-2
4-DOF	CASE A4	CASE B4-1	CASE B4-2

For the input ground motions, we use the east-west component of the 1968 Tokachi-oki Earthquake, recorded at Hachinohe Harbor, Japan (hereinafter denoted as Hachinohe 1968 EW), and the north-south component of the 1940 Imperial Valley Earthquake, recorded at El Centro, CA (hereinafter denoted as El Centro 1940 NS). These input ground motions are scaled by 51.5 % and 61.0 % for Hachinohe 1968 EW and El Centro 1940 NS, respectively, such that the maximum base displacements are 90 mm in Case A4. As shown in Figure 8, the response accelerations for the first mode are almost identical for the two input ground motions, whereas those of El Centro 1940 NS are larger for higher modes.

Figure 8. Acceleration response spectra ($h = 20$ %) of input ground motions and period of specimen

4. RESULTS FOR CASES OF FDC WITHOUT COUPLING

Figure 9 shows time histories of experimental results. For both ground motions, time histories of the base displacements for Cases A1 and A4 show good agreement. Although the time histories of accelerations in both cases are roughly identical, Case A4, especially the 3rd floor, showed larger maximum accelerations compared with Case A1 because of higher frequency components.

The Fourier amplitude spectra of the response acceleration of the 3rd floor (Figure 10) reveal that the 2nd mode component increased the maximum acceleration of Case A4 compared with Case A1.

5. RESULTS FOR CASES WITH FDC

5.1 Time Histories and Hysteresis Loops

Figure 11 shows the results for Cases A4 and B4-1 where the maximum friction force $F_c = 0.5$ kN, the prescribed length $L_s = 50$ mm is shown by a dotted line. For both cases, the accelerations increased twice that of uncontrolled case when the FDC was activated, whereas the response displacement of base isolation was decreased 38 %.

(a) Hachinohe 1968 EW scaled by 51.5 %

(b) El Centro 1940 NS scaled by 61 %
Figure 9. Time histories (Cases A1 and A4)

Figure 10. Amplitude spectrum of acceleration response of 3rd floor (Cases A1 and A4)

Figure 12 shows the hysteresis loops of Cases A4 and B4-1, where shear forces are the sum of the inertial force of each floor. A comparison between Figures 5 and 12 shows that the activated FDC obtained a hysteresis loop as designed.

(a) Hachinohe 1968 EW scaled by 51.5 %

(b) El Centro 1940 NS scaled by 61 %

Figure 11. Time histories of 4-DOF models (Cases A4 and B4-1)

Figure 12. Hysteresis loops for Hachinohe 1968 EW (Cases A4 and B4-1)

5.2 Maximum Responses

Figure 13 shows the maximum responses for all the cases. The mode shape of the 2nd mode (Figure 7) and Fourier amplitudes around the 2nd harmonic explain the maximum floor acceleration distribution for Hachinohe 1968 EW. For the case of El Centro NS, however, Figure 14(b) observes contribution of the 1st to 3rd modes to the maximum floor acceleration distribution.

As shown in Figure 13(b), the maximum displacement for Case A4 (FDC without Coupling) was about 90 mm, which decreased to about 50 to 60 mm for Cases B4-1 and B4-2 (with FDC).

A comparison of Cases B4-1 ($F_c = 0.5$ kN) and B4-2 ($F_c = 0.9$ kN) in Figure 13 shows that the accelerations and inter-story drifts increase as the friction force F_c increases, whereas the maximum base displacement barely changes.

Figure 13. Maximum responses

5.3 Analytical Study in Frequency Domain

Figure 14 shows the Fourier amplitude spectra of the acceleration observed at each floor. The solid lines and dashed lines in Figure 14

(a) Hachinohe 1968 EW scaled by 51.5 %

(b) El Centro 1940 NS scaled by 61 %
Figure 14. Fourier amplitude spectrum of 4-DOF models

respectively represent the fundamental frequencies of the specimen FDC without coupling and those of specimens incorporating the FDC, where the stiffness of the base-isolation layer and the FDC coil spring are 12.45 kN/m and 75.0 kN/m, respectively.

In Cases B4-1 and B4-2, amplitude peaks are observed around the frequencies designated by dashed lines, whereas peaks are barely observed in Case A4. By incorporating FDC, significant increases in the amplitudes of the 2nd and 4th modes are observed compared with the case FDC without coupling (Case A4).

Figure 15. Analytical model

6. ANALYTICAL SIMULATION

We conducted an analytical simulation using the model shown in Figure 15. Newmark's β method ($\beta = 1/4$) is used in non-linear numerical analysis.

The base-isolated specimen is modeled as a 4-DOF system. The mass of each node, the maximum friction force of the linear bearing, the damping coefficient of the oil damper, and each parameter for the FDC are identified in Sections 2 and 3.

Figure 16 compares the experimental and analytical results for Case B4-1 ($L_s = 50$ mm, $F_c = 0.5$ kN).

As for the base displacement time histories, the experimental and analytical result showed good agreement. The acceleration time histories of each floor obtained from experimental and analytical results also agreed well for Hachinohe 1968 EW, whereas those for El Centro 1940

(a) Hachinohe 1968 EW scaled by 51.5 %

(b) El Centro 1940 NS scaled by 61 %

Figure16. Comparison between test and simulation results

NS showed differences, which were irrelevant to the maximum response, in high-frequency components especially in those of the 3rd and 1st floors.

Nevertheless, the maximum accelerations of both test and simulation results for El Centro 1940 NS agreed very well.

Figure17. Comparison between test and simulation results
(El Centro 1940 NS scaled by 61 %)

As shown in Figure 17, experimental result gave larger amplitude around the 3rd and 4th fundamental frequencies compared with those of the analytical results, which explains the errors in acceleration time histories.

Nevertheless, the errors in time histories are irrelevant to the maximum responses. Thus, we can conclude that the maximum acceleration responses for both cases agreed well.

7. CONCLUSIONS

In this paper, we presented a new effective device for controlling the maximum displacement of a base-isolated building structure subjected to severe ground motions. The present device is inactivated in a moderate

seismic event not to impair the base-isolation effect. Once the response displacement exceeds the certain prescribed limit, the device is activated to suppress the displacement.

Although the experimental result of the 4-DOF specimen showed that the maximum acceleration of the upper structure increased about twice that of uncontrolled case, the FDC reduced the maximum base displacement by approximately 38%.

Thus, we can conclude that the FDC is effective device to control the base-isolation displacement in a severe seismic event.

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